Solar Concentrator Demonstrator for PocketQubes

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SOLAR CONCENTRATOR DEMONSTRATOR FOR POCKETQUBES

by

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The ongoing miniaturisation of small satellites generates new constraints due to the size of the vehicles. This project presents an inflatable solar concentrator for PocketQubes designed, manufactured and tested at TU Delft. The system proves the feasibility of using inflatable structures on PocketQubes, demonstrates the high aperture to packaging volume ratio of these structures and sets an important step in the development of a Solar Thermal Propulsion (STP) engine. The concept represents one of the first designs of its kind specifically made for these platforms, which are micro-satellites built out from 5-cm cubes.

This project answers to different needs in the field of small satellites and follows the research lines of the department of Space Systems Engineering of TU Delft on small satellite systems and micro-propulsion. Innovative solutions are required to overcome the limitations of micro-satellites and deployable systems appear as one with a broad range of applications. An example of such deployable system is the solar concentrator proposed in this project, which is a device designed to gather and focus solar radiation to be used on board of a satellite. The development of a concentrator with a large aperture and low packaging volume is one of the steps needed to advance in STP, which could enlarge the range of missions of PocketQubes due to the larger thrust per unite volume and end-to-end efficiency if compared with solar electric propulsion. This technology presents lower specific thrust values than chemical engines but at a higher specific impulse. Although this is the main application of the system designed, the prospective uses include optical, communication and power systems as well.

Following an iterative design based on optical, thermal and structural models, a thin film inflatable mirror has been proposed with an aperture of 0.54 m, a packaging volume of 1 PocketQube Unit and a theoretical power output of 232 W in nominal conditions. Different iterations were used to decrease the shape error caused by both the inflating pressure and the thermal loads, reaching a root-mean-square error of 0.48 mm. The same approach was followed to design the demonstrator, which was built out from 23 µm Kenpro™ Mirror Film and 23 µm Mylar™ Film. A petal-based manufacturing approach was used, employing Kapton™ tape to join the petals. This method consists in cutting portions out of a flat surface with a geometry such that the desired shape is obtained when the petals are joined. The demonstrator was tested using a theatre lamp, resulting in the demonstration of the concept but further research is still required to validate the expected performance.

The main contribution of this study to the field of small satellites is the demonstrated feasibility of employing inflatable structures on board of PocketQubes and their performance capabilities as part of solar power systems. The applicability of these devices to STP micro-engines has been proven. A design of a STP engine was developed considering ammonia as the propellant and using a flat heat exchanger as the receiver. The simulation results showed thrust values over 100 mN and a specific impulse around 200 s. The specific thrust per unit volume, 0.87 mN/cm³, and the end-to-end efficiency, 34%, are higher than electric micro-propulsion systems available in the market. Another key contribution is the high versatility of the system, which could enable the development of PocketQube systems, such as reflectors for antenna or telescopes.
The research project I present now in this document is the final outcome of a long path I started six years ago in Sevilla, Spain. Back then, I decided to start my Bachelor of Science in Aerospace Engineering due to my fascination about the Aerospace field and, specially, space technologies. It was actually the interest in the latest which drove my decisions about the next step in my academic life and the reason why I moved to the Netherlands.

When I first contacted Barry Zandbergen for my literature review, I was slightly sceptical about Solar Thermal Propulsion. It seemed weird to me that a technology with such a potential was not considered at that moment, up to my knowledge, by any institution or company in the field. The literature study allowed me to identify the weak points of this propulsion concept and the gaps which still required further research. I got to understand that nowadays investing the amount of money required to demonstrate the technology appears to be not worthy for big companies given the fact that there are other systems which can do the work despite their disadvantages. However, I also realised that the so-called democratisation of space creates new possibilities to finally prove this concept. All this process took me to the selection of the concentrator as the subsystem I considered more critical to be designed. The multidisciplinary approach required for developing the system seemed challenging but interesting at the same time.

Even though the results did not allow to perform the desired validation of the concept, a design process based on different analysis tools was developed. The project resulted in a design I personally consider to be quite promising. It still needs to be improved before becoming a flight system but no show-stopper has been found to discard the concept. I feel quite enthusiastic about contributing to the research lines of the Chair of SSE and setting an initial step in the introduction of a system which can revolutionise the capabilities of small satellites.

I would like to thank Barry Zandbergen for his guidance and support, not only as Thesis supervisor but also as the Master Profile coordinator. I am also thankful to Prof. Otto von Bergsma for his assistance in the structural design of the system and Dr. Daphne Stam and Dennis Dolkens for being part of the Thesis Committee. The production of the system would not have been possible without the support of Lohmann Technologies Ltd. and, therefore, I would like to acknowledge their contribution to the project.

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# Contents

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>List of Figures</td>
<td>xi</td>
</tr>
<tr>
<td>List of Tables</td>
<td>xv</td>
</tr>
<tr>
<td>List of symbols</td>
<td>xvii</td>
</tr>
<tr>
<td>Abbreviations</td>
<td>xix</td>
</tr>
<tr>
<td>1 Introduction</td>
<td>1</td>
</tr>
<tr>
<td>2 Research framework</td>
<td>3</td>
</tr>
<tr>
<td>2.1 Research's Background</td>
<td>3</td>
</tr>
<tr>
<td>2.1.1 Solar Thermal Propulsion</td>
<td>3</td>
</tr>
<tr>
<td>2.1.2 Concentration Systems for small satellites</td>
<td>4</td>
</tr>
<tr>
<td>2.1.3 Benchmarking Analysis on Power and Propulsion Systems for small Satellites</td>
<td>5</td>
</tr>
<tr>
<td>2.2 Needs and Opportunities. Mission Statement and research questions.</td>
<td>6</td>
</tr>
<tr>
<td>2.2.1 Identification of needs and opportunities. Mission Objective</td>
<td>6</td>
</tr>
<tr>
<td>2.2.2 Main Objective</td>
<td>7</td>
</tr>
<tr>
<td>2.2.3 Research questions</td>
<td>7</td>
</tr>
<tr>
<td>2.3 Project Organisation</td>
<td>7</td>
</tr>
<tr>
<td>2.3.1 Tasks</td>
<td>7</td>
</tr>
<tr>
<td>2.3.2 Project Planning</td>
<td>8</td>
</tr>
<tr>
<td>3 Requirements generation</td>
<td>9</td>
</tr>
<tr>
<td>3.1 Stakeholders and Stakeholders’ Requirements Identification</td>
<td>9</td>
</tr>
<tr>
<td>3.1.1 Key Stakeholders</td>
<td>9</td>
</tr>
<tr>
<td>3.1.2 Key Stakeholders’ Requirements</td>
<td>10</td>
</tr>
<tr>
<td>3.2 Acceptance Criteria and Key Performance Parameters</td>
<td>12</td>
</tr>
<tr>
<td>3.3 Killer Requirements and Key Driver Requirements</td>
<td>13</td>
</tr>
<tr>
<td>4 Concept Generation</td>
<td>15</td>
</tr>
<tr>
<td>4.1 Design Option Tree</td>
<td>15</td>
</tr>
<tr>
<td>4.2 Concept Selection</td>
<td>17</td>
</tr>
<tr>
<td>4.2.1 Identification of obvious losers.</td>
<td>17</td>
</tr>
<tr>
<td>4.2.2 Analysis of Strengths and weaknesses</td>
<td>18</td>
</tr>
<tr>
<td>4.2.3 Definition of the Selection Criteria</td>
<td>18</td>
</tr>
<tr>
<td>4.2.4 Trade-off</td>
<td>19</td>
</tr>
<tr>
<td>4.2.5 Sub-concepts</td>
<td>21</td>
</tr>
<tr>
<td>4.3 Conclusions: Definition of the baseline concept</td>
<td>22</td>
</tr>
<tr>
<td>5 Design and Analysis Tools</td>
<td>25</td>
</tr>
<tr>
<td>5.1 Definition of the Design Strategy</td>
<td>25</td>
</tr>
<tr>
<td>5.2 Ray Tracing Model</td>
<td>26</td>
</tr>
<tr>
<td>5.2.1 2-D Ray Tracing Model</td>
<td>30</td>
</tr>
<tr>
<td>5.2.2 3-D Ray Tracing Model</td>
<td>31</td>
</tr>
<tr>
<td>5.3 Thermal Model</td>
<td>32</td>
</tr>
<tr>
<td>5.4 Structural Models</td>
<td>35</td>
</tr>
<tr>
<td>5.4.1 Finite Element Models</td>
<td>35</td>
</tr>
<tr>
<td>5.4.2 Determination and Analysis of the shape error</td>
<td>36</td>
</tr>
<tr>
<td>5.5 Optimisation Algorithm</td>
<td>37</td>
</tr>
<tr>
<td>5.5.1 Target Functions</td>
<td>37</td>
</tr>
<tr>
<td>5.5.2 Constraints</td>
<td>38</td>
</tr>
<tr>
<td>5.5.3 Optimisation method</td>
<td>40</td>
</tr>
</tbody>
</table>
5.6 Validation and verification assessment of the models ........................................... 40
  5.6.1 Ray tracing tool ......................................................................................... 40
  5.6.2 Thermal Model ......................................................................................... 42
  5.6.3 Structural Model ....................................................................................... 44

6 Preliminary Design 45
  6.1 Initial considerations: requirements and objectives ........................................... 45
  6.2 Geometry definition under ideal conditions ...................................................... 46
    6.2.1 Preliminary outcomes based on the bi-dimensional Ray Tracing Tool ........... 46
    6.2.2 3-dimensional analyses: definition of the optimal design ......................... 48
  6.3 Thermal and Structural design ........................................................................ 49
    6.3.1 Material Selection .................................................................................. 49
    6.3.2 Thermal Analysis .................................................................................. 49
    6.3.3 Structural Analysis .............................................................................. 53
  6.4 Performance of the concentrator under deformed conditions ......................... 58
  6.5 Discussion of the results and selection of the concentrator's shape ................. 60
  6.6 Conclusions ................................................................................................. 63

7 Final Design 65
  7.1 Re-design process ......................................................................................... 65
    7.1.1 Results of the Optimisation strategies ...................................................... 66
    7.1.2 Analysis and Discussion of the results ................................................... 68
  7.2 Final Design Analysis .................................................................................. 69
    7.2.1 Performance under Nominal conditions ................................................... 69
    7.2.2 Sensitivity analysis ............................................................................... 70
    7.2.3 Preliminary design of the inflating system. Micrometeoroid and space debris impact assessment. ................................................................. 70
  7.3 Summary ...................................................................................................... 72

8 Demonstrator Design and Manufacturing 75
  8.1 Demonstrator design .................................................................................... 75
    8.1.1 Introduction: Design requirements ........................................................... 75
    8.1.2 Geometry definition ............................................................................... 76
    8.1.3 Design of the Pressurisation system ......................................................... 77
  8.2 Structural Analysis and re-definition of the geometry ...................................... 78
    8.2.1 FEM Analysis ...................................................................................... 78
    8.2.2 Re-design of the Test Object .................................................................. 78
  8.3 Production of the Test Object ......................................................................... 79
    8.3.1 Manufacturing approach: petals design ................................................... 79
    8.3.2 Manufacturing Procedures ..................................................................... 81
    8.3.3 Manufacturing Results .......................................................................... 82
  8.4 Conclusions .................................................................................................. 84

9 Test Campaign 85
  9.1 Introduction: Tests objectives and organisation ............................................... 85
  9.2 Test Plan ........................................................................................................ 86
  9.3 Design of the Test Set-up and Test procedures ............................................... 87
    9.3.1 Phase A ............................................................................................... 87
    9.3.2 Phase B ............................................................................................... 89
  9.4 Test Results .................................................................................................... 91
    9.4.1 Phase A ............................................................................................... 91
    9.4.2 Phase B ............................................................................................... 93
  9.5 Analysis and Discussion of the test results ................................................... 94
    9.5.1 Phase A ............................................................................................... 94
    9.5.2 Phase B ............................................................................................... 97
  9.6 Conclusions about the Test campaign ............................................................ 98
# List of Figures

2.1 Comparison of the performance capabilities of different propulsion technologies [6] 

4.1 From left to right: On-axis [1] and off-axis inflatable concepts [2] 

4.2 From left to right: Astromesh Reflector [3], Fresnel Zonal Plate [4] and Umbrella Reflector [5] 

4.3 From left to right: dish-type reflector [6], hexagonal deployable reflector [7], flexible petal reflector [8] and petal reflector [9] 

4.4 Sketch of the Option Tree 

4.5 Sketch of the Inflatable Antenna Experiment including the main structural elements [10] 

4.6 Sketch of the concentrator’s structure 

4.7 Image of the Antenna reflector developed by Babuscia et al. [1] 

4.8 System Architecture 

5.1 Design approach without including the test inputs 

5.2 Sketch of the structure of the Ray tracing model, including the inputs, assumptions and outputs 

5.3 Sketch of the concentrator and its main parameters 

5.4 Sketch of the actual and effective apertures with respect to the Sun vector. 

5.5 Sketch of the main working principle of the ray tracing code for 2-D geometries 

5.6 Main elements involved in the calculation of a symmetric line \( t \) to \( r \) with respect to \( s \) 

5.7 Sketch of the structure of the Thermal model, including the inputs, assumptions and outputs 

5.8 Sketch of the discretisation set-up for the thermal model 

5.9 Geometry of one of the reflector’s designs in the Design Modeller of ANSYS. The highlighted profile is the geometry imported from CATIA 

5.10 Finite element mesh for the mirror section (left) and the conical part (right) of the concentrator 

5.11 Sketch of the design made by the research team at MIT [1] 

5.12 Main parameters for the calculation of the concentrator’s surface 

5.13 Maximum aperture of parabolic reflectors as a function of the focal length 

5.14 Maximum aperture of spherical reflectors as a function of the radius. The dotted line corresponds to the ideal maximum aperture, while the other curve is the real effective maximum aperture. 

5.15 Results of the mapping optimisation tool for a spherical reflector with 25x3 values considered. 

5.16 Example of the focusing principle of the parabolic geometry 

5.17 CATIA Verification sketch for a spherical reflector of 0.5 m of aperture and 45 deg of aperture half angle with on-axis rays 

5.18 Error in the power output and computational time with respect to the number of nodes in the x-axis 

5.19 Results of the application of the thermal model to the Astromesh\textsuperscript{TM} reflector under the test conditions mentioned in [11] 

6.1 Comparison between the geometries of a parabolic and a spherical concentrator for \( f = R = 0.5 \) m and an aperture of 0.48 m 

6.2 Comparison of how rays are reflected with a parabolic (left) and a spherical reflector (right) 

6.3 Comparison of the efficiencies of both shapes with respect to the Sun vector for a spherical design of radius 0.5 m and a parabolic design of focal length 0.5 m. Both designs have the same aperture, 0.48 m 

6.4 Power on the receiver w.r.t. the deviation from the nominal attitude for the two preliminary designs and difference in the power output of both designs 

6.5 Finite element mesh for the parabolic (left) and the spherical (right) geometries 

6.6 Temperature field of the parabolic concentrator for \( \eta_{\text{rec}} = 0.85 \) [-] 

6.7 Temperature field of the spherical concentrator for \( \eta_{\text{rec}} = 0.85 \) [-]
6.8 Temperature field on the mirror of the parabolic concentrator for $\eta_{rec} = 0.85 \, [-]$. .......................... 52
6.9 Temperature field on the mirror of the spherical concentrator for $\eta_{rec} = 0.85 \, [-]$. .......................... 52
6.10 Deformations (magnified x12) of the parabolic concentrator for $\eta_{rec} = 0.85 \, [-]$. .......................... 53
6.11 Equivalent Von-Mises Stress field over the parabolic concentrator for $P = 10 \, [Pa]$. .......................... 54
6.12 Shear Stress field over the parabolic concentrator for $P = 10 \, [Pa]$. .......................... 54
6.13 Deformations (magnified x12) of the parabolic concentrator for $P = 10 \, [Pa]$ and the worst case of thermal load .......................................................... 55
6.14 Equivalent Von-Mises Stress field over the parabolic concentrator for $P = 10 \, [Pa]$ and the worst case of thermal load .......................................................... 56
6.15 Shear Stress field over the parabolic concentrator for $P = 10 \, [Pa]$ and the worst case of thermal load .......................................................... 57
6.16 $rms$ error of the reflectors with respect to the inflating pressure for all the cases analysed .......................... 57
6.17 $rms$ error of the reflectors with respect to the inflating pressure for all the cases analysed in the range $P = [1-15] \, Pa$ .......................................................... 57
6.18 Performance of the parabolic reflector under different conditions with respect to the Sun vector .......................... 58
6.19 Performance of the spherical reflector under different conditions with respect to the Sun vector .......................... 58
6.20 Comparison of the performance of both geometries under a pressure load of 10 Pa and the Worst Thermal Case .......................................................... 59
6.21 Contour plots power flux over the receiver's plate for both geometries under the Worst Thermal Case and a pressure load of 10 Pa w.r.t. the deviation of the Sun Vector ($\Delta \Phi$) .......................................................... 60
6.22 Power hitting the receiver integrated in the radial direction for both geometries under a pressure load of $P = 10 \, Pa$ and the worst thermal case .......................................................... 60
6.23 General view of the concentrator and its main geometrical parameters .......................................................... 63

7.1 Main geometrical parameters of the final design in [mm] .......................................................... 66
7.2 $rms$ error as a function of the focal length .......................................................... 66
7.3 $rms$ error as a function of $\Delta z$ .......................................................... 67
7.4 $rms$ error as a function of $\Delta z$ .......................................................... 67
7.5 $rms$ error as a function of the thickness, $t$ .......................................................... 68
7.6 $rms$ error as a function of $\Delta z$ for two values of the thickness .......................................................... 68
7.7 Main geometrical parameters of the final design in [mm] .......................................................... 69
7.8 Flux of objects at an altitude of 600 km according to Grün meteoroid model [12] .......................................................... 71
7.9 Mass lost over time .......................................................... 72

8.1 Sketch of the inflating system, including (1) the CO$_2$ cartridges, (2) the adapter, (3) the valve, (4) the tube and (5) the connection with the interface plate. .......................................................... 77
8.2 Main geometrical parameters of the final demonstrator design in [mm] .......................................................... 78
8.3 Example of the cutting strategy for 4 petals .......................................................... 79
8.4 Space between petals as a function of L(x) .......................................................... 80
8.5 Distribution of the petals over the A4 sample. The red dotted lines represent the perimeter of the sample .......................................................... 80
8.6 Main parameters in the calculation of the cone's petals .......................................................... 80
8.7 Design of a petal of the conical section .......................................................... 81
8.8 3d-printed mould for the petals .......................................................... 81
8.9 Machined mould for assembling the parabolic section .......................................................... 81
8.10 Results of testing the procedures with paper instead of the real materials. .......................................................... 82
8.11 Detailed view of an error obtained while cutting a Kapton$^{TM}$ film .......................................................... 83
8.12 Detailed view of the errors obtained while cutting a Kapton$^{TM}$ film .......................................................... 83
8.13 Detailed view of the centre of the reflector and the shape error induced by the Kapton$^{TM}$ tape .......................................................... 83
8.14 Detailed view of the overlapping between pieces of Kapton$^{TM}$ tape and the wrinkles produced. .......................................................... 83

9.1 Test set-up for Phase A of the test campaign .......................................................... 87
9.2 Theoretical Spectral irradiance of the theatre lamp (black body of $T = 3200 \, [K]$) .......................................................... 88
9.3 CAD representation of the test set-up designed for Test Phase B .......................................................... 90
9.4 Views of the interface designed to connect the concentrator and the set-up. The figure includes (1) the pyranometer, (2) the sealing ring, (3) the interface upper side, (4) the interface rear side and (5) the concentrator. .......................................................... 90
9.5 Average irradiance over a plane located at 1.6 m from the lamp ................................. 92
9.6 Normalised irradiance with respect to the adimensional radius for z = 1.60 m ................. 92
9.7 General view of the test set-up for Phase B before inflating the reflector .................. 93
9.8 Detailed view of the demonstrator assembled on the set-up of Test Phase A before inflation 93
9.9 Test set-up for Phase A of the test campaign ............................................................. 93
9.10 Test set-up for Phase A of the test campaign ............................................................ 93
9.11 Variation of the irradiance with respect to the operating time for test 4 including the inaccuracy of the pyranometer ................................................................. 95
9.12 Average deviation of the measurements w.r.t. the average radial irradiance ............... 96
9.13 Theoretical estimations and experimental data of the relation between the irradiance at the origin and the z-coordinate ................................................................. 96
9.14 Averaged radial distribution of irradiance including the ±10.5% inaccuracy ................ 97

10.1 Optimal and more realistic results of the simulations .................................................. 102
11.1 Design concept STP-A ............................................................................................. 105
11.2 Design concept STP-B ............................................................................................. 105
11.3 Estimated receiver’s temperature as a function of its efficiency .............................. 109
11.4 Initial estimations of the change in enthalpy and temperature for Ammonia .......... 111
11.5 Initial estimations of the change in enthalpy and temperature for Ammonia .......... 112
11.6 Minimum dimensions of the channels for concept STP-A ..................................... 112
11.7 Minimum dimensions of the channels for concept STP-B ..................................... 113

12.1 Comparison of the performance capabilities of different propulsion technologies [6] .... 121

A.1 Gantt Chart ............................................................................................................. 135
C.1 Mylar™ main properties. Obtained from [13]. ..................................................... 142
C.2 Mylar™ optical properties. Obtained from [14]. .................................................. 143
C.3 Kenpro Mirror Film™ main properties. Obtained from [15]. ......................... 144
E.1 Picture of a BBB’s CO₂ cartridge with its main dimensions ................................. 147
E.2 Theatre lamp’s datasheet ([16] ................................................................. 148
E.3 CM3 Pyranometer’s datasheet ([?]) ................................................................. 149
E1 General view of the Test Set-up assembly .............................................................. 151
E2 Drawing of the upper component of the interface .............................................. 152
E3 Drawing of the lower component of the interface .............................................. 153
E4 Drawing of the sealing ring of the interface ...................................................... 154
E5 Drawing of the main support structure .............................................................. 155
LIST OF TABLES

2.1 COTS propulsion systems ................................................... 6
3.1 Key Stakeholders .......................................................... 9
3.2 Key Stakeholders’ Requirements ........................................ 11
3.3 Acceptance criteria ......................................................... 12
3.4 Key Performance Parameters ............................................. 13
4.1 Strengths and Weaknesses of Concepts .............................. 18
4.2 Graphical Trade-off ........................................................ 19
4.3 Selection Criteria Weights as a result of an Analytical Hierarchical Process ........................................... 20
4.4 Pugh Matrix with 4 Criteria ............................................. 20
4.5 Key Requirements derived from the concept selection ............ 24
5.1 Example of the influence of modifying the emissivity of the mirror’s rear side in a parabolic reflector ................................. 43
5.2 Main results and errors of the thermal model applied to the AstromeshTM reflector under the test conditions mentioned in [11] ................................. 44
6.1 Requirements considered for the preliminary design .......... 45
6.2 Optimal design parameters considering only nominal conditions ................................................................. 48
6.3 Optimal design parameters considering nominal conditions and off-axis sun rays ...................................................... 48
6.4 Main results of the thermal model as a function of the geometry (parabolic or spherical) and the receiver’s efficiency (\(\eta_{\text{rec}}\)) ...................................................... 52
6.5 Receiver’s temperature and thermal losses in the receiver due to radiation as a function of the geometry (parabolic or spherical) and the receiver’s efficiency (\(\eta_{\text{rec}}\)) ...................................................... 52
6.6 Main results of the structural analysis of the preliminary designs with respect to the inflating pressure without including the thermal load. The equivalent stress is the Von-Mises equivalent stress ...................................................... 55
6.7 Main results of the structural analysis of the preliminary designs with respect to the inflating pressure including the thermal load. The equivalent stress is the Von-Mises equivalent stress ...................................................... 56
6.8 Optimal design parameters for both concentrator shapes .... 61
6.9 AHP matrix ................................................................. 62
6.10 Trade-off table for the selection of the concentrator’s shape . . . 63
6.11 Parameters of the final design developed for the concentrator . 63
7.1 Driver requirement of the re-design process ....................... 65
7.2 Final Results of the optimisation process. \(P\) refers to pressure load and \(T\) to thermal load. \(\Delta r m s\) refers to the relative increase due to the thermal load ...................................................... 68
7.3 Main geometrical properties of the final design ................... 69
7.4 Results of the sensitivity analysis ........................................ 70
7.5 Parameters of the final design developed for the concentrator . 73
8.1 Optimal design parameters considering nominal and off-axis conditions ...................................................... 76
8.2 Maximum displacements and \(r m s\) error experienced by the demonstrator w.r.t. the inflating pressure based on the Finite Element Models ...................................................... 78
8.3 Main properties of the final demonstrator design ................ 78
8.4 Comparison between the measurements of the design and the manufactured mould ...................................................... 82
8.5 Deviations observed in the demonstrator ............................ 84
9.1 Test campaign objectives and success criteria ................... 85
9.2 Test plan ................................................................. 86
9.3 Averaged results of irradiance as a function of the vertical distance to the lamp .... 92
9.4 Measured and design values of different geometrical parameters ...................... 94
9.5 Results of test phase B ................................................................ 94
9.6 Comparison between the values obtained by Leenders [16] (second and third columns) and those obtained in this project (fourth and fifth columns) ........................................... 95
9.7 Results of test phase B ................................................................... 98
10.1 Results of the simulations ....................................................................... 101
10.2 Results of test phase B ........................................................................ 102
10.3 New results of the simulations with a displacement of 3 [mm] towards the vertex 103
11.1 Results of the design concept STP-A ......................................................... 113
11.2 Results of the design concept STP-B ......................................................... 113
12.1 Key Performance Parameters ................................................................... 118
12.2 Verification of key stakeholders requirements .............................................. 119
12.3 Thrust per unit volume and end-to-end efficiency of COTS propulsion systems 120
A.1 Working packages .................................................................................... 133
B.1 Stakeholders ............................................................................................. 137
B.2 Functional Requirements .......................................................................... 138
B.3 Attribute Requirements ............................................................................ 139
B.4 Constraints ............................................................................................... 140
D.1 Results of the optimisation strategy 1 .......................................................... 145
D.2 Results of the optimisation strategy 2 .......................................................... 145
D.3 Results of the optimisation strategy 3 .......................................................... 146
D.4 Results of the optimisation strategy 4 .......................................................... 146
D.5 Results of the optimisation strategy 5 .......................................................... 146
G.1 Description of the tests performed .............................................................. 158
G.2 Results for test sub-category A-1, including the test identification, the values measured and the maximum deviation, $\Delta_{\text{max}}$ ......................................................... 159
G.3 Results of test sub-category A-2, test 1 ....................................................... 160
G.4 Results of test sub-category A-2, test 2 ....................................................... 160
G.5 Results of test sub-category A-2, test 2 ....................................................... 160
# List of Symbols

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>$F$</td>
<td>Thrust</td>
</tr>
<tr>
<td>$I_{sp}$</td>
<td>Specific impulse</td>
</tr>
<tr>
<td>$P$</td>
<td>Power</td>
</tr>
<tr>
<td>$D$</td>
<td>Aperture diameter</td>
</tr>
<tr>
<td>$V$</td>
<td>Volume</td>
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<tr>
<td>$S$</td>
<td>Solar flux</td>
</tr>
<tr>
<td>$A$</td>
<td>Area</td>
</tr>
<tr>
<td>$\eta$</td>
<td>Efficiency</td>
</tr>
<tr>
<td>$\eta_{rec}$</td>
<td>Receiver efficiency</td>
</tr>
<tr>
<td>$\eta_{mirror}$</td>
<td>Mirror efficiency</td>
</tr>
<tr>
<td>$I$</td>
<td>Irradiance</td>
</tr>
<tr>
<td>$\Delta V$</td>
<td>Orbital velocity change</td>
</tr>
<tr>
<td>$\Phi$</td>
<td>Orientation of the main axis</td>
</tr>
<tr>
<td>$\Delta \Phi$</td>
<td>Angular deviation w.r.t. nominal conditions</td>
</tr>
<tr>
<td>$\Phi_{Sun}$</td>
<td>Sun vector orientation</td>
</tr>
<tr>
<td>$p$</td>
<td>Pressure</td>
</tr>
<tr>
<td>$\theta_C$</td>
<td>Aperture half angle</td>
</tr>
<tr>
<td>$r$</td>
<td>Reflectivity factor</td>
</tr>
<tr>
<td>$r$</td>
<td>Transmittance factor</td>
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<tr>
<td>$a$</td>
<td>Absorptivity factor</td>
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<tr>
<td>$c$</td>
<td>Emissivity factor</td>
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<tr>
<td>$f$</td>
<td>Focal length</td>
</tr>
<tr>
<td>$R$</td>
<td>Radius</td>
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<tr>
<td>$m$</td>
<td>Mass</td>
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<td>Density</td>
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<td>Heat flux</td>
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<tr>
<td>$T$</td>
<td>Temperature</td>
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<td>$R_g$</td>
<td>Gas constant</td>
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<tr>
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<td>Molar mass</td>
</tr>
<tr>
<td>$\kappa$</td>
<td>Conductivity</td>
</tr>
<tr>
<td>$F_{i,j}$</td>
<td>View factor between elements i and j</td>
</tr>
<tr>
<td>$B_{i,j}$</td>
<td>Gebhart factor between elements i and j</td>
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<tr>
<td>$D_h$</td>
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<tr>
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<td>Velocity</td>
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<tr>
<td>$Re$</td>
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<tr>
<td>$Pr$</td>
<td>Prandtl number</td>
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<tr>
<td>$\nu_{poisson}$</td>
<td>Poisson ratio</td>
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<tr>
<td>$W$</td>
<td>Width to be removed between petals</td>
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<tr>
<td>$\Gamma$</td>
<td>Vandenkerckhove function</td>
</tr>
<tr>
<td>$c_f$</td>
<td>Thrust coefficient</td>
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<tr>
<td>$q_{latent}$</td>
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<td>$T_s$</td>
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<tr>
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<tr>
<td>$\mu$</td>
<td>Viscosity</td>
</tr>
<tr>
<td>$C_p$</td>
<td>Heat capacity at constant pressure</td>
</tr>
<tr>
<td>$A_t$</td>
<td>Throat area</td>
</tr>
<tr>
<td>$A_e$</td>
<td>Nozzle exhaust area</td>
</tr>
<tr>
<td>$p_c$</td>
<td>Chamber pressure</td>
</tr>
<tr>
<td>$p_e$</td>
<td>Nozzle exhaust pressure</td>
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</table>
# Abbreviations

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
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</thead>
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<tr>
<td>SSE</td>
<td>Space Systems Engineering</td>
</tr>
<tr>
<td>STP</td>
<td>Solar Thermal Propulsion</td>
</tr>
<tr>
<td>rms</td>
<td>root-mean-square</td>
</tr>
<tr>
<td>IAA</td>
<td>International Academy of Astronautics</td>
</tr>
<tr>
<td>TOF</td>
<td>Time of flight</td>
</tr>
<tr>
<td>COTS</td>
<td>Commercial-out-of-the-shelf</td>
</tr>
<tr>
<td>TU Delft</td>
<td>Technical University Delft</td>
</tr>
<tr>
<td>OAP</td>
<td>Operating Average Power</td>
</tr>
<tr>
<td>STK</td>
<td>Stakeholder</td>
</tr>
<tr>
<td>SE</td>
<td>Systems Engineering</td>
</tr>
<tr>
<td>ADCS</td>
<td>Attitude Determination and Control System</td>
</tr>
<tr>
<td>TBD</td>
<td>To be determined</td>
</tr>
<tr>
<td>AHP</td>
<td>Analytical Hierarchical Process</td>
</tr>
<tr>
<td>FEM</td>
<td>Finite element model</td>
</tr>
<tr>
<td>w.r.t.</td>
<td>with respect to</td>
</tr>
<tr>
<td>DASML</td>
<td>Delft Aerospace Structures and Materials Laboratory</td>
</tr>
<tr>
<td>DEMO</td>
<td>Electronic and Mechanical Support Division</td>
</tr>
<tr>
<td>VLM</td>
<td>Vaporizing Liquid Micro-Thruster</td>
</tr>
</tbody>
</table>
Space technologies have experienced an increase in the use of small platforms, such as micro-, nano-, femto- and pico- satellites (up to around 100 [kg]) [17]. These spacecraft allow low cost missions with the objective of technology demonstration and scientific or commercial research, leading to the so-called “democratisation” process of Space [18] [19] [20]. Space agencies, companies and research institutions have embraced this change by investing in technology miniaturisation and the development of new projects and concepts based on these vehicles. The research lines of the Department of Space Systems Engineering of the Faculty of Aerospace Engineering at TU Delft are also a reflection of this new era in Space Flight. The group has reached a point of high experience, with two CubeSat missions already launched [21] and research projects intended to develop new missions and systems. It is currently intended to launch PocketQube missions in the upcoming years, which are spacecraft built out from 5-cm cubes (resulting in one eighth of a CubeSat volume).

The employment of small satellites still presents clear limitations due to their dimensions, creating challenges which cannot be overcome only with technology miniaturisation [20]. The constraints can be seen, for example, in propulsion capabilities, power generation, resolution of optical systems or communications capacities. While conventional satellites are limited by the size of the launchers, small platforms are more constrained by their own dimensions.

The objective of this research project focuses on the first limitation mentioned above. More efficient propulsion systems have been always a matter of study in Space Engineering [22], [23] with the goal of improving and/or enabling new missions. Cryogenic engines or electrical propulsion are two clear examples of the results of the research made in this field [22], [23]. Other propulsion technologies have been left apart and the prohibitive development costs have decreased the interest of space agencies and companies. This is the case of Solar Thermal Propulsion (or STP), a beamed concept in which solar radiation is used to heat up a propellant that is expanded in a nozzle to generate thrust [22], [23]. Despite the prospective capabilities of STP, no research project was going on in this field up to my knowledge by the time I started researching it. However, there are reasons to bring the topic up again now that small satellites are making their way into the market [19] [24] [16] [25], representing a unique opportunity for technology validation. Designing and launching a STP system would represent the milestone necessary to reactivate the research and trigger its application. Furthermore, the development of an efficient, advanced concept could enhance the performance capabilities of small satellites and broaden the range of possible missions. Previous related projects at TU Delft did not design the solar concentrator [26] [16] [24], which was identified during a literature study [17] as one of the major challenges still to be tackled in STP. There is thus an interest within the department on continuing this research line and the design of the concentrator represents a gap which requires further work.

The research lines of the SSE Department of TU Delft, previous work related to STP and the necessity to develop innovative solutions to overcome the limitations of small satellites create a framework in which the development of a deployable solar concentrator for PocketQubes fits perfectly. Therefore, the main objective of this project can be summarised as follows:
The present Master Thesis will result in the development, performance assessment, manufacturing and testing of a solar concentrator demonstrator for PocketQubes with a packaging volume of 1 PocketQube Unit and an aperture between 5 and 10 times a Unit’s side, capable of providing more than 190 W at an efficiency larger than 70%.

The performance capabilities of the main goal are derived from the power requirements for a STP engine assuming a specific impulse of 200 s and a thrust of 100 mN [26], in accordance to current systems available in the market (the approach to relate the power requirement with these values is explained in chapter 3). The design objectives in terms of packaging volume and aperture are based on similar projects developed for CubeSats [5] [1]. Although the device is initially intended to be part of a STP system, it could represent a milestone in the development of systems for PocketQubes with a broad range of applications. Deployable structures for small satellites have been already considered in the Faculty for inflatable de-orbiting devices [27] and inflatable reflectors for antennae [26]. These structures could enhance the performance of PocketQubes by increasing the dimensions of certain systems with the same launch volume [29]. Antennae with higher gains [1] [5] or telescopes with larger apertures [9] are some examples of possible alternative applications.

The structure of present document is explained hereafter. The main objective, a set of research questions and the main requirements are generated based on the research framework, a previous literature study [17] and a benchmarking analysis (chapters 2 and 3). This initial step allows to identify possible concepts and to select the baseline design (see chapter 4), which is developed using a set of optical, thermal and structural design tools (chapter 5). The first iteration of the design approach results in a preliminary design (chapter 6) which is optimised in a second design loop (chapter 7). The final geometry is re-defined to manufacture the demonstrator (chapter 8) to be tested in order to assess the actual performance of the device (chapter 9). These two tasks (manufacturing and testing the solar concentrator) are seen as main goals of the project since it is required to actually prove the concept proposed. The final design is used, together with the test results, to generate a preliminary design of a STP engine for a PocketQube (chapter 11). The results obtained from the project are discussed (chapter 12) in order to derive the corresponding conclusions and recommendations for future research (chapter 13). Although the project was intended to last 9 months, different delays led to an extension of one month more but continuous updates in the planning allowed to keep a good organisation of the work packages. It is hoped that this research contributes to the PhD project recently started by Fiona Leverone at TU Delft about a dual-mode STP system.

This research project has resulted in a conference paper accepted for a poster presentation during the 11th IAA Symposium on Small Satellites for Earth Observation¹ to be celebrated in Berlin in 2017.

¹More information about the Symposium is available in https://www.dlr.de/iaa.symp/desktopdefault.aspx/tabid-4802/


This first chapter has the intention of guiding the reader throughout the process followed by the researcher in the identification of the needs and opportunities triggering the present project (section 2.2.1). The main goal (section 2.2.2) and the different research questions which will be answered in this document (section 2.2.3) are also presented. A brief summary about the background of this project based on a literature study [17] (section 2.1) is included to have an idea about the current state-of-the-art of Solar Thermal Propulsion (subsection 2.1.1) and concentrator systems for satellites (subsection 2.1.2). Benchmark analyses on Power and Propulsion subsystems for micro- and nano- satellites are also included in section 2.1.3 for an actual industry reference.

## 2.1. Research’s Background

This section guides the reader through the analysis performed about the current situation of STP and solar concentrator systems, based on the main outcomes of a previous literature study [17].

### 2.1.1. Solar Thermal Propulsion

STP is a beamed propulsion technology in which the power source is the solar radiation, which is used to heat up a propellant before it is expanded in a nozzle to generate the desired thrust [22] [23]. Although there are also concepts without a concentration system [34] [35], it is more common to find designs including it to collect and focus the radiation on a given point [2] [6]. Usual STP engines operate according to the following sequence: the solar energy is collected and focused by the concentrator subsystem and transferred to a receiver/absorber subsystem. In the direct gain engines, this receiver is where the thermal power is directly transferred to the propellant [36], whereas it is the subsystem which absorbs and stores the energy in the indirect gain engines [33] [37] [31]. The propellant flows through a heat exchanger, commonly integrated in the receiver/absorber subsystem, and finally expanded and thus accelerated in the thruster. Other critical subsystems are the storage and feed system, the tracking and pointing subsystem, the thermal control subsystem or the power generation subsystem (in case of dual-mode engines).

As concluded in the previous Literature Study [17], STP fits in a unique performance niche with a higher efficiency than chemical engines and lower time of flight than with Solar Electric Propulsion (see figure 2.1). Unlike other advanced designs, it has not been validated in space and it is nowadays in the so-called through of disillusionment of its hype curve. This was confirmed by conversations with the propulsion laboratories of the German Aerospace Center (DLR) and the European Space Agency (ESA), which stopped any activity due to the current low interest of the industry. Despite the low interest in STP over the last years, the current trend in the Space field towards smaller and cheaper spacecraft has triggered different projects developed not only to use these vehicles as validation platforms, but also to increase their limited capabilities and broaden their mission range [25] [6] [32] [33].
One of the main results of the previous literature study [17] was the identification of the main challenges in the development of Solar Thermal Propulsion systems. The design of concentrators with high packaging efficiencies and apertures large enough to provide the required power is one of the issues still to be tackled. Previous related projects at TU Delft resulted so far in basic dimensioning models [26], the design and testing of a STP micro-thruster [16] and the design of a dual-mode engine [24]. However, the concentrator design was not part of the research projects developed at TU Delft. The design and demonstration of such subsystem is regarded as a major breakthrough in the field. Lightweight concentrators have been already researched for small satellites, especially as part of telescopes or antennas [1] [5] [28]. Therefore, the development of a concentrator for STP could be also exported to other fields of interest such as solar power devices, communication systems or optical payloads. Hence, it would be possible to mitigate other limitations of small satellites apart from the propulsion capabilities.

2.1.2. Concentration Systems for Small Satellites

As mentioned before, the performance capabilities of small satellites are strongly limited by their dimensions and the mass constraints [20]. Deployable systems appear as another solution apart from technology miniaturisation. The concepts developed up to now can be classified between inflatable [9][38] [39] [40], membrane [5] [3] and rigid [25] concentrators. The first two categories, the so-called “gossamer” structures, have been researched due to the benefits of low density of membrane materials. It is thus possible to build low mass structures with high packaging efficiencies [29]. The optical performance of rigid concentrators, which is currently unattainable by the other two types, is the reason why space telescopes are still equipped with them [41]. However, inflatable and membrane collectors represent better options in many applications in which attaining low mass and volume is more relevant than aiming for the most accurate system.

Inflatable [1] and membrane [5] structures have already been proposed for the communication systems of CubeSats, with storage volumes between 1 and 1.5 Units and apertures up to 1 [m] (ten times the side of a single unit). Membrane concentrators have been developed as antenna reflectors on board of bigger conventional satellites with high accuracy levels [10] [3]. Moreover, it must be taken into account that there is relevant experience working with Light-Weight structures at the Department of Structural Integrity and Composites at TU Delft and it is possible to develop these structures at the Faculty of Aerospace Engineering (as already proven in [28]).

Nowadays, inflatable structures appear as the most attractive concept for many applications mainly due to their unmatched low mass and low packaging volume. The optical performance is lower than with other concepts but there are ways to mitigate this disadvantage. Membrane structures offer a better performance at the expense of higher mass and packaging volume. These two subsystems can be considered as the best options for Solar Thermal Propulsion and Solar Power purposes. Their applicability to antennas and telescopes must be analysed depending on the specific mission and its requirements [7]. Concentrator systems could be also applied to ground systems for communications [42] or power generation [39].
2.1.3. Benchmarking Analysis on Power and Propulsion Systems for Small Satellites

Before starting with the design of a subsystem, it is necessary to analyse what is required in the space industry. This subsection is intended to provide a better insight on COTS products currently available in the market for small satellites. It must be taken into account although there are many concepts being developed by research institutions and companies apart from those shown hereafter, this section is focused on COTS components and systems developed by TU Delft.

Power systems

Solar cells currently used on small satellites have an efficiency ranging from 10% [43] up to 30% [44], with some new designs reaching values of 40% [45]. The power generated depends strongly on the mission characteristics and the surface of the solar panels. However, it is possible to determine some general power requirements and power generation capabilities for CubeSat missions.

Following Clyde Space’s manual for Power Budget calculations [46], a 3-U spacecraft with 4 panels could provide an average of 4.9 W, with peaks of 9 W. More complex configurations with 12 panels would provide 20.8 W with peaks of 40 W\(^1\). The example budget shown in [46] estimates a requirement of 3.4 W for an average mission. However, the report is 5 year old and it does not consider propulsion systems, which may have larger power requirements (for instance, the delfi-n3xt propulsion system consumes 10 W [47] which would increase the requirement on the peak power). Moreover, there are already solar cells which can provide 6.9 W in 3-U configurations [44]. CubeSatKit.com provides a broader overview on existing solar panels, with power values around 10 W already achievable in 2010 for 3-U CubeSats and an expectation of more than 50 W for new designs developed by Pumpkin Space Systems [46]. Nevertheless, there is no further information about these power systems. Regarding designs made at TU Delft, Delfi-C3 was equipped with thin film cells with an efficiency of 10.3 % [43] and Delfi-N3XT used TEC1D triple junction cells made by Dutch Space [49] with an efficiency of 23%. A single TEC1D panel was able to provided 5.453 W, a value which is closer to those given in [46].

DHV-Technologies provide one of the few COTS power systems developed specifically for PocketQubes, with a generation capability of 368 mW per panel [50]. The efficiency of the panels is not provided by the manufacturer but it can be estimated as follows:

\[
\eta = \frac{P}{S \cdot A} \approx 14.7\% ,
\]

where \( P \) is the power generated, \( S \) is the solar flux (the manufacturer provides a reference solar flux of 1000 W/m\(^2\)) and \( A \) is the area of the cell. This value is far from the 30% of Triple junction cells [44] and it may be due to the fact that the effective area is not equal to the area of one side of the spacecraft. If it is assumed that the effective area is 60% of the total surface, the efficiency would be 24.5%, which is closer to the values provided by other manufacturers.

For future analyses in this project, the efficiency of Triple Junction cells (30%) and the power generated by the COTS panels for PocketQubes (368 mW) will be considered. The application of concentration devices in photovoltaic (PV) systems have two effects: an obvious increase in the collected power and an increase in the efficiency of the cells due to the higher irradiance between 2% (for CdTe cells) and 23% (for mono-crystalline silicon) [51].

Propulsion systems

Table 2.1 shows some of the propulsion modules available in the small satellite market together with designs developed at TU Delft in the past. As can be inferred from the data, the thrust values achieved are usually in the order of 1-10 [mN], except for the designs developed by Rocketdyne [52] and a micro-propulsion system designed at TU Delft [53]. It must be kept in mind that the products offered by Rocketdyne are still under development and barely no data is available. The expected performance capabilities of STP engines would be

\(^1\)These estimations are obtained considering 8 W solar panels as a reference, with an operating average power (OAP) of \( OAP = 0.6 \cdot P_{\text{panel}} = 4.8 \) W.
characterised by lower specific impulse (in the order of 1000 [s]) and higher thrust than with electric propulsion [22] [6] (as seen in figure 2.1).

Table 2.1: COTS propulsion systems

<table>
<thead>
<tr>
<th>Manufacturer</th>
<th>System</th>
<th>Volume [U]</th>
<th>$I_{sp}$ [s]</th>
<th>$\Delta V$ [m/s]</th>
<th>F [mN]</th>
<th>Reference</th>
</tr>
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<tr>
<td>BUSEK</td>
<td>Electrothermal Thruster</td>
<td>1</td>
<td>60–1300</td>
<td>10</td>
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<td>[36]</td>
</tr>
<tr>
<td></td>
<td>Electrospray Thruster - 1 mN</td>
<td>&lt;1</td>
<td>2300</td>
<td>0.1</td>
<td></td>
<td>[35]</td>
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<tr>
<td></td>
<td>Electrospray Thruster - 0.1 mN</td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Ion Thruster BIT-1,3,7</td>
<td>0.5</td>
<td>220</td>
<td>100</td>
<td>500</td>
<td>[37]</td>
</tr>
<tr>
<td></td>
<td>Green Monopropellant Thruster</td>
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<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Rocketdyne</td>
<td>MPS-110</td>
<td>1</td>
<td>10</td>
<td></td>
<td></td>
<td>[52]</td>
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<tr>
<td></td>
<td>MPS-120</td>
<td>1</td>
<td>83–209</td>
<td>280–2790</td>
<td></td>
<td>[52]</td>
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<tr>
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<td>1</td>
<td>130–340</td>
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<td>[52]</td>
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<td>MPS-120XW</td>
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<td>166–440</td>
<td>280–2790</td>
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<td>[52]</td>
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<td>MPS-120XL</td>
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<td>300–539</td>
<td>280–2790</td>
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<td>Ion-Electrospray Propulsion System</td>
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<td>1200</td>
<td>0.1</td>
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<td>Tethers</td>
<td>Hydros</td>
<td>300</td>
<td>50–300</td>
<td>0.1–10</td>
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<td>[60]</td>
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<td>TU Delft</td>
<td>T3yPS</td>
<td>&lt;0.5</td>
<td>&gt;30</td>
<td>6</td>
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<td></td>
<td>Delft propulsion module</td>
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<td>15.4</td>
<td>6.6–2.7</td>
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<td></td>
<td>CubeSat micro-propulsion system</td>
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<td>20.3</td>
<td>4000</td>
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<td></td>
<td>Water-fed CubeSat Resistojet</td>
<td>21.0L</td>
<td>2.01</td>
<td>0.8–1.4</td>
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<td>ISIS</td>
<td>MEMS propulsion system</td>
<td>&lt;1</td>
<td>50–100</td>
<td>0.1–10</td>
<td></td>
<td>[63]</td>
</tr>
</tbody>
</table>

2.2. NEEDS AND OPPORTUNITIES. MISSION STATEMENT AND RESEARCH QUESTIONS.

The needs and opportunities triggering the present project are now derived from the previous literature study and research background. This is followed by the main goal and the research questions.

2.2.1. IDENTIFICATION OF NEEDS AND OPPORTUNITIES. MISSION OBJECTIVE

The research framework generates a clear research opportunity on deployable solar concentrators for PocketQubes based on a set of needs:

- The actual trend in the industry requires the development of space systems with enhanced capabilities within the volume constraints of PocketQubes.
- TU Delft has experience with small satellite systems and there is an increasing interest in the development of PocketQube missions and systems for these vehicles [64].
- STP still presents challenges regarding the development of concentrator systems with low packaging volumes and high apertures. It is necessary to design, manufacture and test this subsystem.
- STP has already been tackled in the past by researchers at TU Delft. However, the concentrator system was not part of the projects.
- Solar concentrators are regarded as a first step in the development of concentrator systems for other purposes (communications and optical systems).

This can be summarised in a Need Statement: There is an ongoing change in the space industry with an increasing interest in small satellites as platforms for technology demonstration and scientific research due to their lower cost and development time compared to conventional satellites. However, there are still large limitations in terms of propulsion capabilities, power, aperture of optical systems and antennae gain. The introduction of deployable structures appears as a solution to overcome the consequences of the size constraints in these spacecraft and to trigger the development of Solar Thermal Propulsion engines.
2.3. **PROJECT ORGANISATION**

2.2.2. **MAIN OBJECTIVE**
The main objective of this project is presented in the following **Mission Statement**:

*The present Master Thesis will result in the development, performance assessment, manufacturing and testing of a solar concentrator demonstrator for PocketQubes with a packaging volume of 1 PocketQube Unit and an aperture between 5 and 10 times a Unit's side, capable of providing at least 190 W at an efficiency larger than 70%.*

The reasons behind the values presented in this main objective are discussed in chapter 3 together with the requirements identification.

2.2.3. **RESEARCH QUESTIONS**

A main research question can be derived at this point and it is as follows: **Is it possible to design a solar concentrator as part of a Solar Thermal Propulsion engine for PocketQubes and, if so, what is its attainable performance?** Different sub-questions can be generated from the main objective of the project. They will be used to define later the tasks to be completed and the corresponding working packages.

1. **What are the characteristics of the design?** It is necessary to define how the design looks like in terms of geometry and performance. The geometry is limited by the dimensions of the spacecraft and it is important to achieve an aperture as large as possible with a low packaging volume. Previous developments for CubeSats [5] [1] attained volumes in the range of 0.5-1.5 [Unit] and apertures from 0.5 to 1 m. Four sub-questions can be derived:

   (a) **What is the geometry of the system?**
   (b) **What is the theoretical performance of the system?**
   (c) **What is the degree of scalability of the system?**

2. **What are the real performance capabilities of the system?** A test campaign is necessary to determine how accurate the analytical predictions are. This task includes measuring the real dimensions and the real performance capabilities. Moreover, the answer to the following questions give an idea of how appropriate the analytical and computational design tools are.

   (a) **How much does the real performance differ from the design estimations?**
   (b) **What is the real geometry of the system?**
   (c) **How representative are the tests performed?**

3. **What would be the prospective performance capabilities of a coupled Solar Thermal Propulsion Engine?** The purpose of the system developed in this research project is to be equipped on a STP engine, so it is necessary to determine if it would be possible to attain performance capabilities as good or better than those of existing systems.

4. **What are the recommended steps to be followed in the development of deployable concentrators for small satellites?** It is clear that the time constraints of a Master Thesis lead to results which must be completed by others in following projects. Therefore, it is necessary to derive recommendations and sketch possible research paths.

2.3. **PROJECT ORGANISATION**

The present section describes the different tasks and work packages to be completed throughout the project, together with the expected schedule. The tasks are also related to the structure of this document.

2.3.1. **TASKS**
The approach to attain the main objective and to answer the research questions is described by the following tasks:

1. **Identification of design requirements and the key design requirements.** The first step consists in the definition of the requirements based on the main objective. The key design requirements lead to the identification of the most important parameters of the design (chapter 3).
2. **Definition of the baseline concept.** A baseline concept is defined based on the design requirements and the conclusions of the previous literature study [17] (chapter 4).

3. **Generation of the design strategy and the modelling tools.** An iterative design process is defined based on a set of design and analysis tools (chapter 5). This task is necessary to answer research question 1.

4. **Design of the Concentrator.** The design process includes the Mechanical, Thermal and Optical design and analysis of the system. Research questions 1.a, 1.b and 1.c are answered with the results of this task. There are certain parameters which must be defined in this step, such as the aperture, the thermal power collected, the concentration ratio, the solar flux at the focal point or the efficiency of the system (chapters 6 and 7).

5. **Manufacturing of the demonstrator.** A test object has to be designed and manufactured. This task requires the definition of the manufacturing procedures, purchasing the components and the production itself (chapter 8).

6. **Testing.** Once the test object is manufactured, its performance has to be assessed to derive conclusions about the real performance of the system. The second research question is partially answered as a result of this work package (chapter 9).

7. **Simulations.** The validation of the design tools is derived from the comparison between the test results and the simulated data. The second research question is completed with this task (chapter 10).

8. **STP engine design.** In order to have an estimation about the prospective performance capabilities of the complete system (research question 3), a thermal and propulsive model of the engine is built up and used to analyse a certain concept (chapter 11).

9. **Design evaluation, discussion and derivation of conclusions and recommendations.** Based on the results of the simulations and the test campaign, the design has to be evaluated to complete the verification and validation process. The identification of following research steps (research question 4) is part of this task. The entire project needs to be discussed and critically analysed (chapter 12), deriving the necessary conclusions about it (chapter 13).

### 2.3.2. PROJECT PLANNING

The Master Thesis project has a workload equivalent to 42 ECTS, which equals 1176 working hours. Estimating that one working day consists of 8 hours of effective work, the Thesis would take 147 working days. Apart from that, it is necessary to consider holidays and one free day per week. Taking March, 1st, as the starting date and including a margin, the project would be expected to be done by the end of September. A couple of weeks are added considering the time required by the committee and the supervisor to go through the final report. Therefore, it is decided to set the green light review on mid-October and the graduation day on mid-November, resulting in a 9-month project. Different delays during the project, especially in the production and testing phases, led to an extension of one additional month. The planning originally set in the kick-off meeting with the supervisor took into account several time constraints which were in the end discarded, allowing for more time for the research. The work packages and the planning were continuously updated to keep a good organisation of the project.

The project is divided in a set of work packages, each of them with expected starting day and duration. Different follow-up meetings are included in the planning to ensure a proper communication between the researcher and the supervisor. For more information, refer to the detailed planning (annex A).
This chapter reflects the preliminary Systems Engineering analysis which resulted in the identification of the stakeholders (subsection 3.1.1), the stakeholders’ requirements (subsection 3.1.2), the acceptance criteria and key performance parameters (section 3.2). The chapter concludes with the identification of the key driver and killer requirements (section 3.3) which will be used afterwards in the concept selection (chapter 4). The objective of this analysis is to have a clear picture of the agents interested and/or involved in the project, what it is required from them and which are the main parameters to be determined during the research project to evaluate its success or failure. All this analysis has been performed following the guidelines presented in [65] and [66].

3.1. Stakeholders and Stakeholders’ Requirements Identification

The present section introduces the main stakeholders of the project (3.1.1) and their requirements (3.1.2). Only the key stakeholders and key stakeholders’ requirements are presented in this chapter, for more information refer to annex B. The reader must keep in mind the absence of similar projects for PocketQubes and the consequential difficulty in the determination of the initial performance requirements. This is reflected in several requirements derived using basic preliminary calculations or bibliographic data and others which present To be determined (TBD) values. It was decided to include them in this document as they are the result of an analysis about the different parameters which should be taken into account during the research project. It is expected that the outcomes of this project allow to determine the values in the requirement and, therefore, they will be rewritten in later stages. Even though this is not the conventional way to design a system, it follows the philosophy employed for the Delfi-PQ mission which consists in the development of systems which fit in the PocketQube and assess their performance afterwards.

3.1.1. Key Stakeholders

A set of active (STK-A-#) and passive (STK-P-#) stakeholders are identified, ranging from the researcher to the Space industry. Table 3.1 introduces the main stakeholders ranked according to their relevance in the project or their level of interaction with the system and the project itself. A rationale is added to explain their relation to the project or the system. The stakeholders presented here and in annex B are the result of a brainstorming process.

<table>
<thead>
<tr>
<th>Id.</th>
<th>Category</th>
<th>Stakeholder</th>
<th>Rationale</th>
</tr>
</thead>
<tbody>
<tr>
<td>STK-A-1</td>
<td>Active</td>
<td>Researcher</td>
<td>Main stakeholder of the research project as the person responsible for the design, manufacturing and testing of the system.</td>
</tr>
</tbody>
</table>
3. REQUIREMENTS GENERATION

<table>
<thead>
<tr>
<th>STK-A-2</th>
<th>Active</th>
<th>Coupled System</th>
<th>The coupled system interacts directly with the concentrator and influences the design. It can be a satellite's system or the test set-up and its instruments.</th>
</tr>
</thead>
<tbody>
<tr>
<td>STK-P-1</td>
<td>Passive</td>
<td>Chair of Space System Engineering of TU Delft</td>
<td>The Chair of SSE of the Faculty of Aerospace Engineering plays a supportive role for the project.</td>
</tr>
<tr>
<td>STK-P-2</td>
<td>Passive</td>
<td>Analogous Systems</td>
<td>Analogous concepts and systems are used as references for the design and to compare the performance of the concentrator.</td>
</tr>
</tbody>
</table>

3.1.2. Key Stakeholders’ Requirements

The interest or influence of the stakeholders in the project is materialised through requirements. It must be kept in mind that this preliminary systems engineering analysis has been performed thinking also about a possible flight system and, therefore, not all of the requirements presented in this document will be effectively used for the design of the demonstrator. This is the case, for instance, of the requirements related to the interaction with other subsystems (REQ-A-5).

Table 3.2 describes the key requirements together with their rationales. The table distinguishes between functional requirements (REQ-F-#), attributes (REQ-A-#) and constraints (REQ-C-#). Moreover, the requirements of each category are presented in order of relevance for the project. The functional requirements were generated using parameters commonly employed to define the performance of concentrator systems [17]. Some of them include TBD values due to the reasons given above. The requirement on the power output (REQ-F-1) is presented as the most important one since it is desired to obtain the highest power possible within the constraints on the packaging volume. Two measures of the quality of the system are included: the rms error and the performance efficiency. The first of them (defined in the previous literature study [17]) is a parameter commonly used to measure the shape accuracy of optical systems and it can be used to compare the design with the results of other projects. The efficiency refers to the ratio between the power output and the power available. It is considered less important because it is more difficult to establish any comparison with analogous systems and it is preferred to have a design with a geometry closer to the optimal one, focusing as much power as possible, respecting the image size limits (REQ-F-3) and generating a spot with a given concentration ratio (REQ-F-4).

The required power output (REQ-F-1) is based on a basic dimensioning model for STP engines developed by Zandbergen [26] under several assumptions:

- The propellant is Ammonia (NH₃), which was identified during the literature study as a common choice instead of hydrogen because of its storability properties and its acceptable performance [17].
- The efficiency of the thruster and the heat exchanger are both 85%, whilst the concentrator’s efficiency is set to 70%. The values for the thruster and the heat exchanger were found in literature [17]. However, the concentrator’s efficiency is slightly more conservative than the usual one found in publications about STP, which is around 85% [67].
- The engine is characterised by a specific impulse of 200 s and a thrust of 100 mN, which are values similar to those found in the market nowadays (see table 2.1). The thrust value assumed is larger than the performance capability of electric propulsion at the expense of a lower specific impulse (see figure 2.1).

The values considered give an idea of the performance desired for the concentrator. However, there is no bibliographic data available to estimate the capabilities of a system developed for a PocketQube. Therefore, it might be necessary to review the requirements by the end of the research project for various reasons:

- There is no design of a STP engine specifically made for PocketQubes and, thus, the power requirement is not clear at this point of the research.
- The values of the efficiency and the power output attainable for the given volume constraint (REQ-A-1) might be too conservative or too optimistic.
The concentrator operates under nominal conditions if the Sun vector and the main axis of the system are aligned. This is the ideal design condition which would provide the highest power. However, it is not possible to avoid deviations due to perturbations, the accuracy of the ADCS and the attitude requirements of other systems. Current COTS ADCS developed for CubeSats can provide a pointing accuracy of less than 1 deg, but there are no clear specifications about dedicated systems for PocketQubes. Therefore, it is decided to set an operating range of ±5 deg as a trade-off between the system’s performance and the requirement on the ADCS (REQ-F-3). As well as the values considered before for the power output and the efficiency, this value may be re-evaluated by the end of this research project or depending on the specific requirements of a certain mission. The image size and the concentration ratio are undetermined at this stage of the research, but they are still included due to the reasons mentioned before in the introduction of this section.

The attributes define how the system shall look like. One of the main objectives of this project is to evaluate whether or not the results obtained for CubeSats [1] [5] in terms of aperture and packaging volume can be extrapolated to PocketQubes (see subsection 2.2.3). There are only two designs available to be used as a reference for estimations of the relation between these two parameters, which consists in deployable antenna reflectors of 0.5 m [5] and 1 m [1] of aperture. This is the reason why the two main attribute requirements include determined values which will guide the design process of the system. It is admitted that the range considered for the aperture is quite broad and it seems to be arbitrary but it is chosen as a starting point for the design based on the only two reference projects available. In case larger apertures are attainable, the requirement will be re-written. The requirement on the simplicity, reliability and mass is better explained in appendix B. It can be divided into three sub-requirements for each of the attributes and they are mainly related to how easy the system is deployed, the number of components required and the mass of the complete system. At this stage of the project it is not necessary to assess the quantification of aspects such as the simplicity or reliability, and they are only considered from a qualitative point of view.

The third requirement category refers to constraints of the research project regarding cost and time. The development of a STP engine requires a larger amount of money, as well as manufacturing and testing a concentrator for a real mission using space standards. However, this project intends to demonstrate the potentials of this concept and, for that purpose, an initial budget of 500€ is considered. The time constraint is set by the researcher in accordance to the Faculty’s regulations.

Table 3.2: Key Stakeholders’ Requirements

<table>
<thead>
<tr>
<th>Id.</th>
<th>Requirement</th>
<th>Rationale</th>
</tr>
</thead>
<tbody>
<tr>
<td>REQ-F-1</td>
<td>The concentrator system shall collect at least 190 W in-orbit.</td>
<td>The power collected by the concentrator depends on the requirements of the coupled system and it represents one of the main performance requirements.</td>
</tr>
<tr>
<td>REQ-F-2</td>
<td>The \textit{rms} error shall be lower than 0.5 mm.</td>
<td>The \textit{rms} error (defined in [17]) must be below a certain limit to ensure a good shape accuracy.</td>
</tr>
<tr>
<td>REQ-F-3</td>
<td>The concentrator system shall be able operate for an angle range of $\Delta \Phi = \pm 5$ [deg] with respect to the nominal orientation.</td>
<td>The nominal orientation is considered to be that in which the Sun vector is aligned with the axis of symmetry of the satellite. The angle range considered results from a compromise between the impact on the requirements on the ADCS and the optimal operating conditions for the concentrator (the closer to the nominal angle, the better [17]).</td>
</tr>
<tr>
<td>REQ-F-4</td>
<td>The concentrator system shall generate an image of less than TBD [mm$^2$].</td>
<td>The requirement on the image size follows from the dimensions of the receiver.</td>
</tr>
<tr>
<td>REQ-F-5</td>
<td>The concentrator system shall achieve a concentration ratio of at least TBD:1.</td>
<td>The concentration ratio is one of the main performance parameters and it is selected as a balance between heat losses at the receiver’s inlet and the required pointing accuracy of the system [17].</td>
</tr>
</tbody>
</table>
REQ-F-6 The concentrator system shall have an efficiency of at least 70%.
The solar collector must operate with a certain efficiency to guarantee that the desired performance capabilities are achieved. The efficiency is defined as the ratio between the incoming solar power and the solar power at the focal plane.

REQ-A-1 The concentrator system shall fit in 1 PocketCube Unit in its packaged configuration.
One of the main challenges of deployable concentrators is to achieve a large aperture with a low packaging volume. This requirement is imposed by the author based on analogous projects for CubeSats [1] [5].

REQ-A-2 The aperture of the concentrator shall be between 5 and 10 times the size of a PocketCube Unit (25-50 cm).
This requirement is imposed by the author based on analogous projects for CubeSats [1] [5].

REQ-A-3 The concentrator system shall be simple and reliable and it shall have a low mass.
The requirement on the packaging volume is the most important but the system shall also verify other attributes. These are common requirements in projects related to small satellites and meeting them is key to trigger the interest of the industry.

REQ-C-1 The overall cost of the project shall not exceed the budget of 500 €.
The budget available for the research project is set to this value as a starting point to demonstrate the concept.

REQ-C-2 The duration of the project shall not exceed 9 months.
The second constraint is about the duration of the project and it is determined by the workload assigned for the research project (42 ECTS) and the schedule proposed by the researcher.

3.2. **Acceptance Criteria and Key Performance Parameters**

Whether or not the design can be considered to be successful according to the requirements depends on the evaluation of a set of acceptance criteria and key performance parameters, which are defined hereafter in tables 3.3 and 3.4. The main goal of the research project and the requirements presented above are now used to define the criteria and the parameters based on the guidelines shown in [65] and [66].

The acceptance criteria are based on the main functional and attribute requirements and they are presented in order of relevance. Each of them includes an objective and a threshold value. These two values define the ideal outcome to be attained and the results of an acceptable design, respectively. As well as in the case of the stakeholders' requirements, there are TBD values present in the acceptance criteria due to the reasons already mentioned (see the introduction to section 3.1).

<table>
<thead>
<tr>
<th>Id.</th>
<th>Requirement</th>
<th>Acceptance Criterion</th>
<th>Rationale</th>
</tr>
</thead>
<tbody>
<tr>
<td>AC-1</td>
<td>REQ-A-1</td>
<td>The volume of the concentrator system in its packaged configuration is between 0.5 (objective) and 1 PocketQube Unit (threshold)</td>
<td>Criterion defined by the author based on similar concepts developed for CubeSats and on the objective of minimising the influence on the volume budget of the satellite [1] [5].</td>
</tr>
<tr>
<td>AC-2</td>
<td>REQ-A-2</td>
<td>The aperture of the concentrator shall be between 5 (objective) and 10 (threshold) times the size of a PocketQube Unit (5 [cm]).</td>
<td>Criterion set by the author based on similar concepts developed for CubeSats [1] [5].</td>
</tr>
</tbody>
</table>
The concentrator system shall collect between 150 (threshold) and 190 (objective) [W] in-orbit. This range is based on the desirable performance of the coupled system and, therefore, it depends on the type of coupled system. The objective value is based on the solar flux at an orbit altitude of 600 km and the objective value for the aperture diameter

The concentrator system shall have a \( \text{rms} \) error between 0.5 (objective) and 1 (threshold) mm. The shape error of the concentrator must be below a certain value to ensure an acceptable optical performance. Although the requirement is set on 0.5 mm, a \( \text{rms} \) error of 1 mm is also considered acceptable.

The key performance parameters are those required to be evaluated in order to assess the compliance of the design with the requirements and the acceptance criteria. They will also be used to compare the resulting design with analogous systems. All the parameters are derived from the previous literature study [17] and they can be traced to their related requirement as seen in table 3.4. It is necessary to evaluate the power collected by the device in order to have estimations of its applicability to different coupled systems and to assess the prospective performance. The concentration ratio and the image size are outputs required to design the interface with the coupled system and to evaluate how well the structure performs compared with previous designs made for conventional satellites. The efficiency and the geometrical error (\( \text{rms} \) error) are used to derive the quality of the design.

Table 3.4: Key Performance Parameters

<table>
<thead>
<tr>
<th>Id.</th>
<th>Requirement</th>
<th>Parameter</th>
<th>Rationale</th>
</tr>
</thead>
<tbody>
<tr>
<td>KPP-1</td>
<td>REQ-F-1</td>
<td>Power Collected ( (P_{in}) )</td>
<td>The power collected by the receiver is a parameter necessary to assess the possible applications of the system and the performance of the coupled device.</td>
</tr>
<tr>
<td>KPP-2</td>
<td>REQ-F-2</td>
<td>( \text{rms} ) Error</td>
<td>This error refers to the shape error of the concentrator with respect to the ideal geometry ([17]).</td>
</tr>
<tr>
<td>KPP-3</td>
<td>REQ-F-4</td>
<td>Image size ( (A_{image}) )</td>
<td>The image size is an evaluation of the concentrator's optical performance and it influences the design of the receiver.</td>
</tr>
<tr>
<td>KPP-4</td>
<td>REQ-F-5</td>
<td>Concentration ratio ( (\kappa) )</td>
<td>The concentration ratio is defined as the ratio between the heat flux at the mirror and the heat flux at the receiver's surface</td>
</tr>
<tr>
<td>KPP-5</td>
<td>REQ-F-6</td>
<td>Efficiency ( (\mu_{conc}) )</td>
<td>The efficiency is defined as the ratio between the power available (considering the solar flux and the mirror's surface) and the power on the receiver's aperture.</td>
</tr>
</tbody>
</table>

3.3. **Killer Requirements and Key Driver Requirements**

The requirements presented before in subsection 3.1.2 are used now for the identification of the killer requirements and the design driver requirements. This is the first step for the concept generation process explained in chapter 4 and it follows directly from the main goal of the project, the previous literature study [17] and all the information given so far in this chapter.

The killer requirements will be used to discard the so-called obvious losers, which are those concepts not able to reach the desired mission objective. They are as follows:

- **REQ-A-1**: The concentrator system shall fit in 0.5-1 PocketQube Unit in the packaged configuration.
• **REQ-A-2**: The aperture of the concentrator shall be between 5 and 10 times the size of a PocketQube Unit (5 [cm]).

It has been considered that attaining a high aperture to packaging volume ratio is the main challenge of the project and, therefore, the requirements referring to it are used to discard non feasible concepts.

On the other side, the *design driver requirements* are those which will be used as guidelines during the design of the system. They are based on the requirements presented before and they are as follows:

• **REQ-A-1**: The concentrator system shall fit within 0.5-1 PocketCube Unit in the packaged configuration.

• **REQ-A-2**: The aperture of the concentrator shall be between 5 and 10 times the size of a PocketCube Unit (5 [cm]).

• **REQ-F-1**: The concentrator system shall collect at least 190 [W] in-orbit.

• **REQ-F-2**: The *rms* error shall be lower than 0.5 [mm]

• **REQ-F-3**: The concentrator system shall be able operate for an angle range of $\Delta \Phi = \pm 5$ [deg] with respect to the nominal orientation.

• **REQ-F-4**: The concentrator system shall generate an image of less than TBD [mm$^2$].

• **REQ-F-5**: The concentrator system shall achieve a concentration ratio of at least TBD:1.

• **REQ-F-6**: The concentrator system shall have an efficiency of at least 70%.

• **REQ-A-3**: The concentrator system shall be simple and reliable and it shall have a low mass.
The present chapter describes the concept generation and selection process, which is based on the previous literature study [17] and the requirements shown in chapter 3. The approach follows the guidelines commonly presented in Systems Engineering manuals and books [65] [66] [68]: a set of driver and killer requirements were identified in the previous chapter (section 3.3), a design option tree is generated to have a better picture of all the possibilities (section 4.1) and a set of selection criteria are defined to choose the best concept based on the requirements (section 4.2). The key system requirements are finally generated based on the stakeholders’ requirements and the concept selected (section ??).

### 4.1. Design Option Tree

Three main categories of concentrator systems (CS) were identified during the previous literature study [17], each of them with different sub-categories. They are presented in the Design Option Tree, DOT, in figure 4.4 and explained hereafter. Although it is not included specifically in the DOT, every concept has two subdivisions depending if either a lens or a mirror is used, except for the Fresnel Zonal Plate because it uses diffraction to concentrate the radiation instead of refraction (lens) or reflection (mirror). The nomenclature used for the concepts is CS-A-B, where CS stands for concentrator system and A and B are the identification labels for the category and the subdivision, respectively. The concepts considered are as follow:

- **CS-I: Inflatable Concentrator.** This concept is deployed using a pressurising gas. The shape can either be attained and maintained with the gas or attained with the gas and maintained by rigidising methods. Two sub-categories depending whether or not the geometry is axysimmetric about the axis of revolution can be distinguished.
  - **CS-I-ON: On-axis Inflatable Concentrator** [1] [28].
  - **CS-I-OFF: Off-axis Inflatable Concentrator** [2].

![Figure 4.1: From left to right: On-axis [1] and off-axis inflatable concepts [2]](image)
• **CS-M: Membrane Concentrator.** This category refers to concepts made of thin layers of materials shaped by a support structure.

  – **CS-M-A: Astromesh™ Reflector [3].** Design developed by Northrop Grumman for antenna systems, which has already been used on board of conventional satellites with excellent results.
  – **CS-M-U: Umbrella-shaped Concentrator [5].** This reflector concept is based on the same mechanism as an umbrella. A system based on this concept was already developed for CubeSats with 0.5 m of aperture and a packaging volume of 1.5 CubeSat Units.

![Figure 4.2: From left to right: Astromesh Reflector [3], Fresnel Zonal Plate [4] and Umbrella Reflector [5]](image)

• **CS-R: Rigid Concentrator.** This last concept consists in structures made of either a single or multiple rigid components.

  – **CS-R-D: Dish-type concentrator [6].** Concepts similar to dish reflectors found in conventional antennae systems.
  – **CS-R-H: Hexagonal Deployable Concentrator [7].** Concept in which the concentrator is divided in hexagonal panels which are integrated in-orbit.
  – **CS-R-FL: Flexible Petal Concentrator [8].** An alternative to the previous concept is the employment of flexible petals which are folded around a central hub.
  – **CS-R-P: Petal Concentrator [9].** Concept based on the deployment of rigid segments which are previously folded as a flower.

![Figure 4.3: From left to right: dish-type reflector [6], hexagonal deployable reflector [7], flexible petal reflector [8] and petal reflector [9]](image)

The Design Option Tree seen in figure 4.4 allows to have a better idea of the different concepts and how they are derived from the main concentrator categories.
4.2. CONCEPT SELECTION

The selection process is explained and summarised hereafter. The steps followed are presented below and they follow the guidelines introduced in [65]. The approach and methods applied were consulted with Dennis Dolkens, a PhD student at TU Delft working in the development of a space telescope for CubeSats, as a more experienced researcher to support the decisions taken.

1. **Identification of obvious losers** (subsection 4.2.1). The killer requirements are first used to discard all the non-feasible concepts.

2. **Identification of strengths and weaknesses** (subsection 4.2.2) of the concepts still considered.

3. **Selection criteria definition** (subsection 4.2.3) to perform a trade-off between the different concepts.

4. **Trade-off** (section 4.2.4). A trade-off is performed using a graphical method and a pugh matrix based on an Analytical Hierarchical Process. The results are discussed and a baseline concept is selected.

4.2.1. **IDENTIFICATION OF OBVIOUS LOSERS**

The first step of the process is the identification and rejection of the obvious losers which are the non-feasible concepts according to the killer requirements. Rigid concentrators (CS-R) cannot meet at the same time the requirements on the packaging volume (REQ-A-1) and the aperture size (REQ-A-2). Therefore, this entire category is rejected.
### 4.2.2. Analysis of Strengths and Weaknesses

The remaining concepts are analysed in order to identify their strengths and weaknesses, which are derived from the results of the literature study [17]. The results of this analysis are presented below in table 4.1.

Table 4.1: Strengths and Weaknesses of Concepts

<table>
<thead>
<tr>
<th>Id.</th>
<th>Concept</th>
<th>Strengths</th>
<th>Weaknesses</th>
</tr>
</thead>
<tbody>
<tr>
<td>CS-I-ON</td>
<td>On-axis Inflatable Concentrator</td>
<td>1. Low mass and packaging volume. 2. Easier to be manufactured than off-axis designs. 3. TRL around 6 for CubeSats (demonstrated on ground). 4. Easier pointing mechanism than with off-axis designs</td>
<td>1. Wrinkles. 2. SC Shadow. 3. Lower power than off-axis designs. 4. Risk of impacts 5. Lower accuracy than membrane reflectors.</td>
</tr>
<tr>
<td>CS-I-OFF</td>
<td>Off-axis Inflatable Concentrator</td>
<td>1. Low mass and packaging volume. 2. Higher power than on-axis designs. 3. There is no shadow of the satellite. 4. Pointing mechanism more independent w.r.t SC’s attitude.</td>
<td>1. Wrinkles. 2. Risk of impacts 3. Lower accuracy than membrane reflectors. 4. Not demonstrated on small satellites</td>
</tr>
<tr>
<td>CS-M-FL</td>
<td>Fresnel Zonal Plane</td>
<td>1. Designed for a CubeSat (FalconSat-7). Tested in zero-gravity flights. 2. No need for a robotic arm. 3. Higher accuracy than inflatable designs.</td>
<td>1. Larger mass and volume due to the deployment system. 2. Lower aperture to packaging volume ratio.</td>
</tr>
</tbody>
</table>

### 4.2.3. Definition of the Selection Criteria

The selection criteria are generated in order to evaluate the concepts presented above. They are developed using the stakeholders’ requirements (chapter 3) and other relevant aspects. Therefore, the key attribute requirements (aperture and packaging volume) are used to generate the first selection criterion (SC-1), while the main functional requirements are combined in the second criterion (SC-2). The simplicity criterion (SC-3) of the concept is derived from requirement REQ-A-3. The reason for taking the simplicity into account is that the concepts present large differences in terms of complexity and it is preferred to select a simple one to reduce risks. The last criterion (SC-4) is included in order to take into account whether or not similar designs have been developed for small satellites. The criteria and their definition are presented hereafter:

- **SC-1: Aperture to packaging volume ratio.** Instead of considering the aperture and the packaging volume as two independent parameters, it is preferred to consider their ratio as a more straightforward parameter. The volume is a constraint given by the killer requirement REQ-A-1, which is derived from the size of the satellite. The aperture is fixed by REQ-A-2.

- **SC-2: Optical Performance and Shape Accuracy.** This criterion is measured by the power output (REQ-F-1), the shape error (REQ-F-2) and the efficiency of the system (REQ-F-5). Although no numerical analyses are available at this point of the research, it is possible to infer comparisons between the concepts based on literature [17].

- **SC-3: Simplicity.** This qualitative property is evaluated according to the number of components of the system, the deployment strategy and the manufacturing methods involved. It is derived from requirement REQ-A-3, which can be found in appendix B.
• **SC-4: Maturity of the concept.** There are no deployable structures developed for PocketQubes and thus the TRL of these concepts is equal to 1. However, concentrator systems have been developed for other platforms and that must be kept in mind for the selection of the concept, especially if it has already been designed for CubeSats. As mentioned before, this criterion is not derived from any requirement, but considered now due to the relevance of having designs to be used as reference points to assess the initial design requirements and to evaluate the performance of the systems.

### 4.2.4. Trade-off

The trade-off between the different concepts using the selection criteria introduced above is summarised now. Two methods are employed in order to derive the corresponding conclusions which will lead to the selection of the most appropriate concept for this research project. They are both derived from the guidelines introduce during the course Space Systems Engineering at TU Delft [65]. It was decided to use two strategies to compare the concepts in order to ensure that the implicit subjectivity of trade-off processes is mitigated. It must be kept in mind that the results of both methods must be critically analysed and they cannot be assumed to be completely valid. Therefore, the concept selection is not directly derived from the results but from the corresponding discussion.

**Graphical Trade-off.**

All the concepts are preliminarily analysed considering how well they perform with respect to each selection criterion. Four colours are used to define four different degrees of compliance (see table 4.2): green (excellent, exceeds requirements), blue (good, meets requirements), yellow (correctable deficiencies) and red (unacceptable) [65]. The widths of the columns of table 4.2 are proportional to the relative relevance of each selection criterion. The aperture to packaging ratio is considered as the most important criterion, followed by the performance and shape accuracy. The simplicity and the maturity of the concepts are the criteria considered to be the least relevant. As can be seen in figure 4.2, the Astromesh™ (CS-M-A) and the Fresnel Lens (CS-M-FL) concepts have unacceptable deficiencies in terms of simplicity (SC-3) compared to other concepts. Both inflatable concepts (CS-I) have the best characteristics in terms of aperture to packaging volume ratio (SC-1). The other three concepts have acceptable ratios, but they do not reach apertures as large as with the inflatable structures. On the other hand, the three membrane concepts (CS-M) have excellent properties in terms of optical performance (SC-4) and shape accuracy (SC-5). This trade-off process is not conclusive and it only allows to derive qualitative comparisons between the concepts and a preliminary notion about which concept might be selected.

Table 4.2: Graphical Trade-off

<table>
<thead>
<tr>
<th>Concept</th>
<th>SC-1</th>
<th>SC-2</th>
<th>SC-3</th>
<th>SC-4</th>
</tr>
</thead>
<tbody>
<tr>
<td>CS-I-ON</td>
<td>Greatest ratio</td>
<td>Wrinkles and misalignments</td>
<td>Low number of components</td>
<td>Developed for CubeSats</td>
</tr>
<tr>
<td>CS-I-OFF</td>
<td>Greatest ratio</td>
<td>Wrinkles and misalignments</td>
<td>Low number of components</td>
<td>Not developed but it presents small differences</td>
</tr>
<tr>
<td>CS-M-A</td>
<td>Acceptable ratio but larger packaging volume</td>
<td>Proven accuracy on conventional satellites</td>
<td>Complex deployment subsystem</td>
<td>Developed for conventional SC but scalability non-proven</td>
</tr>
<tr>
<td>CS-M-FL</td>
<td>Acceptable ratio but larger packaging volume</td>
<td>Used for telescopes</td>
<td>Complex deployment subsystem</td>
<td>Developed for CubeSats</td>
</tr>
<tr>
<td>CS-M-U</td>
<td>Acceptable ratio but larger packaging volume</td>
<td>Excellent accuracy</td>
<td>Simplest deployment subsystem of membrane concepts</td>
<td>Developed for CubeSats</td>
</tr>
</tbody>
</table>

**Pugh matrix based on an Analytical Hierarchical Process (AHP).**

The second method is also a common tool included in Systems Engineering procedures to evaluate concepts with respect to a set of selection criteria [65] [66]. This approach provides numerical outputs which compare...
the overall performance of the concepts according to the criteria. However, the reasons to choose how well each concept meets the criteria is not well founded and, therefore, it is necessary to analyse the results carefully. Moreover, this method is not conclusive and the preference of the researcher might be considered more important than the outcome obtained.

The first step of this method consists in the application of an AHP to compare the different criteria in order to assign weights proportional to their relative relevance, which are shown in table 4.3. The elements of the eigenvector associated to the highest eigenvalue of the matrix (table 4.3) are the resulting weights. In this case, the weights of the four criteria are \( w = [0.7798, 0.5352, 0.2676, 0.1838] \). The consistency ratio (CR) is below 10%, so the approach can be considered numerically valid. More information on how to apply an AHP can be found in [65].

Table 4.3: Selection Criteria Weights as a result of an Analytical Hierarchical Process

<table>
<thead>
<tr>
<th>SC-1</th>
<th>SC-2</th>
<th>SC-3</th>
<th>SC-4</th>
</tr>
</thead>
<tbody>
<tr>
<td>SC-1</td>
<td>1</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>SC-2</td>
<td>1/2</td>
<td>1</td>
<td>3/2</td>
</tr>
<tr>
<td>SC-3</td>
<td>1/3</td>
<td>2/3</td>
<td>1</td>
</tr>
<tr>
<td>SC-4</td>
<td>1/4</td>
<td>1/3</td>
<td>2/3</td>
</tr>
</tbody>
</table>

The weights obtained from the AHP are now used in a Pugh Matrix to evaluate the concepts. In this matrix, every concept is assigned a numerical value according to how well they perform with respect to each criterion: -1 (unacceptable), 0 (correctable deficiencies), 1 (good) to 2 (excellent). The weights are based on the strengths and weaknesses shown before in table 4.1 and the outcomes of the previous literature study [17]. The arguments presented in the graphical trade-off (table 4.2) are also taken into account.

Table 4.4: Pugh Matrix with 4 Criteria

<table>
<thead>
<tr>
<th>SC</th>
<th>Weight</th>
<th>CS-I-ON</th>
<th>CS-I-OFF</th>
<th>CS-M-A</th>
<th>CS-M-FL</th>
<th>CS-M-U</th>
</tr>
</thead>
<tbody>
<tr>
<td>SC-1</td>
<td>0.7798</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>SC-2</td>
<td>0.5352</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>SC-3</td>
<td>0.2676</td>
<td>1</td>
<td>1</td>
<td>-1</td>
<td>-1</td>
<td>0</td>
</tr>
<tr>
<td>SC-4</td>
<td>0.1838</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

| Result: | 2,5462 | 2,5462 | 1,5826 | 1,7664 | 2,034 |
| Weighted Result: | 0.62155369 | 0.69373969 | 0.79883748 |

As seen in table 4.4, the two inflatable concentrators, which obtained identical scores in the selection process, are the best concepts according to this trade-off. The Astromesh\textsuperscript{TM} concept gets the lowest score due to its complexity and the fact that it has not been developed for small satellites, so the scalability still needs to be assessed. Despite their good performance capabilities, the other two membrane concepts received lower grades due to their aperture to packaging volume ratio and their complexity. The Astromesh\textsuperscript{TM} concept has been demonstrated and used in real missions in big conventional satellites, providing high accuracy levels [3]. However, it requires a robotic arm and a complex deployment structure to attain the desired shape. The Fresnel Zonal Plate [4] is an interesting concept since it uses diffraction as the working principle instead of refraction or reflection. It has been used on board of a CubeSats [4] but its packaging volume is larger than that of other concepts, it requires multiple deployment booms and the performance depends on the radiation wavelength. Finally, the umbrella-shaped concentrator [5] also requires a deployment system based on a boom but it can be a single boom with a spring-based deployment mechanism, so the complexity is lower.
4.2. CONCEPT SELECTION

DISCUSSION

Unlike concentrators designed for optical instruments, the objective of this project is to develop a concentrator with the largest aperture possible for a given volume, ensuring an acceptable performance. Inflatable concentrators present a lower accuracy but still within acceptable margins according to previous designs developed for CubeSats [1] and conventional satellites [10]. That is the main reason why both trade-off methods concluded that inflatable concepts are the best ones. However, it is necessary to analyse carefully the results. The reasons for the grades assigned are mainly based on the literature study [17]. Hence, they are mainly qualitative and no analytical calculations are behind the compliance grades. The validation of the results has been assessed in collaboration with Dennis Dolkens, a PhD candidate at TU Delft working in the development of a space telescope for CubeSats. His stronger experience in the field of optical systems for small satellites has been used to validate the conclusions obtained in this chapter. Nevertheless, it would be desirable to consult the validity of the trade-off with more researchers.

Although the trade-off methods are not conclusive by themselves, the resulting best concepts comply with the results of other research projects related to solar power devices. Membrane and rigid concepts are mainly used in projects in which the shape accuracy is prioritised over the packaging volume [7] and only a few designs for STP include them [6].

It is still necessary to decide whether the design should consist in an on-axis or an off-axis structure (see figure 4.1). On-axis designs allow easier pointing strategies but the satellite appears as an obstacle in the field of view of the system if a mirror is chosen for the optical device [17]. This issue may be mitigated by placing the system on a deployable structure away from the satellite but that requires additional support structures and deployment mechanisms, increasing the overall complexity and thus the risks. In off-axis designs, there is no obstacle between the Sun and the concentrator but the symmetry of the geometry is lost and the aperture is smaller.

CONCLUSIONS ABOUT THE TRADE-OFF PROCESS

The results of the trade-off methods presented before implied that an inflatable structure is the best option for this research project. The methods used and the result was validated with the assistance of a researcher in optical systems for small satellites. Due to the requirements on simplicity and to ensure an easier design and manufacturing, the on-axis inflatable concentrator (CS-I-ON) is selected. It is necessary to point out here again that the methods used before are not conclusive by themselves and the comparisons between concepts are based on the results of a literature study [17]. It is admitted that the methods have their flaws and a stronger validation should be made. A way to improve the selection process would be, for instance, the employment of analytical estimations to support the grades presented in the trade-offs. However, this is out of the scope of this project due to the time constraints.

4.2.5. SUB-CONCEPTS

The on-axis inflatable concentrator has been selected as the concept to be developed in this research project. Nevertheless, it is still necessary to discuss different design decisions which can be translated into sub-concepts.

- Employment of a torus. A torus is a structural element used to ensure that the shape of the perimeter stays as required, thus minimising misalignments and the risk of wrinkles (see figure 4.5), which have a clear impact on the system's performance. For instance, Babuscia et al. measured a significant decrease in the antenna gain designed for CubeSats with respect to the ideal design [1]. Three different sub-designs are identified:
  - Concentrator with a Memory metallic wire (e.g. Nitinol) as torus. Memory shape materials are characterised by their ability to return to a specific shape after a stimulus is provided (thermal gradient, voltage difference, magnetic field, etcetera). This property can be used to fold the torus and to attain the desired shape after deployment.
  - Concentrator with an Inflatable torus [28]. Inflatable tubes can be used to increase the stiffness of the structure and thus ensure a higher shape accuracy. However, the inflating pressure of these devices must be higher than that of the main structure of the concentrator. Therefore, the consequences of possible leaks would be more severe and the mass of the deployment system, which is proportional to the amount of pressurisation gas required, is larger.
Concentrator with **no torus**. It is also possible not to include this structural element and either accept the influence on the performance of the shape error or cope with inaccuracies with other methods.

- **Use of struts.** Struts are structures connecting the concentrator and the spacecraft bus (see figure 4.5). These “arms” place the concentrator further away from the spacecraft, attaining a higher manouevrability and avoiding the shadow created by the satellite.

- **Optical working principle: mirror vs. lens.** The literature study performed before this project allowed to draw some conclusions about the differences between using lenses or mirrors for the concentrator system [17]. They can be summarised as seen below:
  - Lenses offer a fair quality when large field views and medium apertures, while mirrors behave better with small fields of view and large apertures.
  - Mirrors have the drawback of requiring more than 100 times better shape accuracy than refractive concentrators.
  - Mirrors offer a more uniform response against radiation whereas the optical behaviour of lenses varies more with the wavelength.

![Figure 4.5: Sketch of the Inflatable Antenna Experiment including the main structural elements [10]](image)

### 4.3. **Conclusions: Definition of the baseline concept**

An on-axis inflatable concentrator is selected as the concept to be designed, manufactured and tested during this research project. Regarding the different sub-concepts explained before, it is decided to develop a device with no torus, with no struts and based on a mirror as the main optical element.

The torus is not considered at this point of the research due to simplicity reasons. As well as in the research project performed by Babuscia et al. [1], the torus can be proposed later depending on the analytical and experimental results. The struts are not included in the design due to the limited packaging volume available, the corresponding increase in complexity and the effects of having additional structural elements inflated at a higher pressure. The third design decision about the sub-concepts is due to the fact that it is desirable to design an optical system capable of offering a uniform performance over the Sun spectrum (≈ 250 - 2500 nm). Moreover, the aperture is preferred to be large to gather a higher level of power and there is no need to design a concentrator with a large field of view since the sunlight is quite directional.

The baseline design consists in an inflatable structure divided into a reflective section and a transparent canopy, both made out of thin films. The working principle is based on the following sequence: the solar rays go through the canopy with barely no refraction, hit the reflective surface and they are reflected onto the receiver (see figures 4.6 and 4.7). These two elements constitute the so-called membrane structure of the device whose geometry will be defined later on in the design phase (chapters 6 and 7). Other subsystems are presented below:
4.3. CONCLUSIONS: DEFINITION OF THE BASELINE CONCEPT

- **Interface.** The interface serves as the connection between the membrane structure, the receiver and the satellite (or the test set-up in case of the demonstrator). The design varies strongly on the coupled system and the specific design of the satellite's bus.

- **Deployment and Pressurisation Subsystem.** This subsystem is in charge of ejecting the system and inflating the structure up to the required final pressure at the desired inflation pressure rate.

- **Controller.** The controller is an element only present in the flight model. It includes all the necessary sensors and actuators to check the status of the system and implement the corresponding measures to regulate the pressure and/or the attitude of the structure. It is also responsible for the interaction with the main on-board computer of the satellite. In case of the demonstrator prototype, it is substituted by the testing instruments.

These subs-systems together with the membrane structure constitute what is considered to be the high level architecture of the solar concentrator. The architecture includes the main elements of the system and the key interactions between them, as seen in figure 4.8. The black boxes are the main subsystems while the others are their main components. The interactions are given by the functions of each subsystem already explained before. For instance, the controller receives from the sensors information about the solar flux, the image size and position or the inflating pressure, which are measured from the membrane subsystem. It must be pointed out that the spacecraft bus is substituted by the test set-up for the demonstrator.
The selection of the baseline concept implies the need of identifying more requirements which could not be generated before in chapter 3 since they are derived from the specific concept and the system architecture. As mentioned in chapter 3, there are many requirements missing since they are only applicable to a flight systems. For instance, withstanding the launch loads, communicating with the on-board computer or mitigating the impact on other subsystems are not requirements needed at this point of the research.

Table 4.5 presents the main or key requirements generated based on the concept selected. Their selection is mainly due to their relation with the main requirements introduced in chapter 3 and their importance considering the baseline concept selected. The requirements are not presented in order of relevance but following those already introduced in chapter 3. As can be observed in the table, there are some undetermined values which is due to the same reasons already explained in chapter 3.

The fact that the baseline concept is an inflatable structure means that there must be requirements concerning the pressurisation system. Cool gas generators are simple, reliable devices and the Chair of SSE has experience working with them (REQ-A-7). The gas selected needs to meet certain safety considerations (REQ-A-7A, REQ-A-7B), not react with the materials (REQ-A-7C) and allow a large fraction of the radiation to get through it without modifying the rays's paths (REQ-A-7D). The pressurisation system is dimensioned based on the geometry of the system and the lifetime, but also on the design pressure (REQ-A-8A). One of the main issues of inflatable systems is their tendency to wrinkle and deform in a non desired way. The pressure rate plays a key role in preventing any violent structural response during the deployment (REQ-A-8B) and taking these deformations into account during the design process contributes to the error mitigation too (REQ-A-9). Finally, in order to attain the lifetime requirement of 1 year (REQ-A-4), the system needs to remain pressurised even if it is punctured (REQ-A-10).

### Table 4.5: Key Requirements derived from the concept selection

<table>
<thead>
<tr>
<th>ID</th>
<th>Requirement</th>
</tr>
</thead>
<tbody>
<tr>
<td>REQ-A-7</td>
<td>The pressurisation subsystem shall be based on a cool gas generator.</td>
</tr>
<tr>
<td>REQ-A-7A</td>
<td>The generated gas shall be non-toxic.</td>
</tr>
<tr>
<td>REQ-A-7B</td>
<td>The generated gas shall be non-flammable.</td>
</tr>
<tr>
<td>REQ-A-7C</td>
<td>The generated gas shall have no reactivity issues with the membrane materials</td>
</tr>
<tr>
<td>REQ-A-7D</td>
<td>The generated gas shall have a transmission coefficient as close as possible to 1 in the solar spectrum.</td>
</tr>
<tr>
<td>REQ-A-8A</td>
<td>The final pressure shall be TBD [Pa]</td>
</tr>
<tr>
<td>REQ-A-8B</td>
<td>The pressurisation rate shall be TBD Pa/s.</td>
</tr>
<tr>
<td>REQ-A-9</td>
<td>Error mitigation measures shall be included in the design of the concentrator.</td>
</tr>
<tr>
<td>REQ-A-10</td>
<td>The system shall be able to continue operating after the impact of space debris and micrometeoroids.</td>
</tr>
</tbody>
</table>
This chapter presents the modelling tools employed during this research project, with the intention of explaining to the reader the design process implemented and the theoretical fundamentals behind it. The design approach, which is presented in section 5.1, is supported by three main models: a ray tracing model (section 5.2), a thermal model (section 5.3) and a structural model (section 5.4). The optimisation algorithm used to obtain the ideal optimal geometry is based on the ray tracing tool and it is developed in section 5.5. The tools employed for the design process are finally subjected to a verification and validation analysis in section 5.6.

5.1. Definition of the Design Strategy

The design approach followed during this project is based on an iterative sequence supported by optical, thermal and structural models, which is based on common guidelines to assess the design of space instrumentation systems [69]. This design process is sketched in figure 5.1 and the steps included are as follows:

1. **Definition of the geometry based on the optical performance.** An optimisation algorithm (section 5.5) based on a ray tracing tool (section 5.2) is used to determine the ideal optimal geometry. The optical model also allows to derive a performance estimation of this first geometry.

2. **Thermal analysis of the structure** in order to obtain the temperature distribution over the surface to define the thermal load the structure is subjected to (section 5.3).

3. **Structural design and analysis.** It is necessary to define the materials to be used for the manufacturing of the structure and Finite Element Models (FEM) are generated in order to assess the deformation and stress fields as functions of the thermal load and the inflating pressure. A more accurate estimation of the actual geometry and its performance can be derived from the results of this phase. Moreover, the shape error (measured with the \textit{rms} error as explained later on) is calculated in order to have an estimation on how well the inflated system approximates the ideal geometry and how it performs compared to other systems.

4. If necessary, **re-iterate** considering the shape error after inflation. Due to the inflating pressure, the shape will differ from the ideal one and it is necessary to analyse the effect of this error on the optical performance. If the test campaign has been completed at this point, the results are included in the design loop for the next iteration.

A preliminary design is first defined in chapter 6, which covers up to the point right before the re-design process in figure 5.1. After that, the geometry is re-evaluated considering the shape error and implementing different mitigation strategies to reduce the difference between the inflated geometry and the optimal one. The design will be evaluated again in chapter 8 considering the available materials and their suitability, trying to manufacture a demonstrator with the same performance as the optimal design or, if it is not possible, as close as the amount and properties of the materials allow it. The results and observations gathered during the manufacturing and testing phases can be included in the design sequence as inputs to be taken into account at the beginning of the iteration. Therefore, it is possible to include the difference between experimental and
modelling results can be considered. In this research project, both tasks were performed after the second design loop was concluded (chapter 7) and, therefore, it was not possible to include the results in the design process. However, certain guidelines for future research will be discussed and included afterwards in chapters 12 and 13.

Every output in red shown in figure 5.1 is taken out of the sequence as a result to be analysed and it is used for the following blocks. The inputs obtained from the test campaign are not included in the sketch but they are inserted at the beginning of the iteration.

Figure 5.1: Design approach without including the test inputs

5.2. Ray Tracing Model

A ray tracing model has been developed to estimate the optical performance of the geometries considered. As can be inferred from its name, ray tracing analyses estimate the path followed by a ray (ray tracing) to determine the intersection with the image plane [69] [70]. It is a tool commonly used in multiple fields apart from optical engineering, such as radio physics or acoustics. Even though there are commercial software with proven accuracy, their non availability at the faculty led to the decision of building an in-house model using MATLAB. It is admitted that the accuracy will be lower than that of commercial models depending on the assumptions made. Its validation and verification will be assessed later on in section 5.6.

The main principle behind the model is that if a set of collimated (parallel) rays resembling the solar radiation is considered, it is then possible to determine how many of them hit the mirror and the receiver and, therefore, estimate the power received by both elements. The tool is built so that it is able to analyse:

- The influence of changes in the Sun vector with respect to the nominal direction. A perfect pointing accuracy may not be always attained either because of the capabilities of the ADCS or due to the pointing requirements of other systems.

- The effect of non-nominal shapes of the reflector. The structure deforms under the operating loads, leading to a geometry different from the designed one.

Two models are built up. The first of them is bi-dimensional and it only considers a cross-sectional profile of the concentrator and solar rays in this plane. In this case, the receiver is modelled as a segment of a given width located at the focal plane. The second model evaluates three-dimensional structures and the receiver
is modelled as a circle of a certain radius at the focal plane. It has been decided to generate these two models mainly due to the following reasons:

- Verification and validation of the tool: It is easier to start generating a bi-dimensional ray tracing model and upgrading it later to a three dimensional one. In other words, it is considered better to develop first a simpler model and verify the working principles instead of going directly to a more complex one. Moreover, the computational time of bi-dimensional models is lower since less rays are needed.

- A 3-dimensional tool is more accurate and allows to analyse the optical behaviour of the entire concentrator, even under deformed conditions.

Both models are developed considering the following assumptions and constants:

- The rays are modelled as unidirectional beams, although it is known that photons are also waves. Hence, diffraction is neglected.

- The solar flux is that of low Earth orbits (LEO): \( S = 1414 \text{ W/m}^2 \).

- The reflectivity coefficient of the mirror is: \( r = 1[-] \).

- The reflectivity is assumed to be specular, no diffusive reflections are modelled.

- The transmittance coefficient of the transparent section is \( \tau_{\text{clear}} = 1[-] \) and the transmittance coefficient of the mirror is \( \tau_{\text{mirror}} = 0[-] \).

- There is no refraction at the transparent section of the concentrator.

- The pressurising gas does not affect the paths followed by the rays.

- The satellite’s geometry is that of a PocketCube and thus its sides are 5 cm long. The area of this field stop is 25 cm\( ^2 \).

The model receives as inputs the Sun vector, the geometry of the concentrator and the receiver’s dimensions and position. This last input can be omitted and substituted by an optimisation algorithm in order to determine the ideal position of the receiver. The discretisation level, measured as the number of rays considered, is a modelling decision to be taken which affects the accuracy of the results and the computational cost. A sensitivity analysis has been performed for the different simulations and a trade-off between the accuracy and the computational time has been made.

The outputs of the models are derived from the requirements and key performance parameters presented in chapters 3: the power received by both the mirror and the receiver (\( \text{REQ-F-1, KPP-1} \)), the power distribution over the receiver’s plane (\( \text{REQ-F-3, REQ-F-4, KPP-3, KPP-4} \)) and the efficiency, which is measured as the ratio between the power on the receiver and the power impinging on the mirror (\( \text{REQ-F-5, KPP-5} \)). The size of the image is derived from the flux distribution, by identifying the point at which the flux is 10% of the maximum value attained (this value is based on common optical design guidelines [70] but it may be redefined later on if necessary). The radial flux is expected to have a Gaussian shape with a peak and a radial decrease with respect to this point. The center of the image varies depending on the Sun vector, as it will be observed in the results shown in following chapters. If more realistic power results are desired, it is necessary to consider the effect of the materials properties and the effective power hitting the receiver is then calculated as follows:

\[
P_{\text{eff}} = \tau_{\text{clear}} \cdot \tau_{\text{mirror}} \cdot P_{\text{ideal}},
\]

where \( \tau_{\text{clear}} \) is the transmittance coefficient of the transparent membrane and \( r \) is the reflectivity of the mirror. This new parameter \( (P_{\text{eff}}) \) takes into account how much radiation the transparent section allows to get to the mirror \( (\tau_{\text{clear}} \cdot P_{\text{ideal}}) \) and which percentage of it is actually reflected \( (\tau_{\text{mirror}} \cdot (\tau_{\text{clear}} \cdot P_{\text{ideal}})) \).

A simple representation of the model’s structure can be seen in figure 5.2, with a description of the assumptions, inputs and outputs described before.
The first step in the ray tracing model consists in the definition of the inputs of the problem, which are defined and explained below. For better understanding of the parameters included, figure 5.3 provides an overview of the majority of the geometrical inputs.

- **Orientation of the Sun vector:** $\Phi_{Sun}$. For simplicity reasons, only variations of the rays direction in the XZ-plane are considered. This modelling decision can be taken due to the fact that collimated rays are always parallel to a given plane and the structure is axisymmetric. In this case, the XZ-plane is chosen.

- **Concentrator’s geometry:** The geometry of the reflector’s side of the structure is defined by the aperture half angle, the orientation of the main axis and a set of parameters which depends on the shape considered.
  
  - **Aperture half angle:** $\theta_c$.
  - **Orientation of the main axis** with respect to the nominal Sun vector ($\Phi_{Sun} = \pi$ [rad]): $\Phi$.
  - **Shape definition and main geometric parameters:** $z = f(x, y)$. Although the model accepts geometries defined by point arrays so that the results from the finite element models can be used as inputs, two ideal options are initially considered:
    
    - **Parabolic concentrator:**
      
      $$ z(x, y) = \frac{1}{4f} \cdot (x^2 + y^2) + c, \quad (5.2) $$
      
      where $f$ is the focal length and $c$ defines the displacement of the vertex with respect to the origin. In order to place the focus on the origin, $c = f$.
    
    - **Elliptical/Spherical concentrator:**
      
      $$ z(x, y) = \pm \sqrt{b^2 + z_0^2 - b^2 \cdot \frac{x^2 + y^2}{b^2}} \quad (5.3) $$
      
      The parameters $a$ and $b$ define the length of the axes and $z_0$ determines the vertical position of the centre. A spherical concentrator is a case of elliptical concentrators in which $a = b = R$.
      
      The geometries are defined in the bi-dimensional model using the same equations shown above with $y = 0$.
      
      The diameter of the aperture area perpendicular to the nominal Sun vector is determined through the calculation of the limit points P1 and P2 (see figure 5.3 for more details):
5.2. Ray Tracing Model

- **Point P1:** Intersection of the concentrator’s geometry projected on the XZ-plane \((y = 0)\) and \(z = \tan(\alpha_1) \cdot x\), where \(\alpha_1 = \frac{\pi}{2} - \left(\pi - \Phi + \theta_c\right)\).

- **Point P2:** Intersection of the concentrator’s geometry projected on the XZ-plane \((y = 0)\) and \(z = \tan(\alpha_2) \cdot x\), where \(\alpha_2 = -3\frac{\pi}{2} + (\theta_c + \Phi)\).

Figure 5.3: Sketch of the concentrator and its main parameters

- **Discretisation accuracy** of the incoming solar radiation. It is necessary to define how many rays are going to be analysed. For that purpose, a grid is generated on the XY-plane with \(N_x\) divisions of the x-axis and \(N_y\) divisions of the y-axis. This scheme results in \(N_x \cdot N_y\) nodes or rays. The area to be discretised is a rectangle placed at a given distance over the focal plane, whose dimensions are given by the aperture of the concentrator projected over a plane perpendicular to the Sun vector (see figure 5.4).

Considering that the sun rays are parallel to the XZ-axis, the projected area is an ellipse whose axes are determined as follows:

\[
D_{x,\text{eff}} = D_x \cdot \cos(\Phi - \Phi_{\text{Sun}}) = D_x \cdot \cos(\alpha) \quad (5.4)
\]

\[
D_{y,\text{eff}} = D_y = D_y \quad (5.5)
\]

where \(D_x, D_y, D_{x,\text{eff}}\) and \(D_{y,\text{eff}}\) are the actual and effective apertures in both axes. They are derived from the coordinates of P1 and P2, which were defined before. It is decided to only consider positive values in the y-axis in order to reduce the computational cost by taking advantage of the symmetry of the problem. Therefore, \(D_y = 0.5 \cdot D_x\).

Figure 5.4: Sketch of the actual and effective apertures with respect to the Sun vector.
This effective aperture, the solar flux and the Sun vector define the power per beam as follows:

\[
P_{\text{beam}} = S \cdot \cos(\Phi - \Phi_{\text{Sun}}) \cdot \frac{(x_{P2} - x_{P1}) \cdot (y_{P4} - y_{P3})}{N_x \cdot N_y} = S \cdot \frac{D_{x,\text{eff}} \cdot D_{y,\text{eff}}}{N} \quad [\text{W}],
\]

where \( S \) is the solar flux; \( \Phi \) and \( \Phi_{\text{Sun}} \) are the nominal and real Sun orientation, \( x_{P2}, x_{P1}, y_{P4} \) and \( y_{P3} \) are the final and initial points of the radiation front and \( N = N_x \cdot N_y \) is the total number of points. The points \( P4 \) and \( P3 \) are the intersection points of the concentrator with the y-axis. For on-axis designs, \( y_{P4} = x_{P2} \) and \( y_{P3} = x_{P1} \). In the bi-dimensional tool, the discretised area is a segment of length \( (x_f - x_i) \cdot \cos(\alpha) \) and \( N = N_x \).

The working principle based on which the outputs are obtained is the same for the two models. Assuming specular reflection, each ray is reflected such that the incoming and the exit rays are symmetric with respect to the normal vector to the concentrator, \( \vec{n} \) (see figure 5.5 for bi-dimensional geometries). The ray tracing tool generates a set of collimated rays with the direction given by the angle Sun vector. The model determines if the ray hits the mirror and, if so, it computes the impact point and the direction vector of the exit ray. This is used to trace the ray back to the receiver’s plane and to determine the intersection point, which is evaluated to know whether or not it falls within the receiver’s area.

![Figure 5.5: Sketch of the main working principle of the ray tracing code for 2-D geometries](image)

Even though the idea behind the models is the same for the bi-dimensional and the 3-dimensional cases, the implementation differs as it will be explained in subsections 5.2.1 and 5.2.2. There are also differences depending on the way the geometry is given. During the thesis it was concluded that if the geometry is introduced as arrays of points, the computational cost is much higher due to the interpolation calculations MATLAB has to perform. If the ideal geometries are considered, the calculations can be done analytically and the computational cost is much lower. This is the reason why a generic ray tracing tool for point arrays and a specific ray tracing tool for each geometry were developed to optimise the computational cost depending on the case analysed.

The specific descriptions of each model are hereafter explained. For the generic ray tracing code, the interpolation functions of MATLAB were used.

### 5.2.1. 2-D Ray Tracing Model

As commented before, the first model developed is bi-dimensional and it is used to have a first estimation of the concentrator’s performance as a function of the geometry and the Sun vector. Only undeformed geometries are considered and, therefore, every result can be calculated analytically to validate the model.
Assuming specular reflection, each ray is reflected such that the incoming and the exit rays are symmetric with respect to the normal vector to the concentrator, \( \vec{n} \) (as seen before in figure 5.5). The ray tracing tool generates a set of parallel rays with the direction given by the angle \( \Phi_{Sun} \). The model determines if the ray hits the mirror, computing the hitting point \((x_i, y_i)\) with the following equation:

\[
y = f(x) = \tan(\beta) \cdot (x - x_0) + y_0, \quad \text{where} \quad \beta = \frac{\pi}{2} - \alpha = \frac{\pi}{2} - \left( \Phi - \Phi_{Sun} \right) \tag{5.7}
\]

The function \( f(x) \) refers to the concentrator's profile, whereas \( \alpha \) is defined with the orientation of the concentrator's main axis and the Sun vector.

The angle \( \theta \) is the slope of the curve at the hitting point (figure 5.5) and it results from the first derivative of the concentrator's equation at the impact point: \( \theta = \arctan(f'(x_i)) \). The angles \( \gamma \) and \( \delta \) are calculated as:

\[
\gamma = -\theta - \alpha \tag{5.8}
\]
\[
\delta = 2\gamma + \alpha \tag{5.9}
\]

Therefore, the power per metre received by the mirror is equal to the number of hitting rays multiplied by the power per metre assigned to each of them. The point of intersection between the exit ray and the focal line is given by the impact point \((x_i, y_i)\), the exit angle \( (\delta) \) and the position of the focal line \((y_{rec})\):

\[
x_{rec} = x_i + \tan(\delta) \cdot (y_{rec} - y_i) \tag{5.10}
\]

If the point of intersection falls within the segment assigned to the receiver, the ray reaches the target. The power per metre received is thus \( P_{beam} \) (as defined before) multiplied by the number of hitting rays. The efficiency is then calculated as the ratio between the number of rays hitting the receiver and the number of rays hitting the mirror.

### 5.2.2. 3-D Ray Tracing Model

The three-dimensional Ray Tracing tool follows the same principles as the bi-dimensional model with the difference that the reflector is a three-dimensional body and the model estimates the path followed by beams in space instead of in a plane. In case the geometry considered is undeformed, all the steps presented hereafter are followed. If the geometry is provided as point arrays, the different intersection points are obtained using numerical interpolation functions of MATLAB and the normal to the surface is evaluated applying the function \textit{surf} norm to the overall structure and interpolating the results on the hitting point.

It is first necessary to recall how lines are defined in space and the procedure to calculate a line symmetric to another one with respect to a third one. The parametric equations for a 3-D line \( r \) are:

\[
r \equiv \begin{cases}
x = x_0 + \lambda \cdot u_x \\
y = y_0 + \lambda \cdot u_y \\
z = z_0 + \lambda \cdot u_z
\end{cases} \tag{5.11}
\]

where \( \lambda \) is a parameter, \([x_0, y_0, z_0]\) is a given point of the line and the vector \( \vec{u} = [u_x, u_y, u_z] \) defines the direction of the line.

Given two lines \( r \) and \( s \), it is possible to obtain a third one, \( t \), symmetric to \( r \) with respect to \( s \) (see figure 5.6). The procedure is as follows:

1. The three lines can be defined using their parametric equations:

\[
r \equiv \begin{cases}
x = x_{0,r} + \lambda \cdot u_x \\
y = y_{0,r} + \lambda \cdot u_y \\
z = z_{0,r} + \lambda \cdot u_z
\end{cases} \quad s \equiv \begin{cases}
x = x_{0,s} + \alpha \cdot v_x \\
y = y_{0,s} + \alpha \cdot v_y \\
z = z_{0,s} + \alpha \cdot v_z
\end{cases} \quad t \equiv \begin{cases}
x = x_{0,t} + \beta \cdot w_x \\
y = y_{0,t} + \beta \cdot w_y \\
z = z_{0,t} + \beta \cdot w_z
\end{cases} \tag{5.12}
\]

where \( \lambda, \alpha, \beta \) are the parameters of the lines and \( \vec{u}, \vec{v} \) and \( \vec{w} \) are the vectors which define their directions.

2. A random point \( P_t \) of \( r \) is computed. It is necessary to use a point different from the intersection point, if it exists, between \( r \) and \( s \).
3. A plane, \( \pi \), perpendicular to \( s \) and which contains \( P_1 \) is defined.

\[
\pi \equiv v_x \cdot x + v_y \cdot y + v_z \cdot z + D = 0,
\]

where

\[
D = -v_x \cdot P_1(1) - v_y \cdot P_1(2) - v_z \cdot P_1(3)
\]

4. The intersection point, \( Q \), between the plane \( \pi \) and the line \( s \) is then calculated by obtaining the parameter \( \alpha \). This point is the closest point to \( P_1 \) in line \( s \).

5. It is possible now to obtain a point \( P_2 \) symmetric to \( P_1 \) with respect to the line \( s \):

\[
\overrightarrow{OP_2} = \overrightarrow{OP_1} + \overrightarrow{P_1P_2} = \overrightarrow{OP_1} + 2 \cdot \overrightarrow{P_1Q}
\]

6. If there is an intersection between lines \( r \) and \( s \), as in this case, the direction vector of \( t \) is defined as:

\[
\vec{w} = \overrightarrow{IP_2},
\]

where \( I \) is the intersection point between \( r \) and \( s \). It is also possible to find curves without an intersection point but that is not the case for the ray tracing tool.

![Figure 5.6: Main elements involved in the calculation of a symmetric line \( t \) to \( r \) with respect to \( s \)](image)

This procedure is applied to the algorithm of the Ray Tracing Tool such that \( r \) is the incoming beam, \( s \) is the line normal to the reflector at the hitting point and \( t \) is the exit beam. The point of intersection is the impact point, which is used in the algorithm as the point to define lines \( s \) and \( t \). The direction of \( r \) is defined by the Sun vector. The Sun vector is defined by the expression shown below. As can be observed, it has only components parallel to the XZ-plane

\[
\vec{u} = \begin{cases} 
\sin(a) & \\
0 & \\
\cos(a) & 
\end{cases},
\]

where

\[
a = \Phi - \Phi_{\text{Sun}}
\]

5.3. **THERMAL MODEL**

The second model developed for the design and analysis of the concentrator estimates the temperature distribution over the surface of the structure in order to be used as an input for the structural analysis. Together with the inflating pressure, the temperature field is the other load causing deformations in the reflector and, consequentially, variations of the performance with respect to the optimal design.

The model is based on a finite element model of the concentrator and it solves the heat balance equations corresponding to each one of the elements, thus taking into account the interactions between the different points of the structure. It is admitted that this model is strongly limited by the assumptions made and the discretisation approach used. Nevertheless, it is a simple conceptual model whose verification is assessed in section 5.6.

Three main elements are considered in the model: the membrane structure, the receiver and the environment. The membrane is divided into multiple quadrilateral finite elements in order to take into account that each point of the reflector receives radiation with a different relative orientation and to include the effects
of conductive heat transfer. As well as with the ray tracing model, the number of nodes is a modelling decision. After performing different preliminary simulations to test the model, it was observed that the maximum number of elements for both the reflective section and the cone is 100 due to the limitations MATLAB has for the size of matrices.

This thermal analysis is performed under the following assumptions:

- The **shape error is equal to zero**. Only ideal geometries are analysed.
- The **sunlight is the only light source** and the Sun vector is aligned with the concentrator’s axis. Other sources, such as albedo, are neglected at this point of the research for simplification reasons.
- There is **no interaction between the concentrator and the walls** of the satellite and no direct heat exchange between the receiver and space is happening.
- The receiver is insulated from the rest of the satellite.
- Steady-state conditions are assumed and thus the transient phase is not considered \( \frac{\partial T}{\partial t} = 0 \).

Apart from the **geometry**, it is necessary to provide as inputs the materials properties of of the three main elements considered: the **reflectivity**, the **absorptivity** and the **emissivity** of the mirror, the transparent cone and the receiver, together with their **density**, **conductivity** and **heat capacity**.

The output parameters include the **surface area of the elements**, the **view factors**, the **Gebhart factors**, the nodes’ **temperature** and the **heat losses** of the mirror and the receiver. The three first set of outcomes are used for validation and verification of the calculations performed. The temperature field is also used for that purpose and as an input for the structural model. The maximum and minimum temperatures as well as the temperature gradient and the maximum temperature difference are parameters which can be derived from the temperature field. The last output (the heat losses) are used to analyse the power lost due to radiation.

All these assumptions, inputs and outputs are seen in figure 5.7. It is also possible to see the modelling sequence, although it misses some intermediate steps such as the calculation of the heat input.

![Figure 5.7: Sketch of the structure of the Thermal model, including the inputs, assumptions and outputs](image)

Each element \( i \) has its thermal behaviour defined by the thermal balance equation seen below, so the model results in a system of differential coupled equations in which the unknowns are the temperatures of the finite elements.

\[
Q_{in,i} - Q_{out,i} = m_i C_{p,i} \cdot \frac{\partial T_i}{\partial t} \quad (5.18)
\]

where,

\[
Q_{out,i} = \sum_j C_{i,j} \cdot (T_i - T_j) + \sum_{j \neq i} B_{i,j} A_i \varepsilon_i \sigma \cdot (T_i^4 - T_j^4) \quad (5.19)
\]
\( Q_{\text{in},i} \) and \( Q_{\text{out},i} \) are the incoming and outgoing power for each element. \( m_i \) and \( C_{p,i} \) are the mass and the specific heat of the element. The conductive \((C_{i,j})\) and radiative \((B_{i,j})\) couplings are calculated for each couple of elements.

Figure 5.8 shows the satellite and the mirror, together with a sketch of a finite element of area \( dS \), normal vector \( \vec{n} \) and relative orientation \( \theta \) with respect to the incoming radiation, given by \( \text{beam}_{in} \).

![Figure 5.8: Sketch of the discretisation set-up for the thermal model](image)

The Gebhart factors, \( B_{i,j} \), are calculated following the guidelines shown in [71] for the analytical calculation of the view factors, first, and the Gebhart factors afterwards. The view factors are obtained by numerical integration using the Monte-Carlo algorithm applied to the theoretical definition of view factor:

\[
F_{i,j} = \int_{A_i} \int_{A_j} \cos(\theta_i) \cdot \cos(\theta_j) \frac{1}{\pi \cdot s^2} dA_i dA_j, \quad (5.20)
\]

where \( \vec{s} \) is the vector joining both points \((i, j)\), \( s \) is its module and \( \theta_1 \) and \( \theta_2 \) are the angles between the normal vectors to the surface and the vector \( \vec{s} \), respectively. For infinitesimal elements \((A_i \to dA_i, A_j \to dA_j)\), the equation above can be approximated by:

\[
dF_{i,j} = \cos(\theta_i) \cdot \cos(\theta_j) \frac{1}{\pi \cdot s^2} dA_j \quad (5.21)
\]

During the development of this model, it was observed that this approximation is invalid for those elements in the connection edge between the mirror and the transparent section if the differential surface area, \( dS \), is not small enough to compensate for the extremely short distance, \( s \), between them. This issue leads to view factors larger than 1. For those elements, the analytical expression for rectangles with one common edge is employed [72]. The system mirror-cone-receiver is treated as a closed one, so the view factor of each element of the cone and the mirror to space is equal to 1.

Regarding the conductive heat transfer, the conductive couplings are calculated for each pair of elements as follows:

\[
C_{i,j} = f(i, j) \cdot k \cdot \frac{A}{L} \quad (5.22)
\]

where \( f_{i,k} \) is a function equal to 1 if the elements \( i \) and \( k \) are in contact and 0, otherwise. \( k \) is the conductivity of the material, \( A \) is the area of the surface of contact and \( L \) is the distance of the path through which the power is transmitted. In this case, \( A = t \cdot l \), where \( t \) is the membrane’s thickness and \( l \) is the contact length. The length \( L \) is defined as the distance between the center points of both elements.

The calculation of the incoming power varies depending if the element is part of the concentrator or the receiver. For the first case, it is as follows:

\[
Q_{\text{in},\text{conc}} = f(x, y, l_{\text{sat}}) \cdot \Phi_{\text{Sun}} \cdot dS \cdot \cos(\theta_i) \quad (5.23)
\]

The function \( f(x, y, l_{\text{sat}}) \) equals 1 if the element receives solar radiation and 0 if the element is in the shadow caused by the satellite. The angle \( \theta \) is determined using the mirror’s geometry and the Sun vector to calculate the angle between the vector normal to the surface and the solar rays (the same procedure as in the
For the second case, power input for the receiver equals:

\[ Q_{\text{in,rec}} = P_{\text{ref}} \cdot (1 - \eta_{\text{rec}}), \]  

(5.24)

where \( P_{\text{ref}} \) is the power received from the mirror and \( \eta_{\text{rec}} \) is the receiver’s efficiency. This efficiency allows to estimate the fraction of the incoming power which is actually transmitted to the propellant or transformed into electrical power. Regarding the power received, it is calculated as \( P_{\text{ref}} = \eta_{\text{mirror}} \cdot r \cdot P_{\text{in}} \), where \( \eta_{\text{mirror}} \) is the efficiency of the mirror and \( r \) is its reflectivity.

5.4. **Structural Models**

The structural design and analysis of the concentrator is performed using finite element models (FEM) built up with the static structural module of ANSYS. This chapter explains how these models are generated and the analysis of the errors in the structure.

5.4.1. **Finite Element Models**

ANSYS is the software package chosen for the structural design of the concentrator due to the experience of the researcher working with it, its availability at the university and its proven accuracy. Although it is difficult to assess the verification and validation of the model without experimental results, a brief discussion about this is included in section 5.6. Different steps are followed to develop the model and to obtain the desired results:

- **Definition of inputs:** the model receives as inputs the type of geometry, the main geometrical parameters, the inner pressure and the temperature field. It is also necessary to determine how the reflector is connected to the receiver’s plane.

- **Geometry:** a cross-section profile of the reflector is firstly generated with CATIA and imported on the Design Modeller module of ANSYS. CATIA is preferred for the profile generation because of its user-friendliness. The reflector is a surface body whose thickness is specified in the Mechanical Module of ANSYS.

![Figure 5.9: Geometry of one of the reflector’s designs in the Design Modeller of ANSYS. The highlighted profile is the geometry imported from CATIA](image)

- **Mesh Generation.** The mesh is generated taking into account that a larger number of elements are required around the connections and interfaces to ensure a good level of accuracy, but the academic license sets a constraint for the number of elements. The mirror surface was meshed using the best quality approach for surfaces with circular perimeter [73] [74] (see figure 5.10, left) and the cone was meshed with quadrilateral elements following a radial distribution (see figure 5.10, right). The geometry was also divided in four sections so that it was possible to specify the number of elements along the cross-sectional profiles.
5. Design and Analysis Tools

Figure 5.10: Finite element mesh for the mirror section (left) and the conical part (right) of the concentrator

- **Model set-up.** It is necessary to set different modelling settings in the software before performing the simulations. First of all, the materials considered in this research project are not in the libraries of ANSYS, so they are generated based on the data-sheets provided by the manufacturer. The main disadvantage of this decision is the limited information provided by the supplier. For instance, there is no information about the variation in the Young’s modulus with respect to temperature or the non-linear coefficients. Hence, the accuracy of the simulations are limited by this issue. Moreover, the non-linearity of the structure, which is commonly claimed to be one of the main problems when dealing with thin-film materials [1] [75] [40], cannot be included. It is decided not to include non-linear effects and large deflections in the model. ANSYS generates a warning message in case the structure deforms such that the small deflections hypothesis is invalid so the second decision is accepted unless this error is obtained.

- **Constraints and loads.** The only constraint imposed in the model is a “fixed support” constraint on the interface between the structure and the receiver. Regarding the loads, there are two main loads: a pressure load on all the inner walls of the structure and a thermal condition which is given by the outputs of the thermal model. The pressure load is a constant value equal to the inflating pressure. The thermal load is given by two temperature distributions (over the mirror and the transparent section) given by a polynomial function based on the results of the thermal model.

- **Results Analysis:** there are different set of results which are of interest for the design cycle of the concentrator. The first of them is the deformation field and the final deformed geometry. This updated geometry will be used to re-calculate the performance of the reflector. It is also important to evaluate the maximum displacements and the regions of the concentrator which experience the largest deformations. Regarding the stress field, it is necessary to look for those points in which there is shear or compression stress since that is an indication of the formation of wrinkles. Knowing where these areas are located will help to include mitigation measures in the design. The deformation fields in each of the three main directions (x, y and z) are exported to EXCEL to be used as inputs of the Ray Tracing Model to estimate the influence of the displacements on the performance.

5.4.2. Determination and Analysis of the Shape Error

The results obtained from the structural models are analysed to calculate the so-called root-mean square (or \( \text{rms} \)) error. This parameter is commonly used in literature to compare designs [7] [28] [75] and it is defined as follows:

\[
error_{\text{rms}} = \sqrt{\int_S (\Delta z)^2 \frac{dA}{A}},
\]

where \( \Delta z \) is the vertical displacement with respect to the ideal geometry, \( dA \) is the element’s surface area and \( A \) is the surface area of the entire concentrator projected on the focal plane. The projected area, \( A \), can be computed using the aperture of the reflector, \( D \).
Since the function $\Delta z$ is only known at the nodes of the FEM, the error is numerically integrated:

$$error_{rms} \approx \sqrt{\sum_i (\Delta z_i)^2 \cdot A_i / A}$$

(5.26)

A broad range of values for the $rms$ error can be obtained from literature, from a few nanometres up to a few millimetres depending on the application and the specific design. For instance, Pearson et al. [75] presented values around 7 mm for a 35 m inflatable antenna in the worst case scenario and a smaller prototype with an aperture of 2.4 m was designed with an estimated $rms$ error below 1 mm. This value complies with the estimations made by Barna for his inflatable reflector [28]. Membrane reflectors present lower errors, such as the 0.025 mm error measured in the Astromesh\textsuperscript{TM} reflector [11]. As commented before, rigid reflectors have no match in terms of shape accuracy. Deployable rigid reflectors present errors ranging from 50 $\mu$m to 1 mm depending on the size of the system [7]. A much precise system is the main mirror of the James Webb Space Telescope, with an $rms$ error of 50 nm [41].

### 5.5. Optimisation Algorithm

An optimisation algorithm is developed in order to obtain those design parameters (focal length or radius, aperture half angle and position of the receiver, as defined in section 5.2) which provide the “optimal performance”. This section is intended to explain the target functions to be optimised (5.5.1), the constraints (5.5.2) and the methods used (5.5.3).

#### 5.5.1. Target Functions

The objective of this optimisation tool is to either maximise the nominal power on the receiver or maximise the nominal power and minimise the sensitivity with respect to the Sun vector. These are the two definitions of performance evaluated and used to define the target functions. The nominal conditions refer to the situation in which the Sun vector is aligned with the concentrator’s axis.

**1st Approach: Maximisation of the power hitting the receiver**

In this first method, only the nominal performance is considered and the target function equals the power received:

$$f_1(f, \theta_c, z_{rec}) = P_{receiver}$$

(5.27)

where:

- $f$: focal length.
- $\theta_c$: aperture half angle.
- $z_{rec}$: position of the receiver.
- $P_{receiver}$: thermal power on the receiver.

The radiation hitting the receiver is calculated as explained before in the 3-D Ray Tracing Model. In this first approximation, the angle $\alpha$ of the collimated set of rays is equal to zero.

**2nd Approach: Power output Maximisation and minimisation of the sensitivity to the Sun vector**

Apart from measuring the performance in nominal conditions, it is also desirable to evaluate the sensitivity of the design to changes in the Sun orientation. A new function, $f_2$, is built based on this definition of the performance and a weight factor ($\nu$) is used as a measure of the relative relevance of the average w.r.t. the nominal performance:

$$f_2(f, \theta_c, z_{rec}) = (1 - \nu) \cdot P_{receiver} + \nu \cdot g$$

where $\nu \leq 1$ (5.28)

The target function $g$ determines the sensitivity of the design with respect to the Sun vector and it is the average power hitting the receiver over a certain angle $\Delta \Phi$. The function $P_{receiver}$ is the same one used in the first target function.
5.5.2. Constraints

The problem has a set of constraints to be respected by the algorithm. They refer to limits on three parameters:

- **Constraints on the focal length.** A lower boundary of 0.1 m is set considering that smaller focal lengths would lead to concentrators with an extremely low performance and focal lengths above 0.5 m are unrealistic for PocketQubes. Therefore, the focal length must verify that:
  \[ 0.1 \leq f \leq 0.5\text{[m]} \]  
  \[ (5.29) \]

- **Constraints on the aperture half angle.** The aperture half angle has an upper boundary given by the maximum surface of the concentrator. There is no lower boundary but it is set to \( \pi/50 = 3.6 \text{ deg} \) since a value is required by the algorithm. The maximum angle is obtained from the available volume to store the concentrator in its packaged configuration together with all the subsystems. The only similar design which can serve as a reference is an inflatable antenna reflector developed at MIT [1]. In that project, the research team managed to fit a 0.5 m focal length parabolic antenna of 1 m of aperture in half a CubeSat Unit (500 cm$^3$).

Although the fact that there is only one design available makes any interpolation statistically invalid, there is no more information until a final design is chosen and manufactured to verify its packaging volume. Therefore, it has been decided to use MIT’s design to extrapolate the possible dimensions of the reflector as a function of the available volume. As well as in this project, their design was based on a transparent conical section and a parabolic reflective section (see figure 5.11).

![Figure 5.11: Sketch of the design made by the research team at MIT [1]](image)

The surface area of such a structure can be thus calculated as follows:

\[ A = A_{\text{parabolic}} + A_{\text{cone}} = \frac{\pi R \left( (R^2 + 4D_{\text{par}}^2)^{3/2} - R^3 \right)}{6D_{\text{par}}^2} + \pi (R_{\text{cone}} + r_{\text{cone}}) \sqrt{h_{\text{cone}}^2 + (R_{\text{cone}} - r_{\text{cone}})^2} \]  
\[ (5.30) \]

where:

- The surface of the parabolic section is calculated using the depth of the disk \( D_{\text{par}} \) and its focal length \( f \). The parameter \( R \) is defined as \( R^2 = 4fD_{\text{par}} \) and the disk’s depth is calculated with the equation below:
  \[ D_{\text{par}} = f - y_{\text{par}} = f - \left( \frac{1}{4f} r_{\text{par}}^2 - f \right) \]  
  \[ (5.31) \]
  where \( r_{\text{par}} \) is calculated using the aperture half angle \( \theta_c \):
  \[ r_{\text{par}} = -\frac{\tan(\pi/2 - \theta_c) - \sqrt{\tan(\pi/2 - \theta_c)^2 + 1}}{1/(2f)} \]  
  \[ (5.32) \]

- The surface of the conical section is calculated using the radius of the base \( r_{\text{cone}} \), the radius of the top edge \( R_{\text{cone}} \) and the height \( h_{\text{cone}} \). The radius of the cone’s base \( r_{\text{cone}} \) is not specified for the reflector made at MIT [1] and it has been approximated as half the side of a CubeSat Unit for the MIT structure and half a PocketQube Unit for this project.

- In case a spherical reflector is used, its surface area is computed using \( A_{\text{sphere}} = 2\pi R \cdot D_{\text{par}} \), where \( R \) refers to the sphere’s radius and \( D_{\text{par}} \) is the height or depth of the reflector.
The main parameters introduced before can be seen below in figure 5.12.

Figure 5.12: Main parameters for the calculation of the concentrator’s surface

The surface area of the MIT design results to be 2.35 m², yielding a surface to packaging volume ratio of 4701.9 m⁻¹. It is thus possible to estimate the maximum surface for the PocketQube Unit (0.587 m²) and the maximum aperture half angle (and aperture) for each value of the focal length or the radius, depending on the shape considered. The parabolic reflector has a maximum aperture of 0.59 m for a focal length of \( f = 0.19 \) m (figure 5.13), which is larger than the requirement initially proposed.

Figure 5.13: Maximum aperture of parabolic reflectors as a function of the focal length

Analogous results can be obtained for a spherical reflector, with a maximum aperture of 0.55 m for \( R = 0.32 \) m and \( \theta_c = 59.3 \) deg (figure 5.14). The spherical reflector is less efficient in terms of surface use since lower apertures are attained for the same surface area. Moreover, the edge of the reflector falls before the receiver’s optimal location for aperture angles larger than 45 deg. It is thus not efficient to employ designs with larger values of \( \theta_c \) since a section of the reflector is not used. That is the reason why figure 5.14 shows the ideal maximum aperture and the real maximum aperture. The maximum effective aperture is 0.53 m for \( R = 0.38 \) m and \( \theta_c = 44.3 \) deg.

Figure 5.14: Maximum aperture of spherical reflectors as a function of the radius. The dotted line corresponds to the ideal maximum aperture, while the other curve is the real effective maximum aperture.
5.5.3. **Optimisation Method**

The optimisation method used is based on a sampling approach: a grid of points is generated, evaluated and compared in order to identify the set of parameters providing the best performance. It is a *trial-and-error* method and its accuracy is limited by the number of points selected. A finer discretisation increases the accuracy but also the computational time. It is decided to lower the number of points and perform an iterative process in which the interval is re-defined in every iteration to consider the range where the maximum is present. Due to the narrowness of the initial interval, it does not take too many iterations until the sample size falls below 1 mm, which is taken as the tolerance. Figure 5.15 shows, for instance, the results of the optimisation tool for a spherical reflector with 25 values of the radius between 0.1 and 1 m. Only three values of the aperture half angle are considered for each radius to limit the computational time.

![Figure 5.15: Results of the mapping optimisation tool for a spherical reflector with 25x3 values considered.](image1)

5.6. **Validation and Verification Assessment of the Models**

It is the intention of this section to verify and validate the models developed in this research project, using for that purpose preliminary analyses and bibliographic data. The validation process at this point of the research is more complex due to the lack of experimental data concerning inflatable concentrator systems for PocketQubes and their validation for other concepts does not ensure that they are valid for the one proposed in this project as well. It is decided to assess the validation only if appropriate bibliographic data is available. It is necessary to gather experimental data to validate the models and, therefore, the results of the test campaign (chapter 9) will be examined with this intention in chapter 10.

5.6.1. **Ray Tracing Tool**

It is discussed now whether or not it is possible to verify and validate the ray tracing tool introduced before in section 5.2. If it is possible, the procedure is explained and supported by analytical and/or experimental results.

The verification process has been done in two steps. It is first analysed if the theoretical focusing capability of parabolic reflectors is obtained. In other words, it is necessary to evaluate if a set of collimated beams parallel to the mirror’s axis is focused on the focal point. As can be observed in figure 5.16, all the rays intersect the axis on the same point, which coincides with the design focal point. The same principle works the other way around: rays originated on the origin are supposed to be reflected into a set of collimated beams. This second rule was also verified. The same verification procedure was successfully applied to the 3-D tool.

![Figure 5.16: Example of the focusing principle of the parabolic geometry](image2)
5.6. **Validation and Verification Assessment of the Models**

A CATIA sketch was generated and exactly the same rays were reproduced in the CAD file and the MATLAB code. The hitting point, the angles between the rays and the normal vector and the impact point on the focal plane were obtained. This procedure verified the tool for off-axis rays, after applying it to both models (bi-dimensional and three-dimensional) and both shapes (spherical and parabolic). Figure 5.17 shows an example of the verification CAD sketch made for a spherical concentrator with rays parallel to the axis.

![Verification Sketch](image)

**Figure 5.17**: CATIA Verification sketch for a spherical reflector of 0.5 m of aperture and 45 deg of aperture half angle with on-axis rays

It is concluded that the working principle of the ray tracing tool is verified. However, it is still necessary to evaluate the errors in the outputs of the tool. There is an implicit error in the calculations derived from the fact that the accuracy depends on the discretisation made. Figure 5.18 shows the error and the computational time as functions of the number of elements considered in the x-axis (the number of points considered in the y-axis is half of the nodes generated on the x-axis). This analysis has been performed using the 3-D model applied to a parabolic reflector of 0.5 m of focal length and an aperture of 0.5 m. The maximum error is 3% for the lowest number of points and, even though it may increase with off-axis rays or if the generic ray tracing tool is used with array points as inputs, it remains below 10%. The tool is, therefore, verified.

![Sensitivity Analysis](image)

**Figure 5.18**: Error in the power output and computational time with respect to the number of nodes in the x-axis

Validating the ray tracing model is not possible at this point of the research due to the lack of experimental data or useful bibliographic resources. Using commercial software already validated, such as Zemax or Code-V, could be an option but they are not available at the University. Nevertheless, bibliographic data shows a good agreement between test results and the estimations of ray tracing algorithms. For instance, Gilpin et al. [37] developed a model for the test set-up of a STP engine, obtaining a maximum divergence between the model and the experimental data of 15%. It must be pointed out though that the researchers employed rigid spherical mirrors, which means that the shape accuracy of their optical systems was higher than that of inflatable structures. Therefore, the theoretical and the experimental results may exhibit a larger difference in the case analysed in this project. It is expected that testing the system will provide additional insight to validate the model.
5.6.2. THERMAL MODEL

The verification of the thermal model is assessed following different steps:

- **Verification of the calculation of the elements’ surface area.** After the definition of the discretisation grid, the model calculates the surface area of each element. This task has been verified by comparing the sum of the surface areas of the elements in the reflector and the conical section and the total surface area of both structural elements. The error obtained is around 5% for both the transparent and the reflective sections, which divided between all the elements can be assumed to be acceptable.

- **Verification of the view factors.** Two ways of verifying the view factors are implemented. The first of them consists in checking if the sum of all the view factors of each element equals 1:

\[
\sum_j F_{i,j} = 1 \quad (5.33)
\]

This requirement is implicit in the definition of the view factors and is met with only an error of 9.9% for one element using the approach presented before in section 5.3. The element concerned is the receiver and the reason for this error may lie on what was already explained about the issue found in the calculation of the view factors between elements close to the edge connecting the structure and the receiver’s plane.

The second way follows the next idea: if the parabolic section is substituted by a disk with a diameter equal to the mirror’s aperture, the view factor from the receiver to the disk must have the same value as the sum of all the view factors from the receiver to the mirror’s elements. Since the receiver does not interact directly with any other element, the result of 1 minus the view factor between the receiver and the disk must be equal to the sum of all the view factors from the receiver to the finite elements of the cone. These statements are summarised in the following equations:

\[
F_{rec, disk} = \sum_i F_{rec, i} \quad 1 - F_{rec, disk} = \sum_j F_{rec, j}
\]

The term \(rec\) refers to the receiver, \(N_{mirror}\) is the number of finite elements in the mirror and \(N_{cone}\) is the number of finite elements in the conical section.

It is possible to compute analytically the view factors between two parallel disks using the formulae found in [72]. The first verification requirement, which concerns the mirror’s elements is successfully met with only an error of 0.34%. The second one provides an error above 100% (the summation of all the view factors give a value around 0.12 while the theoretical value is 0.03) due to the reasons already commented before in section 5.3: the numerical computation of the view factors between elements close to the edge connecting two structural elements (mirror-cone or cone-receiver) results in values larger than what they are supposed to be. The reason for this error is that the elements are not small enough to perform the simplification made in equation 5.21. The source of the error is identified to be in the edge between the cone and the receiver’s plane and it can be mitigated by applying one of the following methods or a combination of them:

- Increasing the number of nodes, which is not possible right now due to the software’s limitations.
- Redefining the grid so that more nodes are concentrated around the edge. This approach leads to smaller elements around the edge.
- Using the analytical formulae for the view factors between rectangles on different planes [72] not only for elements on the edge but for a larger region around it.

The analysis of these solutions is left for future research projects. For the purposes of this research, the error is assumed to be acceptable since it is divided into all different elements, having a lower impact on the temperature field. This error means that the receiver emits more than in reality. However, considering that the interactions with other parts of the satellite are not considered, this error can be also regarded as a way to take into account that not all the elements of the real thermal system are included in the model. However, it is recommended to evaluate the view factors of the structure using a commercial software, which is supposed to provide more reliable results.
5.6. **Validation and Verification Assessment of the Models**

- **Verification of the Gebhart factors.** The only approach used to verify the Gebhart factors is similar to the first one used before with the view factors: the sum of all the Gebhart factors for a given element must be equal to 1 \( \sum_j B_{ij} = 1 \). The main error is found again in the Gebhart factors between the receiver and the rest of the elements, exceeding the theoretical limit value of 1 by 12%. Small errors of up to 2.5% are also found in the elements of the mirror and the cone. These results present larger inaccuracies because (1) the errors are carried over from one calculation to the other and (2) the Gebhart factors are obtained by solving numerically a system of 202 equations, which may not provide a perfect result. The verification requirement can be considered to be met following the same reasons presented for the view factors.

- **Verification of the temperature field.** The ideal way to verify the temperature results would be to generate the same model using another algorithm or software and comparing the results. However, it was not possible to obtain a temporary license for ESATAN-TMS, which is one of the most common software packages in the industry. Therefore, the verification of the temperature field has been done by qualitatively analysing the influence of modifying certain input parameters. The design inputs evaluated are the receiver’s efficiency, the emissivity of the mirror’s rear side (which is the surface facing the environment) and the flux received from the light source. The expected and obtained outcomes obtained from these analyses are as follows:
  
  - An increase in the receiver’s efficiency leads to a decrease in the temperature of the entire structure and, specially, the receiver. This relation is due to the fact that higher values of the efficiency imply more power transmitted to the coupled system and, therefore, a lower temperature of the receiver (see table 6.4 in chapter 6 for numerical values). Since the temperature of the receiver is lower, it emits less heat and, consequently, the temperatures of all the nodes decrease. The receiver is the element of the model with the highest temperature, so the radiation it emits has a strong effect on the temperature distribution over the surface of the concentrator.
  
  - A higher emissivity leads to lower temperatures in the mirror section. If the emissivity of the material is larger, the heat the reflector radiates to space is increased and, therefore, its temperature decreases. Table 5.1 presents the numerical results of increasing the emissivity from 0.05 to 0.88. As can be observed, all the temperatures are decreased, specially those of the mirror.

<table>
<thead>
<tr>
<th>Geometry</th>
<th>( \eta_{\text{rec}} ) [%]</th>
<th>( \epsilon_{\text{rear}} ) [-]</th>
<th>Mirror</th>
<th>Conical section</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( \Delta T ) [K]</td>
<td>( T_{\text{max}} ) [K]</td>
<td>( T_{\text{min}} ) [K]</td>
<td>( \Delta T ) [K]</td>
</tr>
<tr>
<td>Parabolic</td>
<td>30</td>
<td>0.05</td>
<td>20.9921</td>
<td>596.7</td>
</tr>
<tr>
<td></td>
<td>30</td>
<td>0.88</td>
<td>15.9692</td>
<td>312.8515</td>
</tr>
</tbody>
</table>

- An increase in the solar flux causes larger temperatures in all the elements of the device. Considering the design inputs of the first results shown in table 5.1, an increase in the flux from 1414 W/m² to 3000 W/m² yields an average increase in the temperature field of around 130 K.

<table>
<thead>
<tr>
<th>Geometry</th>
<th>( \eta_{\text{rec}} ) [%]</th>
<th>( \epsilon_{\text{rear}} ) [-]</th>
<th>Mirror</th>
<th>Conical section</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
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<td></td>
<td>30</td>
<td>0.88</td>
<td>15.9692</td>
<td>312.8515</td>
</tr>
</tbody>
</table>

The same problems as with the ray tracing tool are found now for the validation of the thermal model. The only similar concept is the antenna reflector designed for CubeSats by Babuschka et al. [1] and their publications do not include any information about thermal analyses. Stegman et al. [11] developed a thermal model similar to the one used in this project for the Astromesh™ concept and they validated the results with experimental data. The Astromesh™ reflector is a membrane reflector which uses a metallic structure for the outer edge and cords to ensure that the desired shape is attained (see section 4.1). They tested the reflector with half of it shadowed by a field stop and the other one subjected the solar radiation. Even though the design is quite different and it is not the appropriate one for the model validation, it is at least possible to evaluate how well it performs. Table 5.2 and figure 5.19 show the temperature distribution and the main values.
Table 5.2: Main results and errors of the thermal model applied to the Astromesh\textsuperscript{TM} reflector under the test conditions mentioned in \cite{11}

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Error</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum temperature</td>
<td>61.024</td>
<td>-16.97</td>
<td>\degree C</td>
</tr>
<tr>
<td>Minimum temperature</td>
<td>-134.92</td>
<td>8.083</td>
<td>\degree C</td>
</tr>
</tbody>
</table>

There are many differences between the model generated by Stegman et al. and the one applied in this research project:

- No structure apart from the membrane has been considered.
- It was not possible to find the optical properties of the material so it was assumed that the same reflective film used in this project is used by Northrop Grumman. Estimating the optical properties of the material is a big assumption which can lead to large errors.

Nevertheless, the same qualitative trend is observed here and in the test results presented in \cite{11}. Both the illuminated and the shadowed areas have relatively uniform temperature distributions and the thermal gradient at $y = 0$ is quite steep. The weird shape of the edge observed in figure 5.19 is due to the discretisation method used. If the quantitative results are compared, the maximum error in the calculations made by Stegman et al. were around 9\degree C, which is not much smaller than the outcomes shown in table 5.2. It can be thus assumed that the thermal model provides good results with an acceptable level of accuracy for the conceptual phase of the research project. More accurate results are expected if the real material’s properties and the interactions with the other structural components of the system are included.

As a conclusion, the lack of experimental results for thermal testing of inflatable structures for small satellites complicates the validation of the model built up during this project. However, it has been applied to the membrane reflector tested by Stegman et al. \cite{11} with good quantitative and qualitative results even though there uncertainties such as the materials properties or the effect of the support structure. Therefore, the model can be assumed be validated for this stage of the research project. It is highly recommended to study ways to test the reflector and measure its temperature distribution in future projects.

5.6.3. Structural Model

Verifying the Finite Element Model built up for concentrator can be performed by qualitatively analysing the influence of changes in the pressure and thermal loads on the deformation field. Greschik et al. \cite{76} performed a sensitivity study of the shape error of inflatable structures w.r.t. these two loads. It was observed that increasing the pressure has two opposite effects: the error is increased because the stress field induced is larger but, at the same time, the errors due to thermal loads are reduced. Another conclusion derived from the same study is the fact that thinner membranes experience larger deformations. All these effects have been observed in the results obtained from the Finite Element Model built up during this research project, whose outcomes are discussed in chapter 6.

The accuracy levels of FEMs is well known, specially if commercial software packages, such as ANSYS, are used. For instance, the FEM generated by Stegman et al. for the Astromesh\textsuperscript{TM} reflector was correlated with errors below 0.28 mm for the shadowed side and 0.03 mm for the illuminated area. Nevertheless, one of the common outcomes of the employment of this technique to thin film materials is the strong influence on the results of any disturbance or non-uniformity, such as structural support components or joining materials (tape or resin, for example) \cite{40} \cite{75}. It is concluded that the validation of the model cannot be performed at this stage of the project. The test campaign planned for this research project does not include structural analyses due to the lack of the equipment needed to measure the deformations experienced by a thin-film structure. Moreover, the model validation would require the development of high precision finite element models to take into account every element in the test set-up and the limitations of the academic license do not allow it.
This chapter describes the first iteration of the design loop previously explained in chapter 5, from the definition of the geometry (section 6.2) and its thermo-structural analysis (section 6.3) until the estimation of the performance of the deformed structure (section 6.4) All the calculations are performed for a receiver with an inlet diameter of 2.5 cm, according to the STP engine designed by Leenders [16].

A preliminary design is obtained as a result of this chapter, together with different observations and conclusions about the behaviour of the concentrator.

6.1. INITIAL CONSIDERATIONS: REQUIREMENTS AND OBJECTIVES

The requirements considered for the generation of the preliminary design are presented in table 6.1, whereas the rationales for the values in them can be found in section 3.1.2 with the rest of the requirements. As can be observed, those functional requirements originally presented as the design driver requirements are not included at this point. Nevertheless, they will be used afterwards to verify the design.

Table 6.1: Requirements considered for the preliminary design

<table>
<thead>
<tr>
<th>Id.</th>
<th>Requirement</th>
</tr>
</thead>
<tbody>
<tr>
<td>REQ-A-1</td>
<td>The concentrator system shall fit in 1 PocketCube Unit in the packaged configuration.</td>
</tr>
<tr>
<td>REQ-A-2</td>
<td>The aperture of the concentrator shall be between 5 and 10 times the size of a PocketCube Unit (25-50 cm)</td>
</tr>
<tr>
<td>REQ-F-3</td>
<td>The concentrator system shall be able operate for an angle range of $\Delta \Phi = \pm 5$ [deg] with respect to the nominal orientation.</td>
</tr>
</tbody>
</table>

As explained before in section 5.5, the dimensions of the concentrator are such that the packaging volume does not exceed the value given by REQ-A-1. Using the design made by Babuscia et al. [1] as a reference, this constraint is translated into a maximum surface area of 0.58 m$^2$. For more information on how this value is obtained and how the surface area is derived from the design parameters, refer to subsection 5.5.2.

For this preliminary design, both spherical and parabolic shapes are considered. The geometrical parameters to be determined, which were defined in chapter 5, are as follows:

- **Parabolic design:** focal length ($f$) and aperture half angle ($\theta_c$).
- **Spherical design:** radius of the spherical cap ($R$) and aperture half angle ($\theta_c$).

The aperture can be derived from these parameters as explained before in section 5.2 and the performance is calculated using the Ray Tracing Tool (section 5.2).

The final objective of this chapter is to make a decision on the concentrator shape, define the optimal geometry and derive an ideal performance estimation and a more realistic one based on the deformations
experienced by the structure. It is also necessary to determine the design point conditions, in terms of inflating pressure and thermal load.

6.2. GEOMETRY DEFINITION UNDER IDEAL CONDITIONS
The first step in the design process is the definition of the optimal geometry under ideal conditions, which means that the concentrator is not deformed. Preliminary analyses based on the bi-dimensional tool are first shown in subsection 6.2.1 to have an idea of the impact of the different design parameters and the main differences between the shapes considered. The geometry is defined afterwards in subsection 6.2.2 using the Optimisation Tool previously introduced in chapter 5.

6.2.1. PRELIMINARY OUTCOMES BASED ON THE BI-DIMENSIONAL RAY TRACING TOOL
This subsection has the intention of analysing the impact of the design variables and the shape on the performance capabilities of the system. The bi-dimensional tool is employed in this case due to the lower computational time compared to the three-dimensional version. As seen in figure 6.1, both shapes are quite similar close to the axis of revolution but the difference between them is increased as we move further from the axis.

Figure 6.1: Comparison between the geometries of a parabolic and a spherical concentrator for f = R = 0.5 m and an aperture of 0.48 m

From an optical point of view, the behaviour of the sphere resembles that of the paraboloid close to the vertex. Moreover, the focal length of the sphere can be approximated as \( f = R/2 \) for small apertures but this assumption loses its validity as we move towards the edge of the mirror. This effect, which is clearer for larger apertures, is the so-called “spherical aberration”, an error independent on the wavelength and only dependent on the reflector’s geometry [69]. It is thus necessary to determine the optimal location of the receiver. This effect can be easily seen in figure 6.2, which shows how the beams behave when they are reflected by both shapes, using \( f = R = 0.5[m] \) and an aperture of 0.48 m. As can be observed, the rays hitting the parabola end up on the same point, the focus. In case of the spherical design (figure 6.2), the intersection points between the reflected rays and the main axis varies depending on where the rays hit the reflector. The rays hitting the mirror on the region close to the axis collide approximately on the same point (\( R/2 \)), while the other beams intersect the axis on points closer to the vertex.

Figure 6.2: Comparison of how rays are reflected with a parabolic (left) and a spherical reflector (right)

The difference in the optical behaviour is the reason why the efficiency, which is measured as the ratio between the power hitting the reflector and the power hitting the receiver, of both shapes differ. The efficiency
with respect to the Sun vector for both shapes is as seen in figure 6.3. The angle $\Delta \Phi_{\text{Sun}}$ is the difference between the nominal Sun vector and the real direction of the solar rays. This figure includes two curves for the spherical shape: one assuming that the focal length equals $R/2$ and a second one which results from optimising the receiver’s position. The difference in terms of efficiency is considerable, with a maximum difference of almost 33% in nominal conditions if $f = R/2$ is assumed for the spherical geometry. This difference almost disappears under nominal conditions if the position is optimised, so it is decided to include this functionality in the 3-dimensional Ray Tracing Tool as well.

![Comparison of the performance of spherical and parabolic reflectors for $R = f = 0.5$ [m] and $D = 0.48$ [m]](image)

Figure 6.3: Comparison of the efficiencies of both shapes with respect to the Sun vector for a spherical design of radius 0.5 m and a parabolic design of focal length 0.5 m. Both designs have the same aperture, 0.48 m

The parabolic concentrator outperforms the spherical design. However, the angle range for which the parabolic reflector works is really narrow, with a cut-off angle of around 1.5 deg. Therefore, a trade-off between the nominal performance and the sensitivity to the Sun vector must be made, which is exactly the purpose of the second target function of the Optimisation Tool (section 5.5) and the rationale for REQ-F-3. Regarding the cut-off angle for spherical concentrators, the reflector keeps providing radiation on the receiver for angles up to almost 5 deg, even though it operates at a really low efficiency (figure 6.3). It is also seen that the efficiency curve for spherical reflectors include a change in the trend for $\Delta \Phi_{\text{Sun}} \approx 3 – 4$ deg. As well as with the parabolic design, these changes in the trends are due to the way the spot moves over on the focal plane.

The analyses about the influence of the design parameters yielded the following conclusions:

- The efficiency of both geometries benefit from reductions in the aperture half angle and the focal length or radius. Moreover, they also exhibit a lower sensitivity to variations in the Sun vector. The influence of the three parameters is explained separately below:
  - **Aperture half angle.** The influence of the Sun vector is larger when the hitting point is further away from the axis. The region close to the axis is the least sensitive to changes in the orientation of the incoming beams. Therefore, the effect is more pronounced for larger apertures. It must be reminded that the power received in each case is proportional area to the aperture and, therefore, larger apertures are more sensitive to the Sun vector but they provide more power. In case of spherical mirrors, the so-called “spherical aberration” is more relevant for larger apertures.
  - **Focal length of parabolic reflectors.** The efficiency is larger for lower focal lengths since they have a lower concentration ratio for the same aperture’s half angle (the aperture is smaller) and thus they are less sensitive to changes in the orientation of the beams. They are also closer to the receiver so the location of the spot is not so sensitive to changes in $\Delta \Phi_{\text{Sun}}$.
  - **Radius of spherical mirrors.** The efficiency is higher for lower values of the radius since the mirror is closer to the receiver and the concentration ratio is smaller. It is thus easier to focus the rays on the receiver’s area and a lower number of beams miss the target.

- The parabolic geometry is more efficient and it reflects a higher level of power to the receiver.
• The parabolic geometry has a more efficient use of the available surface. If we consider a spherical reflector and a parabolic concentrator with the same aperture half angle such that the radius is equal to the focal length, the aperture of the parabolic design is larger.

6.2.2. 3-DIMENSIONAL ANALYSES: DEFINITION OF THE OPTIMAL DESIGN.

The Optimisation Tool based on the 3-D Ray Tracing Model is now used to estimate the optimal design parameters for both the parabolic and the spherical design taking into account the surface area constraints derived from the maximum packaging volume. If only nominal conditions, in which the Sun vector is aligned with the axis, are considered, the best designs are as depicted below in table 6.2.

Table 6.2: Optimal design parameters considering only nominal conditions

<table>
<thead>
<tr>
<th></th>
<th>R or f [m]</th>
<th>(\theta_c) [deg]</th>
<th>(P_{rec}) [W]</th>
<th>(\eta) [%]</th>
<th>D [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parabolic Concentrator</td>
<td>0.175</td>
<td>79.93</td>
<td>379</td>
<td>100</td>
<td>0.58</td>
</tr>
<tr>
<td>Spherical Concentrator</td>
<td>0.567</td>
<td>28.58</td>
<td>320.74</td>
<td>98.24</td>
<td>0.54</td>
</tr>
</tbody>
</table>

The same analysis can be performed taking into account also the performance of the reflector over an angular range of 0 to 5 degrees in the deviation with respect to the nominal orientation (requirement REQ-F-3). This is done using the second target function of the optimisation algorithm (see subsection 5.5.1). The resulting optimal designs, shown in table 6.3 depend on the parameter \(\nu\), which is a measure of how relevant the sensitivity is with respect to the nominal performance.

Table 6.3: Optimal design parameters considering nominal conditions and off-axis sun rays

<table>
<thead>
<tr>
<th>(\nu) [-]</th>
<th>f [m]</th>
<th>(\theta_c) [deg]</th>
<th>(P_{target}) [W]</th>
<th>D [m]</th>
<th>R [m]</th>
<th>(\theta_c) [deg]</th>
<th>(P_{target}) [W]</th>
<th>D [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1</td>
<td>0.175</td>
<td>79.93</td>
<td>381.83</td>
<td>0.59</td>
<td>0.567</td>
<td>28.58</td>
<td>297.12</td>
<td>0.54</td>
</tr>
<tr>
<td>0.2</td>
<td>0.175</td>
<td>79.93</td>
<td>325.45</td>
<td>0.59</td>
<td>0.567</td>
<td>28.58</td>
<td>273.51</td>
<td>0.54</td>
</tr>
<tr>
<td>0.3</td>
<td>0.175</td>
<td>79.93</td>
<td>299.06</td>
<td>0.59</td>
<td>0.567</td>
<td>28.58</td>
<td>249.88</td>
<td>0.54</td>
</tr>
<tr>
<td>0.4</td>
<td>0.175</td>
<td>79.93</td>
<td>272.67</td>
<td>0.59</td>
<td>0.567</td>
<td>28.58</td>
<td>226.26</td>
<td>0.54</td>
</tr>
<tr>
<td>0.5</td>
<td>0.213</td>
<td>69.09</td>
<td>246.45</td>
<td>0.58</td>
<td>0.567</td>
<td>28.58</td>
<td>202.65</td>
<td>0.54</td>
</tr>
<tr>
<td>0.75</td>
<td>0.2125</td>
<td>69.09</td>
<td>181.51</td>
<td>0.58</td>
<td>0.567</td>
<td>28.58</td>
<td>143.60</td>
<td>0.54</td>
</tr>
<tr>
<td>0.9</td>
<td>0.2125</td>
<td>69.09</td>
<td>142.54</td>
<td>0.58</td>
<td>0.567</td>
<td>28.58</td>
<td>108.17</td>
<td>0.54</td>
</tr>
</tbody>
</table>

Comparing both designs, the value of the target function and the nominal power of the parabolic geometry are larger for every value of \(\nu\). The optimal parabolic geometry changes for \(\nu \geq 0.5\), which means that there is a change in the optimal design if the average performance is considered as important or more than the nominal performance. Therefore, the selection of the preliminary design for the parabolic shape depends on the weight factor, \(\nu\). Nevertheless, the optimal spherical design does not change and it is not the same as the one which provides the highest aperture (as seen in figure 5.14). The optimal geometry has a larger radius and a lower aperture's half angle than the design with the highest aperture.

It has been decided that the nominal performance is more relevant and thus \(\nu \leq 0.5\). This decision is taken based on the fact that current COTS ADCS developed for CubeSats are able to attain pointing accuracies lower than 1 degree [77] [78]. Although there are no systems specifically designed for PocketQubes, which is the reason why the parameter \(\nu\) is included, it is assumed that the concentrator will operate around the nominal orientation and deviations will be occasional. However, this design decision may be reviewed depending on the attitude requirements of other systems or the pointing accuracy attainable the ADCS designed for Delfi-PQ.

Hence, the preliminary optimal designs selected for both shapes are those seen in table 6.2 for \(0 \leq \nu < 0.5\). The power provided by these two geometries are as depicted below in figure 6.4 together with the difference in the power output. It can be seen that the spherical design does only outperform the parabolic mirror for an angle around \(\Delta \Phi \approx 4\) [deg] with a really low difference. For lower angle deviations, the difference reaches values up to 74 W. Only five values of the angle \(\Delta \Phi\) are considered due to the computational time.
6.3. THERMAL AND STRUCTURAL DESIGN

As previously mentioned in chapter 2, one of the main issues related to inflatable structures is the shape inaccuracy caused by the deformations of the membrane as a response to the inflating pressure and the thermal loads. It is thus necessary to analyse the real performance of the system taking into account the deformations. After this, it is possible to design a concentrator with a geometry such that it will have the desired shape once pressurised (chapter 7). The steps to be followed involve the selection of the material, the thermal analysis of the structure and the estimation of the deformations. For this last task, finite element models for both the spherical and the parabolic designs are built up and they are simulated for different inflating pressures in the range of 1 to 200 [Pa]. It is decided to perform two separate analysis, considering only the pressure load and including both the pressure and the thermal load, so that the contribution of both loading conditions can be derived.

6.3.1. MATERIAL SELECTION

The first decision to be taken regarding the structural design is the selection of the materials. As a result of the literature study [17], polyimides are identified as the most common materials for space inflatable structures due to their low density and their good thermal and structural performance. For example, Mylar™ and Kapton™, both developed and manufactured by DuPont Teijin Films, are usually employed for space purposes [1] [10]. Equivalent polymers (such as silicone based materials [28]) are developed by other manufacturers but they do not appear as often in the literature about inflatable space devices as the other two materials.

It is decided to use Mylar™ because of its commercial availability, structural properties and the possibility to find it transparent and with reflective coatings. It is also regarded as a good option due to the broad range of thickness in the market. For the following structural design a 23µm sheet is assumed after conversations with the supplier (Lohmann tapes, Inc.). A Kenpro mirror film is considered for the reflective segment of the reflector. The characteristics of both materials can be found in appendix C.

6.3.2. THERMAL ANALYSIS

The main results of the thermal model, which will be used for the structural analysis, are the maximum temperature difference, the thermal gradient, the maximum and minimum temperatures and the location in the structure of these extreme temperatures. The model requires a set of inputs, which were already described in chapter 5. The values used in this chapter are presented hereafter:

- **Concentrator geometry**: both "optimal" geometries are considered (see table 6.2).
- **Ideal power hitting the receiver**: The values presented before in table 6.2 are considered now as the power input for the receiver
- Parabolic design: 379 [W].
- Spherical design: 320 [W].

- **Clear Mylar™ film optical properties:**
  - Transmissivity: $\tau = 0.85$ [-] [14].
  - Absorptivity: $\alpha = 0.05$ [-] [14].
  - Emissivity: $\epsilon \approx \alpha = 0.05$ [-]. The approach to derive this value for the emissivity is explained below.
  - Thermal conductivity: $\kappa = 0.1549116$ [W/m/K] [13].

- **Mirror film optical properties:**
  - Transmissivity: $\tau = 0.1$ [-] [15].
  - Reflectivity: $r = 0.85$ [-] [15].
  - Absorptivity: $\alpha = 1 - r - \tau = 0.05$ [-]. This coefficient is obtained based on the transmittance and reflectivity of the film, which were given by the supplier [15].
  - Front side’s emissivity: $\epsilon_{\text{front}} \approx \alpha = 0.05$ [-]. As well as with the Mylar™ film, the emissivity derivation is explained below.
  - Thermal conductivity: $\kappa = 0.19$ [W/m/K]. This parameter was not given but the supplier, so it was estimated based on usual values for aluminised films from [79].

- **Mirror’s efficiency:** 0.85 [-]. This initial estimation is taken based on [26] until a more accurate efficient is derived.

- **Receiver’s optical properties:** The parameters corresponding to black carbon paint coatings [80] are assumed at this point of the research project.
  - Absorptivity: $\alpha = 0.96$ [-].
  - Emissivity: $\epsilon = 0.96$ [-].

- **Discretisation resolution.** It is necessary to establish the number of points in which the surface is divided. A higher number of elements implies a higher accuracy but also longer computational times. As commented in chapter 5, the number of elements is limited by MATLAB to 202, so the mirror and the cone were divided into 100 elements. The other two elements in the model are the receiver and the environment. The mesh grid generated for both geometries can be seen in figure 6.5, in which every intersection of lines represent a node. The fact that the mesh is not closed is because only nodes are represented and the discretisation accuracy is not high enough.

![Mesh for the parabolic design](image1)
![Mesh for the spherical design](image2)

Figure 6.5: Finite element mesh for the parabolic (left) and the spherical (right) geometries
The emissivity of both membrane materials were estimated since they were not provided by the supplier. The value for the mirror film is based on usual coated films (Domen [81] obtained a value of $\epsilon = 0.044$ [-]) and the one for Mylar™ was taken as a worst case scenario since no bibliographic data was found for clear polyimide films. Kapton™ and transparent plastics have higher emissivities than 0.05 (above $\epsilon \approx 0.5$ [-]) and, therefore, they are able to emit larger amount of heat. If the emissivity of Mylar were similar to these other values, the thermal load on the structure would be lower. That is the reason why assuming that $\epsilon \approx \alpha$ is considered to be the worst case scenario. At this point of the project it was not possible to obtain more accurate values for the emissivities and DuPont Teijin Films communicated that they do not measure this property in standard tests. It is thus highly recommended to perform experimental studies on the mirror film or any analogous material in following phases of the project. The receiver efficiency was not given before. In order to analyse the sensitivity of the thermal performance of the structure with respect to those parameters, values of 30%, 50% and 85% are employed. The first value is close to the efficiency of current thin film photovoltaic systems [82] [43]. The other two are similar to those found in publications about STP [26] [67] [25].

The temperature fields for both geometries considering $\eta_{rec} = 0.85$ [-] is presented below in figures 6.6 and 6.7 as examples of the model results. Both designs have been rotated compared to the mesh grids seen in figure 6.5 to have a better view of the temperature distribution over the mirror. The temperature fields present a maximum on the vertex (figure 6.7) or close to it (figure 6.6) and they decrease until it reaches the minimum value on the edge. It was observed that the region with the maximum temperatures changes depending on the model’s inputs in the case of the parabolic concentrator. For lower values of $\eta_{rec}$, the maximum temperature is on the vertex while, in this case, it is found on a region around the vertex. Two possible non-exclusive reasons have been found:

- The discretisation level may be not fine enough to obtain a more accurate temperature field. However, it cannot be improved due to the limitations imposed by MATLAB and it is not possible to prove this hypothesis.

- The temperature of the receiver changes with its efficiency. It might be possible that the temperature at the vertex and around it behaves as seen in figure 6.6 to reach the heat balance conditions. The mirror receives radiation from the receiver and the Sun. If the efficiency is higher, the radiation received from the receiver decreases and it may be possible that the solar radiation turns to be more relevant. Therefore, the region in the shadow caused by the satellite, which is around the vertex, is colder than its surroundings.

For a better visual analysis of the temperature distribution on the mirror, the temperature contours projected on the XY-plane are presented below in figures 6.8 and 6.9. As can be observed in both figures, the axisymmetry of the temperature field is lost on the outer edge, where the lowest temperature is found. This error is a consequence of the generated mesh, which does not include the edge of the mirror.
Regarding the conical section of the structure, the maximum temperatures are close to the receiver or, in other words, close to the base of the cone. The temperature decreases until it reaches the minimum on the edge. This trend could also be seen in figures 6.6 and 6.7.

All the main results are showed below in table 6.4 as a function of the input parameters. As can be inferred from the data presented, the maximum temperature difference and the maximum and minimum temperatures in both the mirror and the cone decrease as the efficiency of the receiver is larger. This is explained by the fact that a higher efficiency means that larger amounts of power are transmitted to the coupled system and, therefore, the receiver emits less heat to the structure. The temperatures for the spherical design are larger even though the solar power reflected to the receiver is 15.37% lower. However, the temperature distribution is more homogeneous, with lower thermal gradients. The reason is that the region with the highest temperature is more concentrated in the case of the spherical design, while it is more spread in the case of the parabolic reflector.

The model also allows to have an estimation of the receiver’s temperature and the power lost in the receiver due to radiation heat exchange. These values are presented below in table 6.5 with respect to \( \eta_{rec} \). The temperature of the receiver is lower when its efficiency is higher, which is an obvious result since a larger efficiency means that more energy is transmitted to the coupled subsystem and not absorbed by the receiver.

<table>
<thead>
<tr>
<th>Geometry</th>
<th>( \eta_{rec} ) [%]</th>
<th>Mirror</th>
<th>Conical section</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( \Delta T ) [K]</td>
<td>( T_{\text{max}} ) [K]</td>
<td>( T_{\text{min}} ) [K]</td>
</tr>
<tr>
<td>Parabolic design</td>
<td>30</td>
<td>20.99</td>
<td>596.7</td>
</tr>
<tr>
<td></td>
<td>50</td>
<td>18.59</td>
<td>557.71</td>
</tr>
<tr>
<td></td>
<td>85</td>
<td>14.22</td>
<td>461.58</td>
</tr>
<tr>
<td>Spherical design</td>
<td>30</td>
<td>10.75</td>
<td>615.51</td>
</tr>
<tr>
<td></td>
<td>50</td>
<td>10.46</td>
<td>575.15</td>
</tr>
<tr>
<td></td>
<td>85</td>
<td>10.34</td>
<td>472.27</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Geometry</th>
<th>( \eta_{rec} ) [%]</th>
<th>( \epsilon_{\text{rear}} ) [-]</th>
<th>( T_{\text{rec}} ) [K]</th>
<th>( P_{\text{loss}} ) [W]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parabolic design</td>
<td>30</td>
<td>0.05</td>
<td>1579.7</td>
<td>165.61</td>
</tr>
<tr>
<td></td>
<td>50</td>
<td>0.05</td>
<td>1452.7</td>
<td>118.29</td>
</tr>
<tr>
<td></td>
<td>85</td>
<td>0.05</td>
<td>1078.3</td>
<td>35.49</td>
</tr>
<tr>
<td>Spherical design</td>
<td>0.3</td>
<td>0.05</td>
<td>1383.83</td>
<td>139.83</td>
</tr>
<tr>
<td></td>
<td>0.5</td>
<td>0.05</td>
<td>1272.92</td>
<td>99.88</td>
</tr>
<tr>
<td></td>
<td>0.85</td>
<td>0.05</td>
<td>946.41</td>
<td>29.96</td>
</tr>
</tbody>
</table>
The results obtained from these analyses are used as inputs for the structural analysis of the concentrator. Out of all the cases analysed, only two temperature distributions will be used for each geometry, which correspond to the best and the worst cases (those with the highest and lowest receiver’s efficiency, respectively). The influence of using a coating for the mirror’s rear side will be analysed in following steps of the project if it is considered to be necessary to lower the temperature of the reflective side of the structure.

### 6.3.3. Structural Analysis

The designs obtained from the optimisation tool are now analysed under the mechanical and thermal loading conditions to have a better estimation of the geometry of the deployed structure. The following material properties are used:

- **Clear Mylar™ film [13]:**
  - Density: 1.39 g/cm³.
  - Coefficient of Thermal Expansion: $1.7 \cdot 10^{-5}$ K$^{-1}$.
  - Young Modulus: 4895.3 MPa.
  - Poisson’s ratio: 0.3 [-].
  - Tensile Ultimate Strength: 199.95 MPa.
  - Compressive Ultimate Strength: 234.42 MPa.

- **Mirror film [15]:**
  - Density: 2.25 g/cm³.
  - Coefficient of Thermal Expansion: $1.9 \cdot 10^{-5}$ K$^{-1}$.
  - Young Modulus: 2800 MPa.
  - Poisson’s ratio: 0.3 [-].
  - Tensile Ultimate Strength: 196.133 MPa.
  - Compressive Ultimate Strength: 229.9449 MPa.

There is no information available about the Poisson’s ratio for both materials so a value of $\nu_{\text{poisson}} = 0.3$ [-] is assumed. This value is usually employed in structural analyses and it is close to that of Kapton™, which is a material with similar structural properties ($\nu_{\text{poisson, Kapton}} = 0.34$ [83]). The compressive ultimate strength of the Mirror film was neither provided by the supplier nor found after a literature review. Thus, an analogy based on the ratio for the tensile ultimate strength for both materials ($\sigma_{\text{ult, mirror}}/\sigma_{\text{ult, mylar}} = 0.9809$ [-]) is used to have an estimation of the value.

The first set of simulations was performed considering the inflating pressure as the only load. As can be observed in figure 6.10, the maximum deformations are found on the mirror surface with values approximately uniform over it. Wrinkles develop in the interface between the mirror and the transparent cone and this phenomenon is more pronounced for inflating pressures over 10 Pa, while it is almost negligible for $P \leq 10$ [Pa]. In fact, it is necessary to magnify the deformations 12 times to really appreciate the wrinkles for $P = 10$ [Pa] (figure 6.10). The results obtained for this design matches the observations made by Babuscia et al. [1] for their inflatable reflector for a CubeSat. In their publication, Babuscia et al. presented a picture of the reflector inflated inside a vacuum chamber and it is possible to appreciate wrinkles around the interface between the reflective and the transparent sections and the deformation of this area into a more cylindrical shape.

The wrinkles are also observed in the spherical design but the frequency and amplitude are lower. In other words, there are less wrinkles and they are smaller. Another difference with the parabolic design is that the maximum deformation is at the edge of the mirror’s section with the rest of the surface presenting an homogeneous deformation field. As seen in figure 6.10, the parabolic design presents the entire mirror with approximately the maximum deformations. The cone preserves almost its shape with the lowest level of deformations of the entire structure, except for the connection region with the reflective section. As can be inferred, the deformations are larger if the pressure is increased and the amplitude and frequency of the wrinkles are also greater. This observation complies with the conclusions obtained in [76].
The connection is also the location of the largest combined equivalent Von-Mises (see figure 6.11) and shear stresses (see figure 6.12). These results mean that it is necessary to take special care of the joining method between both structural sections to ensure the absence of leaks and to prevent or mitigate the formation of wrinkles, since they are more likely to be found here. The equivalent Von-Mises stress field is relatively uniform for the entire structure except for this region. The gradient in the stress field is quite high, increasing several order of magnitudes in a short distance. It is necessary to analyse if a softer transition from the conical section to the parabolic one would reduce the stress in this region, thus reducing the risk of leaks and wrinkles. The same trend is observed when the shear stress field is analysed. The maximum and minimum values, which are positive and negative, respectively, are found in the interface between the upper and the lower cap. The gradient leads to the formation of the wrinkles. As well as with the equivalent Von-Misses stresses, the shear stresses are relatively uniform in the rest of the structure. The same behaviour with respect to the pressure is observed in both geometries, but the stresses and the shear stress gradients are higher in the parabolic design, which leads to more and larger wrinkles.

Table 6.6 presents three main parameters resulting from the structural analysis of both geometries with respect to the inflating pressure: the maximum displacement in the mirror, the maximum equivalent stress and the so-called \( \text{rms} \) error.
Table 6.6: Main results of the structural analysis of the preliminary designs with respect to the inflating pressure without including the thermal load. The equivalent stress is the Von-Mises equivalent stress.

<table>
<thead>
<tr>
<th>Pressure [Pa]</th>
<th>1</th>
<th>5</th>
<th>10</th>
<th>50</th>
<th>100</th>
<th>150</th>
<th>200</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Parabolic design</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Maximum displacement [mm]</td>
<td>0.78</td>
<td>3.91</td>
<td>7.82</td>
<td>39.09</td>
<td>78.18</td>
<td>117.27</td>
<td>156.36</td>
</tr>
<tr>
<td>Maximum equivalent stress [MPa]</td>
<td>2.17</td>
<td>10.08</td>
<td>21.71</td>
<td>108.57</td>
<td>217.14</td>
<td>325.71</td>
<td>434.27</td>
</tr>
<tr>
<td><em>rms</em> error [mm]</td>
<td>0.73</td>
<td>3.67</td>
<td>7.31</td>
<td>36.69</td>
<td>73.38</td>
<td>110.08</td>
<td>146.79</td>
</tr>
<tr>
<td><strong>Spherical design</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Maximum displacement [mm]</td>
<td>0.21</td>
<td>1.04</td>
<td>2.081</td>
<td>10.40</td>
<td>20.80</td>
<td>31.20</td>
<td>41.61</td>
</tr>
<tr>
<td>Maximum equivalent stress [MPa]</td>
<td>1.12</td>
<td>5.61</td>
<td>11.21</td>
<td>56.07</td>
<td>112.13</td>
<td>168.2</td>
<td>224.26</td>
</tr>
<tr>
<td><em>rms</em> error [mm]</td>
<td>0.17</td>
<td>0.83</td>
<td>1.67</td>
<td>8.35</td>
<td>16.72</td>
<td>25.05</td>
<td>33.42</td>
</tr>
</tbody>
</table>

The second set of simulations is performed including the effect of the temperature field over the concentrator. The two cases mentioned before as a conclusion of the Thermal Analysis (see 6.3.2) are considered, which correspond to the best and worst scenarios analysed. These temperature fields are approximated using polynomial interpolation to be used in ANSYS.

A qualitative analysis of the results can be performed also with this new set of data. In this case, for $P = 1$ [Pa] the maximum displacement is located on the edge of the mirror and the deformations are less uniform over the upper cap. The formation of wrinkles is clearer even for an inflating pressure of 1 Pa. As the pressure is increased, the approximate uniformity over the mirror seen in previous analyses is recovered (as seen in figure 6.13). However, the deformations in the cone are not as close to be constant as in the previous analyses. In this case, there is a negative displacement of all the nodes around the cone’s base associated to the large temperatures in this region. The deformations get slightly lower, before increasing again until the edge. The negative displacements in the vertical axis at the interface region mean that it is necessary to redesign the FEM model to include the base plate to which the concentrator is connected if more realistic results are required. The lack of uniformity in the deformation field of the cone is not seen for inflating pressures $p \geq 50$ [Pa]. Therefore, the thermal effects seem to be mitigated by increasing the pressure. The same trend is observed in the spherical design, although the wrinkles exhibit a lower amplitude and frequency, as previously observed in the FEM analysis without the thermal load. The uniformity in the deformations of the mirror is not attained for $P < 10$ [Pa].

![Figure 6.13: Deformations (magnified x12) of the parabolic concentrator for $p = 10$ [Pa] and the worst case of thermal load](image-url)
Regarding the equivalent Von-Mises stress field, the maximum values are found at the base of the cone for inflating pressures below 10 Pa, while the rest of the structure exhibits a relatively uniform field. For 10 Pa (see figure 6.14), this uniformity is no longer clear, specially for the worst thermal case. If the pressure is further increased, the edge between the mirror and the cone presents important stresses as well as the base. Both the spherical and the parabolic structures have the same behaviour, although the transition from a mostly uniform stress field to the one in which there are two regions of concentrated high stress (the base and the connection edge) happens for pressures slightly higher in the spherical case. At really low pressures, the thermal load is dominant, concentrating the highest stresses around the cone’s base. The values of the stress field in the edge between the mirror and the cone are larger as the pressure is increased. The shear stress field exhibits the same trend as in the analyses performed before (see figure 6.15).

![Figure 6.14: Equivalent Von-Mises Stress field over the parabolic concentrator for P = 10 [Pa] and the worst case of thermal load](image)

![Figure 6.15: Shear Stress field over the parabolic concentrator for P = 10 [Pa] and the worst case of thermal load](image)

The main results are presented in table 6.6 including those for the best (first value) and the worst (second value) thermal cases.

<table>
<thead>
<tr>
<th>Pressure [Pa]</th>
<th>1</th>
<th>5</th>
<th>10</th>
<th>50</th>
<th>100</th>
<th>150</th>
<th>200</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Parabolic design</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Maximum displacement [mm]</td>
<td>2.56-3.18</td>
<td>4.65-4.49</td>
<td>8.34-7.15</td>
<td>39.16-36.49</td>
<td>78.21-73.27</td>
<td>117.29-110.08</td>
<td>156.37-146.91</td>
</tr>
<tr>
<td>Maximum equivalent stress [MPa]</td>
<td>35.09-44.52</td>
<td>35.1-44.52</td>
<td>35.1-44.53</td>
<td>107.65-103.51</td>
<td>216.2-208.3</td>
<td>324.8-313.01</td>
<td>433.33-417.76</td>
</tr>
<tr>
<td>rms error [mm]</td>
<td>1.155-0.814</td>
<td>4.076-3.47</td>
<td>7.74-6.93</td>
<td>37.07-34.5</td>
<td>73.77-68.99</td>
<td>110.477-103.5</td>
<td>147.18-137.99</td>
</tr>
<tr>
<td><strong>Spherical design</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Maximum displacement [mm]</td>
<td>2.63-3.81</td>
<td>3.325-4.42</td>
<td>4.27-5.27</td>
<td>12.12-13.1</td>
<td>22.45-23.37</td>
<td>32.82-33.72</td>
<td>43.21-44.1</td>
</tr>
<tr>
<td>Maximum equivalent stress [MPa]</td>
<td>34.5-47.53</td>
<td>34.5-47.53</td>
<td>34.5-47.53</td>
<td>54.93-54.02</td>
<td>110.99-110.08</td>
<td>167.06-166.15</td>
<td>223.13-222.21</td>
</tr>
<tr>
<td>rms error [mm]</td>
<td>2.04-2.73</td>
<td>2.71-3.4</td>
<td>3.54-4.23</td>
<td>10.21-10.91</td>
<td>18.57-19.27</td>
<td>26.92-27.62</td>
<td>35.27-35.97</td>
</tr>
</tbody>
</table>

The rms error for both geometries under all the conditions is presented below in figure 6.16 as a function of the inflating pressure. As can be observed, the influence of the inflating pressure is much clearer than that of the thermal load. This is mainly due to the fact that the temperature differences considered up to now were low and the thermal expansion coefficients of the materials are quite low (in the order of $10^{-5}$ K$^{-1}$). The rms error of the spherical design is lower than that of the parabolic geometry for the entire range of inflating pressure considered except for 1 Pa.
6.3. THERMAL AND STRUCTURAL DESIGN

The difference in the \textit{rms} error is smaller for extremely low pressures (around 0.01-0.1 mbar) and it becomes more explicit as the pressure is increased. Figure 6.17 shows in detail the \textit{rms} error for this lower range.

The low pressure interval (1-15 Pa) is the most common for space applications. This range is chosen to avoid high flow rates in case of leaks and to lower the mass of the inflating system. For low pressures the highest stress values are concentrated around the cone base, while the stress in the connection between the mirror and the cone increases with pressure becoming as great or greater than that in the base. The shear stress field presents a considerable gradient in the connection between both sections of the concentrator. No conclusion about the relation between the temperature difference and the maximum shear gradient can be inferred since opposite results have been observed in both geometries: the gradient is larger for the best thermal case in the parabolic design and the gradient is larger for the worst thermal case in the spherical one. As was concluded before from the \textit{FEM} results, the effects of the thermal loads are reduced as the pressure is increased. Therefore, a higher pressure means a lower sensitivity to temperature differences at the expense of a heavier inflating system and higher \textit{rms} errors. It is decided to use $p = 10$ Pa as the design point based on a compromise between the different effects observed.
6.4. Performance of the Concentrator Under Deformed Conditions

The previous two sections showed the selection of an optimal geometry and its structural design and analysis. Considering only the ideal performance of the concentrator (see figure 6.4), the parabolic design clearly outperforms the spherical one, with a considerably larger power output under nominal conditions (\(\Delta \Phi = 0\) [deg]) and up to a deviation angle of around 3.75 deg, when the spherical shape gives a slightly higher power output. Based on these results and without considering the deformations, the parabolic design appears as the wisest choice.

However, it was observed in the previous section that the structural response of the device to the load conditions depends on the shape selected. It is necessary to determine what is the performance of the loaded structure to establish the differences with respect to the optimal conditions and derive possible ways to mitigate the influence of the loads. For that purpose, the ray tracing code is now used with the deformed geometries provided by ANSYS. Only the results corresponding to inflating pressures in the range from 1 to 10 [Pa] are considered since they are regarded as the most likely to be used. Considering that the chosen design pressure is 10 Pa, it is strongly encouraged to perform FEM analyses up to 15 or 20 Pa to have more data available around the design point and to perform sensitivity analyses. All the results shown here are obtained assuming ideal values for the reflectivity (\(r\)) and the transmittance (\(\tau\)) of the films:

- Transparent film: \(r_{\text{cone}} = 0\) [-] and \(\tau_{\text{cone}} = 1\) [-].
- Reflective film: \(r_{\text{mirror}} = 1\) [-] and \(\tau_{\text{mirror}} = 0\) [-]

Figures 6.18 and 6.19 show the power output for the system under all the conditions analysed and with respect to variations in the Sun vector orientation (\(\Delta \Phi\)). The optimal performance curve is also included in the figures. In order to reduce the computational cost of the analyses, only 5 values of \(\Delta \Phi\) were evaluated for each case and that is the reason why the curves are not as smooth as it would have been expected. In both cases the influence of the pressure is clearer than that of the thermal load. The power provided by the system decreases with the inflating pressure. The differences with respect to the nominal conditions are easily noticed under nominal conditions (\(\Delta \Phi = 0\) [deg]) and they decrease as the Sun vector changes. In case of the parabolic design, the performance is approximately equal for \(\Delta \Phi \geq 1.25\) [deg]. This means that the effects of variations in the Sun vector orientation are more important than the deformations. It can be actually seen in figure 6.18 that the optimal performance curve shows values below the others. This is due to fact that the ray tracing model uses numerical tools to manipulate the data provided by ANSYS, so the accuracy is limited by the discretisation resolution followed both in MATLAB and ANSYS. It can be also noted that the difference between the curves for pressure loads of 1 Pa and 5 Pa is larger than that seen between 5 Pa and 10 Pa.

![Figure 6.18: Performance of the parabolic reflector under different conditions with respect to the Sun vector](image)

The same behaviour can be observed with the spherical reflector but the performance remains below the optimal values for the entire \(\Delta \Phi\) range except for a orientation deviation of 5 degrees. As well as before, the influence of the pressure is larger than that of the thermal load and the biggest change is seen between the curves corresponding to 1 Pa and 5 Pa.
6.4. PERFORMANCE OF THE CONCENTRATOR UNDER DEFORMED CONDITIONS

If the efficiency is computed for all the cases, it can be seen that the spherical reflector is more efficient under nominal conditions. However, the maximum differences are in the order of 5% and for $\Delta\Phi > 0$ [deg], the parabolic concentrator presents higher values of efficiency. The changes in the optical performance of the system are not as large as it would be expected because the position of the receiver has been optimised for each case. This explains why variations in the $rms$ error from less than 1 mm up to almost 8 mm only cause a decrease in the efficiency of the system from 90.24% to 86.75%. Figure 6.20 shows the performance curves for the design point ($p = 10 \text{ [Pa]}$) under the worst thermal case together with the power difference between both designs. It can be observed that the parabolic reflector presents a better performance over the entire $\Delta\Phi$ range with a lower sensitivity to changes in the orientation of the Sun vector.

The results obtained from the structural analyses are also used to study the image size on the receiver's plate and its variation with respect to the load conditions and the Sun Vector. As seen below in figure 6.21, the parabolic reflector generates a spot with a higher power flux and limited to a smaller region. The spherical design generates a more blurry and diffuse spot. The image generated in both cases moves along the $x$-axis as the Sun vector varies its orientation.
In order to draw clearer conclusions, the power flux shown in figure 6.21 is used to obtain the power integrated over the x-axis using the following equation:

\[ P = \int_A I dA, \] (6.1)

where \( I \) is the irradiance, which is integrated using quadrilateral areas. The results can be seen in figure 6.22, together with lines indicated the 85% and 90% of the total power. The area containing both 85% and 90% of the total power is smaller for the parabolic geometry. In other words, the parabolic concentrator generates a more concentrated image. It must be clarified that the graphs do not start exactly at \( x = 0 \) [m] because of the size of the grid generated.

**Figure 6.22: Power hitting the receiver integrated in the radial direction for both geometries under a pressure load of \( P = 10 \) Pa and the worst thermal case**

### 6.5. Discussion of the Results and Selection of the Concentrator’s Shape.

This chapter has described the first iteration of the design process including all its phases. Both spherical and parabolic shapes, which were proposed during the concept generation, are evaluated considering ideal
conditions and two optimal designs are developed as seen in table 6.8. The objective of the Optimisation Tool is to obtain designs considering not only the performance under nominal conditions, but also changes in the orientation of up to $\Delta \theta = 5 \text{ [deg]}$ (REQ-F-3). Therefore, a design is considered to be optimal if its performance, defined by the second target function of the Optimisation Tool (see subsection 5.5.1, is the maximum possible given the volume constraints (REQ-A-1), which defines the maximum surface area as explained in section 6.1.

<table>
<thead>
<tr>
<th></th>
<th>$R$ or $I$ [m]</th>
<th>$\theta_c$ [deg]</th>
<th>$D$ [m]</th>
<th>$P_{\text{rec,ideal}}$ [W]</th>
<th>$\eta_{\text{ideal}}$ [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parabolic Concentrator</td>
<td>0.175</td>
<td>79.93</td>
<td>0.59</td>
<td>379</td>
<td>100</td>
</tr>
<tr>
<td>Spherical Concentrator</td>
<td>0.567</td>
<td>28.58</td>
<td>0.54</td>
<td>320.74</td>
<td>98.24</td>
</tr>
</tbody>
</table>

It was observed in section 6.2 that the parabolic geometry has a more efficient use of the available surface, reaching larger apertures and providing more power. This design shape provides a larger output power for two main reasons: its better optical performance due to the absence of the so-called spherical aberration and the larger attainable apertures (see figure 6.8 for numerical values).

The results of the thermal model allowed to make estimations of the temperature field over the surface of the system under different conditions, with temperature differences up to around 20 K (section 6.3.2). The second part of the thermo-mechanical analysis of the structure showed the higher sensitivity of the parabolic design to the loading conditions, with larger displacements and $\text{rms}$ error over the majority of the pressure range analysed (section 6.3.3). A design point of 10 Pa was chosen as a result of a trade-off based on the following observations:

- At lower pressures, the thermal loads are more important and they cause deformation distributions which are not uniform over the mirror side and the conical section.

- At higher pressures, the $\text{rms}$ error becomes too large, the consequences of leaks are increased and the pressurisation system is heavier.

Finally, the optical analysis of the deformed geometry (section 6.4) led to the derivation of different observations which will be taken into account in the trade-off for the selection of the concentrator’s shape:

- The parabolic geometry provides higher levels of power under all the cases considered from 1 to 10 Pa as seen in figures 6.18 and 6.19. However, the difference in power under nominal conditions is not too high for the worst case analysed (below 50 W). This design is less sensitive to changes in the Sun vector orientation, which means that the requirements on the ADCS are less demanding.

- The efficiency of the spherical geometry (derived from figure 6.19) remains higher than that of the parabolic design (derived from figure 6.19) under nominal illumination conditions but it drops faster. Therefore, the efficiency for the spherical design is only better under nominal conditions.

- If the worst thermal load and a pressure of 10 Pa are considered, the parabolic reflector provides a higher power output for the entire angular range (figure 6.20).

- The effects of the thermal loads are not as relevant as those of the inflating pressure, which is probably due to the low temperature differences (below 20 [K]) and the low thermal expansion coefficient of the materials (figures 6.18 and 6.19).

- The spherical concentrator generates a blurrier and more diffuse image on the receiver’s plane, while the parabolic mirror generates a more concentrated spot (figures 6.21 and 6.22).

These results allow to perform a trade-off between both designs taking as selection criteria the nominal power (KPP-1), the sensitivity to the pressure and the thermal loads (KPP-2), the sensitivity to changes in the Sun orientation and the concentration ratio (KPP-3, KPP-4). These parameters are directly generated based on the key stakeholders’ requirements (table 3.2) and the key performance parameters (table 3.4). The reasons for their selection were already explained in subsection 3.1.2 and in section 3.2. They are used to choose the best shape since they allow to draw objective conclusions about both optimal geometries.
6. Preliminary Design

The first step in the selection process is the identification of the relative weights of the criteria. For that purpose, an Analytical Hierarchical Process (AHP) is generated. Table 6.9 shows the matrix generated for the AHP, which results in the weights of the criteria: \( w = [0.3620, 0.2132, 0.2504, 0.1745] \). The consistency ratio is below 10% and thus the process can be considered to be consistent. However, the relative weights between the different criteria were generated by the author and they still need to be verified by a more experienced researcher.

Table 6.9: AHP matrix

<table>
<thead>
<tr>
<th></th>
<th>SC-PR-1</th>
<th>SC-PR-2</th>
<th>SC-PR-3</th>
<th>SC-PR-4</th>
</tr>
</thead>
<tbody>
<tr>
<td>SC-PR-1</td>
<td>1</td>
<td>1.7</td>
<td>1.5</td>
<td>2</td>
</tr>
<tr>
<td>SC-PR-2</td>
<td>1/1.7</td>
<td>1</td>
<td>1/1.25</td>
<td>1.3</td>
</tr>
<tr>
<td>SC-PR-3</td>
<td>1/1.5</td>
<td>1.25</td>
<td>1</td>
<td>1.4</td>
</tr>
<tr>
<td>SC-PR-4</td>
<td>0.5</td>
<td>1/1.1</td>
<td>1/1.4</td>
<td>1</td>
</tr>
</tbody>
</table>

Both geometries are evaluated with respect to each criterion using the results of the analyses presented in this chapter. The grading scheme follows the principle that the best concept gets one point while the other gets a proportional grade to the difference in the performance. The grade is designed as \( G# \), where \( # \) is the number of the criterion.

- **SC-PR-1: Nominal power.**

\[
\begin{align*}
P_{\text{nom,parabolic}} &= 320.4 \ [W] \\
P_{\text{nom,spherical}} &= 278.3 \ [W] \\
\Rightarrow \quad & \begin{cases} G_{1\text{parabolic}} = 1 \\ G_{1\text{spherical}} = \frac{278.3}{320.4} = 0.8686 \end{cases} \quad \text{[-]} \\
\end{align*}
\] (6.2)

- **SC-PR-2: Sensitivity to Pressure and Thermal Loads.** In this case, the efficiency difference between the ideal design and the results for the worst thermal case under 10 Pa is used to evaluate both designs. It might seem inconsistent to use the efficiency instead of the power difference as done with the criteria SC-PR-1 and SC-PR-3. However, it is considered more objective to use the efficiency to compare the impact of the loading conditions on the performance of the system since it shows the relative difference in the power output. It is still a parameter related to the power output but it can be used to derive the sensitivity with respect to the ideal conditions.

\[
\begin{align*}
\Delta \eta_{\text{parabolic}} &= 14.06 \ [%] \\
\Delta \eta_{\text{spherical}} &= 9.63 \ [%] \\
\Rightarrow \quad & \begin{cases} G_{2\text{parabolic}} = 14.06 \ [\%] = 0.6849 \ [-] \\ G_{2\text{spherical}} = 1 \ [-] \end{cases} \\
\end{align*}
\] (6.3)

- **SC-PR-3: Sensitivity to variations in the Sun vector orientation.** The grades for the two geometries are computed with the average power for \( \Delta \Phi > 0 \ [\text{deg}] \), as done with the second target function of the Optimisation Tool (section 5.5).

\[
\begin{align*}
P_{\text{av,parabolic}} &= 116.6874 \ [W] \\
P_{\text{av,spherical}} &= 74.2875 \ [W] \\
\Rightarrow \quad & \begin{cases} G_{3\text{parabolic}} = 1 \\ G_{3\text{spherical}} = \frac{74.2875}{116.6874} = 0.6366 \ [-] \end{cases} \quad \text{[-]} \\
\end{align*}
\] (6.4)

- **SC-PR-4: Concentration ratio.** The concentration ratio is measured using the area which concentrates 90% of the total energy.

\[
\begin{align*}
A_{90\%,\text{parabolic}} &= 10^{-4} \ [m^2] \\
A_{90\%,\text{spherical}} &= 1.3225 \cdot 10^{-4} \ [m^2] \\
\Rightarrow \quad & \begin{cases} G_{4\text{parabolic}} = 1 \ [-] \\ G_{4\text{spherical}} = \frac{10^{-4}}{1.3225 \cdot 10^{-4}} = 0.756 \ [-] \end{cases} \\
\end{align*}
\] (6.5)

These grades combined with the weights obtained before allow to perform a numerical trade-off which is presented below in table 6.10.
6.6. CONCLUSIONS

The parabolic design appears as the best geometry according to the trade-off and it is decided to choose this shape as the preliminary design for the demonstrator and as a possible flight system. Moreover, this design is preferred due to the existing interest in other fields in parabolic reflectors. For instance, optical and communication systems are usually preferred to be equipped with parabolic structures due to their focusing capabilities. Therefore, and taking into account the initial requirement on developing a versatile system (STK-A-7), the parabolic design is considered as a better option.

6.6. CONCLUSIONS

The preliminary design of an inflatable solar concentrator is defined in this chapter as a result of the design process described in chapter 5 and following the requirements presented in chapter 3. Table 6.11 includes all the parameters of the preliminary design developed until now. Figure 6.23 eases the identification of the geometrical parameters.

Table 6.11: Parameters of the final design developed for the concentrator

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shape</td>
<td>Parabolic</td>
<td>NA</td>
</tr>
<tr>
<td>Focal length, $f$</td>
<td>175</td>
<td>mm</td>
</tr>
<tr>
<td>Aperture half angle, $\theta_c$</td>
<td>79.89</td>
<td>deg</td>
</tr>
<tr>
<td>Height, $h_{conc}$</td>
<td>175</td>
<td>mm</td>
</tr>
<tr>
<td>Distance to receiver, $d_{rec}$</td>
<td>175</td>
<td>mm</td>
</tr>
<tr>
<td>Aperture, $D$</td>
<td>586.63</td>
<td>mm</td>
</tr>
<tr>
<td>Base diameter, $D_{rec}$</td>
<td>40</td>
<td>mm</td>
</tr>
<tr>
<td>Thickness, $t$</td>
<td>23</td>
<td>µm</td>
</tr>
<tr>
<td>Surface area</td>
<td>0.585</td>
<td>m²</td>
</tr>
<tr>
<td>Cross-sectional area</td>
<td>0.268</td>
<td>m²</td>
</tr>
<tr>
<td>Packaging volume</td>
<td>125 $\cdot 10^{-3}$</td>
<td>m³</td>
</tr>
<tr>
<td>Inner volume</td>
<td>0.022</td>
<td>m³</td>
</tr>
<tr>
<td>Mass</td>
<td>0.0248</td>
<td>kg</td>
</tr>
<tr>
<td>Packaging ratio</td>
<td>4693.04</td>
<td>m²⁻¹</td>
</tr>
<tr>
<td>Design Pressure</td>
<td>10</td>
<td>Pa</td>
</tr>
<tr>
<td>Conical section Material</td>
<td>Mylar™ Type D</td>
<td>NA</td>
</tr>
<tr>
<td>Conical section transmittance</td>
<td>90</td>
<td>[%]</td>
</tr>
<tr>
<td>Mirror material</td>
<td>Aluminised Mylar™</td>
<td>NA</td>
</tr>
<tr>
<td>Mirror reflectivity</td>
<td>80</td>
<td>[%]</td>
</tr>
<tr>
<td>rms error</td>
<td>7.32</td>
<td>mm</td>
</tr>
<tr>
<td>$D_{rec}$</td>
<td>2.5</td>
<td>cm</td>
</tr>
<tr>
<td>Power input</td>
<td>382.18</td>
<td>W</td>
</tr>
<tr>
<td>Theoretical $P_{nom}$</td>
<td>320.4</td>
<td>W</td>
</tr>
<tr>
<td>Realistic $P_{nom}$</td>
<td>230.68</td>
<td>W</td>
</tr>
<tr>
<td>Efficiency, $\eta_{conc}$</td>
<td>60.36</td>
<td>[%]</td>
</tr>
<tr>
<td>$\Delta \Phi_{max}$</td>
<td>5</td>
<td>deg</td>
</tr>
</tbody>
</table>

Figure 6.23: General view of the concentrator and its main geometrical parameters
Some of the parameters are explained hereafter whereas the rest of them were already defined before.

- The **height** is defined as the distance from the base of the conical section up to the vertex.
- The **surface area** refers to the surface area of the entire system.
- The **cross-sectional area** is the area facing the Sun, which is defined by the aperture’s diameter and the cross-sectional area of the satellite.
- The **packaging ratio** refers to the ratio between the aperture’s diameter and the packaging volume.
- The **rms error** was defined before and the error under pressure and thermal load is presented.
- The **distance to the receiver** is the distance between the reflector’s vertex and the receiver.

Three values of the power are presented: the total power input available based on the aperture and the solar flux, the theoretical power output resulted from the ray tracing tool and a more realistic value including the effects of the transmittance and the reflectivity of the materials.

Other conclusions derived from the results of this chapter are as follows:

- Future research projects should include structural analyses for 15 Pa to evaluate the sensitivity of the structure to changes around the design point.
- The power decreases too fast with respect to the deviation of the Sun vector. Therefore, it is necessary to consider more important the minimisation of the sensitivity to variations in the Sun vector (see subsection 5.5.1) and/or to increase the $\Delta \Phi$ range above 5 deg.
- The **rms** error of the parabolic geometry around the design point is above those usually found in literature (see subsection 5.4.2). This means that there is still room for improvement and it is necessary to analyse the structural behaviour of geometries such that once inflated they are closer to the ideal shape.
- Although the deformed shape still meets the requirement on the power output ($\text{REQ-F-1}$), it does not meet the requirements on the **rms error** ($\text{REQ-F-2}$) and the efficiency ($\text{REQ-F-3}$).
- There is a considerable decrease in the efficiency of the system compared to the ideal value (60.36% vs. 100%) due to the deformations. It is thus clear that the design process requires the evaluation of the effects of the load conditions to generate a proper design which meets all the initial requirements.
- The use of a coating on the rear side of the reflector is an option to have a more uniform temperature distribution and that will be examined in later stages of the project.
The preliminary design generated in chapter 6 presents a \textit{rms} error of 7.74 mm (see table 6.11 in section 6.6). The influence of this error on the performance was mitigated by adjusting the position of the receiver. However, it is necessary to consider that the concentrator might experience pressure variations and different thermal loads during the mission and the location of the receiver cannot be continuously optimised without increasing the complexity of the system. Moreover, possible alternative applications for the concentrator (communications and optical systems) would require lower error values (see the values shown in subsection 5.4.2). Therefore, it is the objective of this chapter to generate a geometry such that the inflated system resembles better the ideal one proposed in section 6.2. The requirement guiding the re-design process was already explained in chapter 3 together with its rationale and it is also presented below in table 7.1.

Table 7.1: Driver requirement of the re-design process

<table>
<thead>
<tr>
<th>Id.</th>
<th>Requirement</th>
</tr>
</thead>
<tbody>
<tr>
<td>REQ-F-2</td>
<td>The \textit{rms} error shall be lower than 0.5 mm</td>
</tr>
</tbody>
</table>

As explained in chapter 3, an error of 0.5 mm is above the values attainable by membrane and rigid structures but it is close to those obtained in similar projects and it is considered to be a good initial step for the concept demonstration. It is also admitted that the fact that the design sequence is iterative means that this should not be the last iteration, but a two iteration process is considered good enough given the time constraints.

The preliminary design is reviewed in this chapter using different optimisation methods (section 7.1), leading to the selection of a final design which will be analysed to assess its performance, the sensitivity with respect to different parameters and the required pressurising gas to inflate it (section 7.2). The results are finally summarised in section 7.3.

7.1. \textbf{Re-design process}

The approach to accomplish an \textit{rms} error below 0.5 mm is to test the influence of modifications in the geometry to be manufactured. The finite element models developed with ANSYS are used now to evaluate the final geometry, which will be compared with the optimal one proposed in subsection 6.2.2. The geometries are first tested considering only the pressure load and, once the requirement is met, the thermal load is applied to confirm that the error still complies with the objective. This approach is selected to have an idea of the influence of the thermal load since the evaluation of the error under both conditions to have an estimation of the error range expected during the in-flight operation. Even though the Best Thermal case is the one corresponding to a \textit{STP} engine, the Worst Thermal case is the one applied so that it is ensured that the requirement is met also with other coupled systems and under more extreme conditions.
The strategies employed to reduce the $rms$ error are based on the observations derived from the structural analysis of the preliminary design (subsection 6.3.3). It was seen that the structure expands due to the loads (the vertex is around 7 mm away from the original position). It is expected that changing different parameters would reduce the displacement or lead to a deformation such that the final shape is closer to the optimal one. The parameters considered are the focal length ($f$), the height ($h_{conc}$) and the thickness of the film ($t$). It is expected that a structure with a lower focal length would expand such that it would be closer to the optimal design. The same effect is expected if the height of the system is reduced by displacing the vertex a distance $\Delta z$ towards the base (see figure 7.1). The stiffness of the membrane depends on its thickness and thus an increase in this parameter should lead to a decrease in the deformations and, consequently, the shape error. All these changes refer to the geometry to be manufactured whereas the optimal design remains as described in subsection 6.2.2.

Therefore, five different methods are applied:

1. **Change in the focal length keeping the aperture constant.**
2. **Change in the concentrator's height by displacing the entire parabolic section of the mirror along the z-axis ($\Delta z$).**
3. **Combination of strategies 1 and 2:** Change in the focal length keeping the aperture constant and displacement along the z-axis of the entire parabolic section of the mirror.
4. **Increase of the film's thickness maintaining the focal length and the aperture.**
5. **Combination of strategies 2 and 4:** Increase of the film's thickness and displacement along the z-axis of the entire parabolic section of the mirror, while keeping the focal length and the aperture constant.

### 7.1.1. RESULTS OF THE OPTIMISATION STRATEGIES

The results of the different optimisation strategies are presented hereafter. For more information about the concepts simulated and the numerical results, refer to appendix D.

**Method 1**

A trial and error approach is followed until a minimum value is obtained. The $rms$ error decreases with the focal length yielding an error of 1.52 mm for $f=168$ [mm]. If the focal length is further reduced, the $rms$ error increases since the manufactured geometry is too far from the desired one. Moreover, the deformations decrease if the focal length is lower due to the reduced curvature radius (the stress in the structure induced by the pressure are approximately proportional to this parameter [28]). As observed in figure 7.2, none of the geometries exhibit an error below the requirement and, thus, this approach is not successful.
7.1. RE-DESIGN PROCESS

METHOD 2
The analysis of the influence of $\Delta z$ in the error is performed by displacing the reflector firstly a distance equal to the original $rms$ error and, then, displacing the geometry iteratively $\pm$ error$_{rms}$. This approach is followed until a minimum point is found, which is an error of 0.13 mm for $\Delta z = 9.08$ mm. Figure 7.3 presents the $rms$ as a function of this displacement. The direction of the positive displacement corresponds to that from the vertex towards the focal plane (see figure 7.1). The reasons for the results seen in figure 7.3 are similar to those corresponding to method 1: the difference between the inflated and the optimal geometries decreases as we move the paraboloid along the $z$-axis until a minimum is found. Additional displacements result in geometries too far from the desired shape to yield better results.

Figure 7.3: $rms$ error as a function of $\Delta z$

METHOD 3
The same procedure used in the second method is now applied in combination with the first strategy. In other words, the geometry found in method 2 which provided the minimum $rms$ error is now moved along the $z$-axis in order to find the minimum point. The results of this method are shown in figure 7.4 together with the results of the previous one. The $rms$ error obtained for $f = 0.168$ [m] with the first method is almost the best result attainable with that geometry. The results of method 2 are still better.

Figure 7.4: $rms$ error as a function of $\Delta z$

METHOD 4
As mentioned before, it is expected that a higher stiffness leads to a design with a lower shape error. That is actually the results of this fourth approach (figure 7.5). It is necessary to consider that a change in the thickness implies a variation in the volume of the structure. Although the increase is significant, the extrapolation method used to derive the maximum surface for a given volume was based on a design made of 512 [$\mu$m] and 256 [$\mu$m] films [1]. It can be thus concluded that the thickness range presented in figure 7.5 would not violate the volume constraints. This fourth method is not successful.
METHOD 5
This last method is based on a combination of methods 2 and 4: film thickness is increased and the reflector is moved along the z-axis. Only the designs with a thickness of 75 [µm] and 100 [µm] are considered. They are chosen because of their good results (see figure 7.5). The thickest design (t=125 [µm]) is not selected because of the increase in volume. The error is decreased to values below 0.5 mm.

7.1.2. ANALYSIS AND DISCUSSION OF THE RESULTS
It is possible to obtain designs which meet the requirements under pressure loads using methods 2 and 5. However, as can be inferred from the tables in appendix D, these designs require displacements in the z-axis with a precision below 1 µm. More sensible values are required from a manufacturing point of view as it is explained now. Laser cutting is probably the most accurate method available nowadays to manufacture the reflector. Although it presented some issues in the past with polyimides, CO\textsubscript{2} and UV lasers have been improved so that the problems have been minimised [84]. When it comes to evaluate the accuracy of these systems, recent technical reports claim that the systems can attain accuracies of around 10 microns [85] [86]. It is going to be assumed that the maximum accuracy is in the order of 10 [µm] to define the geometrical parameters of the final design. Three designs (mod B-6, mod E-1 and mod E-4) are re-defined now considering this level of accuracy (no geometrical parameters with a precision of the order of 1 [µm]) and tested considering the thermal loads, yielding the results seen in table 7.2. An additional parameter is included in the table, which is the relative increase in the rms error due to the thermal load. It has been decided to include both rms error values in order to have a better idea of the range expected during operation. The data corresponding to the pressure and thermal loads is the worst case scenario expected during operation, whereas the pressure load condition is just an ideal situation with no temperature differences.

Table 7.2: Final Results of the optimisation process. P refers to pressure load and T to thermal load. ∆rms refers to the relative increase due to the thermal load.
7.2. Final Design Analysis

Now that a final geometry has been selected (see table 7.3 and figure 7.7 for the main geometrical parameters), it is necessary analyse it to have an estimation of its performance (subsection 7.2.1) and to determine its sensitivity to changes in different parameters (subsection 7.2.2). For that purpose, the material’s optical properties considered in chapter 6 will be used again (table 6.11). Due to the computational cost of the calculations, only simulations under nominal conditions are performed. This analysis is complemented by a preliminary assessment of the inflating system and the risk of micrometeoroid and space debris impact in subsection 7.2.3.

Table 7.3: Main geometrical properties of the final design.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Focal length</td>
<td>175</td>
<td>[mm]</td>
</tr>
<tr>
<td>Aperture's half angle</td>
<td>79.89</td>
<td>[deg]</td>
</tr>
<tr>
<td>Aperture</td>
<td>586.63</td>
<td>[mm]</td>
</tr>
<tr>
<td>Thickness</td>
<td>23</td>
<td>[µm]</td>
</tr>
<tr>
<td>Vertex Position</td>
<td>-9.07</td>
<td>[mm]</td>
</tr>
<tr>
<td>$rms$ error (P)</td>
<td>0.13</td>
<td>[mm]</td>
</tr>
<tr>
<td>$rms$ error (P+T)</td>
<td>0.48</td>
<td>[mm]</td>
</tr>
</tbody>
</table>

Figure 7.7: Main geometrical parameters of the final design in [mm]

7.2.1. Performance under Nominal Conditions

The performance of the system is evaluated under the design point conditions (inflating pressure of 10 Pa) and the Worst Thermal case. The ray tracing tool provides the optimal position of the receiver for both conditions ($z_{rec}$). The values obtained are averaged in order to fix a position for the receiver which is used to estimate the performance of the system. It is decided to use the average location instead of the one corresponding to the Worst Thermal Case since the concentrator will experience a varying thermal load. The optimal locations for both cases ($z_{rec,P}$ and $z_{rec,P+T}$) and the average position ($z_{rec,av}$) are as follows:

$$z_{rec,P} = -0.45 \quad [mm]$$
$$z_{rec,P+T} = 0.15 \quad [mm]$$

$$\Rightarrow z_{rec,av} = -0.15 \quad [mm]$$

(7.1)
The concentrator provides 320.28 W under pressure load and the worst thermal case. More realistic estimations of the power output can be obtained if the transmittance coefficient of the transparent section and the reflectivity of the mirror film are taken into account, yielding 231.40 W.

7.2.2. Sensitivity Analysis

It is necessary to evaluate how would the performance be affected by changes in the design or the operating conditions. Three parameters (focal length, displacement $\Delta z$ and thickness) and one operating condition (pressure) are analysed. The structural behaviour has been evaluated with the FEM (under the pressure and worst thermal loads) and then analysed with the ray tracing tool. Table 7.4 shows the nominal values of the parameters, the new ones and the power delivered by the system, together with the relative decrease.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Nominal value</th>
<th>$P_{nom}$ [W]</th>
<th>Value A</th>
<th>$P$ [W]</th>
<th>$\Delta P$ (%)</th>
<th>Value B</th>
<th>$P$ [W]</th>
<th>$\Delta P$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Focal length</td>
<td>0.1750 [m]</td>
<td>320.28</td>
<td>0.18 [m]</td>
<td>316.65</td>
<td>-1.33</td>
<td>0.17 [m]</td>
<td>282.24</td>
<td>-11.87</td>
</tr>
<tr>
<td>$\Delta z_{rec}$</td>
<td>-0.15 [mm]</td>
<td>320.28</td>
<td>0.85 [mm]</td>
<td>318.63</td>
<td>-0.51</td>
<td>-1.15 [mm]</td>
<td>309.71</td>
<td>-3.30</td>
</tr>
<tr>
<td>Pressure</td>
<td>10 [Pa]</td>
<td>320.28</td>
<td>11 [Pa]</td>
<td>318.59</td>
<td>-0.53</td>
<td>9 [Pa]</td>
<td>311.08</td>
<td>-2.87</td>
</tr>
</tbody>
</table>

The influence of changes in the focal length and the thickness yields the highest power changes, which is an obvious outcome since the design has been optimised for the design values. If these parameters are changed, the design process should be repeated since the deformations experienced and thus the performance change. The impact is clearer for changes in the thickness (between $\approx 10$ and $\approx 35\%$ of decrease in the power), whereas the effect of modifying the focal length or the receiver position is not so strong. Considering that power losses of up to 5% can be allowed, a focal length of 0.18 m is allowed but not 0.17 m. This allows to derive a conclusion about the manufacturing tolerance for the focal length ($f = 0.1750 + 0.005$ m) although it is still necessary to determine the point in the interval $[0.17, 0.175]$ m for which the power is decreased by 5% to define the lower boundary. Both values of the receiver position yield acceptable power variations, which means that a tolerance of $\pm 1$ mm can be fixed for this design parameter. Further analyses should be performed to determine a more accurate interval. Regarding the only operating condition considered in this sensitivity analysis, variations of $\pm 1$ Pa are allowed since the performance of the concentrator exhibits acceptable changes.

7.2.3. Preliminary Design of the Inflating System. Micrometeoroid and Space Debris Impact Assessment

Now that the geometry of the concentrator and the inflating pressure are defined, it is possible to perform a preliminary estimation of the amount of gas required to pressurise the structure. It is necessary to evaluate the losses due to the material permeability and impacts of space debris and micrometeoroids. When applicable, it is considered that the system is designed for an orbit altitude of 600 km (REQ-A-5) and a mission duration of 1 year (REQ-A-4).

The nominal amount of gas required can be estimated using the inner volume of the concentrator and the design pressure. Considering the state-of-the-art of cool gas generators [87], the previous experience in the Chair of SSE of TU Delft [47] and the low permeability of Mylar$^\text{TM}$ to nitrogen [88], cool gas generators equipped with nitrogen are considered for this preliminary design.

$$m = \frac{V}{R \cdot T} \cdot M_g = 2.415 \cdot 10^{-7} \ [kg/Pa]$$

Where $m$ is the gas mass required, $p$ is the design pressure, $V = 0.021 \ m^3$ is the volume of the system, $R$ is the ideal gas constant, $T = 293 \ [K]$ is the gas pressure assumed and $M_g = 28.0134 \ [g/mol]$ is the molecular mass of the gas. For a pressure of 10 Pa, it is necessary to use 2.415 mg of nitrogen.

The pressurising gas lost due to the permeability of the material depends on the temperature of the film. The worst case scenario analysed with the thermal model yielded an average temperature of 181.2 °C, which is above the range for which the permeability is given by the supplier [88]. Assuming a linear correlation
7.2. **Final Design Analysis**

between temperature and permeability, the permeability at the average temperature is 16.6 cc/100 in²/24 hr/atm/mil, which expressed in more useful units, equals 2.9786 \times 10^{-6} mg/m²/µm/Pa/ 24 hr. The mass lost in a 1-year mission due to the permeability of the material is then 3.52 mg. It must be kept in mind that the permeability is reduced if metallised coatings are used [88] and it is necessary to assess the total reduction since no data could be found.

The other source of mass losses is the impact of micrometeoroids and space debris. Grossman and Williams [89] presented a method to assess the effects of debris and micrometeoroids. There are three possible scenarios depending on the size of the objects with respect to the thickness of the membrane:

- If the object diameter is much larger than the thickness of the membrane, it creates two holes in the structure whose diameter can be estimated around 1.1 times the object size. For this preliminary assessment, it is considered that objects in this category have a diameter larger than five times the thickness of the membrane.

- If the object diameter is in the same order as the thickness of the membrane, only one hole of the same dimension as the object is created. It is considered that objects in the same order have a diameter ranging from a fifth of the membrane thickness up to five times its value.

- If the object diameter is much smaller than the thickness of the structure, no hole is created.

**SPENVIS** [12] is used to estimate the flux of objects intersecting the trajectory of the satellite. Figure 7.8 shows the results of the Grün meteoroid model for an altitude of 600 km. The curve indicates the number of objects with a diameter equal or greater than the value found on the x-axis per square metre and per year.

![Figure 7.8: Flux of objects at an altitude of 600 km according to Grün meteoroid model](image)

The impacts on the concentrator over a year of operation are estimated to be around 73, creating a total hole area of 4.72 \times 10^{-8} m². For this calculation, the maximum cross-sectional area of the system is considered to be the projected aperture’s area, which is 0.27 m². Since the environment is almost at vacuum, the mass flow rate exiting the structure can be modelled as a choked flow:

\[
\dot{m} / A = \rho \cdot v = p / RT \cdot \gamma R_g T = 0.04012 \left( \frac{kg}{s \cdot m^2} \right),
\]

where \(\dot{m}\) is the mass flow rate, \(A\) is the hole area, \(\rho\) is the density, \(v\) is the flow velocity, \(p\) is the inner pressure, \(R\) is the ideal gas constant, \(T\) is the temperature, \(R_g\) is the specific gas constant and \(\gamma\) is the gas heat ratio.
The total mass flow rate by the end of the mission is 0.00189 $mg/s$. This value cannot be directly multiplied by the mission time to estimate the pressurising gas lost since that would imply that the structure was punctured 73 times at the beginning of the mission. Therefore, it has been decided to have a more accurate estimation by expressing the objects flux (figure 7.8) per day instead of per year and integrating the mass lost over time. The evolution of the mass lost over time is shown in figure 7.9. However, it must be kept in mind that it has been assumed a uniform distribution of objects over the year whereas it is more likely to find scenarios with varying concentration of debris and micrometeoroids in certain moments of the mission.

Figure 7.9: Mass lost over time

The total mass lost is 29.9 g. Considering the size of cool gas generators supplied by CGG [87], it is not possible to fit a system which provides that amount of gas since the only appropriate one for a PocketQube is the Micro Cool Gas Generator (used already for the micro propulsion system of the Delfi n3Xt CubeSat [47]) with 125 milligrams of gas. There is another system with a capacity of 4 grams which would increase the lifetime up to 134 days, but its dimensions are too large for a PocketQube. If only one generator is included, the lifetime of the structure would be limited to 22 days which is clearly below the lifetime requirement. Different solutions are proposed:

- An increase in the thickness of the membrane would reduce the amount of holes and thus the mass lost due to them. For instance, if a film of 100 $\mu$m were used, the losses would be reduced to 19.21 grams in 1 year. This mass lost could be further reduced to 12.69 grams per year if the selected thickness were 250 $\mu$m. However, these changes would imply higher packaging volumes and stronger effects of the thermal loads, as discussed in chapter 6.

- The inflating pressure can be reduced below 10 Pa but this would imply a higher effect of the thermal loads as explained in chapter 6.

- A different pressurising gas can be considered. For instance, Babuscia et al. [1] considered the use of benzoic acid, which has a higher molar mass (122.12 g/mol) than nitrogen, leading to a mass flow rates per unit area around 2% of the value presented before in equation 7.3, which means that the lifetime of the system with 125 milligrams of powder is 256 days. A lifetime of 1 year is feasible with approximately 250 milligrams of benzoic acid. This change should be assessed with the manufacturer [87] or tackled in an additional research project.

The trade-off between the different solutions proposed should be assessed with further analyses in following research projects.

7.3. SUMMARY

A final design resulting from the second iteration of the design process has been generated and analysed throughout this chapter with the intention of meeting the requirement of 0.5 mm on the $rms$ error (REQ-F-2). Five different strategies were proposed to modify the preliminary design obtained in chapter 6 resulting in
the selection of a final design which presents a \( \text{rms} \) error below 0.5 mm under the worst load conditions. The analyses performed include a nominal performance evaluation (subsection 7.2.1) and a sensitivity analysis (subsection 7.2.2) with the objective of knowing how much power the system provides under nominal conditions and how is the performance affected by small changes in the design parameters and the operating conditions (see table 7.4). The second set of analyses allowed to derive some conclusions about the manufacturing tolerances.

The mass of pressurising gas required to inflate the system up to 10 Pa was also assessed together with the mass lost due to the permeability of the materials and the impacts of space debris and micrometeoroids (subsection 7.2.3). The latter is the most important constraint, limiting the lifetime of the system below the requirements if nitrogen is used. Therefore, different strategies were defined to mitigate the effects of the holes created by objects puncturing the structure were defined.

The final design meets the requirements on the power output \((\text{REQ-F-1})\), the \( \text{rms} \) error \((\text{REQ-F-2})\), the operating angle interval \((\text{REQ-F-3})\) and the packaging volume \((\text{REQ-A-1})\). The requirement on the efficiency \((\text{REQ-F-6})\) is not met mainly due to the limitation imposed by the materials properties, which set the maximum attainable value on \( \eta_{\text{max}} = \tau_{\text{Mylar}} \cdot \tau_{\text{mirror}} = 0.75 \). The requirement on the aperture size \((\text{REQ-A-2})\) is exceeded since it is 11.72 times the side of a PocketQube Unit instead of 10 times. All the main parameters are presented below in table 7.5.

Table 7.5: Parameters of the final design developed for the concentrator

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shape</td>
<td>Parabolic</td>
<td>NA</td>
</tr>
<tr>
<td>Focal length</td>
<td>175</td>
<td>[mm]</td>
</tr>
<tr>
<td>Aperture’s half angle</td>
<td>79.89</td>
<td>[deg]</td>
</tr>
<tr>
<td>Height</td>
<td>165.99</td>
<td>[mm]</td>
</tr>
<tr>
<td>Aperture</td>
<td>586.63</td>
<td>[mm]</td>
</tr>
<tr>
<td>Base diameter</td>
<td>40</td>
<td>[mm]</td>
</tr>
<tr>
<td>Distance to receiver</td>
<td>169.84</td>
<td>[mm]</td>
</tr>
<tr>
<td>Thickness</td>
<td>23</td>
<td>[(\mu)m]</td>
</tr>
<tr>
<td>Surface area</td>
<td>0.587</td>
<td>[m(^2)]</td>
</tr>
<tr>
<td>Cross-sectional area</td>
<td>0.2678</td>
<td>[m(^2)]</td>
</tr>
<tr>
<td>Packaging volume</td>
<td>125(\cdot)10(^{-6})</td>
<td>[m(^3)]</td>
</tr>
<tr>
<td>Inner volume</td>
<td>0.021</td>
<td>[m(^3)]</td>
</tr>
<tr>
<td>Mass</td>
<td>0.0248</td>
<td>[kg]</td>
</tr>
<tr>
<td>Packaging ratio</td>
<td>4693.04</td>
<td>[m(^2)]</td>
</tr>
<tr>
<td>Design Pressure</td>
<td>10</td>
<td>[Pa]</td>
</tr>
<tr>
<td>Conical section Material</td>
<td>Mylar(^{TM}) Type D</td>
<td>NA</td>
</tr>
<tr>
<td>Conical section transmittance</td>
<td>90</td>
<td>[%]</td>
</tr>
<tr>
<td>Mirror material</td>
<td>Aluminised Mylar(^{TM})</td>
<td>NA</td>
</tr>
<tr>
<td>Mirror reflectivity</td>
<td>80</td>
<td>[%]</td>
</tr>
<tr>
<td>( \text{rms} ) error</td>
<td>483.1</td>
<td>[(\mu)m]</td>
</tr>
<tr>
<td>( D_{\text{rec}} )</td>
<td>2.5</td>
<td>[mm]</td>
</tr>
<tr>
<td>Power input</td>
<td>382.18</td>
<td>[W]</td>
</tr>
<tr>
<td>Theoretical ( P_{\text{nom}} )</td>
<td>322.28</td>
<td>[W]</td>
</tr>
<tr>
<td>Realistic ( P_{\text{nom}} )</td>
<td>232.042</td>
<td>[W]</td>
</tr>
<tr>
<td>( \Delta \Phi_{\text{max}} )</td>
<td>5</td>
<td>[deg]</td>
</tr>
</tbody>
</table>


**DEMONSTRATOR DESIGN AND MANUFACTURING**

A final design was generated and analysed in chapter 7 based on the project requirements (chapter 3), the concept selected (chapter 4) and the outcomes of the preliminary design (chapter 6). The main objective (subsection 2.2.2) does not only include the design and performance assessment of the concentrator but also its **manufacturing and testing** in order to define the manufacturing procedures and assess their quality.

Therefore, it is necessary to design and manufacture a test object, which is the purpose in this chapter. The same design approach presented in chapter 5 and applied for the preliminary (chapter 6) and final designs (chapter 7) is implemented now again. The demonstrator design is described in section 8.1 and analysed using a **FEM** in section 8.2 to assess its final shape. The manufacturing procedures and the production results are explained in section 8.3, leading finally to a set of conclusions (section 8.4).

### 8.1. DEMONSTRATOR DESIGN

The design of the test object is described in this section, including the definition of the design requirements (subsection 8.1.1), the generation of the geometry (subsection 8.1.2) and the design of the pressurisation system (subsection 8.1.3).

#### 8.1.1. INTRODUCTION: DESIGN REQUIREMENTS.

The device to be manufactured is also a parabolic inflatable concentrator to be consistent with the final design presented in chapter 7 and because it provides a better performance. Moreover, it is more efficient in terms of surface area utilisation (larger apertures for the same surface area as seen in subsection 6.2.1). The geometry obtained in the previous chapter took into account the volume of the satellite as the only limitation for the design (see section 5.5). In this case, there is an additional constraint to be added which is the materials availability. This constraint is included in the optimisation tool as it was done before with the satellite volume limitation, resulting in an optimal design given the available materials.

As commented before, thin film materials such as Mylar™ can be found with a broad range of optical properties and thickness. Mylar™ was already identified in the previous literature study [17] and in the Thermo-Structural design of the preliminary design (see section 6.3) as the most common material employed for inflatable space devices due to its structural and optical properties and availability. After contacting different suppliers, Lohmann Technologies (UK) Ltd. offered their collaboration with this project by sending samples of transparent Mylar™ type A and Kenpro™ Mirrorfilm. The Mirror film supplied by Lohmann Technologies Ltd. is not the ideal material for a space mission due to its relatively high transmittance coefficient (15%) and relatively low reflectivity (74.29%) (see appendix C). The reflectivity value was derived from the value given in Gloss Units in C using the conversion guidelines presented in [90]. Film coatings with reflectivity coefficients above 90% can be obtained [91] but the film offered by Lohmann Technologies (UK)

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LTD. appears as an acceptable choice for the purposes of the test campaign considering the time and budget constraints and the fact that it is only intended for demonstrating purposes. Moreover, there are no resources available at TU Delft to apply a coating to a polyimide with silver or aluminium. In future research projects, it is necessary to consider whether or not this supplier is the most appropriate one.

The samples provided by Lohmann Technologies (UK) LTD. are A4 sheets (297x210 mm$^2$). In total, the following items were received:

- **Kapton**$^\text{TM}$ film: 1 sheet of 12.5 [$\mu$m] of thickness and 2 sheets of 25 [$\mu$m] of thickness.
- **Mylar**$^\text{TM}$ film: 4 sheets of 23 [$\mu$m] of thickness.
- **Kenpro**$^\text{TM}$ Mirror film: 2 sheets of 23 [$\mu$m] of thickness.

Only the Mylar$^\text{TM}$ and Kenpro$^\text{TM}$ Mirror films are actually used for manufacturing the prototype, whilst the Kapton$^\text{TM}$ film is used in case spare materials are needed to test the manufacturing procedures. All the properties of the three film materials can be found in appendix C.

The requirements previously explained in this subsection can be summarised below:

1. The shape of the demonstrator shall be parabolic.
2. The surface area of the reflective section of the demonstrator shall be lower than 0.125 m$^2$.
3. The surface area of the transparent section of the demonstrator shall be lower than 0.249 m$^2$.

### 8.1.2. Geometric Definition

The optimisation tool is now used considering the available resources described before. The film surface available for the mirror is $S_{av} = 2 \cdot 0.210 \cdot 0.297 = 0.1274$[m$^2$]. Not all the available surface is effectively used due to the shape of the reflector and this is included in the calculations through an efficiency coefficient. An initial estimation of $\eta_{use} = 0.75$ [-] is considered.

Assuming identical illumination conditions to those employed for the preliminary design, the optimal designs seen in Table 8.1 are obtained as a function of the parameter $\nu$. The focal length and the radius were limited to 0.5 [m] since values above this one are not attainable considering the available materials. As was explained before, the target function presented in Table 8.1 includes the average power over the angle range $\Delta \Phi \leq 5$ [deg] for the deviation of the Sun vector with respect to the nominal conditions (Sun vector aligned with the concentrator axis).

<table>
<thead>
<tr>
<th>$\nu$ [-]</th>
<th>$f$ [m]</th>
<th>$\theta_c$ [deg]</th>
<th>$D$ [m]</th>
<th>$f_{target}$ [W]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.5</td>
<td>19.51</td>
<td>0.34</td>
<td>127.77</td>
</tr>
<tr>
<td>0.1</td>
<td>0.5</td>
<td>19.51</td>
<td>0.34</td>
<td>118.16</td>
</tr>
<tr>
<td>0.2</td>
<td>0.233</td>
<td>39.99</td>
<td>0.34</td>
<td>110.72</td>
</tr>
<tr>
<td>0.3</td>
<td>0.1667</td>
<td>53.37</td>
<td>0.33</td>
<td>104.59</td>
</tr>
<tr>
<td>0.5</td>
<td>0.1333</td>
<td>63.57</td>
<td>0.33</td>
<td>95.04</td>
</tr>
<tr>
<td>0.75</td>
<td>0.1167</td>
<td>70.03</td>
<td>0.33</td>
<td>84.34</td>
</tr>
<tr>
<td>0.9</td>
<td>0.1167</td>
<td>70.03</td>
<td>0.33</td>
<td>78.17</td>
</tr>
</tbody>
</table>

The design aperture, and thus the nominal output power, does not vary significantly under the current constraints so it is preferred to use a design with a lower sensitivity to Sun vector variations. The reason for this choice is based on the fact that the theatre lamp to be used in the Test Campaign emits non-collimated rays. Therefore, a value of $\nu = 0.3$ [-] is selected, which yields a weighted average power of 104.59 W and a nominal power of 120.17 W. The focal lengths, radius and apertures shown in table 8.1 are quite unrealistic in terms of manufacturability and they must be rounded to more sensible values. However, it is first necessary to tackle the manufacturing approach before taking this decision.
8.1.3. Design of the Pressurisation System

Even though the pressurising system is part of the test set-up and, therefore, its design would be expected in the next chapter, it is necessary to evaluate the pressure attainable for the evaluation of the final shape. After considering different options, such as using the pressurised air supply at the DASML, the low pressure levels desired for the test campaign and the cost and time constraints favoured the selection of a system based on CO₂ cartridges. These small bottles are usually employed to inflate bike tires, they are COTS components, easy to be purchased and quite cheap. The inflating system is based on the sketch shown in figure 8.1.

Each cartridge has 16 grams of CO₂ pressurised under ambient temperature (see annex E for further information). The final pressure inside the concentrator depends on the room conditions, the volume of the entire pneumatic line, the cylinder(s) and the structure. After the transient phase, a steady-state condition is reached and the pressure inside the line is estimated using the ideal gas law and assuming that:

- No deformation occurs in the reflector.
- The entire line is under the same pressure and temperature. After opening, the bottle cools down as CO₂ expands. In this case it will be assumed that a steady state condition is reached in which the temperature of the entire system is uniform and equals the ambient temperature (estimated around 293.15 K).
- No leak occurs in the entire system. This last assumption refers to the usual permeability of materials to CO₂. It is therefore assumed that the system is closed and no representative gas mass is lost during the duration of the test. The permeability of mylar to carbon dioxide is 16 cm³/(100 in²)/(24 hr)/atm/mil, which is translated into a leak of 5.6574·10⁻⁵ g/s under normal conditions (293.15 K and 1 atm). This mass flow is thus negligible.

The volume of the concentrator is given by the equation below, using parameters already explained in figure 5.12.

\[
V_{\text{conc}} = V_{\text{cone}} + V_{\text{par}} = \frac{1}{3} \pi h_{\text{cone}} (R_{\text{cone}} + r_{\text{cone}})^2 + \frac{1}{2} \pi R_{\text{cone}}^2 D_{\text{par}} = 6.82056 \cdot 10^3 \quad [\text{cm}^3] \quad (8.1)
\]

This value needs to be added to the volume of the CO₂ cartridge and the pipe connecting the valve and the concentrator. At this moment the pipeline volume is neglected since the diameter is expected to be small enough to result in a volume considerably lower than that of the concentrator. The pressure in the system can be evaluated as:

\[
p = \frac{nRT}{V} = 1.2943 \quad [\text{bar}],
\]

where \(n\) is the number of CO₂ moles, \(R\) is the ideal gas constant, \(T\) is the temperature and \(V\) is the volume of the system.

The pressure measured by the weather station located at the Faculty of Elektrotechniek, Wiskunde en Informatica at TU Delft shows a pressure between 1010.60 and 1025.91 mb during the first days of November, 2016. These values are close to the mean average provided by the National Institute for Meteorology (Koninklijk Nederlands Meteorologisch Instituut) for this period of the year\(^2\). Therefore, the pressure attained with a single CO₂ cartridge is more than enough to provide the necessary pressure difference (\(\Delta P = 275 \quad [\text{mbar}]\)). It is actually too high compared with the values considered during the design of the concentrator so it is recommended to open the valve slowly and to try to limit manually the pressure in the concentrator.

\(^2\)Data Source: KNMI Climate Explorer, https://climexp.knmi.nl/
8.2. STRUCTURAL ANALYSIS AND RE-DEFINITION OF THE GEOMETRY
The geometry obtained in section 8.1 is analysed to evaluate the deformations expected during the test campaign. The results are used to perform a brief re-design process with the intention of reducing the expected $\text{rms}$ error. Due to the schedule constraints, it is decided not to go through all the optimisation methods used in chapter 7 and only the best one is used.

8.2.1. FEM Analysis
The structure is analysed using only the pressure load. The reason is that the results of the thermal model were based on orbital conditions, which are different from those found during the test campaign. There is still no data available about the irradiance the demonstrator will be subjected to. Therefore, it is decided to have just preliminary estimations of the deformed geometry due to the pressure load. The maximum deformation and the $\text{rms}$ error are included in table 8.2. The equivalent Von-Mises stress and shear stress fields were qualitatively analysed, resulting in the same trends already explained in chapter 6.

Table 8.2: Maximum displacements and $\text{rms}$ error experienced by the demonstrator w.r.t. the inflating pressure based on the Finite Element Models

<table>
<thead>
<tr>
<th>$P$ [Pa]</th>
<th>Maximum displacement [mm]</th>
<th>$\text{rms}$ error [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>0.06</td>
<td>0.05</td>
</tr>
<tr>
<td>10</td>
<td>0.64</td>
<td>0.57</td>
</tr>
<tr>
<td>20</td>
<td>1.29</td>
<td>1.16</td>
</tr>
<tr>
<td>50</td>
<td>3.23</td>
<td>2.90</td>
</tr>
<tr>
<td>100</td>
<td>6.45</td>
<td>5.80</td>
</tr>
<tr>
<td>200</td>
<td>12.91</td>
<td>11.62</td>
</tr>
</tbody>
</table>

The deformations are larger than those obtained for the preliminary design, which is due to the smaller size of the demonstrator. This observation can be explained using the membrane stress experienced by a pressurised sphere, which is a function of the pressure ($p$), the radius ($R$) and the membrane’s thickness ($t$): $\sigma \approx \frac{pR}{t}$. Hence, the stress is lower if the radius is decreased. The stress field in a paraboloid is obviously different but it is still valid to say that smaller paraboloids lead to lower stresses and, therefore, smaller deformations.

8.2.2. Re-design of the Test Object
The design review applied for the demonstrator is not as extensive as the one in chapter 7. This decision is due to the schedule constraints and the fact that the manufacturing procedures followed do not allow the same level of precision. The design optimisation performed in chapter 7 showed that displacements in the $z$-axis such that the receiver is closer to the vertex represent the best way to reduce the error in the geometry. Therefore, a displacement is induced in the demonstrator’s design based on the $\text{rms}$ error values obtained.

The inflating pressure remains still unknown but it is considered more likely to fall in the range between 1 and 100 Pa. The average error is around 2 mm, so it is decided to reduce the initial height of the conical structure from 124.58 to 122. Rounding the height to an integer number in millimetres is easier for manufacturing it. The final design characteristics are seen in table 8.3.

Table 8.3: Main properties of the final demonstrator design.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Focal length</td>
<td>166.7</td>
<td>[mm]</td>
</tr>
<tr>
<td>Aperture’s half angle</td>
<td>53.37</td>
<td>[deg]</td>
</tr>
<tr>
<td>Aperture</td>
<td>335.18</td>
<td>[mm]</td>
</tr>
<tr>
<td>Thickness</td>
<td>23</td>
<td>[$\mu$m]</td>
</tr>
<tr>
<td>Height</td>
<td>164</td>
<td>[mm]</td>
</tr>
</tbody>
</table>

Although the design approach defined in chapter 5 is based on an iterative strategy, it is preferred now to use the geometry resulted from this first iteration for the demonstrator due to the time required for manufac-
turing the mould and the concentrator itself.

8.3. PRODUCTION OF THE TEST OBJECT

This section intends to explain to the reader the manufacturing approach and the results obtained.

8.3.1. MANUFACTURING APPROACH: PETALS DESIGN.

The manufacturing approach, which is selected based on the previous literature study [17], is a petal-based strategy [92] [1]. It is a simple method which provides an acceptable shape accuracy to demonstrate the concept (around 1 cm of error in the focal length according to [92]). The basic idea is that if a paraboloid is cut in different sections and each of them is placed on a planar surface, it is possible to define a perimeter which allows to do the inverse operation. In other words, if petals are cut off from a planar surface with a defined shape and joined together, the resulting geometry is equal to a paraboloid [92].

Any profile of the reflector (see figure 8.3, left), is defined by the following equation:

\[ z(x) = \frac{1}{4f} \cdot x^2 \quad x \in [0, D/2], \quad (8.3) \]

where \( f \) is the focal length and \( D \) is the aperture. This equation is not the same as the one presented in section 5.2 for the bi-dimensional ray tracing tool since it is not necessary to displace the vertex of the parabola to have the focus on the origin.

The 3-dimensional geometry can be approximated by cutting off petals from a planar circle (see figure 8.3, right) and joining them. The total surface to be removed is defined using the space between petals (\( \Delta W \)), which is given by the following expressions:

\[ W = 2\pi \cdot (L - x) \quad \Rightarrow \quad \Delta W = \frac{W}{2N}, \quad (8.4) \]

where \( W \) is the total perimeter to be removed and \( N \) is the number of petals. The variable \( \Delta W \) varies with the coordinate \( x \) and it depends on the length of the profile \( L \), defined as:

\[ (dL)^2 = (dx)^2 + (dz)^2 \quad (8.5) \]

\[ dz = \frac{1}{2f} \cdot x \cdot dx \quad \Rightarrow \quad (dL)^2 = \left(1 + \frac{1}{4f^2} \cdot x^2\right) \cdot (dx)^2 \quad (8.6) \]

Figure 8.3: Example of the cutting strategy for 4 petals

The integration of the function \( L(x) \) is as follows:

\[ L = L(x) = \int_0^x \sqrt{1 + \frac{1}{4f^2} \cdot x^2} \cdot dx = \frac{1}{4} \cdot x \cdot \sqrt{\frac{x^2}{f^2} + 4 + f \cdot sinh^{-1}\left(\frac{x}{2f}\right)} + L(x = 0) \quad (8.7) \]

Using the optimal parameters given in table 8.3, the space between petals as a function of the length of the profile is presented in figure 8.4. Greschik et al. [76] concluded that increasing the number of petals lead to more accurate designs. However, the petals are cut manually and the precision required is higher if the distance between petals is reduced, which is a direct consequence of using more petals. Therefore, it
is decided to use four petals as a compromise between these two effects. The space increases as we move towards the edge of the parabola and the space to be remove is considerably low, summing up to 2.06% of the total surface of the circle.

Figure 8.4: Space between petals as a function of L(x)

After trying different ways to place the petals over the sample, the best approach in terms of surface use is as seen in figure 8.5. A margin of 5 mm is left from each side of the paper and both petals are separated 10 mm, so that cutting them is easier.

Figure 8.5: Distribution of the petals over the A4 sample. The red dotted lines represent the perimeter of the sample

Regarding the conical section, it does not require such a complex approach to define its planar shape. Given the height, the diameter of the base and the aperture of the concentrator, it is possible to determine the required shape to be cut off from the Mylar™ samples. Figure 8.6 shows the main parameters of which the difference \( h_2 - h_1 \) (122 mm) and the diameters \( D \) (335.176 mm) and \( D_{\text{base}} \) (65 mm) are known from the design. The rest of the parameters are determined using the following formulae:

\[
\begin{align*}
\alpha &= \arctan \left( \frac{D - D_{\text{base}}}{2 \cdot (h_2 - h_1)} \right) = 47.55 \text{ [deg]} \quad (8.8) \\
h_1 &= D_{\text{base}} \cdot \tan(\alpha) = 29.73 \text{ [mm]} \quad (8.9) \\
h_2 &= D \cdot \tan(\alpha) = 153.32 \text{ [mm]} \quad (8.10) \\
l_1 &= h_1 / \cos(\alpha) = 44.05 \text{ [mm]} \quad (8.11) \\
l_2 &= h_2 / \cos(\alpha) = 227.14 \text{ [mm]} \quad (8.12) \\
\beta &= \frac{\pi D_{\text{base}}}{l_1} = 265.62 \text{ [deg]} \quad (8.13)
\end{align*}
\]

Figure 8.6: Main parameters in the calculation of the cone’s petals

Since the entire geometry does not fit in a single A4 sample, it was decided to divide it in four sections and to include different flanges for the assembly process (see figure 8.7). The flanges on the lateral side and the
upper contour are 10 mm width whereas the one along the base is 30 mm long, to ease the assembly on the set-up.

Figure 8.7: Design of a petal of the conical section

8.3.2. MANUFACTURING PROCEDURES
The production plan is defined in this section, including the different steps to be followed and the required materials.

The components required for manufacturing the demonstrator are listed below:

• **Moulds.** The accuracy of cutting the mirror petals off the A4 samples depends on the method use and it has an impact on the final shape accuracy. The relation between both errors is not tackled in this project but it is regarded as an important task for future projects. A laser cutting machine or composites cutting machines, such as the one available at TU Delft, would be better choices, but the non-availability when the manufacturing took place led to the decision of cutting the petals manually. For that purpose, a mould of the petal was 3D-printed (figure 8.8). Moreover, assembling flat elements to produce a double-curvature surface cannot be done without a mould, which was designed with CATIA according to the demonstrator design and machined at the DEMO workshop of TU Delft (see figure 8.9).

Figure 8.8: 3d-printed mould for the petals

Figure 8.9: Machined mould for assembling the parabolic section

• **Surgical blade.** A sharp knife is necessary to ensure that the thin films are cut without inducing wrinkles and with an accuracy determined by the thickness of the blade (less than 1 mm).

• **Mylar™ and Kenpro Mirrorfilm™ Samples.**

• **Kapton™ tape.** It is chosen for assembling the different pieces of the concentrator due to its similarity to Mylar™ and its availability at the Chair of SSE.

• **Others:** it is necessary to print the shape of the cone petals in A4 sheets of paper to use them as a guide. It is also highly recommended to use gloves to ensure that no dirt is deposited on the materials.

The manufacturing procedures are hereafter explained:

1. Cut the paraboloid petals from the Kenpro™ Mirror film. For that purpose, place the petal mould on one corner of the sample, leaving a margin of about 5 mm from each edge. Apply pressure over the mould to ensure that it does not move during the process and cut the petal following the perimeter with the blade.
2. Cut the petals of the cone from the Mylar™ film. A similar procedure is followed now with the elements of the cone, with the difference that there is no mould. The sheet of paper with the contour printed on it is placed below the film and it is cut off with the blade while applying pressure on the film to avoid displacements.

3. Join the petals of the paraboloid following the sequence presented below:
   
   (a) Place the petal over the mould, using the contour and the centre to find the right position. Fix the petal using tape.
   (b) Repeat the procedure with a second petal making the edges coincide along the same straight line.
   (c) Join the petals using the Kapton™ tape.
   (d) Iterate until the four petals are on the mould and joined together.

4. Join the different pieces of the cone using, for that purpose, the flanges (see figure 8.7).

5. Join the parabolic and conical sections with Kapton™ tape

6. Visually inspect the resulting structure and report any issue.

   It is highly recommended to follow the manufacturing procedures using first paper or a similar material since manipulating thicker membranes is much easier and, therefore, they are better to get used to the procedures (see figure 8.10).

   ![Figure 8.10: Results of testing the procedures with paper instead of the real materials.](image)

During this project it was also decided to test the manufacturing procedures for the paraboloid cap with the Kapton™ samples received from the supplier.

### 8.3.3. Manufacturing Results

Different issues were identified during the manufacturing process and they are presented and described hereafter. It must be kept in mind that acceptable tolerances for optical systems are: curvature errors in the range ±0.5%, diameter errors around ±0.1 mm and central depth error within ±0.2 mm [93]. These values will be used to determine whether or not the manufactured item is acceptable

- The mould was measured prior to starting the production. As seen in table 8.4, there are differences between the design and the manufactured item. The uncertainty in the aperture diameter results from measuring it at different locations. As can be inferred from the measurements, the mould does not meet the tolerance requirements introduced above.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Design value</th>
<th>Measurement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aperture’s diameter [mm]</td>
<td>335.17</td>
<td>336 ± 1</td>
</tr>
<tr>
<td>Paraboloid’s depth [mm]</td>
<td>42.12</td>
<td>41</td>
</tr>
</tbody>
</table>

The curvature of the mould could not be verified until the petals were cut and laid on it. It was then observed that it was not possible to adapt the membrane perfectly to the surface, which implies that it was not manufactured with the desired tolerances. It is admitted that the tolerances were not explicitly communicated to the technician, but agreed during a meeting with him. The same applies to the material of the mould, which was not the one initially chosen and it turned to be quite sandy, which led to
8.3. PRODUCTION OF THE TEST OBJECT

a dirty mirror. It was decided to stick to the plan instead of manufacturing it again due to the schedule constraints.

- Cutting the petals with a knife can produce wrinkles, geometrical errors and cracks (see figures 8.11 and 8.12). It is necessary to apply pressure on the 3d printed mould while cutting the petals and use a properly sharp surgical blade. A more accurate geometry is obtained if a new blade is used.

![Figure 8.11: Detailed view of an error obtained while cutting a Kapton™ film](image1)

![Figure 8.12: Detailed view of the errors obtained while cutting a Kapton™ film](image2)

- It was found out that the help of a second person is key to obtain a good result.

- The petal mould was not polished and it left marks on the mirror film due to the pressure applied.

- Kapton™ tape increases the stiffness of the structure in the regions where it is placed. The tape available at the Chair of SSE of TU Delft is 10 mm width, which leads to relatively big regions with a higher stiffness thus causing wrinkles and shape errors. Moreover, the tape does not allow for a continuous connection and overlapping is necessary to ensure that the structure is sealed. This creates localised stiffer points which have an influence in the overall shape (see figures 8.13 and 8.14).

![Figure 8.13: Detailed view of the centre of the reflector and the shape error induced by the Kapton™ tape](image3)

![Figure 8.14: Detailed view of the overlapping between pieces of Kapton™ tape and the wrinkles produced.](image4)

- Manipulating 23µm films is quite complex due to its fragility and its tendency to get attached to any surface.

The exact geometry of the system cannot be determined or measured given the tools available. Photogrammetric techniques appear as an option already used in the past in experimental measurements of membrane systems [11] and it could be also applied for the characterisation of the demonstrator. However, researching this techniques is out of the scope of this project.

The test item exhibits multiple deviations with respect to the design presented in subsection 8.2.2. Although the exact characterisation of the structure is not possible, visual inspections are used to conclude that it is not accurate enough to be used as a flight system but it can still be used for the concept demonstration since the shape and the symmetry are approximately achieved. The observations of the visual inspection were already described above and they are summarised in table 8.5. Each deviation is considered to be acceptable or unacceptable depending on their impact.
Table 8.5: Deviations observed in the demonstrator

<table>
<thead>
<tr>
<th>Id.</th>
<th>Description</th>
<th>Impact assessment</th>
</tr>
</thead>
<tbody>
<tr>
<td>DEV-1</td>
<td>The average mould diameter is 336, whereas the design value is 335.17 mm</td>
<td>Acceptable: the diameter does not affect significantly the final result.</td>
</tr>
<tr>
<td>DEV-2</td>
<td>The paraboloid depth of the mould is 41 mm, whereas the design value is 42.12 mm</td>
<td>Unacceptable: this deviation is an indication of the inaccuracy in the paraboloid shape.</td>
</tr>
<tr>
<td>DEV-3</td>
<td>The petals cannot adapt to the paraboloid shape</td>
<td>Unacceptable: it is an indication of the inaccuracy in the paraboloid shape.</td>
</tr>
<tr>
<td>DEV-4</td>
<td>The petals present wrinkles and errors</td>
<td>Unacceptable: the petals are designed to match each other on the mould with no overlapping. Any inaccuracy in the cutting process leads to inaccuracies in the final shape.</td>
</tr>
<tr>
<td>DEV-5</td>
<td>The material of the mould is sandy and there are particles spread all over the working area</td>
<td>Unacceptable: the deposition of particles on the membrane deteriorates its optical properties. Moreover, the deposition on the Kapton™ tape makes the assembly more difficult.</td>
</tr>
<tr>
<td>DEV-6</td>
<td>The stiffness of the structure is increased in the joining areas where the tape is used</td>
<td>Unacceptable: the tape used is too wide for the structure manufactured and the area affected is too large, leading to wrinkles and deformations. This deviation could be acceptable with a thinner tape.</td>
</tr>
<tr>
<td>DEV-7</td>
<td>The joining method is not continuous.</td>
<td>Unacceptable: there are many locations where the tape presents overlapping, thus increasing the stiffness and generating wrinkles. Moreover, the risk of leaks is increased due to the discontinuities.</td>
</tr>
</tbody>
</table>

8.4. CONCLUSIONS

At this point of the research project, a demonstrator is designed, analysed and manufactured. The design is done following the same design process proposed for the real system (chapter 5), aiming for a device with a performance as close as possible to the final design presented in chapter 7 but considering the constraint imposed by the material availability (see subsection 8.1.1 for the demonstrator design requirements and their rationales). The final design can be found in table 8.3. A test item has been produced based on the manufacturing approach (subsection 8.3.1) and following a set of procedures (subsection 8.3.2).

The manufactured demonstrator appears to present several deviations from the designed one, as mentioned before in subsection 8.3.3. Sources of errors have been identified, with the mould’s shape inaccuracy, the cutting approach and the joining method as the three major issues. The errors are severe and thus the device is not acceptable as flight system. The design and the manufacturing approach must be reviewed in future research projects.

The first problem can be solved by manufacturing a more accurate mould, preferably made of a different material so that it is possible to perform the assembly in the clean room and prevent the deposition of any particle on the mirror membrane. The cutting approach should be changed since doing it manually causes wrinkles, errors and discontinuous contours (see figures included in subsection 8.3.3). Laser cutting and automatic cutting machines are more accurate options. The final issue can be mitigated by using a continuous joining method such as epoxy resin [1]. It is impossible to avoid discontinuities in the stiffness distribution but they can be reduced. It would be also advisable to design a mould for the entire structure or to use wires to make the concentrator stiffer while manufacturing and assembling it.

Given the time and budget constraints, the manufacturing phase of the project resulted in a prototype considered acceptable for the concept demonstration. Several recommendations about how to solve the problems identified have been proposed in this concluding section and throughout section 8.3.
This chapter covers the complete planning (sections 9.2 and 9.3), simulation (section 10.1) and results (section 9.4) of the test campaign of this research project. It includes the discussion of the results in section 9.5, followed by a set of conclusions (section 9.6). The objective of this chapter is to derive the real performance of the system and the procedure to obtain it.

9.1. Introduction: Tests objectives and organisation

The test campaign is performed in order to achieve different objectives which are presented below in table 9.1 together with their corresponding success criteria. Each objective is considered to be successful if all the criteria are met, whereas it is partially successful if at least one of them is met and unsuccessful if none of them are achieved.

Table 9.1: Test campaign objectives and success criteria

<table>
<thead>
<tr>
<th>Id.</th>
<th>Objective</th>
<th>Success criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td>TEST-OBJ-1</td>
<td>Development of a simple, low cost set-up to test inflatable reflectors.</td>
<td>- The set-up is built using materials available in the faculty of Aerospace Engineering.  &lt;br&gt; - The set-up is leak-proof.  &lt;br&gt; - The components and instruments are suitable for the test campaign  &lt;br&gt; - No component or instrument is damaged.</td>
</tr>
<tr>
<td>TEST-OBJ-2</td>
<td>Demonstration of the inflating process.</td>
<td>- The inflating system is sealed.  &lt;br&gt; - The demonstrator is successfully pressurised: the majority of the wrinkles disappear and the design shape is attained.</td>
</tr>
<tr>
<td>TEST-OBJ-3</td>
<td>Evaluation of the manufacturing procedures by performing a leak test.</td>
<td>- The concentrator is leak-proof.  &lt;br&gt; - The shape is maintained during all the test campaign.</td>
</tr>
<tr>
<td>TEST-OBJ-4</td>
<td>Determination of the demonstrator's performance.</td>
<td>- The concentrator is not damaged during the tests.  &lt;br&gt; - The power reflected is successfully measured.  &lt;br&gt; - The repeatability of the tests is demonstrated.</td>
</tr>
<tr>
<td>TEST-OBJ-5</td>
<td>Validation of the ray tracing tool.</td>
<td>There is a maximum difference of power between theoretical estimations (section 10.1) and experimental data (subsection 9.4.2) of ±20% [37].</td>
</tr>
</tbody>
</table>

In order to achieve these objectives, the demonstrator is tested using a theatre lamp as the light source (see annex E for the specifications). It is decided to divide the test campaign into two phases:
• **Test Phase A: Light source characterisation.** The first part consists in the determination of the performance of the light source. It is also necessary to determine how representative the results are compared with respect to orbit conditions.

• **Test Phase B: Concentrator demonstrator characterisation.** The second part of the test campaign covers the determination of the demonstrator performance. This objective is pursued by measuring the performance of the device with a theatre lamp.

The reader must keep in mind that this project does not intend to manufacture and test a space qualified system but a demonstrator but to prove that the concept and the design tools work.

### 9.2. Test Plan

The general test plan in presented in table 9.2. The test phases previously introduced are now divided in sub-categories with the purpose of attaining different objectives. The number of tests to be performed for each test case is just a preliminary value. Three tests are considered enough to characterise the lamp and the concentrator performance and two tests seem to be enough to assess the inflating system and the sealing of the set-up. However, the numbers can be re-defined depending on the results.

Table 9.2: Test plan

<table>
<thead>
<tr>
<th>Test Phase</th>
<th>Sub-category</th>
<th>Objective</th>
<th>Number of tests</th>
<th>Success criteria</th>
</tr>
</thead>
</table>
| A          | A-1          | Characterisation of the lamp w.r.t. time | 3               | - The irradiance is characterised w.r.t. time.  
- Average values are obtained.  
- The measurements show a deviation in the order of 5% w.r.t. the average values.  
- The light source and the measurement instrument are suitable for the tests. |
| A          | A-2          | Characterisation of the lamp w.r.t. direction at a given distance | 3               | - The irradiance is characterised w.r.t. the direction.  
- Average values are obtained.  
- The measurements show a deviation in the order of 5% w.r.t. the average values.  
- The light source and the measurement instrument are suitable for the tests. |
| B          | B-AUX-1      | Demonstration of the inflating process | 2               | See the criteria for TEST-OBJ-2 in table 9.1. |
| B          | B-AUX-2      | Leak-test | 2               | See the criteria for TEST-OBJ-3 in table 9.1. |
| B          | B-1          | Evaluation of the on-axis performance of the concentrator | 3               | See the criteria for TEST-OBJ-4 in table 9.1. |
| B          | B-2          | Evaluation of the off-axis performance of the concentrator | 3               | See the criteria for TEST-OBJ-4 in table 9.1. |

All the tests except for B-AUX-1 and B-AUX-2 have numerical results, which are registered in files using *Microsoft Excel* with names following the template `test_TP_TS_no_N_dd_mm_yy`, where `TP` refers to the test phase, `TS` is the test sub-category, `N` is the test number and the last three inputs `dd_mm_yy` indicate the test date. The data processing is performed with *MATLAB*. 
9.3. Design of the Test Set-up and Test Procedures

The Set-up and the Test plans are specifically designed for each phase of the test campaign. It is intended to use the resources already available at Chair of SSE of TU Delft to lower the cost and minimise possible schedule delays.

9.3.1. Phase A

The light source characterisation is a key task of the test campaign in order to conclude how representative the tests are and how far they are from representing the conditions during an hypothetical space mission. This phase of the test campaign is also relevant for the comparison of the analytical and the experimental results, and to assess the real efficiency of the system. The description of the test set-up and the test plan are presented hereafter.

Test Set-up

A pyranometer is used to measure the irradiance emitted by the light source. This instrument is a sensor designed to measure the solar radiation over a broad spectral range, producing a voltage output proportional to the irradiance [94]. In this case, it is moved in three dimensions with respect to the source to obtain different measurements at different locations. Regarding the source, it is hanged from the ceiling, resulting thus in a vertical set-up (as seen in figure 9.1). The reason for this decision is due to the fact that the concentrator could be affected by gravity if placed in horizontal position.

The test set-up includes the following components:

- **Theatre lamp**: A theatre lamp available at the Chair of SSE (Sylvania PAR64 1000W SP) is chosen as the light source due to its aperture and high power (see annex E for the datasheet).

- **Pyranometer**: a CM3 pyranometer developed by Kipp & Zonen is used because of its performance capabilities, its availability and its size (see annex E for the product brochure and [94] for the instructions manual).

- **Multimeter**: the pyranometer provides a signal output ranging from 0 to 50 [mV]. A portable multimeter is necessary to keep track on this signal.

- **Measure tape**: it is used to verify distances during the tests.

- **Gridded surface**: It is used to place the pyranometer on the desired spots.

- **Others**: it may be necessary to include extra elements such as a chain to hang the lamp, tape to fix the gridded surface to the floor or a watch to measure the time.

All the components are either already available or easy to be manufactured or purchased, following the requirements concerning the utilisation of the faculty’s resources (REQ-C-3) and designing a low cost test set-up (REQ-C-1).

A similar test was performed by Leenders [16] during the development of a set-up for a STP engine. However, this previous characterisation was done in 2008 (eight years before this research project), which means that the performance of the lamp may have changed, and the number of tests performed by then are not considered enough to mitigate the instabilities the author reported [16]. More experimental results are required to determine the repeatability of the lamp, which is one of the main disadvantages of choosing this light source.

Before starting with the tests, it is necessary to analyse if the pyranometer could be damaged and if it covers the entire spectrum of the lamp’s emission. The main specifications of the pyranometer are as follows [94] [16]:

![Diagram of test set-up for Phase A of the test campaign]
- Spectrum waveband: 305-2800 [nm].
- Maximum irradiance: 4000 [W/m²].
- Operating Temperature: [-40,80] [Celsius].
- Sensitivity: 10 - 32 [µV W⁻¹ m²].
- Inaccuracy: there is a maximum uncertainty of ±10.5%, which has to be taken into account when analysing the test results. This error is divided between different sources:
  - Temperature Dependence: ±6 [%] (from -10 to 40 [Celsius]).
  - Non-linearity: ≤±2.5 [%] (up to 1000 [W/m²]).
  - Tilt Response: ≤±2 [%] (at 1000 [W/m²]).
  - Expected accuracy for daily sums: ±10 [%]

Regarding the lamp, the datasheet claims that it has a colour temperature of 3200 [K], which allows to have an approximation of the lamp’s spectrum. As seen in figure 9.2, the peak is 4308.4 [W · m⁻² · nm⁻¹]. The spectrum region for which the irradiance is 10% of the maximum is between 394 and 3027 [nm], whereas the pyranometer covers from 305 up to 2800 [nm]. The range omitted can be considered small, so the pyranometer is suitable for the tests. This decision is also supported by the analysis of the total irradiance resulting from integrating the spectrum from 1 [nm] up to 10,000 [nm], which equals to 5.9142 [MW/m²] (close to the value given by Stephan Boltzmann’s law, 5.9454 [MW/m²]). Around 90% of the total irradiance is reached for a wavelength \( \lambda \approx 2800 \) [nm]. Considering this value and the range mentioned above, the waveband of the pyranometer is suitable for the tests since only a small fraction of the radiation is missed.

\[
\Phi = \frac{0.25 \cdot 1000}{\pi \cdot (D_{lamp} + 2 \cdot z \cdot \tan(\alpha))^2},
\]

Figure 9.2: Theoretical Spectral irradiance of the theatre lamp (black body of \( T = 3200 \) [K])

The other issue to be studied is the suitability of the pyranometer in terms of the maximum irradiance it measures. The lamp provides an output beam of 1000 [W] which has a spread angle without the casign of 23 [deg] for the 10% wavefront (see annex E). Leenders reported in [16] an efficiency of 25%, which is going to be used as a first approximation. The efficiency value will be improved using the experimental measurements but it is necessary to perform this preliminary assessment. Therefore, assuming that all the rays have the same power, the flux reaching the pyranometer would be equal to:
It can be thus concluded that the pyranometer can be used for this test campaign to measure the irradiance emitted by the theatre lamp, covering the relevant spectral range of it, without being damaged due to excessive power flux.

**Test Procedures**

The basic idea behind this radiometric test consists in the determination of the irradiance at different positions with respect to the lamp. The accuracy of this set-up is limited by the size of the pyranometer's cap and the own accuracy of the instrument, which was already discussed before. Using the specifications given by the manufacturer, the cap's diameter can be estimated to be \( \approx 30 \text{ [mm]} \). This value means that the pyranometer is not measuring the irradiance at a single point but in an area of \( 706.85 \text{ [mm}^2 \text{]} \). It is decided to take measurements every 50 [mm] in order not to have overlapping between them. Unlike the procedures followed by Leenders [16], it is preferred to perform all the tests in a vertical disposition instead of placing the lamp horizontally.

The test procedures are defined as follows:

1. A gridded sheet with a spacing of 50 [mm] between lines and a side length of 500 [mm] is generated.

2. A work area of the size of the sheet is cleared of any other object to prevent reflections and to ensure that the lamp does no damage anything nearby.

3. The lamp is hanged from the ceiling and the distance to the testing surface is measured.

4. The sheet is placed right below the lamp and it is fixed to the floor using tape. The alignment between the sheet and the lamp is ensured by using four ropes attached to different positions on the lamp.

5. The pyranometer is first calibrated following the guidelines of the manufacturer [94]: it is covered to ensure that it receives no radiation, it is connected to the multimeter and the voltage output is recorded. The expected measurement is equal to 0 [mV].

6. Once without the cover, the pyranometer is placed on the center of the sheet, the lamp is connected and the output voltage is recorded with respect to time. The results of the time variations observed in the irradiance are used to determine time required to reach the steady-state conditions are reached.

7. Using the testing time deduced from the previous step, the pyranometer is placed at each location over the gridded sheet and the voltage is recorded once a stable value is observed.

8. The procedure is re-iterated to assess the repeatability and the stability of the lamp.

In case of test sub-category A-1, step 6 is skipped since it is only necessary to take measurements with respect to time at the origin. For the test sub-category A-2, it is decided to perform the test 1.6 m away from the lamp due to the length of the ropes used to hang it from the ceiling and the height of the demonstrator.

**9.3.2. Phase B**

The second phase of the test campaign involves testing the solar concentrator already manufactured using for that purpose the theatre lamp. Both the test set-up and the test procedures will be hereafter explained.

**Test Set-up**

The test set-up is similar to the one employed before in Phase A, with the difference that the mirror's reflective section is facing the lamp instead of the pyranometer. This new set-up requires the design of the interface between the pyranometer, the pressurisation system and the concentrator. For this second phase of the test campaign, the pyranometer has almost the ideal size considered in the design (a diameter of 3 [cm] instead of 2.5 [cm]), so the set-up is representative in this sense. Figure 9.3 shows an overview of the set-up designed for this second phase of the test campaign. All the components have been 3-D printed using the Makerbot printer available at the laboratory of the Chair of SSE at TU Delft. The drawings of all the components can be found in appendix F.
Figure 9.3: CAD representation of the test set-up designed for Test Phase B.

Figure 9.4 shows two views of the interface, which is designed to connect the set-up and the concentrator (5). It has also the role of fixing the pyranometer (1) at the correct position and ensuring that there are no leaks. In order to make the assembly process easier, the interface is divided into two parts (3 and 4), with an orifice on one side for the pressurising line and the pyranometer's cable. A sealing ring (2) is designed to connect the pyranometer with the interface. The tolerances of the ring are selected to have a press fit between the interface, the ring and the pyranometer. After printing the components, it was observed that the roughness of the surfaces was not low enough to ensure the sealing of the system. It was decided to sand down the surfaces and place tape on them. The pyranometer is connected to the rear side with M5 screws which are left loose until the interface is assembled. Hence, the pyranometer can move and fitting the ring and the interface front side is easier. Both the rear (4) and front (3) sides are finally connected with M6 screws, which are strongly tightened to seal the system. The interface is designed such that the pressure of these screws forces the sealing ring to exert enough pressure on the pyranometer's surface to prevent any leaks. The connection region (4) is designed as an interface with a conical shape. The joining method to be used in this region is either silicon or glue, both placed with a gun.

Figure 9.4: Views of the interface designed to connect the concentrator and the set-up. The figure includes (1) the pyranometer, (2) the sealing ring, (3) the interface upper side, (4) the interface rear side and (5) the concentrator.

Considering the height of the room and the dimensions of the test set-up and the lamp, the demonstrator vertex is placed at 1.6 m from the entrance of the lamp casing. According to the results obtained by Leenders, the irradiance at this distance is safe for the pyranometer.

**Test Plan**

The procedures to perform this second part of the test campaign are explained hereafter:

1. Repeat steps 1 to 5 of the test procedures of Phase A.

2. Assemble all the components according to the following instructions:
   
   (a) Screw the rear side of the interface to the support structure.
   
   (b) Screw the pyranometer to the rear side of the interface leaving it loose, orienting it such that the cable is on the proper side of the interface.
   
   (c) Attach the pyranometer’s cable to the support structure so that it does not impact the field of view.
(d) Mount the CO\textsubscript{2} cartridge with its valve on the support structure and connect it to the pipe using a bicycle’s valve. It was observed that if the bicycle’s valve is connected to the inflating device, the air comes out from the lateral walls, so it was necessary to drill the front area to remove its spherical valve. The CO\textsubscript{2} inflating device has already a manual valve so it is not necessary to have a second one in the system.

(e) Fix the pipe to the structure and connect it to the sealing ring.

(f) Attach the concentrator to the interface frontal element using a glue gun. It is necessary to first position the concentrator with tape so that it does not move while the glue is deposited. This task must be carefully done because of the high temperature of the glue and the impact of any misalignment on the final performance of the system.

(g) At this point, before the system is closed, perform a leak test for the inflating system. Report any problem found.

(h) Place the interface frontal element with the sealing ring on it over the pyranometer and screw both halves of the interface until the structure is closed.

(i) Perform a visual inspection and report any inconsistency. Measure the distance between the focal plane and the paraboloid’s vertex, the aperture, the distance between the paraboloid’s edge and the receiver and the distance to the floor.

3. Perform a leak test:

   (a) Open slowly the valve of the CO\textsubscript{2} inflating device.
   
   (b) Observe the behaviour of the structure.
   
   (c) Identify any leakages and report them. If possible, fix them.
   
   (d) Disassemble the CO\textsubscript{2} cartridge and empty the concentrator. Assemble a new bottle and close the system.

4. Place the set-up over the gridded paper and align it.

5. Open slowly the valve of the CO\textsubscript{2} inflating device until the best shape observed in the leak test is attained. Leave it slightly open as a compensation measure for any pressure loss in the system.

6. Turn on the theatre lamp and take measurements of the output voltage and the time.

7. Repeat the test twice to assess the repeatability.

After this first test is performed, it is also required to perform one with the lamp’s axis displaced with respect to the concentrator’s axis. The purpose of this second test is to evaluate how the concentrator behaves if the source is not aligned with its axis and to obtain measurements with a configuration in which the central region of the lamp, which is the one with the highest irradiance, falls onto the device.

9.4. TEST RESULTS

The results obtained from the different tests performed are presented in this section, whereas the analysis and discussion of the results can be found in section 9.5. For both test cases, a conversion factor $\nu = 15 \cdot 10^{-3} \text{mV/}(\text{W/m}^2)$ is used based on the pyranometer datasheet to convert the voltage measurements to irradiance (see appendix E). The description of the tests performed, the files produced and brief summaries about the information included in each file can be found in table G.1 in appendix G.

9.4.1. PHASE A

Fifteen different tests were performed in order to characterise the time variation of the irradiance emitted by the lamp at different locations along the vertical axis. The pyranometer was positioned at seven distances with respect to the lamp’s entrance, with more tests performed for $z = 1.6 \text{ [m]}$ since the concentrator is expected to be located around this position according to the set-up design (see subsection 9.3.2). The complete set of data can be found in table G.2 in appendix G, whereas the averaged results are presented below in table 9.3 together with the maximum deviations observed. From the complete set of results, it can be inferred that the time required to obtained steady state conditions is below 30 seconds.
Table 9.3: Averaged results of irradiance as a function of the vertical distance to the lamp

<table>
<thead>
<tr>
<th>z [m]</th>
<th>1.035</th>
<th>1.25</th>
<th>1.4</th>
<th>1.5</th>
<th>1.6</th>
<th>1.7</th>
<th>1.71</th>
<th>1.82</th>
</tr>
</thead>
<tbody>
<tr>
<td>Φ [W/m²]</td>
<td>4136.7</td>
<td>3407.8</td>
<td>2986.7</td>
<td>2736.1</td>
<td>2443.8</td>
<td>2195.0</td>
<td>2170.5</td>
<td>2021.4</td>
</tr>
<tr>
<td>Max. deviations [%]</td>
<td>1.05</td>
<td>0.23</td>
<td>0.67</td>
<td>3.76</td>
<td>4.79</td>
<td>2.05</td>
<td>1.05</td>
<td>2.05</td>
</tr>
</tbody>
</table>

As can be observed in table G.2, the number of measurements taken for test 1.3 (z = 103.5 m) is lower than for the rest. It was decided to stop measuring after noticing that the irradiance was above the instrument limits. Only one test was performed for a distance of 1.25 m (test 4.8), 1.4 m (test 4.7) and 1.5 m (test 4.6). The reason is that the reflector is more likely to be located at larger distances according to the set-up design (see subsection 9.3.2 for the general description and appendix F for the drawings of the set-up).

As commented before in subsection 9.3.1 and in table 9.2, the second part of this first testing phase consists in the characterisation of the lamp’s irradiance at different positions over the same plane. For this purpose, a vertical distance of 1.6 m from the lamp was selected (see subsection 9.3.2 for the reasons of this decision). Four different tests were performed (see table G.1 in appendix G), yielding the average results presented in figure 9.5. It can be observed that there is a peak at the centre and a steep decrease in the radial direction with values in the order of 20 W/m² at 0.55 m from the centre.

The test data is processed to express the irradiance as a function of the radial position. This way, it will be easier to perform simulations and to determine the irradiance distribution of the lamp. The data is averaged and normalised using the highest irradiance value (corresponding to the origin) and the image diameter, resulting in the curve observed in figure 9.6. It can be observed that an irregular curve is obtained instead of the expected Gaussian-type curve. The reason lies on the facts that it is the result of averaging several measurements and that the lamp is quite unstable both in time and direction.
9.4.2. Phase B

The results of the second phase of the test campaign are divided between qualitative and quantitative outcomes and they are both hereafter presented.

Qualitative assessment of the Demonstrator

A visual inspection of the assembled set-up was performed prior to the performance test. Two different views of the set-up before inflating the reflector can be found in figures 9.7 and 9.8. The concentrator appears to be partially inflated due to the remaining air inside it. In order to avoid this from happening, it would be necessary to fold the reflector and take all the air from it before the final assembly. However, this is not among the objectives of this test campaign. It is also possible to observe additional pieces of tape around the base of the cone, which were placed to solve small cracks created during the assembly process.

![Figure 9.7: General view of the test set-up for Phase B before inflating the reflector](image)

![Figure 9.8: Detailed view of the demonstrator assembled on the set-up of Test Phase A before inflation](image)

The first leak test was performed with the gas line disconnected from the concentrator so that it was possible to look for leaks in the gas assembly. The tube's exit was covered in order to allow the pressure in the system to increase and no leak was identified. The leak test done with the concentrator connected indicated the presence of several holes in the structure, which are a direct consequence from the production phase and the way it is assembled on the test set-up. The connection area between the demonstrator and the interface was analysed and all the holes were covered. However, it was found out that identifying leaks in the edge between the parabolic and conical sections was not easy. The major leaks were solved but there was still a small pressure decrease, which can be due to the non-continuous connection.

Figures 9.9 and 9.10 present different views of the concentrator during the last leak test. Although there were still small gas losses, the test was considered to be successful. As observed in both pictures, the central area of the reflector has an almost flat shape. Different wrinkles along the connections were identified and the conical section did not maintain the straight shape of its lateral surface as predicted by the FEM analyses. The reason for this last observation is the non consideration of the tape in the computational model. Pressurising the device did not solve these issues.

![Figure 9.9: Test set-up for Phase A of the test campaign](image)

![Figure 9.10: Test set-up for Phase A of the test campaign](image)

Another observation made during the leak test is the influence of the pressurisation ratio on the final shape. The manual valve was used to modify the mass flow rate. At high rates, the concentrator experienced strong asymmetric deformations.

The inflated shape of the concentrator was slightly tilted (estimated around 5 deg using the horizontal displacement of the vertex, \( \approx 1 \text{ cm} \), and the total height of the concentrator presented in table 9.4). Different
design and measured geometrical parameters are presented in table 9.4.

Table 9.4: Measured and design values of different geometrical parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Design value</th>
<th>Measured value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aperture’s diameter</td>
<td>335.1</td>
<td>330</td>
<td>[mm]</td>
</tr>
<tr>
<td>Total height</td>
<td>164</td>
<td>183</td>
<td>[mm]</td>
</tr>
<tr>
<td>Paraboloid depth</td>
<td>42.12</td>
<td>30</td>
<td>[mm]</td>
</tr>
</tbody>
</table>

**Quantitative Results**

Although three tests were originally planned for test sub-categories B-1 and B-2 (see table 9.2), the results obtained in the first test forced to change the plan. Hence, two tests were performed with the lamp aligned with the concentrator’s axis (Tests B-1.1 and B-1.2) and another one with the lamps displaced 7 cm with respect to the axis in the direction perpendicular to the support structure of the set-up (Test B-2.1). The displacement was selected as an approximate middle point between the axis and the edge of the concentrator. It was observed in the three of them that the irradiance values were way above the limits of the pyranometer (4000 W/m²). This issue caused that after around 30 seconds, the voltage measured stopped decreasing and it dropped to 0 quite fast. It is inferred that reflecting more irradiance than what is allowed led the instrument to shut itself down. Therefore, it was decided to perform really short tests (below 20 seconds) and limit the number of tests to 3. These issues are analysed more extensively in section 9.5.

The results of the tests can be observed in table 9.5, together with the calculation of the power hitting the receiver which is estimated by multiplying the irradiance by the area.

Table 9.5: Results of test phase B

<table>
<thead>
<tr>
<th>Test id.</th>
<th>V [mV]</th>
<th>( \Phi ) [W/m²]</th>
<th>P [W]</th>
</tr>
</thead>
<tbody>
<tr>
<td>B-1.1</td>
<td>109</td>
<td>7266.7</td>
<td>5.14</td>
</tr>
<tr>
<td>B-1.2</td>
<td>105.1</td>
<td>7006.7</td>
<td>4.95</td>
</tr>
<tr>
<td>B-2.1</td>
<td>130.1</td>
<td>8673.3</td>
<td>6.13</td>
</tr>
</tbody>
</table>

**9.5. Analysis and Discussion of the Test Results**

The results presented before in section 9.4, which are complemented by the data included in appendix G, are analysed and discussed in this section.

**9.5.1. Phase A**

The characterisation of the time evolution of the lamp irradiance (test sub-category A-1 in table 9.2) was successfully performed, with maximum deviations below the 5% limit considered in the test plan. The repeatability of the results is proven by the low variations observed with respect to the average values presented in table 9.3. There are of course uncertainties, some of which are identified and, if possible, assessed hereafter:

- Alignment errors between the lamp and the gridded sheet. Ropes, each of which attached to a metallic nut on one extreme, were hung from four points of the lamp to identify the projection of the casing contour over the plane. A laser was used to verify the accuracy of the alignment process. The lamp and the sheet were aligned with an approximate precision in the order of ±1 cm. From the interpolated data obtained in test sub-category A-2, it was observed that variations of 1 cm caused deviations lower than 1% in the irradiance measured (see figure 9.6). Therefore, the errors caused by misalignments do not cause significant changes in the results.

- The inclination of the lamp. A spirit level was used to determine the inclination of the lamp. However, the precision of this analogical instrument could not be determined.

- Measurement of the distance from the lamp to the plane. A tape measure with a minimum spacing of 1 mm was used. Different measurements were taken to mitigate the errors due to the straightness of the tape.
9.5. Analysis and Discussion of the Test Results

- Pyranometer inaccuracy. As commented in subsection 9.3.1, the maximum error of the pyranometer is ±10.5%, which is translated into inaccuracies of around ±250 W/m² for tests performed at the origin and at 1.6 m from the casing entrance (see figure 9.11). However, it is not clear how the relation between the conditions and the errors can be obtained from the datasheet (see appendix E).

![Figure 9.11: Variation of the irradiance with respect to the operating time for test 4 including the inaccuracy of the pyranometer](image)

The values obtained show discrepancies if compared with those measured by Leenders [16], which may be due to inaccuracies, the ageing effects or the way the data was taken. It was not possible to compare the data for z>1.4 [m]. What is even more surprising is that the values measured by Leenders at 1.05 m from the lamp casing were still 1000 W/m² below the pyranometer limit. This is a clear proof of the difference in the measurements obtained. Table 9.6 presents the values obtained by Leenders [16] \( \Phi_{\text{Leenders}} \), the measurements taken during this research project \( \Phi \) and irradiance values calculated by interpolating the measurements of this project \( \Phi_{\text{int}} \). As can be observed, the frequency in the measurements taken in this project was not so high since there was a higher interest in gathering data around z = 1.6 [m].

<table>
<thead>
<tr>
<th>z [cm]</th>
<th>Test 1 - ( \Phi_{\text{Leenders}} ) [W/m²]</th>
<th>Test 2 - ( \Phi_{\text{Leenders}} ) [W/m²]</th>
<th>( \Phi ) [W/m²]</th>
<th>( \Phi_{\text{int}} ) [W/m²]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.45</td>
<td>1963.1</td>
<td>1930.2</td>
<td>2896.7</td>
<td>3048.0</td>
</tr>
<tr>
<td>1.4</td>
<td>2068.5</td>
<td>2048.7</td>
<td>2896.7</td>
<td>3048.0</td>
</tr>
<tr>
<td>1.35</td>
<td>2325.4</td>
<td>2173.3</td>
<td>3234.0</td>
<td></td>
</tr>
<tr>
<td>1.3</td>
<td>2365.0</td>
<td>2351.8</td>
<td>3437.7</td>
<td></td>
</tr>
<tr>
<td>1.25</td>
<td>2463.8</td>
<td>2457.2</td>
<td>3407.8</td>
<td>3661.0</td>
</tr>
<tr>
<td>1.2</td>
<td>2648.2</td>
<td>2608.7</td>
<td>3907.2</td>
<td></td>
</tr>
<tr>
<td>1.15</td>
<td>2892.0</td>
<td>2780.0</td>
<td>4178.5</td>
<td></td>
</tr>
<tr>
<td>1.10</td>
<td>3017.1</td>
<td>2977.6</td>
<td>4479.9</td>
<td></td>
</tr>
<tr>
<td>1.05</td>
<td>3208.2</td>
<td>3181.8</td>
<td>4136.7</td>
<td>4814.0</td>
</tr>
</tbody>
</table>

Ageing is supposed to cause the opposite effect in the performance of the lamp than what is obtained now. The differences are not within the 10.5% of maximum uncertainty given by the pyranometer so that is not the reason. The procedures followed in both projects were identical, with the difference that the layout in Leenders’ setup was horizontal. The pyranometer was calibrated before performing every test in this project following the guidelines presented by the manufacturer in [94] and no anomalies were detected. Different working conditions or different data processing strategies appear as possible sources of error. However, after carefully analysing the information presented by Leenders in [16] and reviewing every step of the test campaign, no reason was deduced. Moreover, the results of this test campaign are backed by 15 tests, with a proven repeatability as said before. The pyranometer malfunction is also regarded as an option even though the calibration process was successful.

The test sub-category A-2 intended to characterise the directional distribution of irradiance emitted by the lamp. Figure 9.5 presented the averaged data over the plane, which is transformed into the radial curve seen in figure 9.6. As well as before and in order to assess the success criteria presented in table 9.2, the repeatability of the test is assessed now.
The comparison of each measurement with the average interpolated curve yields average deviations which vary strongly as a function of the radial distance (9.12). The maximum average deviations exceed 20%, supporting the initial claim about the directional instability of the lamp. These results imply that the success criterion concerning the directional characterisation of the lamp (test A-2 in table 9.2) is not met.

The radial distribution of irradiance is used to compute the power emitted by the lamp as follows:

\[ P = \int_A \Phi(x, y) dA = 2 \cdot \pi \int_0^{r_{max}} \Phi(r) \cdot r \cdot dr = 356.28 \text{ [W]} \]  

(9.2)

This value means that the efficiency of the lamp is 35.62%, which is 10% larger than the one obtained by Leenders [16]. The same observations as those derived from table 9.6 apply to this result too. This test subcategory was performed taking more points (270 in total) than the measurements Leenders took (100 [16]. It was also decided to evaluate points out of the x and y axes, which was not done by Leenders. The test campaign can be thus considered to be more extensive but, as commented before, there are many other factors to take into account to judge which measurements are valid.

The measurement taken at 0.55 m from the centre is lower than 1% of the central peak value so this point is taken for the image size at this position in the z-axis. The diameter of the casing and the size of the image 1.6 m away allow to determine the spread angle of the light source:

\[ \tan(\alpha_{\text{lamp}}) = \frac{D_z - D_0}{2 \cdot z} = \frac{2 \cdot 0.55 - 0.18}{2 \cdot 1.6} \Rightarrow \alpha_{\text{lamp}} = 16.04 \text{ [deg]} \]  

(9.3)

\( \alpha_{\text{lamp}} \) refers to the spread angle of the lamp, \( D_z \) is the spot diameter at a distance \( z \) and \( D_0 \) is the spot diameter at the exit of the casing. The value obtained is quite similar to the one obtained by Leenders (19 deg) [16].

Considering the conservation of energy, the power emitted by the lamp is the same at every distance. This means that it is possible to know the theoretical irradiance value along the z-axis:

\[ \Phi = \text{constant} \Rightarrow \Phi_z, i \cdot \frac{\pi}{4} \cdot D^2_z = \Phi_z, j \cdot \frac{\pi}{4} \cdot D^2_z, \]  

(9.4)

where \( \Phi_z, i \) and \( \Phi_z, j \) are the irradiance values at the central point at distances \( z_i \) and \( z_j \), respectively. The diameter of the image can be estimated using the spread angle: \( D_z = D_0 + z \cdot \tan(\alpha) \). Figure 9.13 shows the results of equation 9.4 at different locations compared with the averaged measurements. As can be inferred from the image, there is a good agreement between the theoretical estimations and the experimental results, especially for the interval between \( z = 1.4 \text{ [m]} \) and \( z = 1.8 \text{ [m]} \). The non-correlation for lower values is a direct consequence of assuming that the flux can be calculated using equation 9.4 instead of taking into account the radial distribution of irradiance, as seen in figure 9.6.
A final issue to be discussed is derived from the pyranometer error which imply an uncertainty of ±10.5%. There is no information on how to derive the relation between the testing conditions and the error. It was decided to repeat the tests to assess the repeatability and to check the calibration of the instrument according to the manual [94] but nothing else could have been done since an attempt to contact the manufacturer was made with no success. Figure 9.14 shows the averaged radial distribution of irradiance at 1.6 m from the casing together with the maximum error of the instrument. As can be inferred from the curve, the uncertainty can increase up to almost 250 W/m² at the centre.

![Figure 9.14: Averaged radial distribution of irradiance including the ±10.5% inaccuracy](image)

The theatre lamp was characterised during this phase of the test campaign. It was observed that the time and directional variations of the irradiance are quite big. Multiple tests were performed in order to mitigate the effects of the lamp’s instabilities, but there are still uncertainties. The test objectives presented in 9.2 were completely fulfilled for the sub-category A-1 but partially met for the sub-category A-2. The averaged results exhibit variations larger than the 5% considered. However, it could be inferred from the tests these variations are implicit in the lamp performance and a higher level of accuracy is not attainable. The differences observed between the measurements taken for this project and those gathered by Leenders [16] are considerably substantial and worrisome. Different reasons are analysed but no conclusion can be derived.

It can be concluded that the light source selected is not representative if compared with the solar radiation. The instabilities observed in the radiation emitted by the lamp and the spread angle differ from the uniform collimated Sun rays the system would receive once in orbit. Therefore, the tests can be used to demonstrate the concept and validate the design tools, but not to validate the expected behaviour during flight.

9.5.2. Phase B

The second test phase was performed after having qualitatively assessed the demonstrator and the test set-up. After manufacturing the reflector, it was already observed that the kapton™ tape was increasing the stiffness of the regions where it was placed. Moreover, multiple wrinkles were observed and the paraboloid was almost flat around the vertex. Connecting the demonstrator and the interface was quite complex due to the low accessibility to this area, the fragility of the membrane, which led to the formation of cracks in the structure, and the size of the glue gun, which was too large for this task. The set-up was proved to be sealed, which means that the objectives of test B-AUX-1 were attained. The poor quality of the manufactured demonstrator led to a failed leak test (B-AUX-2) but it was decided to continue with Phase B since it was observed that the geometry did not experience major changes due to the deflating process.

After illuminating the reflector with the theatre lamp, it was observed that the pyranometer was not suitable for this test since the irradiance values measured exceeded the instrument limit. Therefore, it is not possible to determine if the values measured correspond to steady-state conditions or if the pyranometer was working properly until it shut down. Possible solutions include increasing the distance from the lamp to the reflector or placing a field stop. Nevertheless, the first option is not feasible due to the limitations imposed by the height of the room. The second one should be consider for future projects. An alternative to
making changes in the light source is to substitute the pyranometer by a piece of copper and derive the power received from the temperature change.

The evaluation of the system’s efficiency is performed using the results obtained during phase A to estimate the power falling on the mirror. The integration of the power flux at 1.6 m away from the lamp over the cross-sectional area of the demonstrator (subtracting the field stop caused by the set-up) yields a value of 105.52 W. The results of the tests are presented again in table 9.7 together with the efficiency.

Table 9.7: Results of test phase B

<table>
<thead>
<tr>
<th>Test number</th>
<th>V [mV]</th>
<th>Φ [W/m²]</th>
<th>P [W]</th>
<th>η [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>B-1.1</td>
<td>109</td>
<td>7266.7</td>
<td>5.14</td>
<td>4.86</td>
</tr>
<tr>
<td>B-1.2</td>
<td>105.1</td>
<td>7006.7</td>
<td>4.95</td>
<td>4.69</td>
</tr>
<tr>
<td>B-2.1</td>
<td>130.1</td>
<td>8673.3</td>
<td>6.13</td>
<td>5.81</td>
</tr>
</tbody>
</table>

Different reasons for the low efficiency measured have been identified:

1. Due to the problems found during the manufacturing process (described in chapter 8), the geometry of the concentrator does not have a good quality, which lowers the performance capabilities of the system.

2. A fraction of the power is lost due to the transmittance coefficient of the Mylar™ Type A film (see appendix C). The efficiency loss due to this issue can be computed by integrating the theoretical spectral irradiance of the lamp multiplied by the spectral transmittance of the material and dividing the result by the integrated spectral irradiance of the lamp:

   \[ η_{mylar} = \frac{\int λ \tau_{mylar} \cdot Φ_{λ,lamp} dλ}{\int λ Φ_{λ,lamp} dλ} \cdot 100 = 49.20\% \] (9.5)

   This means that almost half of the power is lost due to the low transmittance of the membrane material.

3. The reflectivity coefficient of the mirror film used for the demonstrator is 74.29% and thus 26.71% of the power is lost (see appendix C). The conversion from Gloss Units to percentage was previously explained in subsection 8.1.1.

4. The demonstrator is not designed for rays with an off-axis deviation larger than 5 degrees, whereas the theatre lamp emits rays between 0 and 16.34 deg. Therefore, part of the radiation is not reflected back to the receiver because the source does not produce collimated rays.

This second phase of the test campaign is considered to be partially successful. Even though different measurements were gathered and the inflating system worked, the non suitability of the pyranometer for the tests does not allow to derive clear conclusions about the performance capabilities of the demonstrator.

9.6. CONCLUSIONS ABOUT THE TEST CAMPAIGN

This test campaign has been performed in order to attain different objectives presented in table 9.1. The simple, low cost set-up was designed and manufactured (TEST-OBJ-1). However, the pyranometer selected resulted not to be suitable for the purpose of the experiments if combined with the theatre lamp. This issue should have been identified in advance by the researcher based on the lamp theoretical power. Nevertheless, previous data obtained during a previous project showed that the lamp had a strongly directional irradiance, with a quite high peak and a fast decrease in the radial direction [16]. Since the phase A was not performed yet, no more information could have been known. Time constraints led to the decision to continue with the test campaign and perform the tests taking care of the pyranometer. Future research projects should take into account this issue and substitute the lamp by a less powerful one, place a field stop to reduce the power emitted or use another way to measure the power reflected. For instance, a metallic component can be used to monitor its temperature and deduce the power absorbed.

The inflating process (TEST-OBJ-2) was demonstrated but the leak test exhibited different weak points in the structure which caused losses of gas. Nevertheless, the shape was maintained despite the losses. The discontinuous connections and the way the concentrator was assembled to the interface were the two main
reasons identified for the leaks (TEST-OBJ-3).

The tests results showed that even though there is still room for improvement in the manufacturing procedures and the test set-up, the system has the potential to focus more than 10% of the energy it receives, if the transmittance and reflectivity factors are not taken into account (TEST-OBJ-4).

The last test objective, which refers to the validation of the Ray Tracing Tool (explained in section 5.2) will be tackled in the next chapter.
10

Validation Assessment of the Ray Tracing Model

The last objective of the test campaign (TEST-OBJ-5) consisted in the validation of the ray tracing tool introduced in section 5.2. This chapter tackles this aim by performing simulations representing the test conditions (section 10.1) and discussing the results (section 12.2.2) compared to the data gathered during the test phase B (see section 9.4.2).

10.1. Simulations

The Ray tracing tool developed for the design and analysis of the concentrator (section 5.2) has been modified in order to model non-collimated beams with non-uniform power distributions. The objective of this adaptation is to validate the model and to draw conclusions about the differences obtained. The results of the simulations under different conditions are presented in table 10.1 assuming that (1) the receiver is located at the design focal plane and not at the optimal distance and (2) the light source is aligned with the concentrator.

Table 10.1: Results of the simulations

<table>
<thead>
<tr>
<th>Pressure [Pa]</th>
<th>$P_{\text{mirror}}$ [W]</th>
<th>$P_{\text{rec}}$ [W]</th>
<th>$\eta_{\text{rec}}$ [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>95.34</td>
<td>46.2</td>
<td>48.46</td>
</tr>
<tr>
<td>50</td>
<td>93.29</td>
<td>56.96</td>
<td>61.05</td>
</tr>
<tr>
<td>100</td>
<td>92.01</td>
<td>70.76</td>
<td>76.9</td>
</tr>
</tbody>
</table>

The efficiency increases with the pressure which may be seen as an inconsistent result at first sight. However, as it was observed in previous chapters, there is an optimal location for the receiver for each load case. Therefore, it is possible that the location analysed in this case is closer to the optimal one for 100 Pa. It is necessary to consider that the inaccuracy in the determination of the receiver’s position (see table 9.4) may lead to different results, as observed in figure 10.1. The graph shows the performance of the system under different inflating pressures, considering both the ideal power output and the effect of the transmittance and the reflectivity of the materials, which are derived from the materials data sheets (see appendix C) as explained in section 9.5. The optimal values are the ideal attainable values if the transparent film were able to transmit all the radiation and the mirror film were able to reflect all the radiation. As seen in figure 10.1, the materials properties affect the performance considerably (63.45% power lost).
The test plan (see table 9.2) included the realisation of off-axis tests (test sub-category B-2). This conditions are also simulated, resulting in an ideal output power of 42.72 W and a more realistic estimation of 14.28 W if the transmittance and reflectivity coefficients are taken into consideration. It is decided to perform only a simulation with the ideal geometry and not the deformed one due to the computational time required and the schedule constraints.

10.2. DISCUSSION

The data presented in table 9.5 in chapter 9 are now compared with the results of the simulations. The differences are discussed and possible reasons are derived.

The simulations results considered for the comparison are those presented in table 10.1 and the power output of the off-axis simulation. As discussed before in section 9.5 and inferred from the simulations results, the optical properties of the materials have an important effect in the concentrator performance. Unlike the general efficiency factor, which is defined as the ratio between the power output and the total available power, a new efficiency coefficient is introduced in order to distinguish the influence of the materials properties from the capabilities of the design. This factor, $\eta_{rec}$, defines the efficiency attainable by the device if the materials properties were ideal ($\tau_{mylar} = 1$ and $r_{mirror} = 1$):

$$\eta = \tau_{mylar} \cdot r_{mirror} \cdot \eta_{ref} \tag{10.1}$$

Table 10.2 presents the results of the tests and the simulations. Different parameters are presented in order to derive conclusions about the validation of the Ray Tracing tool (section 5.2). In case of the test data, the power received by the mirror ($P_{mirror}$) is calculated by integrating the lamp irradiance (see subsection 9.4.1). This parameter is multiplied by the Mylar™ transmittance factor for a more accurate estimation, $P_{mirror,eff}$. The ideal power on the receiver, $P_{rec}$, does not include the effect of the materials properties. The values for this parameter corresponding to the simulations are numerically calculated (see table 10.1) whereas the test data are derived from the measurements by dividing them by the transmittance and reflectivity factors. The second power output, $P_{rec,eff}$ includes the effect of $\tau_{mylar}$ and $r_{mirror}$. The two efficiency coefficients were already explained before.

Table 10.2: Results of test phase B

<table>
<thead>
<tr>
<th>Id.</th>
<th>$P_{mirror}$ [W]</th>
<th>$P_{mirror,eff}$ [W]</th>
<th>$P_{rec}$ [W]</th>
<th>$P_{rec,eff}$ [W]</th>
<th>$\eta$ [%]</th>
<th>$\eta_{rec}$ [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test B-1.1</td>
<td>105.52</td>
<td>51.92</td>
<td>14.08</td>
<td>5.14</td>
<td>4.86</td>
<td>13.30</td>
</tr>
<tr>
<td>Test B-1.2</td>
<td>105.52</td>
<td>51.92</td>
<td>13.56</td>
<td>4.95</td>
<td>4.69</td>
<td>12.83</td>
</tr>
<tr>
<td>Test B-2.1</td>
<td>99.23</td>
<td>46.91</td>
<td>16.79</td>
<td>6.13</td>
<td>6.17</td>
<td>16.9</td>
</tr>
<tr>
<td>Simulation 0 Pa</td>
<td>95.34</td>
<td>46.91</td>
<td>46.2</td>
<td>16.89</td>
<td>17.71</td>
<td>48.46</td>
</tr>
<tr>
<td>Simulation 50 Pa</td>
<td>93.29</td>
<td>45.90</td>
<td>56.96</td>
<td>20.82</td>
<td>22.33</td>
<td>61.05</td>
</tr>
<tr>
<td>Simulation 100 Pa</td>
<td>92.01</td>
<td>45.27</td>
<td>70.76</td>
<td>25.86</td>
<td>25.11</td>
<td>76.9</td>
</tr>
<tr>
<td>Simulation 0 Pa - off axis</td>
<td>85.32</td>
<td>42.96</td>
<td>42.72</td>
<td>14.28</td>
<td>16.74</td>
<td>45.79</td>
</tr>
</tbody>
</table>
The total efficiency values have differences between 10.61% of 19.296% depending on the case considered. The best agreement is obtained for the off-axis case. A possible reason is the fact that the central rays of the lamp, which are the ones with the lowest angular deviation with respect to the axis, fall on the mirror instead of on the set-up structure. Therefore, the errors derived from the estimations made for the irradiance distribution and the angles of the rays emitted by the lamp are reduced.

The irradiance is interpolated from the averaged values presented before in figure 9.6. This decision implies the assumption that the same radial distribution is found at different distances from the lamp, which may not be true. However, measuring the irradiance at the exit of the casing is not possible due to the limitations of the pyranometer. The angle of the rays are assumed to vary linearly between 0 at the axis and $\alpha_{\text{lamp}} = 16.04$ at the contour of the lamp casing. A different angular distribution would yield different results due to the fact that the performance depends on the angle between the concentrator axis and the rays (see 6.3 for an example of the performance variation w.r.t. the angle).

The efficiency factor $\eta_{\text{rec}}$, which assumes perfect transmittance and reflectivity, exhibits a much larger difference between theoretical and experimental results. The deviations, which are between 28.9% (Test B-2.1) and 60% (Test B-1.2) are much larger than differences found in the literature [37]. It was decided before in section 5.6, that the Ray tracing code can be considered to be validated if the differences compared to experimental values remain within $\pm 20\%$. Therefore, the optical model cannot be validated with the tests performed in this project.

Nevertheless, it is possible to identify possible reasons for such differences in order to deduce relevant conclusions and recommendations for future research:

- The distance between the demonstrator vertex and the pyranometer was measured with tape measure (total height in table 9.4). However, the shape of the concentrator was not accurately attained as discussed in section 9.5 (figures presented in subsection 9.4.2 show the wrinkles and deformations). Hence, the measurement has an implicit inaccuracy, which is not possible to be determined. Small deviations from the position simulated could lead to large changes in the result and a higher level of correlation with the test data (see figure 10.1). For instance, a displacement of 3 [mm] towards the paraboloid vertex yields the following results:

<table>
<thead>
<tr>
<th>Id.</th>
<th>$P_{\text{mirror}}$ [W]</th>
<th>$P_{\text{mirror},\text{eff}}$ [W]</th>
<th>$P_{\text{rec}}$ [W]</th>
<th>$P_{\text{rec,eff}}$ [W]</th>
<th>$\eta$ [%]</th>
<th>$\eta_{\text{rec}}$ [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simulation 0 Pa</td>
<td>95.3401</td>
<td>46.9073</td>
<td>26.49</td>
<td>12.62</td>
<td>13.24</td>
<td>36.158</td>
</tr>
<tr>
<td>Simulation 50 Pa</td>
<td>93.2948</td>
<td>45.90</td>
<td>36.52</td>
<td>17.64</td>
<td>18.91</td>
<td>51.7991</td>
</tr>
<tr>
<td>Simulation 100 Pa</td>
<td>92.0091</td>
<td>45.27</td>
<td>39.93</td>
<td>20.92</td>
<td>22.72</td>
<td>62.2357</td>
</tr>
</tbody>
</table>

This small change shortens the difference in 10%. It is thus concluded that a higher accuracy is required for measuring the demonstrator dimensions.

- The low shape accuracy of the demonstrator (as discussed in sections 9.4 and 9.5) leads to a geometry which can be hardly measured. Therefore, there are differences between the item tested and the shape simulated. Since measuring the deformations experienced by a thin film structure is not easy, it is preferable to tackle this issue by improving the manufacturing procedures so that the shape accuracy is improved (see subsection 8.3.3).

- As commented before in chapter 9, the irradiance values measured exceeded the limitations of the pyranometer. Although the instrument worked during the 30 seconds required to attain the steady-state conditions, it is not clear if this time interval is also applicable for off-limits measurements. Moreover, it is not possible to know if the measurements taken were correct.
INTEGRATION IN THE STP ENGINE

A simple and very basic model of a possible Solar Thermal Propulsion engine coupled with the concentrator has been developed with the intention of evaluating its prospective performance in terms of thrust, specific impulse and thrust per unit volume. These analyses allow to verify whether or not the initial assumption on the performance made in subsection 3.1.2 ($F = 100 \text{[mN]}, I_{sp} = 200 \text{[s]}$) is achievable. A comparison with existing propulsion systems will also be derived from the results. It is desirable to know if the employment of the STP system overcomes the performance of the systems presented in section 2.1.3 which would mean that occupying 1 entire PocketQube Unit can be justified.

Two possible concepts are proposed in section 11.1 and models for both the receiver and the thruster are generated (section 11.2). The results are finally presented (section 11.3) and discussed (section 11.4). It must be kept in mind that this is a preliminary design intended to prove the capabilities of the engine and more analyses are required to optimise the system.

11.1. STP ENGINE CONCEPT

Unlike usual STP designs based on a cavity used to collect the energy and transfer it to the propellant [6] [30] [2], the concepts proposed in this research project are based on the employment of a flat heat exchanger for the direct transfer of energy to the propellant. This concept does not have the same capabilities as the cavity-based designs but it can be compact and have a low mass (the exact values will be presented in section 11.4), key properties to be part of a PocketQube. Two concepts are proposed:

• **Concept STP-A.** A single channel inside the flat heat exchanger is created, with multiple turns to ensure that the energy transfer is efficient. A sketch of this concept and its main parameters is presented in figure 11.1. The spacing between turns ($s_{\text{channel}}$) can be substituted by the number of turns.

• **Concept STP-B.** Multiple channels are used in this concept, dividing the total mass flow rate. Figure 11.2 includes a sketch of the concept and its main design parameters.

![Figure 11.1: Design concept STP-A](image1)

![Figure 11.2: Design concept STP-B](image2)
Regarding the possible material for the receiver, Tungsten can be laser cut [95] and now also 3d printed [96] with high quality results (precision levels below 1 mm). It presents good properties in terms of melting temperature (3695 K) and thermal conductivity (173 W/m/K). Its heat capacity (134 J/kg/K), which is relatively low if compared with silicon carbide (1465 J/kg/K) or boron (293 J/kg/K), and its high cost are the main drawbacks of this material. However, the heat capacity is not that much of a problem if the engine is intended to be direct gain (direct transmission of power to the propellant). Hence, tungsten is considered for this research project but it must be kept in mind that it might be necessary to consider cheaper or more easily manufactured materials instead (a complete list of materials can be found in [17]).

The geometrical constraints set for the receiver are a maximum total height of 5 mm for the receiver and a side length of 25 mm. The latest is chosen because it is exactly the receiver size considered for the design of the concentrator (see chapter 6). The maximum receiver height is chosen as a compromise between three facts:

- The walls of the receiver are required to withstand high thermal stresses so their thickness have a lower limit such that the structural integrity of the device is guaranteed [35].
- A lower height has a lower impact on the volume budget of the satellite.
- A higher receiver implies a larger mass, which means that more heat is stored but also that the system is heavier.

The maximum size of 5 mm is set as a preliminary requirement which might be reviewed and/or optimised in future projects. The volume occupied by the concentrator is estimated around a PocketQube Unit (based on the correlation performed in section 5.5). Since the deployment and inflating subsystem has not been designed and the volume required for the propellant storage subsystem is still unknown, the use of 1/10 of the total Unit for the receiver appears as a reasonable first choice.

### 11.2. STP ENGINE MODEL

This section has the purpose of describing the models developed for this preliminary design, including the heat exchanger model (subsection 11.2.1) and the thruster model (subsection 11.2.2). They are built based on a set of assumptions:

- The model is based on the assumptions of Ideal Rocket Theory [97]:
  - Homogeneous fluid composition.
  - The ideal gas law defines the behaviour of the gas.
  - The nozzle flow is modelled as one-dimensional, steady and isentropic.

  These assumptions are used since the Ideal Rocket Theory yields results of an acceptable quality for first estimations [97].

- The effects of two-phase flows are not taken into account. Modelling two-phase flows is too complex for the objectives of this chapter, but it would be necessary to consider it for future detailed designs.

- The temperature of the receiver is homogeneous over its surface. Hanselaar [98] proved the validity of this assumption for Silicon-based microthrusters. Although it is necessary to prove it also for a STP engine, the high conductivity of tungsten allows to use this assumption also for these first estimations. It implies that there is no thermal gradient between the surface receiving the radiation and the channels walls and no temperature difference between the inlet and outlet surfaces, even though it is known that convection is not uniform.

- The propellant considered is Ammonia (\( \text{NH}_3 \)). The maximum capabilities of Solar Thermal Propulsion are attained with Hydrogen but it presents its storability as main drawback [17]. Ammonia was identified in the literature study [17] as a more reasonable alternative, since it can be easily stored in liquid phase and the performance is still good.

- The propellant is assumed to be stored at the critical temperature of Ammonia at 1 [bar]: 240 K. It is also assumed that it reaches the heat exchanger with the same temperature.
• The heat exchanged by radiation and conduction between the walls and the propellant is negligible compared to that transferred by convection.

• The system is thermally isolated from the rest of the spacecraft.

It is decided to use rectangular pipes since they are easier to be manufactured than circular shapes. The design parameters to be selected are the height \( h_{\text{pipe}} \), width \( w_{\text{pipe}} \) and the spacing between channels \( s_{\text{channel}} \) (see figures 11.1 and 11.2).

11.2.1. RECEIVER AND HEAT EXCHANGER MODEL

The model developed for the design and analysis of the receiver is hereafter explained. The receiver is the element in charge of collecting the energy concentrated by the reflector and transferring it to the propellant. This subsection is organised such that the fluid properties used in the model are first introduced and then the heat exchanger model is explained.

FLOW PROPERTIES

It is first necessary to define the flow properties required for the thermal model. Based on the assumption mentioned before, the relation between the density \( \rho \), the pressure \( p \) and the temperature \( T \) is defined by the ideal gas law:

\[
p = R_g \cdot \rho \cdot T, \quad (11.1)
\]

where \( R_g \) is the specific gas constant, computed dividing the ideal gas constant \( R \) by the molar mass of the propellant. In case the fluid is in its liquid phase, the data obtained from NIST Webbook [99] is interpolated.

The mass flow rate is related to the flow velocity, the density and the cross-sectional area as follows:

\[
\dot{m} = \rho \cdot U \cdot A_{\text{pipe}} \quad (11.2)
\]

Two non-dimensional parameters must be also defined now due to their relevance in the model: the Reynolds number \( Re \) and the Prandtl number \( Pr \).

\[
Re = \frac{\rho U \cdot D_h}{\mu} \quad (11.3)
\]
\[
Pr = \frac{\mu c_p}{\kappa} \quad (11.4)
\]

Where \( \rho \), \( U \), \( \mu \), \( c_p \) and \( \kappa \) are the density, the velocity, the dynamic viscosity, the heat capacity and the conductivity of the fluid, respectively. \( D_h \) refers to the hydraulic diameter of the tube, defined using the perimeter \( P_{\text{pipe}} \) and the cross-sectional area \( A_{\text{pipe}} \):

\[
D_h = \frac{4 \cdot A_{\text{pipe}}}{P_{\text{pipe}}} \quad (11.5)
\]

The viscosity of the fluid can be estimated using Sutherland’s equation [24] if it is known at a certain reference temperature \( T_0 \):

\[
\mu = \mu_0 \left( \frac{T}{T_0} \right)^{3/2} \quad (11.6)
\]

The coefficient \( S \) and the viscosity \( \mu_0 \) at the reference temperature \( T_0 \) are values obtained from literature [100].

HEAT EXCHANGER MODEL

The propellant enters the heat exchanger with its properties defined by the mass flow rate and the temperature and pressure conditions assumed for the storage subsystem. It is necessary to evaluate how they develop along the pipe(s) as they exchange heat with the walls and lose pressure due to friction.
The heat exchanged between the receiver and the propellant is mainly through convection, which is defined by Newton's law of cooling [97]:

\[ q_c = h_c \cdot (T_s - T_f), \]  

(11.7)

where \( q_c \) is the heat flux, \( h_c \) is the convective heat transfer coefficient, \( T_s \) is the surface temperature and \( T_f \) is the fluid reference temperature, which in this case refers to the average between the inlet, \( T_i \), and outlet, \( T_e \), temperatures. The convective heat transfer coefficient, \( h_c \), can be calculated using the Nusselt number:

\[ h_c = \frac{Nu \cdot \kappa}{D_h} \]  

(11.8)

\( Nu \) is the Nusselt number, \( \kappa \) is the fluid’s thermal conductivity and \( D_h \) is the hydraulic diameter of the pipe, which is calculated using the cross-sectional area, \( A \), and the perimeter, \( P \), of the tube: \( D_h = 4 \cdot A/P \).

The Nusselt number is an adimensional coefficient which defines the relative difference between the convective and conductive heat exchange processes. It is determined by the following equations:

- If the flow is laminar (\( Re_D < 2300 \)), Stephan’s expression is employed [97]:

\[ Nu_D = 3.657 + \frac{0.067 \cdot (Re \cdot Pr \cdot D/L)^{1.33}}{1 + 0.1 \cdot Pr \cdot (Re \cdot D/L)^{0.3}} \]  

(11.9)

- If the flow is turbulent (\( 10^4 < Re_D < 10^7 \)), Colburn’s formula is used [97]:

\[ Nu_D = 0.023 \cdot Re_D^{0.8} \cdot Pr^{1/3} \]  

(11.10)

All the flow properties except for the viscosity in Reynold’s equation must be evaluated at the mean bulk temperature, which is the average temperature between the inlet (\( T_i \)) and the exit (\( T_e \)). The viscosity has to be calculated using the average between the mean bulk temperature and the wall temperature. Unlike others, both equations take into account the entrance length of the tube. The heat absorbed by the propellant is used to raise its temperature and change phase, if applicable, and it must be equal to the heat transmitted from the wall to the fluid by convection:

\[ \dot{m} \cdot \left( c_p \cdot \Delta T + q_{\text{latent}} \right) = Q_{\text{conv}} = h_c \cdot A_{\text{tube}} \cdot (T_s - T_f) \]  

(11.11)

Therefore, the exit temperature \( T_e \) can be computed using the previous equation:

\[ T_e = T_i + \frac{c_p}{\dot{m}} \cdot \left( h_c \cdot A_{\text{tube}} \cdot (T_s - T_f) - \dot{m} \cdot q_{\text{latent}} \right) \]  

(11.12)

Apart from experiencing an increase in its temperature due to the heat exchanged with the wall, the propellant losses pressure due to friction which is calculated using the Darcy-Weisbach friction factor \( f \):

\[ \Delta p = f \cdot \frac{L}{D} \cdot \frac{1}{2} \cdot \rho \cdot v^2, \quad \text{where} \quad f = \begin{cases} 
64 \cdot Re_D^{-1} & \text{if } Re_D < 2320 \\
0.316 \cdot Re_D^{0.25} & \text{if } 2320 < Re_D < 2 \cdot 10^4 \\
0.184 \cdot Re_D^{0.2} & \text{if } 2 \cdot 10^4 < Re_D < 2 \cdot 10^6 
\end{cases} \]  

(11.13)

**Algorithm**

The final temperature is one of the requested final outcomes but it is also necessary to compute the flow properties and the convective heat transfer coefficient. Moreover, it is required to know the wall temperature, which does not only depend on the amount of heat transferred to the propellant but also the interactions with the other elements of the system. The thermal model built up for the design of the concentrator (section 5.3) estimated the receiver temperature as a function of its efficiency. Hence, the receiver heat exchanger model and the concentrator’s thermal model are decoupled. This issue was foreseen and solved by calculating the wall temperature as a function of the receiver’ efficiency. Figure 11.3 shows the receiver temperature with respect to its own efficiency.
An iterative algorithm similar to the one presented by Preijde [24] for the design of a dual-mode STP engine is developed:

- A value of the heat exchanger’s efficiency and, therefore, of the wall temperature is assumed (see figure 11.3).
- For this value of the wall temperature, the exhaust temperature is calculated using the following sequence:
  - An initial value of the exhaust temperature is assumed to be equal to the wall temperature and used to calculate the flow properties and the convective heat flow.
  - A new temperature value is calculated using equation 11.12.
  - This process is repeated until the output temperature converges with a given tolerance. In this case, a tolerance of 0.001 K is assumed.
- The final temperature resulting from the previous sequence is used to calculate the heat transferred to the flow and the efficiency of the system.
- The process is repeated until the efficiency initially assumed and the real efficiency obtained from the model are equal.

### 11.2.2. Thruster Model

Once the conditions at the exit of the heat exchanger are known, it is possible to compute the thrust generated by the engine, using the equation below [97]:

\[
F = c_F \cdot p_c \cdot A_t, \quad \text{where} \quad c_F = \Gamma \cdot \sqrt{\frac{2\gamma}{\gamma - 1} \left(1 - \left(\frac{p_e}{p_c}\right)^{\frac{\gamma-1}{\gamma}}\right) + \frac{p_e}{p_c} \cdot \frac{A_e}{A_t}}
\]  

All the parameters included in the equation above are explained hereafter:

- \(c_F\): Thrust coefficient.
- \(p_c\): chamber’s pressure.
- \(A_t\): cross-sectional area of the nozzle’s throat.
- \(\Gamma\): Vandenkerckhove function, which is \(\Gamma = \sqrt{\frac{2\gamma}{\gamma - 1} \left(1 - \left(\frac{p_e}{p_c}\right)^{\frac{\gamma-1}{\gamma}}\right) + \frac{p_e}{p_c} \cdot \frac{A_e}{A_t}}\).
- \(\gamma = \frac{c_p}{c_v}\): propellant’s specific heat ratio.
- \(p_e\): nozzle’s exit pressure.
- \(A_e\): cross-sectional area of the nozzle’s exit.
Therefore, there are some parameters to be determined before the thrust is computed. First of all, a relation between the flow velocity and the pressure ratio can be derived from the conservation of mass and energy and the assumption of isentropic flow:

\[
\begin{align*}
\dot{m} &= \rho \cdot U \cdot A = \text{constant} \\
c_p \cdot T + \frac{U^2}{2} &= \text{constant} \\
\frac{T_1}{T_2} &= \left(\frac{p_1}{p_2}\right)^{\gamma-1}
\end{align*}
\]

\[U = \sqrt{\frac{2}{\gamma-1} \cdot T_c \cdot \left(1 - \left(\frac{p}{p_c}\right)^{\gamma-1}\right)} \tag{11.15}\]

where \(T_c\) is the chamber’s temperature. In this case this temperature refers to the flow temperature at the exit of the heat exchanger.

If it is imposed that the nozzle is choked, it is possible to rework the previous equation to relate the area of the nozzle’s throat and the mass flow rate:

\[U_t = \sqrt{\gamma \cdot R \cdot T_t} \quad \Rightarrow \quad \dot{m} = \Gamma \cdot \frac{p_c \cdot A_t}{\sqrt{R \cdot T_c}} \tag{11.16}\]

And, finally, the relation between the pressure ratio and the expansion coefficient \((A_e/A_t)\) is determined by the equation below. If either one of the two parameters are known, it is thus possible to determine the other one.

\[
\frac{A_e}{A_t} = \frac{\Gamma}{\sqrt{\frac{2\gamma}{\gamma-1} \left(\frac{p_e}{p_c}\right)^{2/\gamma} \cdot \left(1 - \left(\frac{p_e}{p_c}\right)^{\gamma-1}\right)}} \tag{11.17}\]

Although it is not necessary for calculating the thrust, the exhaust velocity is necessary to evaluate the efficiency of the engine and it can be determined using equation 11.18.

\[
\frac{A_e}{A_t} = \left(\frac{2}{\gamma + 1}\right)^{1/2} \cdot \left(\frac{2}{\gamma + 1}\right)^{1/2} \cdot \left(\frac{p_e}{p_c}\right)^{1/\gamma} \cdot \sqrt{\gamma \cdot R \cdot T_c} \cdot u_e \tag{11.18}\]

In order to compare the system with others already available and assess the advantages of developing a Solar Thermal Propulsion engine for PocketQubes, the specific impulse, the engine efficiency and the overall efficiency of the system are calculated:

- **Specific impulse:** \(I_{sp} = \frac{F}{m_{g0}}\).

- **Engine efficiency:** \(\eta_{\text{engine}} = \frac{P_j}{P_{in}} = 0.5 \cdot \frac{\dot{m} \cdot u_e}{P_{in}}\), where \(P_j\) is the jet power and \(P_{in}\) is the power received from the concentrator.

- **Thruster efficiency:** \(\eta_T = \frac{P_j}{P_{prop}}\), where \(P_{prop}\) refers to the heat transferred to the propellant by convection. The engine efficiency is the result of multiplying the receiver efficiency and the thruster efficiency.

- **Overall efficiency:** \(\eta_{\text{total}} = \eta_{\text{engine}} \cdot \eta_{\text{mirror}} = \frac{P_j}{P_{av}}\), where \(P_{av}\) is the total power available obtained by multiplying the total cross-sectional area of the mirror by the solar flux.

- **Volumetric specific thrust.** The thrust per unit volume is an important parameter to compare the system with others.

### 11.3. Design Process and Results

The process followed for the design of the STP engine is described in this section. Initial estimations are calculated to choose a design point (mass flow rate), which is used to perform a more detailed design of the system.
11.3. DESIGN PROCESS AND RESULTS

11.3.1. INITIAL ESTIMATIONS AND DEFINITION OF THE DESIGN POINT

The ideal power focused by the concentrator was 322.28 W according to the analysis of the final design under the load conditions of the design point (see table 7.5 in chapter 7). Assuming a Mylar\textsuperscript{TM} transmittance coefficient of 90\% (see appendix C) and a mirror’s reflectivity of 80\%, a more realistic power would be 232.042 W. The black paint carbon coating assumed for the receiver has an absorptivity of 0.96, which means that 222.76 W are actually absorbed by the system. Assuming a heat exchanger efficiency of 80\% [67] [26], the attainable enthalpy change would be determined as follows:

\[ \Delta H = \frac{P \cdot \eta_{rec}}{\dot{m}} = \frac{222.76 \cdot 0.8}{\dot{m}}, \]  

(11.19)

where \( \dot{m} \) is the mass flow rate.

Assuming an initial temperature of 240 K and no phase change, the ideal final temperature can be derived from the enthalpy change using the data available in NIST Webbook for Ammonia [99]. However, it is also necessary to consider that the maximum attainable temperature of the propellant is the wall temperature of the heat exchanger. Figure 11.3 shows that the wall temperature for an efficiency of 0.8 is around 1000 K. This constraint must be taken into account such that the enthalpy change cannot be higher than the corresponding to an increase in the flow temperature up to 1000 K. If the available enthalpy change (equation 11.19) is higher, it means that not all the estimated power can be effectively transferred, which implies that the assumption made about the efficiency of the heat exchanger is not valid.

Figure 11.4 shows the available energy, the effective available energy and the final temperature with respect to the mass flow rate. The available energy is the one calculated with equation 11.19, while the effective one takes into account the temperature limitation. As can be observed, there is an excess in the power available for mass flow rates below 65.5 [mg/s]. The interval considered for the mass flow rate is chosen based on usual values for micropropulsion systems. It is also selected in order to attain high temperatures that ensure high \( I_{sp} \) values.

All the parameters included in the equations were previously defined in the model.

\[ I_{sp} = \frac{1}{g_0} \cdot \sqrt{\frac{2 \gamma}{\gamma - 1} \cdot R_e \cdot T_c} \]  

(11.20)

\[ F = \dot{m} \cdot g_0 \cdot I_{sp} \]  

(11.21)

Figure 11.4: Initial estimations of the change in enthalpy and temperature for Ammonia w.r.t. the mass flow rate

An ideal value of the specific impulse and the thrust can be obtained using equations 11.20 and 11.21. They are ideal values because they do not consider the expansion process in the nozzle (the nozzle is assumed to be adapted) and no correction coefficients are included to mitigate the implications of the Ideal Rocket Theory. The results can be observed in figure 11.5. As can be observed, higher temperatures lead to designs with higher \( I_{sp} \) values but the thrust is lower since the mass flow rate is also lower.
The design point has to be selected as a trade-off between the thrust and the specific impulse, taking also into account that low mass flow rates lead to an inefficient use of the available power (as seen in figure 11.4) and high mass flow rates have an impact on the size of the system. A mass flow rate of 80 mg/s is selected since it is possible to reach thrust values around 200 mN and specific impulses around 240 s. Both values are above those obtained by Hanselaar [98] for the vaporizing liquid micro-thruster (or VLM) designed for the Delfi mission. They are also higher than the characteristics of the nanosatellite propulsion system sold by ISIS [63] and in the same order of other COTS systems (see subsection 2.1.3). If lower mass flow rates are required, the concentrator can be scaled down to provide less energy.

The first step in the design of the concepts is the definition of the design parameters, which are the number of turns (concept STP-A) or channels (concept STP-B) and the width and height of the channel(s). In case of concept STP-A, it is also necessary to define the length of the channel. It must be considered that small channels would imply less mass and volume but they would imply higher flow velocities and, therefore, higher pressure losses. The minimum cross-sectional area of the channels is determined setting a maximum flow velocity of 12.5 m/s for liquids and a maximum Mach number of 0.3 for gases [97].

### 11.3.2. Concept STP-A

Considering the limitation on the flow velocity, it is possible to define the relation between the width and minimum height of the channel depending on the number of turns. The total width of the receiver occupied by the channel can be defined as follows:

$$w_{\text{total}} = n_{\text{turns}} \cdot (s_{\text{channel}} + w_{\text{channel}}) + n_{\text{turns}} \cdot (s_{\text{channel}} + w_{\text{channel}}),$$

where $n_{\text{turns}}$ is the number of turns, $s_{\text{channel}}$ is the spacing between turns and $w_{\text{channel}}$ is the width of the channel. A turn is defined as the U-shaped loop the channel does going from one side of the receiver to the other and back. The distance between channels is fixed to be twice the channel’s width to reduce the thermal stresses [35]. As inferred from figure 11.6, an increase in the number of turns decrease the maximum width the channels can have ($w_{\text{max}}$) and a decrease in the width leads to channels with a larger height.

![Figure 11.5: Initial estimations of the change in enthalpy and temperature for Ammonia](image)

![Figure 11.6: Minimum dimensions of the channels for concept STP-A](image)
A larger number of turns would lead to a longer channel and, therefore, a higher surface through which the heat is transferred. However, it also implies that the channel has to be narrower and taller. Assuming that the total height of the receiver needs to be at least three times that of the channel to reduce the thermal stress, the channel’s height is limited to 1.5 mm. It is decided to test two designs: one with a single turn (STP-A-1) and another with two turns (STP-A-2). The former has a width of 5 mm and a height of 0.5 mm. These values are selected to make a more efficient use of the receiver width and to reduce the height of the channel. Concept STP-A-2 is designed with a width of 1.9 mm and a height of 1.5 mm since it is the widest channel possible due to the height constraint.

The thrust and specific impulse are calculated as a function of the nozzle’s expansion ratio. Larger ratios lead to higher values of $F$ and $I_{sp}$ but they have a mass penalty. The simulations have been done for a range from 10 to 200, but it has been considered that going beyond 90% of the maximum $I_{sp}$ implies such a low increase in the performance parameters that it is not worthy to increase the mass and volume of the system. Therefore, this is the design point for each concept considered.

### Table 11.1: Results of the design concept STP-A

<table>
<thead>
<tr>
<th>Id.</th>
<th>$\dot{m}$ [mg/s]</th>
<th>$n_{\text{turns}}$ [-]</th>
<th>$w_{\text{channel}}$ [mm]</th>
<th>$h_{\text{channel}}$ [mm]</th>
<th>$T_{\text{prop}}$ [K]</th>
<th>$\eta_{\text{rec}}$ [%]</th>
<th>$A_e/A_t$ [-]</th>
<th>$I_{sp}$ [s]</th>
<th>$F$ [mN]</th>
<th>$\eta_{\text{engine}}$ [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>STP-A-1</td>
<td>80</td>
<td>1</td>
<td>5</td>
<td>0.5</td>
<td>917.18</td>
<td>62.05</td>
<td>17.66</td>
<td>192.92</td>
<td>151.4</td>
<td>57.96</td>
</tr>
<tr>
<td>STP-A-2</td>
<td>80</td>
<td>2</td>
<td>1.9</td>
<td>1.5</td>
<td>883.51</td>
<td>58.12</td>
<td>17.28</td>
<td>188.59</td>
<td>148.0</td>
<td>55.4</td>
</tr>
</tbody>
</table>

### 11.3.3. Concept STP-B

As well as with Concept STP-A, the minimum dimensions of the channels are obtained using the constraint on the flow velocity. It is considered that the distance between channels is at least twice their width in order to reduce the effects of the thermal loads. Figure 11.7 shows the different minimum dimensions as a function of the number of channels considered. As can be observed, the width of the channel is reduced as the number channels increases, which is an expected outcome. The graph also presents the constraint of 1.5 mm on the channel height as commented before for concept STP-B.

Three cases have been simulated, with 1 (STP-B-1), 3 (STP-B-2) and 5 (STP-B-3) channels, respectively. The dimensions selected for each case are intended to use the width of the receiver as much as possible and to reduce the height. Nevertheless, as mentioned before, this is a preliminary design, more detailed analyses are required to optimise the system.

### Table 11.2: Results of the design concept STP-B

<table>
<thead>
<tr>
<th>Id.</th>
<th>$\dot{m}$ [mg/s]</th>
<th>$n_{\text{channels}}$ [-]</th>
<th>$w_{\text{channel}}$ [mm]</th>
<th>$h_{\text{channel}}$ [mm]</th>
<th>$T_{\text{prop}}$ [K]</th>
<th>$\eta_{\text{rec}}$ [%]</th>
<th>$A_e/A_t$ [-]</th>
<th>$I_{sp}$ [s]</th>
<th>$F$ [mN]</th>
<th>$\eta_{\text{engine}}$ [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>STP-B-1</td>
<td>80</td>
<td>1</td>
<td>15</td>
<td>0.3</td>
<td>1028.7</td>
<td>75.74</td>
<td>18.75</td>
<td>206.73</td>
<td>162.2</td>
<td>66.51</td>
</tr>
<tr>
<td>STP-B-2</td>
<td>80</td>
<td>3</td>
<td>3</td>
<td>0.3</td>
<td>977.18</td>
<td>69.29</td>
<td>18.28</td>
<td>200.45</td>
<td>157.3</td>
<td>62.55</td>
</tr>
<tr>
<td>STP-B-3</td>
<td>80</td>
<td>5</td>
<td>2.5</td>
<td>0.3</td>
<td>1030.1</td>
<td>75.91</td>
<td>18.76</td>
<td>206.91</td>
<td>162.4</td>
<td>66.63</td>
</tr>
</tbody>
</table>
11.4. Discussion
The results obtained in section 11.3 and the procedures followed (section 11.2) are now analysed and discussed.

11.4.1. Analysis of the Results
Five different designs have been analysed in order to estimate their performance in terms of thrust and specific impulse. As said before, the design parameters have not been optimised and only preliminary values have been used. That is the reason, for instance, for the decrease of thrust and $I_{sp}$ observed in table 11.1 between the designs with one and two turns. It would be expected to have an increase in the propellant exit temperature since the channel is larger. However, this effect is not obtained and the reason lies on the fact that the cross-sectional area is different.

The designs analysed for concept STP-B do not show any correlation between the number of channels and the results obtained, which is also a consequence of the changes in the flow properties as result of the different cross-sectional area. The values chosen are arbitrarily chosen from figure 11.7 and the optimisation is still lacking.

It can be observed that the thrust and $I_{sp}$ obtained for the concept STP-B meet the original requirement of 100 mN and 200 s, respectively. The two designs proposed for STP-A have a slightly lower $I_{sp}$, but it is still over 90% of the requirement. Once again, it must be said that no conclusion can be derived from these results, since their purpose is just to demonstrate the capabilities of the system. Therefore, it is not possible to infer any conclusion about the relation between the concept, its design parameters and the performance at this point of the research. Conclusions about the different correlations between the design parameters and the performance could be obtained if the optimal design were derived for each concept proposed.

Another important point to be discussed is the fact that the thruster model does not include efficiency losses apart from the non-adapted nozzle. Other relevant losses which should be taken into account are as follows:

- The propellant losses temperature and pressure as it is transported from the receiver to the nozzle. Friction and convection are required to be included in the model.
- The nozzle design implies losses due to its shape but also because of the interactions between the flow and the walls.
- The system cannot be perfectly insulated from the rest of the satellite and part of the thermal energy is lost.

11.4.2. Validation and Verification Assessment
The results obtained using the STP engine model described in 11.2 are required to be verified and validated. The validation of the results cannot be performed at this stage of the project since it is necessary to test the design and compare the results. However, it is possible to verify the model using data found in scientific publications. The efficiency of other heat exchangers designed for STP are now compared with the values presented in tables 11.1 and 11.2 in order to conclude if they make sense.

Nakamura et al. [32] tested a thruster using a light source of 200 W with Argon at room temperatures. The propellant exhibited a change in temperature from ≈300 K up to 1250 K. Considering the mass flow rate (0.2533 g/s) and the specific heat capacity of the fluid at the average bulk temperature (775 K), the power transmitted to the flow is 125.21 W, yielding an efficiency of 62.6%. The researchers performed also different tests with different flow rates, obtaining a linear relation between the heat transfer efficiency and the mass flow rate. Values above 75% were obtained for larger mass flow rates.

Another research project, performed by Henshall and Palmer [25], consisted in the simulation of the performance of a STP engine with a cavity receiver. The researchers considered Ammonia stored at 8 bar and at 300 K, resulting in a thrust of 56 mN with a specific impulse of 280 s. Considering that the propellant was expected to attained 1100 K in the first 5 cm of the heat exchanger and the power input was 67.5 W, the effi-
ciency of the heat exchanger can be estimated around 71%.

Sahara [33] calculated the efficiency based on experimental results, yielding a value of 70%. However, it is not clear how the value was obtained and there is not sufficient information in the publication to derive the value from the test data. Other publications included efficiency values without any rationale or calculations and, therefore, it is not possible to analyse how they were obtained. This is the case of the STP engine designed by Gerrish [67] based on the assumption of a heat exchanger efficiency of 80%. It is not clear how the researcher got this value.

As can be inferred from the values provided here, the efficiency of the heat exchanger subsystem of STP engines is found in the interval 60-70%, with some researchers claiming that 80% is attainable [67]. This complies with the values obtained in this project, which vary between 58 and 76%. The thermal model can be thus considered to be verified, but its validation cannot be done unless experimental data are gathered.
This research project has the main objective of developing a solar concentrator for PocketQubes with a certain geometry and performance characteristics. The results obtained are now discussed with the objective of determining whether or not the main goal (subsection 2.2.2) and the requirements (subsection 3) driving the design have been attained. This general discussion complements the individual ones included in every chapter together with the corresponding results.

The final concept proposed (see table 7.5 in chapter 7) is the result of two iterations of a design process defined in chapter 5. This procedure is based on a set of tools which have been verified but not validated and it resulted in a concentrator similar to the one designed by Babuscia et al at MIT [1] for CubeSats. The main difference between both concentrators, apart from the purpose (the design made at MIT is intended to be part of a communication system and the one proposed in this project is developed for solar power devices), is that the ratio between the aperture and the satellite's side length is actually larger in this project. An aperture 10 times the side length of a Unit requires a package volume of half a unit for a Cubesat whereas it is necessary to use an entire Unit for PocketQubes. The scalability of inflatable concentrators between CubeSats and PocketQubes can be thus considered to be feasible but not immediate. The scalability between PocketQubes and satellites larger than CubeSats cannot be assessed with the results obtained in this project. However, it is advisable to look for other solutions instead of using a conical connection and pressurising the entire system due to the larger internal volumes.

The design point selected in chapter 6 of 10 Pa for the inflating pressure was selected to balance the effects of the thermal and pressure loads. The reflector was optimised for this condition and the worst temperature field derived from the thermal analysis (subsection 6.3.2), resulting in a device with an efficiency of around 60% and capable of reflecting more than 200W under nominal conditions (see table 7.5 for all the design characteristics). The selection of the materials appears to be crucial for the performance of the system, since the transmittance and reflectivity of the membranes set the limit for the maximum ideal efficiency of the concentrator (72% in this case). This is probably the main drawback derived from purchasing COTS membranes instead of polyimides specifically made for this purpose.

A preliminary estimation of the amount of pressurising gas required to inflate the structure was obtained based on the inner volume and the losses due to the permeability of the membrane and the impacts of space debris and micrometeoroids (subsection 7.2.3). The latest was found to be dominant in the dimensioning of the pressurising subsystem, limiting the lifetime of the concentrator below the requirement of 1 year. Decreasing the pressure, using thicker films or employing a gas with a larger molar mass than nitrogen are the options identified which still require further research, as discussed in subsection 7.2.3.

The testing phase of the project had the intention of validating the Ray Tracing tool and demonstrating the performance capabilities expected for the system. However, as commented in section 12.2.2, this objective was not achieved due to the large differences observed between analytical and experimental results. The poor performance of the light source, which was found to be unstable with respect to time and the direction (see subsection 9.4.1), the low transmittance of Mylar Type A, the relatively low reflectivity of the mirror...
film (see appendix C) and the inaccuracies in the manufacturing process led to reflector’s efficiencies in the order of 12 to 15%, which are considerably lower than the results obtained from the simulations (between 48 and 77% as seen in section 10.1). The shape error of the manufactured prototype is a consequence of the cutting approach, the width of the tape used, the inaccuracy of the mould and the thickness of the films. These issues can be mitigated if the recommendations presented in chapter 8 are followed, so the petal-based manufacturing approach can still be implemented with better results. Despite these observations and the fact that further research and testing are required to have better estimations of the attainable performance, the test campaign performed is enough to prove the feasibility of the system as discussed in chapter 10.

Another decision to be discussed is the selection of the film thickness ($23 \mu m$), which was initially made based on decreasing the volume occupied by the concentrator. However, it turned to have two main drawbacks: it is quite difficult to manipulate, cut and join the petals; and the system is more vulnerable to impacts.

Finally, the performance estimations obtained in chapter 7 are used in chapter 11 to assess the prospective capabilities of a Solar Thermal Propulsion engine for PocketQubes. The thrust and specific impulse meet the requirements initially considered of 100 mN and 200 s, respectively. Even though the design was not optimised, the engine turned to provide an end to end efficiency of 34%, taking into consideration the efficiency of the concentrator, the heat exchanger and the thruster. This value together with the third performance capability considered, the specific thrust per unit volume, will be used to compare the system with others in section 12.2.2.

12.1. REQUIREMENTS VERIFICATION

This section evaluates the results obtained for the final design (table 7.5) in order to assess whether or not the concentrator proposed meets the requirements presented in table 3.2 (chapter 3). The acceptance criteria (table 3.3) are also considered as a way to define if the design meets the main research goal.

The theoretical performance is now defined using the key performance parameters ($KPP$) presented in chapter 3. The power collected ($KPP-1$) is 232.04W, which only considers the effect on the efficiency of the mylar’s transmittance, the mirror’s reflectivity and the deformations obtained with the ANSYS model and not the shape error due to manufacturing inaccuracies. The $rms$ error ($KPP-2$) is similar to those obtained by other research groups for inflatable antenna reflectors but it is still above the values attainable by rigid and membrane concepts (see subsection 5.4.2). The image size ($KPP-3$) has been estimated using the area which concentrates 90% of the total power hitting the receiver’s plane and it is smaller than the size of the receiver (2.5 cm), which confirms the good concentrating capabilities of parabolic structures. However, the concentration ratio ($KPP-4$), estimated as the ratio between the solar heat flux and the flux at the receiver (considering the image area instead of the receiver’s area), is below common limits obtained for solar concentrators for STP, which are $\approx 10,000:1$ [2] [30]. Finally, the efficiency ($KPP-5$) is, for example, below the value considered by Gerrish [67] and Zandbergen [26] ($\approx 80-85\%$) and it still needs to be validated. These values are presented here to make the evaluation of the requirements easier.

<table>
<thead>
<tr>
<th>Id.</th>
<th>Parameter</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>KPP-1</td>
<td>Power Collected ($P_{in}$)</td>
<td>232.04</td>
<td>[W]</td>
</tr>
<tr>
<td>KPP-2</td>
<td>$rms$ Error</td>
<td>483.1</td>
<td>[$\mu m$]</td>
</tr>
<tr>
<td>KPP-3</td>
<td>Image size ($A_{image}$)</td>
<td>100</td>
<td>[mm$^2$]</td>
</tr>
<tr>
<td>KPP-4</td>
<td>Concentration ratio (κ)</td>
<td>1641.03</td>
<td>[-]</td>
</tr>
<tr>
<td>KPP-5</td>
<td>Efficiency ($\eta_{conc}$)</td>
<td>60.71</td>
<td>[%]</td>
</tr>
</tbody>
</table>

The requirements need to be verified in order to evaluate the results of the research project. Only the key requirements included in table 7.5 are evaluated below in table 12.2. Those requirements with $TBD$ values and requirement $REQ-A-3$ are not considered since there is no numerical value in them to evaluate their verification or similar projects to compare them. The last column (V?) refers to the verification process, with yes (Y) or no (N) as the answer depending on whether or not the requirement is met. For the detailed description of the requirements and their rationales, refer to chapter 3.
The concentrator meets all the requirements except the efficiency and the duration of the project. The latest was affected by several delays mainly in the manufacturing and testing phases of the project. The non-verification of the former one may be due to different reasons:

- The efficiency requirement was set based on literature about STP as a preliminary value (see subsection 3.1.2). However, the concepts found in literature are not the same as the one proposed in this project and they can yield different efficiency values.

- The efficiency of the concentrator is limited by the materials properties to a value \( \eta_{\text{max}} = \tau_{\text{trans}} \cdot r_{\text{ref}} \), where \( \tau_{\text{trans}} \) is the transmittance coefficient of the transparent section and \( r_{\text{ref}} \) is the reflectivity of the mirror side. In this case, considering the values presented in table 7.5, the maximum attainable efficiency is 72%. Therefore, the selection of the materials play a key role in the efficiency of the device.

- The concept proposed in this research does not include any rigidisation method or auxiliary structure (such as a torus) to ensure that the shape is maintained. This design decision results in higher deformations.

The acceptance criteria (see table 3.3) are successfully met, with the packaging volume \((AC-1)\) reaching the threshold of 1 Unit; the aperture \((AC-2)\) and the power output \((AC-3)\) exceeding their corresponding objectives of 50 cm and 190 W; and the \( \text{rms} \) error \((AC-4)\) meeting the objective of 0.5 mm. The fact that the aperture and power objectives are exceeded means that the system is oversized because the design was based on the packaging volume. Therefore, the system can be designed to occupy a smaller fraction of the PocketQube, still reaching the other objectives. Nevertheless, the manufacturing phase showed that the petal-based production approach has inherit inaccuracies and it is a good idea to have a larger system to compensate for the power lost due to the shape error.

### 12.2. Benchmark Comparison

A benchmarking analysis was included in chapter 2 in order to have an initial notion about the power and propulsion systems available nowadays. The results obtained then are now recalled to establish comparisons in terms of performance and to justify the employment of this system. The packaging volume, which refers to the entire system including the receiver and not only the concentrator’s membrane, is one PocketQube Unit (125 mm\(^3\)) for power systems and 1.25 PocketQube Unit (156 mm\(^3\)) for propulsion systems.

#### 12.2.1. Power Systems

The possible application of the solar concentrator to a power subsystem is assessed using two parameters: the power to volume ratio and the power to surface ratio. In this case, the surface is defined as the cross-sectional area. The concentrator has an output of 232.04 W, which could be transformed into electric power...
with an efficiency around $\eta \approx 30\%$, thus yielding $69.61$ W of power. The ratios are then:

$$\frac{P}{V} = 556880 \quad [W/m^3]$$

$$\frac{P}{S} = 118.44 \quad [W/m^2]$$

The power to surface ratio would be even higher if the area of the receiver were considered instead of the cross-sectional area. The end to end efficiency of the system results around 18%.

As commented before, the only COTS power system specifically designed for PocketQubes provide $368$ mW per panel [50]. Considering a 3-Unit PocketQube with all its sides covered by solar cells, the operating average power would be $OAP = 0.6 \cdot 12 \cdot P_{\text{panel}} = 2.65$ W. The coefficients mentioned before are:

$$\frac{P}{V_{\text{cell}}} = 44160 \quad [W/m^3]$$

$$\frac{P}{S_{\text{cell}}} = 88.32 \quad [W/m^2]$$

The volume required by the solar cells to generate 1 W is larger than the value obtained with the concentrator due to its thickness. The same applies to the specific power per unit surface. Nevertheless, thin film solar cells have a thickness around 1.6 mm [50], which means that their impact on the volume budget of the satellite is much lower.

Although the concentrator induces a loss in efficiency in the power system, it also allows to gather much more power. The size of the concentrator can be changed depending on the power requirements of the satellite, thus modifying the packaging volume. It can be concluded that the use of a concentrator would be recommended if high power values are required. If that is not the case, solar cells are a better choice.

12.2.2. PROPULSION SYSTEMS
The comparison of the STP engine performance proposed in chapter 11 is compared now with other propulsion systems available in the market or developed by TU Delft in the past. For that purpose, the results obtained for the concept STP-B-3 (see table 11.2) are considered. This decision means that the thrust is 162.4 mN and the specific impulse is 206.91 s. The end-to-end efficiency of the system, defined as the ratio between the propellant jet power and the total available power, is 34%. This parameter together with the specific thrust per unit volume (0.87 mN/cm$^3$ in this case) are used to derive the pertinent comparisons.

Table 12.3 presents the two performance characteristics mentioned before for the engines introduced in chapter 2 and the one designed in this project, which is presented in first place under the name STP engine for PocketQubes. The end-to-end power is only calculated for electric propulsion systems and it is derived using the specific impulse ($I_{sp}$), the thrust ($F$) and the required input power ($P_{in}$) (see table 2.1):

$$P_J = \frac{1}{2} F \cdot u_e = \frac{1}{2} \cdot \frac{F^2}{\dot{m}}, \quad \text{where} \quad \dot{m} = \frac{F}{I_{sp} \cdot g_0} \quad (12.5)$$

$$P_{av} = \frac{P_{in}}{\eta_{gen}} \quad (12.6)$$

where $\dot{m}$ is the mass flow rate, $g_0 = 9.81$ [m/s$^2$] is the gravitational acceleration and $\eta_{gen}$ is the efficiency of the electric power generation. For this subsection an efficiency of $\eta_{gen} = 0.3$ [-] is assumed as an usual value for solar cells [51].
The specific thrust per unit volume of the STP engine designed in this project is only overcome by chemical engines \[53\] \[60\] \[52\], whereas it exceeds considerably the values obtained by electric propulsion technologies. The specific impulse is lower than the values of some of the solar electric engines, such as the electrospray thrusters of BUSEK or the ion electrospray thruster developed by MIT. Regarding the efficiency of the system, it is higher than the values of electric propulsion engines, which is an expected result since the electronic components between the power generation system (solar cells) and the thruster are removed. These outcomes define exactly the performance niche which characterises Solar Thermal Propulsion as can be seen in figure 12.1.
CONCLUSIONS AND RECOMMENDATIONS

This chapter describes the final conclusions derived from the research project based on all the results and observations obtained up to now. A set of general conclusions (subsection 13.1) are followed by recommendations and guidelines for future research projects (section 13.2).

13.1. CONCLUSIONS

The progressive scalability of space systems to smaller platforms generate a set of unique conditions for research and technology demonstration never seen in the space field. However, there are still important issues to be tackled, some of which are obvious consequences of the dimensions of the spacecraft. This project is embedded in the research lines followed at TU Delft about Solar Thermal Propulsion and the systems for PocketQubes, as an attempt to demonstrate that these spacecraft can serve as platforms for more than educational projects.

The concept proposed in this project is an inflatable solar concentrator meant for PocketQubes, which has been designed, manufactured and tested. The inflatable concept was chosen instead of membrane or rigid concentrators due to its performance capabilities and, specially, because of its aperture to packaging ratio which was proven to be $D/V = 4693 \text{ m}^{-2}$. This value is larger than that of the structure developed at MIT which has been used as a reference throughout this project. As explained in chapter 4, the concentrator has a conical transparent section through which the radiation reaches the parabolic reflective side and is finally reflected towards the receiver plane (see subsection 4.3).

The design has been developed using an iterative process based on different models for the optical, thermal and structural analysis of the system (chapter 5). The optical model is based on ray tracing, which basically estimates the path followed by different rays to evaluate the radiation hitting the receiver. The thermal model uses a finite element model and the heat balance equations to evaluate the temperature field over the structure. It was necessary to build an in-house model due to the non-availability of dedicated commercial software. The structural model was generated using ANSYS, a commercial software commonly used for engineering purposes. The three models have been verified evaluating qualitative results as functions of the models’ inputs. Neither of them could be validated due to the lack of data about inflatable reflectors for PocketQubes. Nevertheless, the thermal model was compared with the test results of a membrane reflector [11], providing results with errors below 20%. The actual validation has to be performed by testing the system designed in this project.

The selection of the parabolic shape instead of a spherical one was the result of the first iteration, which showed that the former has better performance capabilities even under the pressure and thermal loads. It was observed in subsection 6.3.2 that the structure is subjected to a thermal load which varies with the efficiency of the coupled system, experiencing maximum temperature differences in the order of 20 K between the vertex and the outer edge. Another observation derived is that the conical section is subjected to high temperatures at its base, which means that the design of the interface needs to analyse carefully this region to prevent any possible damage. The structural analysis (subsection 6.3.3) allowed to derive the deformations ex-
CONCLUSIONS AND RECOMMENDATIONS

The effect of the thermal load is more important at low inflating pressures whereas the latest becomes more dominant as it is increased. A design pressure of 10 Pa was selected based on the results as a compromise between the different effects of the thermal and pressure loads and considering that an increase in pressure also means a larger inflating system. It was concluded in chapter 6 that the power drops too fast under variations of the Sun vector and it is necessary to evaluate how to increase the angle range under which the concentrator works. This issue can be solved by decreasing the focal length and the aperture’s half angle, as discussed in subsection 6.2.1. There would be a consequential loss of power under nominal conditions but the system would be less sensitive to variations. It is also necessary to evaluate if it is possible to design a geometry in between a spherical and a parabolic one, so that the disadvantages of both of them would be mitigated, at the obvious expense of a loss in nominal power.

The re-evaluation of the design performed in chapter 7 resulted in a concentrator with a \( \text{rms} \) errors below 0.5 mm. The final design presented in table 7.5 proposed has still an error way larger than rigid concentrators but with a much lower packaging volume and mass. The performance of the system, presented also in table 7.5, is characterised by a total efficiency of 60.71\% and an output power of 232.04 W under nominal conditions, defined as the situation in which the Sun vector is aligned with the concentrator axis. The materials properties are found to be a major constraint for the efficiency, since its maximum achievable value is the product of multiplying the reflectivity of the mirror and the transmittance of the clear side. The gas losses due to the impact of space debris and micrometeoroids is found to be the dominating process in the dimensioning of the pressurising system, leading to a lifetime below 1 year if nitrogen is used. The solutions proposed in subsection 7.2.3 should be taken into account for future projects.

The production and testing phases had the intentions of demonstrating the manufacturing approach based on petals, the performance capabilities of the system and the validity of the ray tracing tool. None of these objectives were fully attained as discussed in chapters 8, 9 and 10. The reasons for the differences between the expected performance and the data gathered during the test campaign include several conclusions and recommendations about the how these two phases should have been performed (see section 12.2.2).

The performance capabilities of a \( \text{STP} \) engine coupled with the concentrator meets the requirements of a thrust of 100 mN, a specific impulse of 200 s and an end-to-end efficiency of 34\% (see chapter 11). These values verify the expected outcomes found in the literature study [17]: the thrust per unit volume is between solar electric and chemical propulsion systems and the end-to-end efficiency is higher than the values of electric propulsion devices as a consequence of not using intermediate electronic subsystems and solar cells (see subsection 12.2.2).

The main objective of the research project has been successfully achieved: the system has been designed with the dimensions required, it has been manufactured and tested. All the requirements, except for the duration of the project and the efficiency have been met. The efficiency value initially required was not met mainly due to the materials properties as discussed in chapter 12. The manufacturing process still has room for improvement and the test campaign yielded results which were not enough to validate neither the analytical predictions nor the tool used to estimate them. Nevertheless, it can be concluded that no showstopper has been found, the concept capabilities justify its further research towards a flight system, not only for solar power purposes but also for communications or optical devices.

13.2. RECOMMENDATIONS

This project intended to serve as a first step in the development of deployable inflatable concentrators for PocketQubes. The design process has been developed and a design has been proposed. However, there are still tasks to be performed. One general recommendation is not to tackle the entire design, manufacturing and testing of the system in a project of the same duration as this one. It was decided to do so in order to prove that the concept works and to generate the necessary design tools. However, it is now necessary to split the work and analyse each aspect of the device separately.
13.2. **RECOMMENDATIONS**

13.2.1. **DESIGN**

The strategy generated for this research covers the entire optical, thermal and structural design of the device. However, the models’ assumptions must be reviewed to provide a better insight. For instance, it is necessary to include in the Ray Tracing Tool the effects of diffusive reflectivity and the refraction at the transparent section, which may turn to be relevant for the evaluation of the output power. The thermal model should be optimised to include a larger number of nodes and thus increase its accuracy or it could built up using a dedicated commercial software which are widely used in the industry due to their precision and good results, such as *ESATAN-TMS*. It is also necessary to evaluate the temperature distribution of the deformed geometry and to investigate the changes in the temperature with respect to time, including for that purpose the transient effects. These analyses would allow to know how the geometry deforms along the orbit and how the performance changes due to it.

Regarding the structural mode, one of the main issues is the definition of the materials’ properties in ANSYS, which are limited due to the information given by the manufacturer. Experimental analyses should be performed to assess the variation of the properties with respect to pressure, temperature and radiation. Moreover, it is necessary to generate a model which includes the petals and the joining approach used, so that the shape error due to the manufacturing approach can be estimated.

The amount of gas required pressurisation subsystem was estimated in chapter 7 and it was observed that the lifetime of the structure was limited by the holes created by space debris and micrometeoroids. It is necessary to evaluate the solutions proposed in subsection 7.2.3 to mitigate the losses and increase the lifetime.

Another recommendation for future research is performing further analyses around the design point to investigate the sensitivity of the device to small changes. It is also necessary to evaluate if the range considered for the Sun vector deviation can be increased in order to reduce the impact on the attitude system of the satellite.

A possible research line derived from the design results is the analysis of new shapes derived from a combination of the spherical and the parabolic geometries, so that the disadvantages of them are mitigated.

13.2.2. **MANUFACTURING**

The manufacturing approach followed is considered to be able to provide a geometry with an acceptable shape accuracy if the recommendations included in chapter 8 are followed:

- A mould with a good curvature accuracy is key for assembling the petals and the material should not leave any residuals on the mirror. The system should be assembled in the clean room to avoid any particle deposition which could damage the reflective properties of the film.

- It is necessary to investigate ways to design a mould for the entire structure so that joining the conical and parabolic sections can be done with a higher accuracy.

- A continuous joining method, such as epoxy resin, is better than Kapton™ tape. It would still generate regions of concentrated higher stiffness but the area affected would be smaller. Moreover, the possibility of having leaks in the system is reduced.

- Another cutting method different from doing it manually with a surgical blade should be used. Laser cutting appears as the best solution but it is also possible to use the composites cutting machine available at the Delft Aerospace Structures and Materials Laboratory.

- As discussed in chapter 12, manipulating, cutting and joining 23 μm films is quite complex due to its tendency to get attached to any surface and its fragility. It is thus necessary to re-evaluate the thickness selected to make the manufacturing phase easier and obtain better results.

Another important recommendation for future phases of the development of an inflatable concentrator is the feasibility analysis of the employment of a torus to guarantee that the shape of the contour is maintained during the operation. An inflatable torus or a shape-memory metallic wire are two options already identified as promising alternatives.
13.2.3. TESTING
The manufacturing and testing phases of this project are the ones which still require more work and analysis. In this case, it is possible to derive a set of recommendations about the way the system was tested, as was already explained in sections 9.5 and 12.2.2:

- The pyranometer is not suitable for testing the solar concentrator. Hence, it is necessary to either find another light source with a lower power or a pyranometer with a higher irradiance limit. Another solution is to employ a metallic component and evaluate the temperature change in order to evaluate the power it receives.

- The light source used experiences large variations with respect to time and the direction. It was possible to estimate average irradiance distributions but it would be preferable to have a more stable and predictable source.

- The connection between the set-up and the concentrator must be reviewed to prevent any leaks.

- The inflating system was based on CO$_2$ cartridges, which have a proper amount of gas to pressurise the system. However, it is necessary to include a pressure regulator in the system such that the testing conditions are known.

13.2.4. COUPLING BETWEEN THE TARGET SYSTEM AND THE SATELLITE
It is still necessary to design the interface subsystem between the satellite and the concentrator, analysing also its impact on the system’s performance. As was observed during the manufacturing phase (see subsections 8.3.3 and 9.4.2), joining the concentrator and the interface is not an easy task and can lead to the formation of wrinkles and cracks in the structure. Moreover, the deployment and pressurisation systems were not tackled in this project and they are key subsystems still to be designed.

A basic analysis on the prospective performance capabilities of a Solar Thermal Propulsion system was performed in chapter 11 but this design still needs to be optimised and analysed using more advanced tools. The receiver was designed but others subsystems such as the propellant storage and feed subsystem, the nozzle or the thermal control subsystem are still missing, as well as the mechanical integration in the PocketQube.

13.2.5. ALTERNATIVE APPLICATIONS
The fact that this device should be used in communications or optical systems has been mentioned several times throughout this document. These claims are based on previous conclusions obtained during a literature review [17] but they must be demonstrated now that there is a design. Therefore, it is necessary to assess the capabilities of the concentrator as part of other systems.


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[54] BET-1mN Busek Electrospray Thruster, datasheet (BUSEK, 2016).


[57] Busek RF Ion Thrusters, datasheet (BUSEK, 2013).


[63] Nanosatellite Micropropulsion system, online datasheet (The CubeSat Shop) accessed on 08/05/2016.


[84] UV lasers today’s trend (PennWell, 2012).
[90] A. Andersson, Gloss standard calibration by spectrophotometer reflectance measurement-suggested method, in 9th International Conference on New Developments and Applications in Optical Radiometry (Swedish National Testing and Research Institute, 2005).


# Planning Details

## A.0.6. Working Packages

The tasks to be completed during the Master Thesis are divided into working packages which must be completed to reach the project's objectives and answer to the research questions (see chapter 2).

Table A.1: Working packages

<table>
<thead>
<tr>
<th>Label</th>
<th>Name</th>
<th>Starting date</th>
<th>End date</th>
<th>Duration [days]</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>M1</td>
<td>Kick-off meeting</td>
<td>22/02/2016</td>
<td>22/02/2016</td>
<td>1</td>
<td>Meeting to discuss the contents of the Thesis and start the project. Deliverable: Proposal and Kick off form</td>
</tr>
<tr>
<td>WP-1</td>
<td>Reporting</td>
<td>01/03/2016</td>
<td>10/12/2016</td>
<td>227</td>
<td>Generation of the Master Thesis report as a continuous task throughout the project. Deliverable: Master Thesis Report</td>
</tr>
<tr>
<td>WP-2</td>
<td>Requirements identification</td>
<td>01/03/2016</td>
<td>08/03/2016</td>
<td>7</td>
<td>Preliminary Systems Engineering Analysis of the project including: stakeholders identification, requirements generation, identification of acceptance criteria and key performance parameters.</td>
</tr>
<tr>
<td>WP-3</td>
<td>Baseline Concept Definition</td>
<td>07/03/2016</td>
<td>24/03/2016</td>
<td>16</td>
<td>Concept generation and selection using the requirements to perform the trade-off.</td>
</tr>
<tr>
<td>WP-4</td>
<td>Design and Analysis Tools</td>
<td>25/03/2016</td>
<td>16/06/2016</td>
<td>72</td>
<td>Development of the necessary tools for the design and analysis of the structure.</td>
</tr>
<tr>
<td>WP</td>
<td>Task</td>
<td>Start Date</td>
<td>End Date</td>
<td>Duration</td>
<td>Details</td>
</tr>
<tr>
<td>-----</td>
<td>--------------------------</td>
<td>------------</td>
<td>-----------</td>
<td>----------</td>
<td>-------------------------------------------------------------------------</td>
</tr>
<tr>
<td>WP-5</td>
<td>Preliminary design</td>
<td>02/06/2016</td>
<td>22/08/2016</td>
<td>70</td>
<td>Preliminary design of the structure using the baseline concept and the requirements in combination with the design tools.</td>
</tr>
<tr>
<td>M6</td>
<td>Mid-Term Review</td>
<td>16/06/2016</td>
<td>16/06/2016</td>
<td>1</td>
<td>Mid-term meeting to discuss the on-going work with respect to the initial objectives. Deliverable: Mid-term Report and Presentation</td>
</tr>
<tr>
<td>WP-6</td>
<td>Final design</td>
<td>23/08/2016</td>
<td>18/10/2016</td>
<td>49</td>
<td>Final design as an improvement of the preliminary design based on analytical and experimental results.</td>
</tr>
<tr>
<td>WP-8</td>
<td>Test Campaign Procedures</td>
<td>10/10/2016</td>
<td>12/11/2016</td>
<td>30</td>
<td>Definition of the test procedures.</td>
</tr>
<tr>
<td>WP-9</td>
<td>Simulations</td>
<td>27/10/2016</td>
<td>15/11/2016</td>
<td>15</td>
<td>Simulation of the test object under the test set-up conditions.</td>
</tr>
<tr>
<td>WP-10</td>
<td>Manufacturing</td>
<td>15/10/2016</td>
<td>10/11/2016</td>
<td>23</td>
<td>Manufacturing of the structure to be tested and the test set-up.</td>
</tr>
<tr>
<td>WP-11</td>
<td>Test Campaign</td>
<td>12/11/2016</td>
<td>15/11/2016</td>
<td>3</td>
<td>Test campaign following the procedures defined before.</td>
</tr>
<tr>
<td>WP-12</td>
<td>Test Data Analysis</td>
<td>12/11/2016</td>
<td>19/11/2016</td>
<td>7</td>
<td>Analysis of the test results and comparison with the simulations.</td>
</tr>
<tr>
<td>M11</td>
<td>Graduation</td>
<td>21/12/2016</td>
<td>21/12/2016</td>
<td>1</td>
<td></td>
</tr>
</tbody>
</table>

### A.0.7. GANTT CHART

All the tasks described before can be found depicted in figure A.1 as a Gantt Chart.
Figure A.1: Gantt Chart
This chapter complements the preliminary Systems Engineering analysis of chapter 3, including additional information about the stakeholders (B.1) and their requirements (B.2). The requirements derived from the baseline concept proposed in chapter 4 are also presented in this appendix.

B.1. Stakeholders

The table below shows the stakeholders identified during the preliminary Systems Engineering analysis of the project. They are divided between active (STK-A-#) and passive stakeholders (STK-P-#), depending on their interaction with the project, and ranked according to their relevance. As mentioned before, the stakeholders are the result of a brainstorming process.

<table>
<thead>
<tr>
<th>Id.</th>
<th>Category</th>
<th>Stakeholder</th>
<th>Rationale</th>
</tr>
</thead>
<tbody>
<tr>
<td>STK-A-1</td>
<td>Active</td>
<td>Master Thesis Student</td>
<td>Main active stakeholder as the designer, manufacturer and tester of the system.</td>
</tr>
<tr>
<td>STK-A-2</td>
<td>Active</td>
<td>Coupled system</td>
<td>The system which receives the output power interacts with the concentrator and affects its design. It can be the satellite's system or the test set-up.</td>
</tr>
<tr>
<td>STK-A-3</td>
<td>Active</td>
<td>Spacecraft</td>
<td>In a real mission, the concentrator system would interact with the spacecraft and it is necessary to consider the interfaces between both elements and other subsystems.</td>
</tr>
<tr>
<td>STK-A-5</td>
<td>Active</td>
<td>Support companies</td>
<td>External companies can join the project to support it during its different stages.</td>
</tr>
<tr>
<td>STK-P-1</td>
<td>Passive</td>
<td>Space System Engineering Department at TU Delft</td>
<td>The SSE Department of the Faculty of Aerospace Engineering plays a role of support for the project.</td>
</tr>
<tr>
<td>STK-P-2</td>
<td>Passive</td>
<td>Analogous Systems</td>
<td>The performance of the system compared with other designs would determine the success of the project.</td>
</tr>
<tr>
<td>STK-P-4</td>
<td>Passive</td>
<td>Small Satellite Standards</td>
<td>The characteristics of small satellites are extensively standardised, which affects the design of the system.</td>
</tr>
<tr>
<td>STK-P-5</td>
<td>Passive</td>
<td>Small Satellite Market</td>
<td>The Space Industry and especially those companies developing small satellites could benefit from the results of this Master thesis.</td>
</tr>
</tbody>
</table>
B.2. REQUIREMENTS

A broader overview of the stakeholder’s requirements is shown hereafter, complementing those already presented in chapters 3 and 4. As mentioned back then, they are divided into functional requirements, attributes and constraints. The key requirements of each category are highlighted in green. All the requirements derived from the concept selected in chapter 4 turn to be attributes and they are included after requirement REQ-A-6.

**FUNCTIONAL REQUIREMENTS**

The only functional requirement not considered to be key for the design is REQ-F-6, which refers to the performance of the coupled system. Although it is clear that launching a satellite with the system proposed in this project would make no sense if it does not outperform analogous systems, it is not a key requirement at the initial stage of a research intended to demonstrate the capabilities of the concentrator.

**Table B.2: Functional Requirements**

<table>
<thead>
<tr>
<th>Id.</th>
<th>Stakeholder</th>
<th>Requirement</th>
<th>Rationale</th>
</tr>
</thead>
<tbody>
<tr>
<td>REQ-F-1</td>
<td>STK-A-1</td>
<td>The concentrator system shall collect at least TBD [W] in-orbit.</td>
<td>The power collected by the concentrator depends on the requirements of the coupled system and it represents one of the main performance requirements.</td>
</tr>
<tr>
<td>REQ-F-2</td>
<td>STK-A-1</td>
<td>The rms error shall be lower than TBD [mm].</td>
<td>The rms error (defined in [17]) must be below a certain limit to ensure a good shape accuracy.</td>
</tr>
<tr>
<td>REQ-F-3</td>
<td>STK-A-1</td>
<td>The concentrator system shall be able operate for an angle range of ∆Φ = ±5 [deg] with respect to the nominal orientation.</td>
<td>In order to reduce the impact on the ADCS, the system shall be able to operate under non nominal conditions.</td>
</tr>
<tr>
<td>REQ-F-4</td>
<td>STK-A-3</td>
<td>The concentrator system shall generate an image of less than TBD [mm²].</td>
<td>The requirement on the size image follows from the size of the receiver.</td>
</tr>
<tr>
<td>REQ-F-5</td>
<td>STK-A-3</td>
<td>The concentrator system shall achieve a concentration ratio of at least TBD:1.</td>
<td>The concentration ratio is one of the main performance parameters and it is selected as a balance between heat losses at the receiver’s inlet and the required accuracy of the system [17].</td>
</tr>
<tr>
<td>REQ-F-6</td>
<td>STK-A-1</td>
<td>The concentrator system shall have an efficiency of at least TBD [%].</td>
<td>The solar collector must operate with a certain efficiency to guarantee that the desired performance capabilities are achieved. The efficiency is defined as the ratio between the incoming solar power and the solar power at the focal plane.</td>
</tr>
</tbody>
</table>

**ATTRIBUTE REQUIREMENTS**

Apart from the attribute requirements presented already in chapter 3, others were also identified. Requirement REQ-A-3 is split into three other sub-requirements corresponding to each of the attributes: simplicity (REQ-A-3-1), reliability (REQ-A-3-2) and low mass (REQ-A-3-3). It was decided to group all of them together to derive an unique selection criterion to choose a concept. Moreover, there is no precise way to define how to assess these three attributes of the system at this stage of the project. It is also necessary to design a system which is not affected by the satellite (REQ-A-4) and does not affect other systems’ performance (REQ-A-5). Requirement REQ-A-6 is derived from the previous literature study, in which it was concluded that the thermal loads is one of the sources of error due to the deformations induced and, therefore, the materials shall be selected to minimise this effect. The last attribute refers to the versatility of the concept in order to make it more interesting for other fields apart from power generation and propulsion (REQ-A-7).
## B.2. Requirements

### Table B.3: Attribute Requirements

<table>
<thead>
<tr>
<th>Id.</th>
<th>Stakeholder</th>
<th>Requirement</th>
<th>Rationale</th>
</tr>
</thead>
<tbody>
<tr>
<td>REQ-A-1</td>
<td>STK-A-1</td>
<td>The concentrator system shall fit in 1 PocketCube Unit in the packaged configuration.</td>
<td>One of the main challenges of deployable concentrators is achieving the desired aperture with a low packaging volume ([1], [4]).</td>
</tr>
<tr>
<td>REQ-A-2</td>
<td>STK-A-1, STK-P-4</td>
<td>The aperture of the concentrator shall be between 5 and 10 times the size of a PocketCube Unit (5 [cm]). The concentrator system shall be simple and reliable and it shall have a low mass.</td>
<td>One of the main objectives of the project is to research if it is possible to achieve similar apertures than with other concentrators designed for CubeSat ([1], [3]). The requirement on the packaging volume is the most important but the system shall also verify other characteristics (or attributes). These are common requirements in projects related to small satellites and meeting them is key to trigger the interest of the industry.</td>
</tr>
<tr>
<td>REQ-A-3</td>
<td>STK-P-5, STK-P-7</td>
<td>The concentrator system shall be simple and reliable and it shall have a low mass.</td>
<td>The simplicity is evaluated by the number of components and the ease of deployment.</td>
</tr>
<tr>
<td>REQ-A-3A</td>
<td>STK-P-5, STK-P-7</td>
<td>The concentrator system shall be simple.</td>
<td>The reliability is evaluated by the determination of the risks of the system and the ease of deployment.</td>
</tr>
<tr>
<td>REQ-A-3B</td>
<td>STK-P-5, STK-P-7</td>
<td>The concentrator system shall be simple and reliable (ease of deployment and low risk) and have a low mass (design criteria).</td>
<td>The design process shall aim for a low mass system such that the impact on the mass budget is minimised.</td>
</tr>
<tr>
<td>REQ-A-3C</td>
<td>STK-P-5, STK-P-7</td>
<td>The mass of the system shall be lower than TBD [kg].</td>
<td>Lifetime based on usual estimations of mission duration for CubeSats.</td>
</tr>
<tr>
<td>REQ-A-4</td>
<td>STK-A-1</td>
<td>The lifetime of the concentrator shall be 1 year.</td>
<td>Usual altitude of Low Earth Orbits selected as a starting point when required in the design process.</td>
</tr>
<tr>
<td>REQ-A-5</td>
<td>STK-A-8</td>
<td>The system shall be designed to operate at an altitude of 600 km.</td>
<td>The uneven solar illumination conditions due to the shape of the concentrator generates deformations in the structure which affect the performance and the accuracy.</td>
</tr>
<tr>
<td>REQ-A-6</td>
<td>STK-A-1</td>
<td>The materials shall be selected such that the effect of thermal gradients is minimised.</td>
<td>Cool gas generators and sublimating powders are the simplest ways to inflate the concentrator and they have been extensively researched. There is experience in the faculty and start-up companies (TNO, ISIS) working with gas generators. Pressurised gas bottles can be easily purchased for the test campaign.</td>
</tr>
<tr>
<td>REQ-A-7</td>
<td>STK-A-1</td>
<td>The pressurisation subsystem shall be based on a cool gas generator, a sublimating powder or a pressurised gas bottle.</td>
<td>The generated gas shall be non-toxic.</td>
</tr>
<tr>
<td>REQ-A-7C</td>
<td>STK-A-1</td>
<td>The generated gas shall have no reactivity issues with the membrane materials.</td>
<td>Safety considerations and a measure to ensure that the optical properties of the film do not change.</td>
</tr>
</tbody>
</table>
The generated gas shall have a transmission coefficient as close as possible to 1 in the solar spectrum.

The inflating gas shall be selected such that the reduction in the efficiency of the system is minimised.

The pressurisation subsystem shall be designed according to the final pressure and the pressurisation rate.

The design process must determine two main parameters: the inflating pressure and the pressurisation rate.

The final pressure shall be TBD Pa.

The inflating pressure is chosen to ensure that the required geometry is attained.

The pressurisation rate shall be TBD Pa/s.

Mitigation strategy to prevent the formation of wrinkles.

Error mitigation measures shall be included in the design of the concentrator.

Misalignments and accuracy levels are common in inflatable structures and this disadvantage and its consequences must be considered during the design process.

The system shall be able to continue operating after the impact of space debris and micrometeoroids.

One of the major risks of inflatable structures is the possibility of being hit by space debris or micrometeoroids.

### Constraints

<table>
<thead>
<tr>
<th>Id.</th>
<th>Stakeholder</th>
<th>Requirement</th>
<th>Rationale</th>
</tr>
</thead>
<tbody>
<tr>
<td>REQ-C-1</td>
<td>STK-A-6</td>
<td>The overall cost of the project shall not exceed the budget of 500 [€].</td>
<td>The budget available for the Master Thesis is by far the most important constraint.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>The duration of the project shall not exceed 8.5 [months].</td>
<td>The second constraint is about the duration of the project and it is determined by the workload assigned for the Master Thesis (42 ECTS) and the schedule designed by the student.</td>
</tr>
<tr>
<td>REQ-C-2</td>
<td>STK-P-6</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
C

MATERIAL PROPERTIES
Mylar®

polyester film

Physical-Thermal Properties

Mylar® polyester film retains good physical properties over a wide temperature range (−70 to 150°C [−94 to 302°F]), and it is also used at temperatures from −250 to 200°C (−418 to 392°F) when the physical requirements are not as demanding. Some physical and thermal properties of Mylar® are summarized in Table 1. Detailed information and other physical and thermal properties are described in the remaining pages of this bulletin.

<table>
<thead>
<tr>
<th>Property</th>
<th>Typical Value</th>
<th>Unit</th>
<th>Test Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gauge and Type End Use</td>
<td></td>
<td>92A Industrial</td>
<td></td>
</tr>
<tr>
<td>Ultimate Tensile Strength, MD</td>
<td>20 (29)</td>
<td>kg/mm² (kpsi)</td>
<td>ASTM D 882</td>
</tr>
<tr>
<td>TD</td>
<td>24 (34)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Strength at 5%, Elongation</td>
<td>10 (15)</td>
<td>kg/mm² (kpsi)</td>
<td>ASTM D 882</td>
</tr>
<tr>
<td>F−5, MD</td>
<td>10 (14)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>TD</td>
<td>490 (710)</td>
<td>kg/mm² (kpsi)</td>
<td>ASTM D 882</td>
</tr>
<tr>
<td>Modulus, MD</td>
<td>510 (740)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>TD</td>
<td>116</td>
<td>%</td>
<td>ASTM D 882</td>
</tr>
<tr>
<td>Elongation, MD</td>
<td>91</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Surface Roughness</td>
<td>38</td>
<td>nm</td>
<td>Optical profilometer</td>
</tr>
<tr>
<td>Density</td>
<td>1.390</td>
<td>g/cm³</td>
<td>ASTM D 1505</td>
</tr>
<tr>
<td>Viscosity</td>
<td>0.56</td>
<td></td>
<td>ASTM D 2857</td>
</tr>
<tr>
<td>Melt Point</td>
<td>254</td>
<td>°C</td>
<td>DSC*</td>
</tr>
<tr>
<td>Dimensional Stability</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>at 105°C (221°F), MD</td>
<td>0.6</td>
<td>%</td>
<td>DuPont test</td>
</tr>
<tr>
<td>TD</td>
<td>0.9</td>
<td></td>
<td></td>
</tr>
<tr>
<td>at 150°C (302°F), MD</td>
<td>1.8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>TD</td>
<td>1.1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Specific Heat</td>
<td>0.28</td>
<td>cal/g°C</td>
<td></td>
</tr>
<tr>
<td>Coefficients of Thermal Expansion</td>
<td>1.7 × 10⁻⁴</td>
<td>in/in°C</td>
<td>ASTM D 696</td>
</tr>
<tr>
<td>Thermal Conductivity (Mylar® 1000A)</td>
<td>3.7 × 10⁻³</td>
<td>cal·cm⁻¹·°C</td>
<td>30–50°C (86–122°F)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>cm²·sec·°C</td>
<td>25–75°C (77–167°F)</td>
</tr>
<tr>
<td>UL54 Flame Class</td>
<td>See UL file # E93687</td>
<td>VT M</td>
<td></td>
</tr>
</tbody>
</table>

*Different Scanning Calorimeter

Figure C.1: Mylar™ main properties. Obtained from [13].
Mylar®
polyester film

Optical Properties

Transmission of Radiation
Type D Mylar® polyester film transmits light very similar to window glass throughout the absorption spectrum at low wavelengths as shown in Figure 1. Figure 2 illustrates substantial difference at high wavelengths. Type A Mylar® transmits much less radiation due to its light-scattering characteristic (as shown in Figure 1 for a film having a 54% haze).

Refractive Index
The refractive index of Mylar® polyester films is between 1.640 and 1.670.

Figure 1. Absorption Spectrum for Mylar® (Low Range)

Figure C.2: Mylar™ optical properties. Obtained from [14].
Kenpro Mirror Film
23um polyester film substrate

**Description:** Kenpro K813 is a single-sided metallised polyester film with a highly reflective mirror finish. The non-metallised surface is specially treated to promote ink adhesion to many industrial inks and coatings. This film can be laminated to another surface.

**Availability:** Kenpro K813 is supplied in standard rolls 610mm wide, slit reels, sheeted or die-cut components.

**Key Features:** * Super bright mirror finish  * Excellent printability  * UV resistant  * thermal stability

### SPECIFICATION

<table>
<thead>
<tr>
<th>Properties</th>
<th>Test Method</th>
<th>Unit</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Physical</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Film thickness</td>
<td>-</td>
<td>micron</td>
<td>23</td>
</tr>
<tr>
<td>Unit weight</td>
<td>-</td>
<td>g/m²</td>
<td>32</td>
</tr>
<tr>
<td>Density</td>
<td>-</td>
<td>g/cm³</td>
<td>2.0 to 2.5</td>
</tr>
<tr>
<td>Area yield</td>
<td>ASTM D1505</td>
<td>m²/kg</td>
<td>31.1</td>
</tr>
<tr>
<td><strong>Optical</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total light transmission</td>
<td>ASTM D1003-77 (Gardner hazemeter)</td>
<td>%</td>
<td>0.15</td>
</tr>
<tr>
<td>Reflectivity of metallised surface</td>
<td>Dr Lange Glossometer (85° position)</td>
<td>-</td>
<td>120</td>
</tr>
<tr>
<td><strong>Mechanical</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tensile strength @ Break(minimum) MD</td>
<td>ASTM D882</td>
<td>Kgf/mm²</td>
<td>20.0</td>
</tr>
<tr>
<td>Elongation @ Break MD</td>
<td></td>
<td>%</td>
<td>125</td>
</tr>
<tr>
<td><strong>Thermal</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Upper melt temperature</td>
<td>ASTM E794-85</td>
<td>°C</td>
<td>255 to 260</td>
</tr>
<tr>
<td>Coefficient of Thermal Expansion MD</td>
<td>-</td>
<td>cm/cm°C</td>
<td>19 x 10⁻⁶</td>
</tr>
<tr>
<td>Shrinkage MD</td>
<td>5 min at 190°C</td>
<td>%</td>
<td>3.0</td>
</tr>
</tbody>
</table>

Health and Safety Summary

- **Toxicity:** Non toxic, unlikely to be ingested
- **Combustibility:** Ignition will occur over 180°C
- **Storage:** May degrade or decompose, keep dry and below 30°C
- **Handling:** Use suitable handling equipment and safety shoes and gloves
- **Disposal:** Suitable for normal recycling and refuse handling systems

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Kenpro Mirror Film™ main properties. Obtained from [15].
RESULTS OF THE OPTIMISATION PROCESS

This appendix supports chapter 7, including all the numerical results obtained during the optimisation process.

D.1. METHOD 1

Table D.1: Results of the optimisation strategy 1

<table>
<thead>
<tr>
<th>Id.</th>
<th>Focal length [m]</th>
<th>rms error</th>
</tr>
</thead>
<tbody>
<tr>
<td>ideal</td>
<td>0.175</td>
<td>0</td>
</tr>
<tr>
<td>nominal</td>
<td>0.175</td>
<td>7.316</td>
</tr>
<tr>
<td>mod A-1</td>
<td>0.165</td>
<td>2.7324</td>
</tr>
<tr>
<td>mod A-2</td>
<td>0.17</td>
<td>2.2929</td>
</tr>
<tr>
<td>mod A-3</td>
<td>0.167</td>
<td>1.7477</td>
</tr>
<tr>
<td>mod A-4</td>
<td>0.172</td>
<td>4.0047</td>
</tr>
<tr>
<td>mod A-5</td>
<td>0.166</td>
<td>2.2145</td>
</tr>
<tr>
<td>mod A-6</td>
<td>0.168</td>
<td>1.5226</td>
</tr>
<tr>
<td>mod A-7</td>
<td>0.1665</td>
<td>1.9531</td>
</tr>
<tr>
<td>mod A-8</td>
<td>0.1675</td>
<td>1.5909</td>
</tr>
<tr>
<td>mod A-9</td>
<td>0.16725</td>
<td>1.6599</td>
</tr>
<tr>
<td>mod A-10</td>
<td>0.16775</td>
<td>1.5545</td>
</tr>
</tbody>
</table>

D.2. METHOD 2

Table D.2: Results of the optimisation strategy 2

<table>
<thead>
<tr>
<th>Id.</th>
<th>Focal length [m]</th>
<th>Δz [mm]</th>
<th>rms error</th>
</tr>
</thead>
<tbody>
<tr>
<td>ideal</td>
<td>0.175</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>nominal</td>
<td>0.175</td>
<td>0</td>
<td>7.316</td>
</tr>
<tr>
<td>mod B-1</td>
<td>0.175</td>
<td>7.316</td>
<td>1.2727</td>
</tr>
<tr>
<td>mod B-2</td>
<td>0.175</td>
<td>8.5887</td>
<td>0.3408</td>
</tr>
<tr>
<td>mod B-3</td>
<td>0.175</td>
<td>6.0433</td>
<td>2.2358</td>
</tr>
<tr>
<td>mod B-4</td>
<td>0.175</td>
<td>8.9295</td>
<td>0.1486</td>
</tr>
<tr>
<td>mod B-5</td>
<td>0.175</td>
<td>8.2479</td>
<td>0.5884</td>
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<td>mod B-6</td>
<td>0.175</td>
<td>9.0781</td>
<td>0.1351</td>
</tr>
<tr>
<td>mod B-7</td>
<td>0.175</td>
<td>8.7809</td>
<td>0.2241</td>
</tr>
<tr>
<td>mod B-8</td>
<td>0.175</td>
<td>9.2132</td>
<td>0.1835</td>
</tr>
</tbody>
</table>

D.3. METHOD 3
### D.4. Method 4

Table D.4: Results of the optimisation strategy 4

<table>
<thead>
<tr>
<th>Id.</th>
<th>Focal length [m]</th>
<th>Thickness [µm]</th>
<th>$\Delta z$ [mm]</th>
<th>$rms$ error</th>
</tr>
</thead>
<tbody>
<tr>
<td>ideal</td>
<td>0.175</td>
<td>23</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>nominal</td>
<td>0.175</td>
<td>23</td>
<td>0</td>
<td>7.316</td>
</tr>
<tr>
<td>mod D-1</td>
<td>0.175</td>
<td>36</td>
<td>0</td>
<td>3.6363</td>
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<tr>
<td>mod D-2</td>
<td>0.175</td>
<td>50</td>
<td>0</td>
<td>2.257</td>
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<tr>
<td>mod D-3</td>
<td>0.175</td>
<td>75</td>
<td>0</td>
<td>1.2256</td>
</tr>
<tr>
<td>mod D-4</td>
<td>0.175</td>
<td>100</td>
<td>0</td>
<td>0.7929</td>
</tr>
<tr>
<td>mod D-5</td>
<td>0.175</td>
<td>125</td>
<td>0</td>
<td>0.5625</td>
</tr>
</tbody>
</table>

### D.5. Method 5

Table D.5: Results of the optimisation strategy 5

<table>
<thead>
<tr>
<th>Id.</th>
<th>Focal length [m]</th>
<th>Thickness [µm]</th>
<th>$\Delta z$ [mm]</th>
<th>$rms$ error</th>
</tr>
</thead>
<tbody>
<tr>
<td>ideal</td>
<td>0.175</td>
<td>23</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>nominal</td>
<td>0.175</td>
<td>23</td>
<td>0</td>
<td>7.316</td>
</tr>
<tr>
<td>mod E-1</td>
<td>0.175</td>
<td>75</td>
<td>1.2256</td>
<td>0.0836</td>
</tr>
<tr>
<td>mod E-2</td>
<td>0.175</td>
<td>75</td>
<td>1.3092</td>
<td>0.0485</td>
</tr>
<tr>
<td>mod E-3</td>
<td>0.175</td>
<td>100</td>
<td>0.7929</td>
<td>0.033</td>
</tr>
</tbody>
</table>
E.1. CO₂ CARTRIDGE

The properties of a single cartridge were derived from measurements taken by the researcher:

- Weight: 60 g when filled with CO₂; 43-44 g if empty.
- Material: Lightweight aluminium ($\rho_{Al} \approx 2.720 \text{ g/cm}^3$).
- Maximum diameter: $D_{\text{max}} = 22 \text{ [mm]}$.
- Total length: $L_{\text{total}} = 88 \text{ [mm]}$.
- Connection section: $L_{cone} = 5 \text{ [mm]}$.
- Threaded section:
  - maximum diameter: 9.5 [mm].
  - minimum diameter: 8.5 [mm].
  - pitch diameter: $\approx 0.5 \cdot (8.5 + 9.5) = 9 \text{ [mm]}$.
  - Length: $L_{thread} = 11 \text{ [mm]}$.
- Approximate volume of Material: $V = \frac{m_{\text{empty}}}{\rho_{Al}} = 16.1764 \text{ [cm}^3\text{]}$.

It is thus possible to estimate the inner volume calculating the total volume of the bottle as:

$$
V_{\text{bottle}} = V_{\text{cyl}} + 2 \cdot V_{\text{sphere}} + V_{\text{cone}} - \frac{\pi}{4} D_{\text{max}}^2 \cdot (L_{\text{total}} - D_{\text{max}} - L_{cone} - L_{cone}) + \frac{4}{3} \pi \cdot \left(\frac{D_{\text{max}}}{2}\right)^3 + \\
+ \frac{\pi}{4} D_{\text{pitch}}^2 \cdot (L_{\text{thread}}) + \frac{1}{3} \cdot \pi \cdot L_{cone} \cdot \left(\frac{D_{\text{pitch}}}{2}\right)^2 + \left(\frac{D_{cone,0}}{2}\right)^2 + \left(\frac{D_{cone,0}}{2} \cdot \frac{D_{\text{pitch}}}{2}\right) = 25.8092 \text{ [cm}^3\text{]} \quad (E.1)
$$

Therefore, the approximate volume inside the bottle is $V_{\text{CO}_2,0} = V_{\text{bottle}} - V_{\text{Al}} = 9.6328 \text{ [cm}^3\text{]}$, which would yield an initial inner pressure of 919.6 [MPa]. However, the pressure of CO₂ is limited by its vapour pressure, which is around 57.089 [bar] at 293.15 [K] [99]. This value will be taken as an approximation of the initial pressure inside the bottle.
## E.2. SYLVANIA THEATRE LAMP

![Theatre Lamp Datasheet](image)

### Product selected: PAR 64 1000W SP

<table>
<thead>
<tr>
<th>Applications</th>
<th>Features</th>
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<tbody>
<tr>
<td>• Theatre lighting</td>
<td>• Pressed-glass reflector lamps</td>
</tr>
<tr>
<td>• Displays</td>
<td>• High illuminance levels</td>
</tr>
<tr>
<td>• Museums</td>
<td></td>
</tr>
<tr>
<td>• Churches</td>
<td></td>
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<tr>
<td>• Towers</td>
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<td>• Exhibitions</td>
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<tr>
<td>• Gardens</td>
<td></td>
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<td>• Discos</td>
<td></td>
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### Product Attributes

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### Fixture Rating

![Fixture Rating](image)

### Burning Position

![Burning Position](image)

### Lamp Cap

![Lamp Cap](image)

---

Figure E.2: Theatre lamp's datasheet ([16](#))
**E.3. PYRANOMETER**

---

**Solar Radiation Sensor**

**Model CM3**

The CM3 is a rugged pyranometer manufactured by Kipp & Zonen. It is fully compliant with all ISO-9060 second class pyranometer performance specification criteria. The CM3 measures solar radiation with a high-quality blackened thermopile protected by a dome. The blackened thermopile provides a flat spectral response for the full solar spectrum range, which allows the CM3 to be used under plant canopies or lamps, when the sky is cloudy, and for reflected radiation measurements. The CM3 produces a millivolt signal that is measured directly by a Campbell Scientific datalogger.

**Mounting**

To ensure accurate measurements, the CM3 should be leveled using a 14282 leveling fixture which incorporates a bubble level and three adjusting screws. The 14282 leveling fixture mounts to a tripod or tower using the CM225 mount. For most applications, Campbell Scientific recommends attaching a CM225 to a CM202, CM204, or CM206 crossarm. The CM225 can also be attached to a tripod or tower mast.

**Ordering Information**

- **CM3**: Pyranometer, includes 15’ lead length.
- **14282**: Leveling Fixture, includes mounting and leveling screws.
- **17906**: CM225 Mount for attaching to the 14282 and sensor to a tripod, tower, or vertical pipe.

**Specifications**

- **Light Spectrum Waveband**: 305 to 2800 nm
- **Maximum Irradiance**: 2000 W m⁻²
- **Signal Output**: 0 to 50 mV
- **Sensitivity**: 10 to 35 μV W⁻¹ m⁻²
- **Operating Temperature**: -40°C to +80°C
- **Temperature Dependence**: ±6% (−10°C to +40°C)
- **Non-linearity (0 to 1000 W m⁻²)**: <±2.5%
- **Tilt Response (±80°)**: <±2% at 1000 W m⁻²
- **Expected accuracy for daily sums**: ±10%
- **Dimensions**: 2.1” (5.4 cm) diameter, 2.3” (5.8 cm) height
- **Weight (with cable)**: 12 oz (343 g)
- **ISO Classification**: Second Class

Note: Second class pyranometers are acceptable for providing the solar radiation data used in stability estimations (EPA Meteorological Monitoring Guidance for Regulatory Modeling Applications, pages 2-10).

---

Figure E.3: CM3 Pyranometer's datasheet (1/7)
The drawings of the set-up components are included in this section. They are scaled to fit in the report template, while the original PDF files, CAD files and, if applicable, Makerbot files can be accessed by contacting the author of the report or the supervisor. The mass of the components is not included since it is not considered to be relevant for the project.

Figure E1: General view of the Test Set-up assembly
Figure F.2: Drawing of the upper component of the interface
Isometric view
Scale: 1:3

Detail A
Scale: 2:1

Figure F.3: Drawing of the lower component of the interface.
Figure E.4: Drawing of the sealing ring of the interface
Figure E5: Drawing of the main support structure
ADDITIONAL TEST DATA
**Table G.1: Description of the tests performed**

<table>
<thead>
<tr>
<th>Phase</th>
<th>Sub-category</th>
<th>Description</th>
<th>Test no.</th>
<th>File</th>
<th>File</th>
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<td>Measurements of the irradiance reflected by the concentrator for an on-axis layout</td>
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**Description**
- **Phase**: Identify the category of the test performed.
- **Sub-category**: Specify the specific type of test or setup.
- **Description**: Provide a brief explanation of what the test involves.
- **Test no.**: Number of the test.
- **File**: Name of the file containing the data for the test.

---

**Additional Test Data**
- **Measurements**
  - **w.r.t. time at the origin**: Provides time measurements at the origin for different vertical distances.
  - **along the x and y axis**: Provides measurements along the x and y axis at a specific distance.
  - **at a distance of 160 cm**: Specifies measurements at a distance of 160 cm.
  - **at a distance of 160 cm**: Specifies measurements at another distance of 160 cm.
  - **at a distance of 160 cm**: Specifies measurements at yet another distance of 160 cm.
  - **at a distance of 160 cm**: Specifies measurements at a final distance of 160 cm.

---

**Files**
- **test_A_A1_1_28_09_2016.xlsx**: Data file for the first test.
- **test_A_A1_2_30_09_2016.xlsx**: Data file for the second test.
- **test_A_A1_3_07_10_2016.xlsx**: Data file for the third test.
- **test_A_A1_4_04_11_2016.xlsx**: Data file for the fourth test.
- **test_A_A2_1_28_09_2016.xlsx**: Data file for the first on-axis test.
- **test_A_A2_2_30_09_2016.xlsx**: Data file for the second on-axis test.
- **test_A_B-AUX-1_1_28_09_2016.xlsx**: Data file for the first leak test.
- **test_A_B-AUX-2_1_28_09_2016.xlsx**: Data file for the second leak test.
- **test_B_B1_1_28_09_2016.xlsx**: Data file for the first on-axis test.
- **test_B_B1_2_28_09_2016.xlsx**: Data file for the second on-axis test.
- **test_B_B2_1_28_09_2016.xlsx**: Data file for the first on-axis test.
- **test_B_B2_2_30_09_2016.xlsx**: Data file for the second on-axis test.
- **test_B_B2_3_07_10_2016.xlsx**: Data file for the third on-axis test.
- **test_B_B2_4_04_11_2016.xlsx**: Data file for the fourth on-axis test.
- **test_B_B2_5_07_10_2016.xlsx**: Data file for the fifth on-axis test.
- **test_B_B2_6_04_11_2016.xlsx**: Data file for the sixth on-axis test.
Table G.2: Results for test sub-category A-1, including the test identification, the values measured and the maximum deviation, $\Delta_{max}$

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</table>

Irradiance [W/m²] w.r.t. time [s]
### Table G.3: Results of test sub-category A-2, test 1

<table>
<thead>
<tr>
<th>x (mm)</th>
<th>y (mm)</th>
<th>x (mm)</th>
<th>y (mm)</th>
<th>Resistance (W/m²)</th>
<th>x (mm)</th>
<th>y (mm)</th>
<th>Resistance (W/m²)</th>
<th>x (mm)</th>
<th>y (mm)</th>
<th>Resistance (W/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0 1.0</td>
<td>0.1 1.1</td>
<td>0.2 1.2</td>
<td>0.3 1.3</td>
<td>...</td>
<td>0.4 1.4</td>
<td>0.5 1.5</td>
<td>...</td>
<td>0.6 1.6</td>
<td>0.7 1.7</td>
<td>...</td>
</tr>
</tbody>
</table>

### Table G.4: Results of test sub-category A-2, test 2

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<th>x (mm)</th>
<th>y (mm)</th>
<th>x (mm)</th>
<th>y (mm)</th>
<th>Resistance (W/m²)</th>
<th>x (mm)</th>
<th>y (mm)</th>
<th>Resistance (W/m²)</th>
<th>x (mm)</th>
<th>y (mm)</th>
<th>Resistance (W/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0 1.0</td>
<td>0.1 1.1</td>
<td>0.2 1.2</td>
<td>0.3 1.3</td>
<td>...</td>
<td>0.4 1.4</td>
<td>0.5 1.5</td>
<td>...</td>
<td>0.6 1.6</td>
<td>0.7 1.7</td>
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</tr>
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</table>

### Table G.5: Results of test sub-category A-2, test 2

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<th>y (mm)</th>
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<th>x (mm)</th>
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<th>Resistance (W/m²)</th>
<th>x (mm)</th>
<th>y (mm)</th>
<th>Resistance (W/m²)</th>
</tr>
</thead>
<tbody>
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<td>0.0 1.0</td>
<td>0.1 1.1</td>
<td>0.2 1.2</td>
<td>0.3 1.3</td>
<td>...</td>
<td>0.4 1.4</td>
<td>0.5 1.5</td>
<td>...</td>
<td>0.6 1.6</td>
<td>0.7 1.7</td>
<td>...</td>
</tr>
</tbody>
</table>