Modular impulsive green-monopropellant propulsion system for micro/nano satellites high-thrust orbital maneuvers (MIMPS-G)

Nosseir, A.E.S.; Cervone, A.; Pasini, A

Publication date
2020

Document Version
Accepted author manuscript

Published in
71st International Astronautical Congress (IAC)

IAC-20-C4.8-B4.5A (57488)

MODULAR IMPULSIVE GREEN-MONOPROPELLANT PROPULSION SYSTEM FOR MICRO/NANO SATELLITES HIGH-THRUST ORBITAL MANEUVERS (MIMPS-G)

A. E. S. Nosseir [ab]*, A. Pasini [a], A. Cervone [b]

[a] *Ingegneria Aerospaziale , Università di Pisa, 56122 Pisa (PI), Italy*
a.nosseir@studenti.unipi.it and angelo.pasini@unipi.it
[b] *Department of Space Engineering, Faculty of Aerospace Engineering, Technische Universiteit Delft,* 2628 CD Delft, Netherlands.
a.e.s.nosseir@student.tudelft.nl and a.cervone@tudelft.nl
* Corresponding Author

Abstract

Innovation in small-satellite modern space missions and applications require propulsion capabilities to enable active operations in orbit, such as formation flying, rendezvous operations, orbital altitude & inclination changes, and orbital transfers,– generally, operations demanding high-thrust impulsive maneuvers. In addition, Green-monopropellants are current state-of-the-art of liquid propellants for small satellites space propulsion due to their safety, stability, storability, relative design simplicity, and high performance. These facts were the motive behind the design of the *Modular Impulsive Propulsion System*– namely MIMPS-G – that utilizes *Green-monopropellants* and is a prospect solution for micro- and nano- spacecraft, particularly CubeSats, requiring a modular propulsion system for high-thrust impulsive orbital maneuvers. The baseline design is a standard 1U that can be expanded depending on the spacecraft size, required thrust level, and mission's ΔV requirements. System analysis and preliminary design of MIMPS-G are discussed, and system architecture is presented. Different *pressurization-systems* are investigated – conventional and unconventional relative to small-satellites – emphasizing on *autogenous-pressurization* system utilizing *micro electric pump,* since the choice of the pressurization-system will further affect the propulsion system overall performance, onboard power consumption, and the spacecraft size optimization. A tradeoff study with regards to the performance and characteristics of suitable monopropellants, to be utilized by MIMPS-G, is carried out to give insights for system design and architecture possibilities, as well as future studies concerned with monopropellant propulsion systems for various classes of space propulsion. Finally, candidate propulsion system utilizing a 0.5 N thruster – designated as MIMPS-G500mN – is introduced elaborating system's architecture, analysis, design, and CAD models. MIMPS-G500mN offers total impulse $I_{tot} \cong$ *850 to 1350 N.s* per 1U or $> 3000\ N.s$ per 2U expanded-layout depending on used propellant, which makes the latter a modular expandable propulsion system suitable for Lunar missions. Comparative results of the propulsion system properties using different monopropellants are tabulated – focusing on *alternatives* for the highly stable Hydroxyl-ammonium nitrate (HAN-) based monopropellant AF-M315E, that is the state-of-art of green-monopropellants.

Keywords: Liquid Rocket Engine; CubeSat; Small-satellites; Green-propellant; Monopropellant; Micro Electric Pump-feed; Multimode Propulsion System.

Nomenclature

m_{prop}	propellant mass
m_f	final mass of spacecraft
m_i	initial mass of spacecraft
$m_{wet\ P.S.}$	wet mass of propulsion system at BOL
m_{inert}	inert/dry mass of all propulsion system components
$m_{payload}$	mass of all spacecraft parts outside the propulsion system envelope
I_{tot}	total impulse
I_{sp}	gravimetric specific impulse
ρI_{sp}	volumetric specific impulse

Acronyms/Abbreviations

MIMPS-G Modular Impulsive Monopropellant Propulsion System – Green.
ECHA European CHemicals Agency.
REACH Registration, Evaluation, Authorization, and restriction of Chemicals.
SVHC Substances of Very High Concern.
EIL Energetic Ionic Liquid.
HAN- Hydroxyl Ammonium Nitrate.
ADN- Ammonium Dinitramide.
AF-M315E Air Force Monopropellant 315E.
AFRL Air Force Research Laboratory
HNP- High-performance Non-detonating Propellant.
LMP-103S Liquid Monopropellant 103S.
FOI Swedish Defence Research Agency.
FLP- Liquid Propellant developed by FOI.
HPGP High Performance Green Propulsion.
MPS- Modular Propulsion System by Rocketdyne.
PMD Propellant Management Device.

1. Introduction

The current trend in rocket propulsion field is directed toward greenifying the use of propellants. Monopropellant Hydrazine was *classically* wide used and favored for thrusters and gas generators due to its high performance, systems' simpler design, and 'clean' – relatively cool – exhaust products as compared to bipropellant systems at that time [1]. ECHA through REACH has included Hydrazine on the list of Substances of Very High Concern SVHC for authorization, thus ending the availability and affordability of hydrazine and its derivatives [2]. Moreover, transportability and handling of hydrazine extend an economic burden on the space industry. Accordingly, greener alternatives that would compensate for these drawbacks are being studied and developed rapidly nowadays [3] [4]. Since the beginning of their development, modern green propellants possess higher performance not only in terms of specific impulse and density, but also in operability, cost, and environmental safety [5]. A brief survey was made for state-of-art of green-monopropellants that were considered for MIMPS-G design. Feed & pressurization systems are highlighted and classified to conventional and unconventional systems from the point of view of small-sized spacecraft propulsion system design. A survey of relevant propulsion systems currently available on the market is presented. Further in this paper sections, the preliminary design and system analysis for MIMPS-G500mN is elaborated.

1.1. Green-Monopropellants (EIL)

AF-M315E, the term stands for Air Force Monopropellant, was developed by the Air Force Research Laboratory AFRL in 1998 [6]. It is a Hydroxylammonium Nitrate HAN- based green monopropellant, and when decomposed produces an adiabatic flame temperature around 2100K which is much higher than that of Hydrazine (nearly 1200K). AF-M315E offers 13% increase of specific impulse and 63% increase in density over Hydrazine [7], which makes it superior in miniaturization of propulsion systems over the latter. This propellant possesses high solubility and negligible vapor-pressure of all its solution constituents, thus promoting low toxicity hazards and high mixture stability even at very low temperatures, which makes exposure in open environment have no safety issues [8]. An advantage AF-M315 possesses over current state-of-art green propellants is its maturity. Thorough development has taken place to reach this product and be able to test in space on 1N and 22N thrusters through the GPIM Green propellant Infusion Mission launched 2019 [9].

ADN- based green propellants development started at the Swedish Defense Research Agency (FOI) in Europe in 1997 [10] [11] [12]. The ADN- based monopropellants family mainly consists of LMP-103s, FLP-103,105,106, and 107. LMP-103S is the most mature among the ADN-based green propellants, and was qualified by the European Space Agency (ESA) and in-space demonstrated through the high performance propulsion system (HPGP) on Mango-PRISMA satellite launched June 2010 [13] [14]. Advantages of LMP-103S over AF-M315E include lower combustion temperature which allows using materials with lower melting point and simpler designs for thruster development. Moreover, flexibility in using different ignition techniques and not just being restricted to catalytic decomposition for ADN-based green monopropellants would allow for development of novel light-weight monopropellant thrusters [15] [13].

HNP2xx is a HAN/HN- based family of green propellants that have been under development for over 10 years by IHI Aerospace co. in Japan. This green monopropellant family consists of HNP209, HNP221, and HNP225, and they are formulated from HAN, HN, Methanol, and Water [16]. They all possess volume specific impulse (ρI_{sp}) superior to hydrazine, but what characterizes them most is their relatively low adiabatic flame temperature compared to other energetic ionic liquid monopropellants such as AF-M315E. HNP225 has specific impulse of 213 s (at chamber pressure of 1.0 MPa and expansion ratio of 100) [17] [18]). HNP225 is the one with the least adiabatic flame temperature around 1000 K (even less than Hydrazine ≈1200 K [19] [16]. The low temperature combustion gasses allowed IHI Aerospace co. to develop low-cost thrusters since the need for high heat resistant materials for the thruster's combustion chamber is no more required. The HNP2xx family of propellants are ignited using catalytic decomposition. Igarashi et al. 2017 [19] performed tests with newly developed catalysts and showed excellent response and combustion pressure stability compared to Hydrazine, either in continuous mode or pulsed mode operation, with preheating temperatures starting from 200 ºC and 300 ºC for HNP221 and HNP225 respectively.

1.2. Feed & Pressurization Systems

Feed system of liquid propulsion engine main duty is to deliver propellant from storage volume to the thruster with predefined pressure levels and propellant mass flow rate. The pressurization-system is used to maintain or provide a certain level of pressure inside the propellant tanks for controlling storage state of propellant and to provide stable expulsion of propellant throughout the feed-system [20]. In case of the *conventional* pressure-fed systems – which is widely used for small sized spacecraft and CubeSats – pressurization is provided through external pressurant tanks "high-pressure stored gas" or through pre-launch pressurized ullage part of propellant tanks "Blow-down system".

Autogenous pressurization is an old concept that has been utilized in space systems since 1968 [21]. It has been used mainly in pump-fed engines. The system uses vaporized propellants to pressurize tanks by passing streams of cool propellant through a heat source such as thrust chamber cooling jackets, heat exchangers, or electric heaters. This approach is practical with high vapor pressure propellants. Some contexts, such as Humble et al., considers feeding back combustion products at required temperature and pressure levels to pressurize the propellant tanks. These combustion products can be a tap-off flow from the combustion chamber or products of using a dedicated gas generator [22]. The feed-back of catalytically decomposed combustion product can be of undesirable consequences since it may decompose the stored propellant within a time frame sooner than the proposes mission life-time. However, using tank separators such that in a differential area piston or in elastic diaphragm tanks may solve this problem. Adding that, it will be a great advantage, from the overall system perspective, to use this separated decomposed gas in auxiliary propulsion – for example with warm gas thrusters described in a relatively similar system by Whitehead et al [23] – and may increase overall system performance if considering a Multi-mode propulsion system approach. Another advantage of autogenous pressurization is that propulsion systems in small-satellites incorporating this approach can be launched unpressurized, which is a safety requirement obliged by most launch services especially in rideshares.

Electric pump-fed systems can be considered *unconventional feed & pressurization system* from the perspective of micro- and nano- spacecraft. Low ullage pressure has to be maintained in a way to provide propellant to the pump at required pump inlet conditions, which is essential for stable feed operation and protects against pump cavitation and pressure pulsation. High tank pressure levels occur in pressure-fed systems, typically in range of operating pressure between 1.3 and 9 MPa, while much lower levels are only needed for *pump-fed systems,* typically 0.07 and 0.34 MPa) [20] [22] [24]. High tank pressurization comes at the cost of tank structure mass, which means heavier structures needed to accommodate higher pressures, that will increase the spacecraft final mass. However, pressure-fed systems, with designated high tank pressures, reduce the overall system design complexity. On the other hand, much lighter tanks structure is used in case of pump-fed systems but with the cost of high system complexity. Although pump-fed systems are not currently used for CubeSats – perhaps proposed – the technological advancements in *micro electric pumps* show possibility to use this pressurization technique on the scale of micro- and nano- spacecraft. A COTS low-cost micro e-Pump [25] is used, that has a mass of only 45 g and cylindrical dimensions of $\emptyset 22.0 - 70.60\ mm$, and provides mass flow rate ($\dot{m}$) and output pressure up to 30 ml/min and 2.2 MPa respectively, at nominal 12 VDC and 7 W with high viscosity fluids, which makes it a candidate for MIMPS-G.

1.3. MIMPS-G Propulsion System Schematic

Micro e-Pump-feed system is considered *unconventional* for in-space propulsion, especially for small-size spacecraft. The concept of this e-Pump-fed system (see Fig. 1) is to circulate streams of propellant for evaporation and use the evaporated (non-decomposed) liquid propellant to keep the storage tank at the required minimal pressure levels for proper pump operation – typical autogenous pressurization system as elaborated in the second paragraph of section 1.2. Beside propellant circulation through the system, the micro e-Pump is responsible for the delivery of propellant from very low-pressure storage to high pressure requirements of the thrust chamber at a given mass flow rate. One of the advantages of this concept is that no separation within the tank is required – no need to separate the feedback vapor unlike the case of feeding back catalytically decomposed gaseous propellant – thus avoiding actuating mechanisms as in case of piston expelled tanks, or material compatibility problems with green-propellants in case of using bellows or elastic diaphragms. Option (a) represents a *vapor auxiliary propulsion for reaction control/attitude control* requirements. This optional subsystem incorporates a small catalytic bed and lighter weight thrusters compared to the primary monopropellant thruster – and shall present a *'Multimode'* propulsion system when incorporated. The catalytic bed shall increase the temperature of the vapor, thus increasing performance, moreover, ensures homogenous exhaust. This concept is complemented and reinforced by the research work of Rhodes & Ronney (2019) on H_2O_2 vapor propulsion

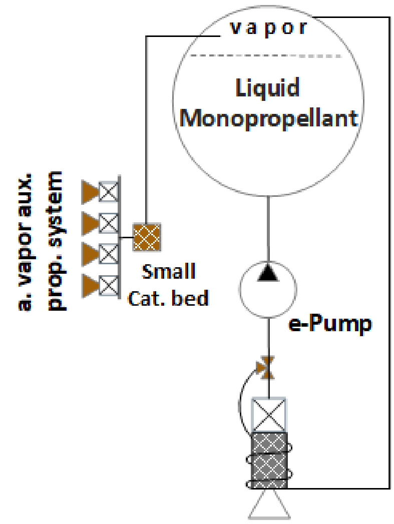

Figure 1 Micro e-Pump-fed System – ('Multimode' option a. Vapor auxiliary/RCS propulsion system)

system [26] – the auxiliary system will not be incorporated in the design stage in this article. A 3-way micro flow control valve is required to control the flow from the micro e-Pump outlet to the thruster and the autogenous heating mechanism. It should be noted that, technological advancements and availability of *controlled micro valves* is inevitable for such feed and pressurization system to succeed on this small-size scale. One final advantage, but not last, of this propulsion system is the ability to precisely control the propellant mass flow rate to the thruster, thus controlling and maintaining a constant thrust value over almost the whole life-time of the mission. This unconventional approach is applicable as well for feed and pressurization systems of liquid bipropellant propulsion of small-satellites and spacecraft.

1.4. CubeSat Propulsion Systems state-of-art

Current state-of-art in CubeSat monopropellant propulsion systems utilizes thrusters with a range of thrust typically from 0.1 N to 1 N. Some of the prominent systems in the market are namely, EPSS C1 by NanoAvionics [27], BGT-5X by Busek Company Inc. [28] [6], and CubeSat Modular Propulsion System MPS-130 by Aerojet Rocketdyne [29] [6]. The former system uses an ADN- based green propellant, while the latter two systems use the HAN- based AF-M315E [30]. Morris et al. [30] discusses the development of the MPS propulsion system with both the Hydrazine and the green-propellant AF-M315E system designations. The development and manufacturing process incorporated the use of state-of-art in additive manufacturing techniques and processes of advanced materials such as Inconel-625® and Ti-6Al-4V (Ti64) alloys which helped significantly in the development of such modular system suitable for CubeSats strict envelope and mass constraints. All the above-mentioned systems incorporate a pressurant gas for a conventional pressure-fed system. However, new systems proposed by Aerojet Rocketdyne under the MPS propulsion system family are using Pump-feed with propellant management device PMD, such as the MPS-135-4U [29].

2. MIMPS-G Analysis and Design Methodology

Based on the before-mentioned mission objectives, literature review, and market analysis, the requirements and design considerations of the proposed propulsion system will be presented in the following, refer to Fig. 2.

2.1 Design considerations and Requirements

The propulsion system – designated MIMPS-G – is aimed to be a primary propulsion system that enables high-thrust impulsive maneuvers. MIMPS-G operates on *Green-monopropellants* classified as Energetic Ionic Liquids EILs. Following section 1.1 that discussed state-of-art in this class of propellants, the study interest and focus was oriented to study HAN- based and ADN- based

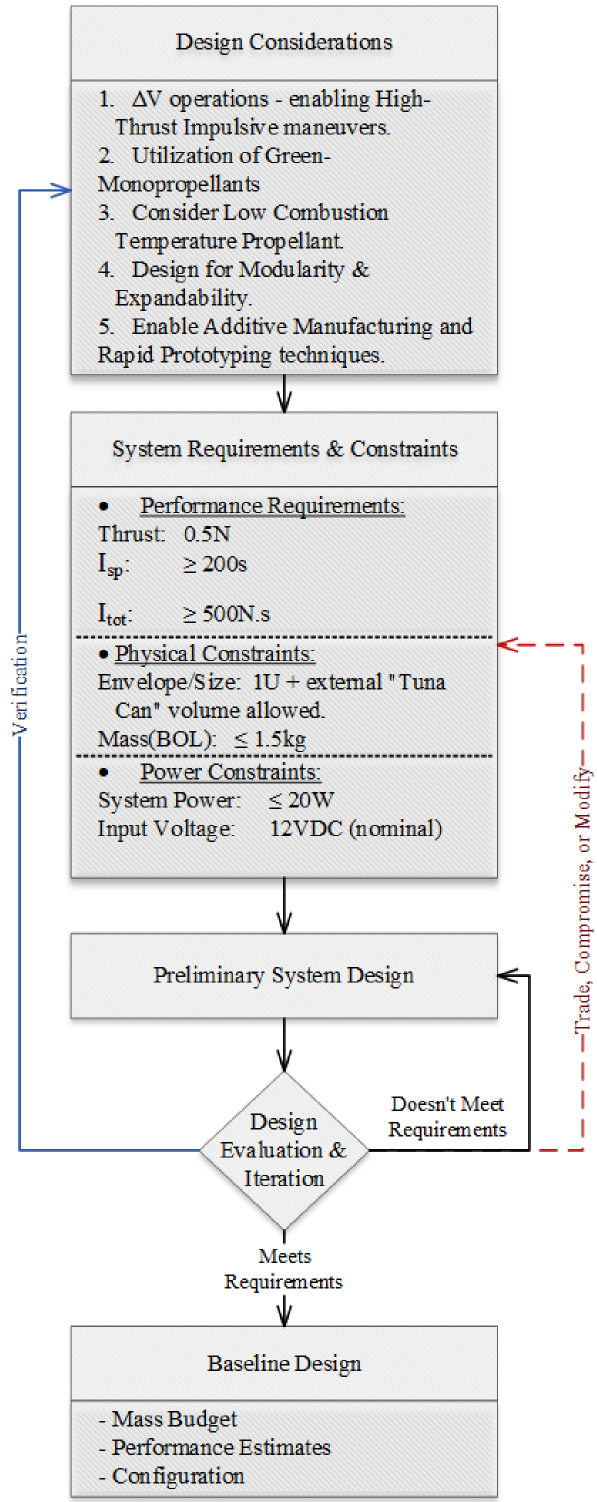

Figure 2 UML schematic diagram of MIMPS-G Design Process

propellants, and a special focus was given to low combustion temperature formulations. As AF-M315E is considered the most mature and widely used and proposed green-monopropellant, other alternatives were sought to allow system design and performance improvement. During the mechanical design of the propulsion system, emphasis was made on system modularity and expandability, were the former will allow to easily orient components within a spacecraft with different standard CubeSat sizes and make best use of allowable space. The latter, namely the expandability, is a unique design criteria that will further impact CubeSat utilization of COTS propulsion system, along with modularity, will give ability to increase propellant tanks and even thrust level on a *plug-and-play* basis. Recently, researchers in the field of Micro-/Nano- satellites are seeking low-cost and rapid manufacturability [19] by employing additive manufacturing techniques. Metal 3D-printing nowadays utilize exotic space alloys such as Inconel-625® and Ti-6Al-4V (Ti64). This manufacturing technique will help in reducing parts number in a design and thus overall part mass, as well as reducing manufacturing and prototyping processes.

Design requirements, refer to Fig.2, imply having thrust level of 0.5 N, gravimetric specific impulse ≥200 s, and total impulse ≥500 N.s which is almost the lowest value in this class of commercial propulsion systems that are discussed in section 1.4. Concerning the value of the gravimetric specific impulse mentioned, as widely *interpreted* by design literature, the higher I_{sp} is considered better, but this *is not always the correct interpretation* since it *usually* comes on cost of higher combustion temperatures, and thus higher weight materials used in thruster's development and thermal management. Of course, I_{sp} depends on both combustion temperature and molecular mass of a given propellant, and high I_{sp} can still be acquired at *relatively low temperatures* if the molecular mass of decomposition products is low enough. Therefore, choosing an *optimal specific impulse value*, not necessarily a high value, for a given propellant that tend to have lower adiabatic flame temperature will impact positively the propulsion system overall performance, cost, and project lead time. Thruster with low-weight materials might not necessarily have a great impact on the propulsion system mass reduction, however, to enable Additive Manufacturing techniques, a further limitation on combustion temperature is imposed to respect the melting point of certain 3D printing metal alloys such as Inconel-625® ($\cong 1563.15\ \mathrm{K}$). In this study a commercial thruster model operating on high combustion temperature was considered in the preliminary design and serves as a worst-case scenario. Further development steps will consider designing thruster that operates only low adiabatic flame temperature monopropellants to further reduce system mass and increase performance.

Physical constraints set on the design implies developing a 1U standard CubeSat unit size while allowing extra protrusion, for the thruster, referred to as "Tuna Can" volume. The size of this extra volume occupies the ejection spring of the CubeSat deployer and it varies from model to model and depends on manufacturer [31] [32] [33], a suitable deployer allowing protrusion volume of $\emptyset 86.0 - 78.0\ mm$ was considered. The initial BOL mass requirement set was ≤1.5 kg in order to have a competitive advantage over state-of-art commercial propulsion systems – it will be shown in following design sections that this requirement was fulfilled for some propellants, while reducing the mass of other propellants is required to maintain the value ≤1.5 kg. Otherwise the requirement can be modified by increasing the constraint to get use of allowable propellant volume in the tank. Finally, as per the electric power requirements, a system power of ≤20 W and nominal 12 VDC was considered after studying the electrical properties of the system parts and will be briefly presented in Table 6.

The preliminary design process did not follow the conventional design flow of first identifying a certain mission ΔV requirements and further proceeding with a design to fulfil this requirement. However, broad types of space missions were surveyed to highlight maneuvers requirements and to set a baseline for ΔV, total impulse, and thrust level requirements. From this point, and refereeing to the previously mentioned design considerations, the design flow proceeded with identifying the – and allowing for a – maximum allowable propellant volume for a 1U unit. The development and use of unconventional novel, with respect to CubeSat, *autogenous* feed and pressurization system concept was the main aspect to reach a new maximum allowable propellant volume – as compared to conventional pressure-fed system discussed extensively in section 1.2 – refer to Fig.3 preliminary design flow chart.

2.2 Propellant Trade-off Study

Among the state-of-the-art green-monopropellants surveyed in section 1.1, four EILs were considered for a trade-off study, either for their maturity, or potential. It is worth noting, at this point especially, that innovation in this class of micro-/nano- green-propulsion system design, shall rely on novel propellants considering their thermodynamical and thermochemical properties as well as the specific impulse performance parameter, altogether as a whole, and neither considering each aspect solely nor biasing to one aspect over others. Propellant requirements set for the trade-off study are described in Table 1.

Trade-off criteria (refer to Table 2) were set to fulfil previously elaborated design goals and the rationale behind each criterion is described in the following. First criterion is the specific impulse I_{sp} *(s)* that is one of the

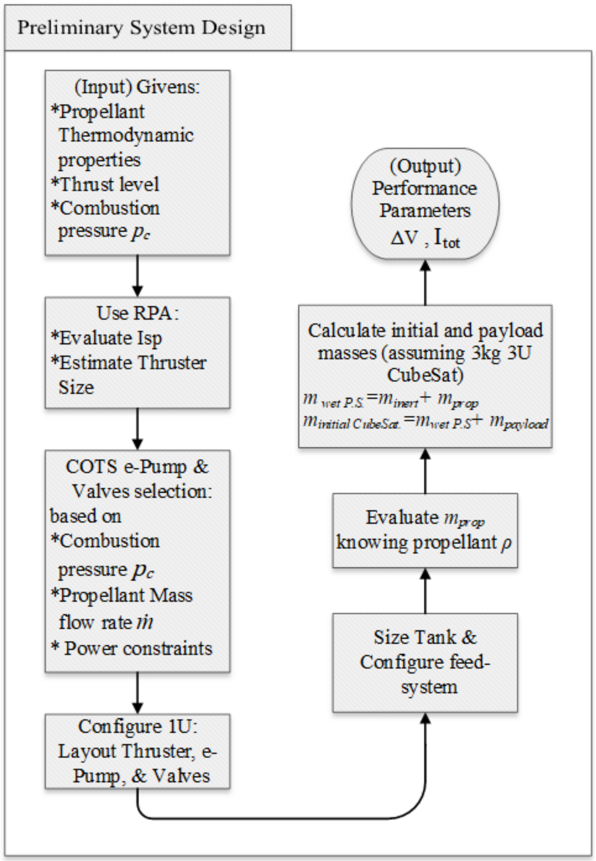

Figure 3 Preliminary Design Flow Chart

most important performance parameters for design and evaluation stages. And as highlighted before, it is not necessarily that the higher value of such parameter would be better for the system, but an optimal value must be chosen to achieve highest performance while maintaining suitable *system inert mass*. The I_{sp} *(s)* criterion was evaluated for the considered propellants by a knockout condition of $Isp \geq 200$ s as expressed in requirement 3 in Table 1, all propellants fulfilling this criterion shall score equally the highest score. The second criterion is the volumetric specific impulse ρI_{sp} *(g.s/cm³)*, generally, the higher density of high-performance propellant shall occupy lower tank volume, thus the higher value is considered better, and the score is evaluated accordingly. Third criterion, the combustion temperature T_c *(K)*, is one of the most important parameters in this trade-off study, as conceptualized in section 2.1. The Lowest combustion temperature value is considered the best for all considered propellants, and a weight-factor of (×2) is imposed to emphasise the importance of this criterion.

Freezing temperature T_F *(°C)* – or service temperature as a more accurate term, since some EILs undergo precipitation [34] or glass transition as in case of AF-M315E [35] – is the fourth criterion assessed in the trade-

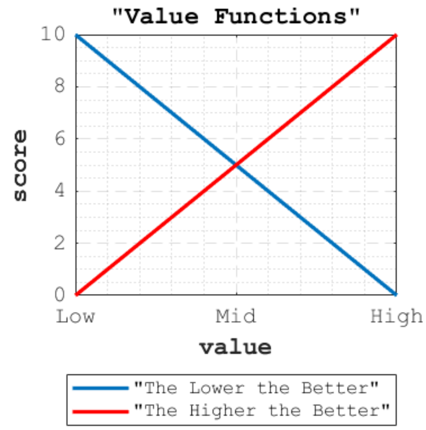

Figure 4 Value Function scoring graph

off study. Low freezing point is required for propellant storable and operational stability over long time and is important to reduce tank heating power consumption. The final criterion is the vapor pressure; EIL green-monopropellants are characterized by very low vapor pressure that allows for stable ground storability and transportability as well as in-space operability. Since this study focused on unconventional autogenous pressurization, the use of low vapor pressure propellants is crucial for the propulsion system operational stability and safe storability. Vapor phase of some green-propellants – such as H_2O_2 which is not considered in this study – can be dangerous in case of possessing detonation properties, thus care must be taken with selection of such propellants. Higher vapor pressures, to some extent, would definitely optimize the use of electric heating power for thruster feed and tank pressurization, however in early development phases the lower vapor pressure is more appreciated. Table 2 presents the propellant trade-off methodology, showing method of calculation and evaluation for each criterion as well as the value function considered.

Table 1 Propellants Trade-off Requirements

Requirement	Description
1	Use of Green propellant complying with ECHA – REACH directive articles.
2	Use of monopropellants classified as EIL.
3	EIL Green Monopropellants should have specific impulse performance of Isp ≥200 s.
4	Freezing temperature of the propellant shall be ≤-10 °C.
5	Propellant must be liquid within pressure range [0.1,3] MPa & temperature range [-30, +80] °C.
6	Propellant shall possess Low Vapor Pressure, typically below 20kPa at room temperature (LMP-103S is ~14 kPa @ 25 °C).

Table 2 Propellant Trade-off Criteria

Trade-off Criteria	Symbol	Method of Calculation	Value Function
Specific Impulse	I_{sp} (s)	RPA simulations and literature.	Knockout condition per Requirement #3
Volumetric Specific Impulse	ρI_{sp} (g.s/cc)	RPA simulation and Propellant Thermodynamic properties Literature.	The Higher the better
Combustion Temperature	T_c (K)	RPA simulation and Propellant Thermochemical Literature.	The Lower the better
Freezing Temperature	T_F (°C)	Literature	The Lower the better
Vapor Pressure	P_{vap} (kPa)	Literature	The Lower the better

The 'Value Function' is a tool to assist in scoring each propellant against the trade-off criteria. Two main types of value functions are used – namely 'The Higher the Better' and 'The Smaller the Better' – and one is a knockout condition. The latter condition would discard any propellant with theoretical specific impulse ≥200 s, while the other two value functions will be graded on a [0, 10] scale with the minimum and the maximum values depend on each value function type, refer to Fig.4.

Propellant characteristics and performance parameters for the four considered propellants (AF-M315E – LMP-103S – FLP-106 – HNP225) are presented in Table 3. The values of performance parameters and propellant thermochemical properties were calculated using Rocket Propulsion Analysis RPA analysis tool, Academic version, for some propellants along with literature review for other propellants with proprietary formulations. The physical and thermodynamical properties of all propellants were collected from literature. Table 3 presents analytic data used for the considered propellants. Finally, the propellant trade-off results and ranks are presented in Table 4.

3. MIMPS-G Preliminary Design

As shown in Figure 3, the preliminary design of the propulsion system started by assessing the performance, thermochemical, and thermodynamic properties of the first three ranked propellants in the trade-off study. RPA Academic was used in propellants assessment. For propellants with precise known formulation, such as LMP-103s and FLP-106, the inputs for the analysis tool were the chemical formulae, molecular weights, heat of formation, and weight percent of the formula constituents. Predefined values for the monopropellant engine were 0.5 N thrust value and iterations between 1 – 2 MPa combustion pressures. The expansion ratio of the nozzle was also iterated between 50 – 100:1. Further thermodynamic properties were extracted such as the combustion temperature and specific heats and specific heat ratio for the thruster different regions. Theoretical (ideal) performance as well as Estimated delivered performance were assessed, namely the effective exhaust velocity and weight specific impulse at vacuum condition. Other proprietary propellants such as HNP225, with unknown precise formulation weight fractions, were not possible to be simulated in the analysis tool and acquire accurate results, thus it was relied on the published literature to acquire above mentioned data.

Micro electric pump and microvalves were chosen COTS parts based on the operation pressure, propellant mass flow rate, size constraints, and electric power constraints. As mentioned before, the thruster considered in the preliminary design is the commercial model of Busek 0.5 N green propellant thruster [28] [40] [41]. After laying out the main propulsion system components, the propellant tank was sized and verified for operation pressures, temperatures, material compatibility, and design modularity and expandability. The tank will use a PMD consisting of vanes and a sponge on the outlet with light weight compatible materials to the green monopropellants. The design of the tank considered a titanium wetted inner structure reinforced by carbon fibre composites on the outside to ensure long term propellant material compatibility [42]. The tank design dedicated a rough 10% and 5% volume for the PMD and ullage, respectively.

Table 3 Propellant Characteristics and Performance Parameters (@2MPa chamber pressure & 50:1 exp. ratio) [47] [10] [48] [49]

Propellant	I_{sp} *(s)*	ρI_{sp} *(g.s/cm³)*	T_c *(K)*	T_F *(°C)*	Vapor Pressure*	Maturity
AF-M315E	266	391	2166	<-80	1.4	High
LMP-103S	252	313	1903 [36]	-7 [37]	13.6 [38]	High
FLP-106	255	346.0	2263.15	0 [34]	2.1 [38]	Medium
HNP225**	213	245	990 [39]	≤-10	Uncertain	Low

***Vapor pressure (kPa) at 25 °C**
**** The calculation conditions are Pc = 1.0 MPa, Ae/At= 100**

Table 4 Trade-off study results and propellants ranking

Propellant	Score per criterion					Overall score (Ranked)
	I_{sp}	ρI_{sp}	T_c	T_F	*Vapor Pressure*	
AF-M315E	10	10	2	10	10	42
HNP225	10	0	20	2	0/Uncertain	32
LMP-103S	10	5	6	3	3.5	27.5
FLP-106	10	7	0	0	9	26

3.1 Equations and Formulae

Following are the fundamental equations of ideal rocket theory that are used to produce the design data.

$$I_{tot} = I_{sp}\, m_{prop}\, g_o \quad (1)$$

$$m_f = m_i - m_{prop} \quad (2)$$

$$m_i = m_{wet\ P.S.} + m_{payload} \quad (3)$$

$$m_{wet\ P.S.} = m_{inert} + m_{prop} \quad (4)$$

$$\Delta V = -I_{sp}\, g_o \ln({}^{m_f}/_{m_i}) \quad (5)$$

4. Results and Discussion

The sized storage tank empty volume is 420 cc and after considering PMD and ullage volume of 15% of this value, the allowable propellant volume is 357 cc, while for the extension tank, Fig.[10-12], 474.16cc is the allowable propellant volume per tank considering 20% PMD and ullage. Further the mass of each propellant along with the total impulse is calculated and presented in Table 5 using the fundamental equations in section 3.1.

Table 6 presents the mass budget of dry components within the propulsion system. COTS components data were collected from the data sheets according to design requirements. Storage tank was sized to operate under more than 1.2 MPa of pressure and considering a design margin for manufacturability, thus having a 1mm thickness titanium wet part and an outer carbon fibre composite reinforcement. Of 2 mm thickness. The 3-way micro control valve is made of the state-of-art acetal homopolymer Delrin® that possess great anti corrosion properties and light weight. The PMD consists of a combination of vanes and a sponge structure at the outlet considering Delrin® and Titanium alloy for these parts respectively. The mass of the storage tank and the feed system was calculated using the CAD model software while considering a conservative error margin.

"Tuna Can" protrusion volume existing within the CubeSat deployer springs differ from deployer model to another which depends on the manufacturer. A deployer design allowing for protrusion volume of $\emptyset 86.0 - 78.0\ mm$ offered by a European manufacturer [33] was considered.

Control & computing unit was considered in the MIMPS-G design although the propulsion system control can be handled by the spacecraft main computer unit. The preliminary design considered extra free volume to allow for further tuning of internal components. The current design is a result of many iterations to optimize available space and allow for dynamic stability of the spacecraft.

Table 7 presents the physical properties and performance parameter of MIMPS-G500mN utilizing state-of-art propellants. Although HNP225 has the lowest I_{tot} and ΔV, but it allows for the greatest payload mass onboard the spacecraft and still complies with the design requirements and constraints mentioned in Fig. 2 (i.e. ≈1.5 kg BOL mass and I_{tot} = 858.027 N.s). HNP225 if considered for MIMPS-G500mN will allow for the use of 3D printed low-cost thruster that would impact positively the propulsion system inert mass and thermal control due to its low combustion temperature. The latter can be a point of advantage in the first prototypes of the propulsion system with respect to autogenous pressurization management and control.

5. Conclusion

Finally, liquid monopropellant propulsion systems for small-size spacecraft that utilize autogenously-pressurized electric micropump-fed systems is believed, from the author point of view, to have a great impact on propulsion miniaturization and increasing performance, despite the obvious complexity. Such complex systems can be one-step closer toward realization due to the existence of modern technologies, such as rapid additive manufacturing, advanced materials for space-use such as carbon fibre and high heat resistance super alloys, and most importantly the advancements in miniaturized

Table 5 MIMPS-G total impulse I_{tot} with different green-monopropellants

Total Tank Empty Volume = **420cc**			
PMD & Ullage = **15%**			
Allowable Propellant Volume			***= 357cc***
	Propellants		
	AF-M315E	***HNP225***	***LMP-103S***
ρ (g/cc)	1.4699	1.15023	1.2420
m_{prop}**(g)**	524.75	410.632	443.394
I_{tot} **(N.s)**	*1369.310*	*858.027*	*1096.123*
Extension Tank Allowable Prop. Volume = 474.1cc			
I_{tot} **(N.s)**	*1818.721*	*1139.627*	*1455.859*

micro valves and electric pumps. With the availability of advanced onboard computers, real-time onboard control – especially with the help of *Machine Learning* – such multivariable system shall demonstrate feasibility. Although, autogenous pressurization is considered a premature concept for small spacecraft liquid propulsion systems due to its high complexity, with the utilization of safe green-monopropellants, this novel approach for tank pressurization can be a drastic-change towards high-performance miniaturized spacecraft and small-satellites.

Table 6 Inert Mass Budget for the Propulsion System

Part	Materials/Comments	Mass (g)
Cover	Carbon Fibre Reinforce Composites ρ = 1.430 g/cc	65
Base	Aluminium 6061-AHC ρ = 2.79 g/cc Carbon-Carbon Laminate ρ = 1.7 g/cc	101
Micro e-Pump	COTS micro gear pump (7W – 12VDC)	75
3-way solenoid micro FCV	COTS Acetal polymer (Delrin®) [a] Material Compatibility A-Excellent with Alcohols & aqueous Ammonium nitrate [43] [44] [42] (2W)	45
Piezo Microvalve – Thruster FCV	Piezo tech/Titanium-wet (200mW)	67
Thruster 0.5N	Niobium/Titanium (Heaters 7-12W; 12Vdc) without FCV	80
Storage Tank	CFRP 2mm thick. ρ = 1.430 g/cc Ti64 1mm thick. ρ = 4.43 g/cc	148 228
Tank I/O ports	5ports x20g *"Rough estimate"*	~100
Tank Heater	Polyimide Thermofoil™ Heaters (4W; 6-12Vdc)	4
PMD§	Titanium alloys & Acetal (Delrin®) Sponge and Vanes [45] [46] (no steel, no CFRP) *"Rough estimate"*	~50
Microtube/Piping	Titanium alloy Grade 1 ϕ_{out} 3mm/t=0.5mm total length = 363.6mm	≤10
Computer, Controls, & Connectors	1 SBC*; 1 Driver; 1 PMMA** rack; Copper-wiring	≤120
	Total Inert Mass (w.c.s¥)	1093

[a] Delrin® acetal homopolymer (Polyoxymethylene POM)
§Propellant Management Device
* Single Board Computer
** Poly (methyl methacrylate)
¥ Worst Case Scenario

Table 7 Physical properties and performance

propellant	AF-M315E	LMP-103S	HNP225
Propulsion system		1U + "Tuna Can" protrusion volume	
m_{inert} **(g)**		1093	
m_{prop} **(g)**	524.75	443.394	410.632
$m_{wet\ P.S.}$ **(g)**	1617.75	1536.394	1503.632
Spacecraft		3U – 3kg	
m_f **(kg)**	2.47525	2.556606	2.589368
$m_{payload}$ **(kg)**	1.38225	1.463606	1.496368
Thrust		0.5N	
I_{sp} **(s)**	266*	252*	213**
ΔV **(m/s)**	501.723	395.370	307.575

*@2.0MPa chamber pressure and 50:1 expansion ratio
@1.0MPa chamber pressure and 100:1 expansion ration **[39]

Appendix A (3D Technical Model)

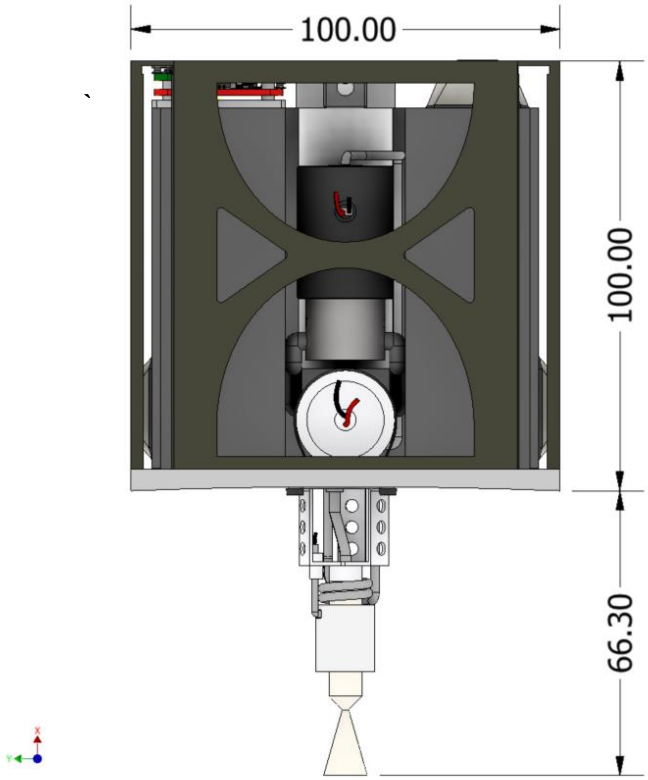

Figure 3 MIMPS-G500mN propulsion system outer dimensions (mm)

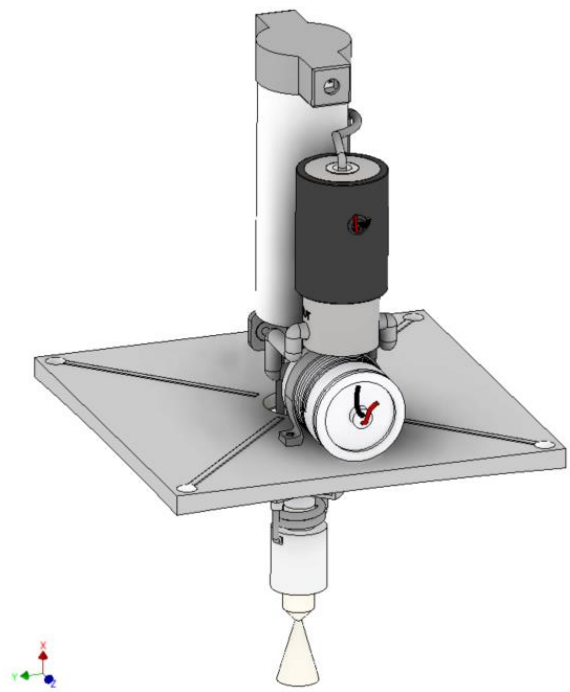

Figure 7 Autogenous Feed & Pressurization System - Perspective Orthographic View

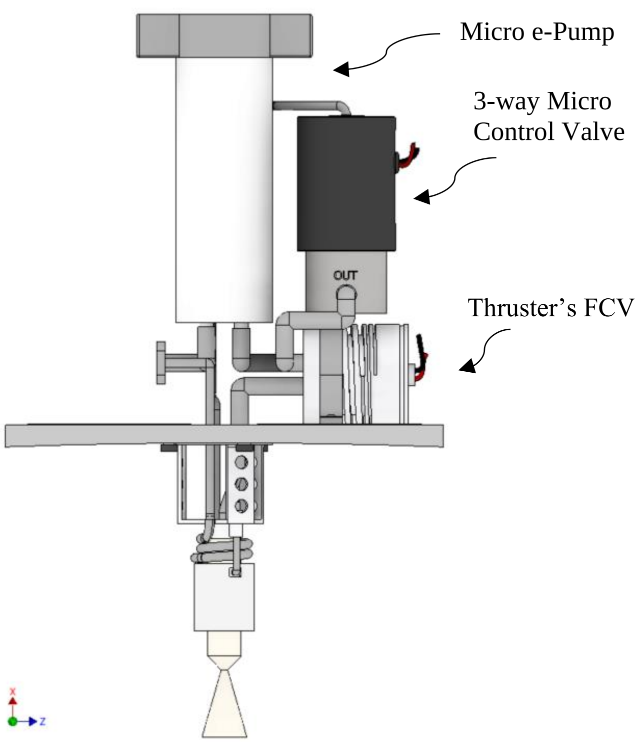

Figure 4 Autogenous Feed & Pressurization System - Side View

Figure 8 MIMPS-G500mN Technical illustration - without outer structure (cover)

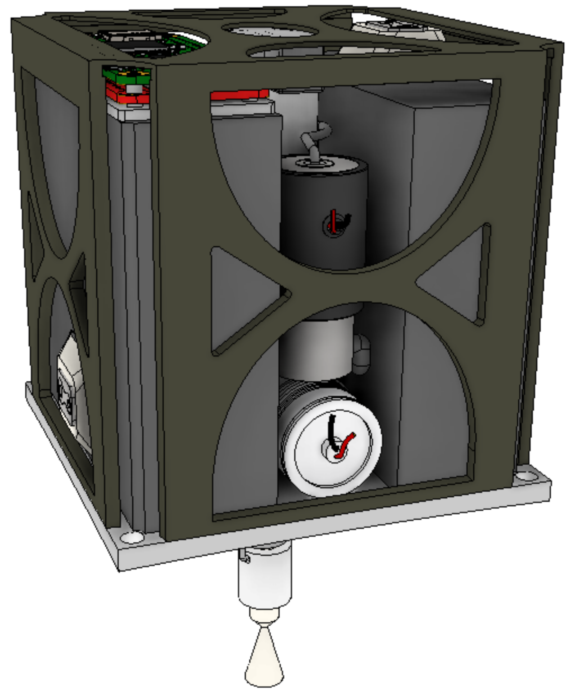

Figure 9 MIMPS-G500mN Technical Illustration - Perspective Orthographic View

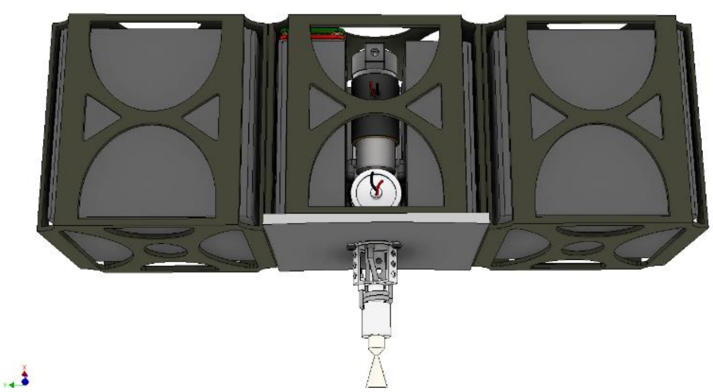

Figure 10 MIMPS-G500mN on a 9U CubeSat with two extension side tanks. $I_{tot} \cong 5000$ (N.s) AF-M315E (refer to Table 5 for alternative propellants)

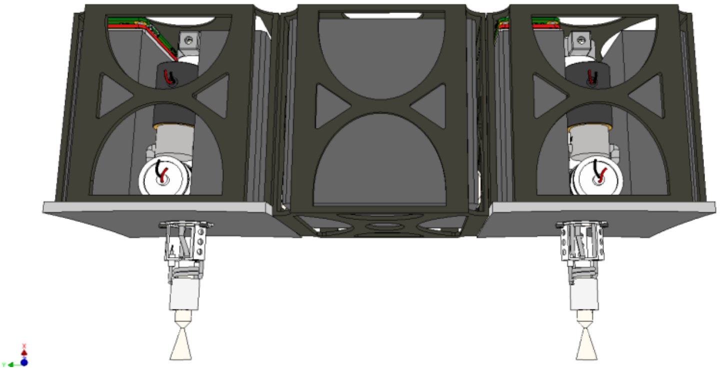

Figure 11 MIMPS-G500mN on a 9U CubeSat, 1 N Thrust, and one extension tank. $I_{tot} \cong 4500$ (N.s) AF-M315E

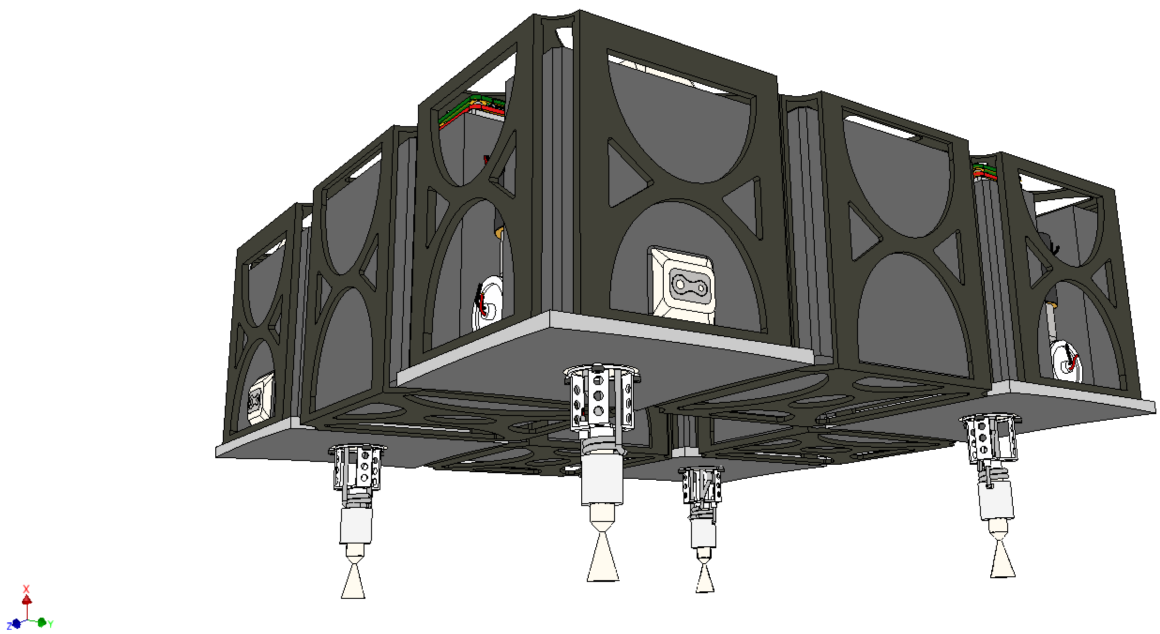

Figure 12 MIMPS-G500mN on a 27U CubeSat, 2 N Thrust, and four extension tanks.

References

[1] D. D. Evans, T. W. Price, "The Status of Monopropellant Hydrazine Technology - Technical Report 32-1227," Jet Propulsion Laboratory, NASA, California, USA, 1968.

[2] ECHA European Chemicals Agency, " Candidate List of substances of very high concern for Authorisation," 20 June 2011. [Online]. Available: https://echa.europa.eu/documents/10162/c5b972a9-f57f-4fd5-8177-04b4e46c5e93. [Accessed 1 April 2020].

[3] W. Wieling, A. Mayer, "Green Propulsion Research at TNO the Netherlands," *Transactions of The Institute of Aviation,* vol. 4, no. 253, pp. 1-24, 2018.

[4] H. Uramachi, D. Shiraiwa, T. Takai, N. Tanaka, T. Kaneko and K. Furukawa, "Green Propulsion Systems for Satellites - Development of Thrusters and Propulsion Systems using Low-toxicity Propellants -," *Mitsubishi Heavy Industries Technical Review,* vol. 56, no. 1, pp. 1-7, 2019.

[5] R. S. Jankovsky, "HAN-Based Monopropellant Assessment for Spacecraft - NASA Technical Memorandum 107287," in *32nd Joint Propulsion Conference AIAA/ASME/SAE/ASEE*, Florida, USA, 1996.

[6] K. Lemmer, "Propulsion for CubeSats," *Acta Astronautica*, vol. 134, pp. 231-243, 2017.

[7] M. Tsay, D. Lafko, J. Zwahlen and C. William, "Development of Busek 0.5N Monopropellant Thruster," in *27th Annual AIAA/USU Conference on Small Satellites*, 2013.

[8] R. K. Masse, M. Allen, E. Driscoll and R. A. Spores, "AF-M315E Propulsion System Advances & Improvements," in *52nd AIAA/SAE/ASEE Joint Propulsion Conference*, Salt Lake City, UT, 2016.

[9] NASA, "Green Propellant Infusion Mission (GPIM) Overview," NASA, 5 12 2019. [Online]. Available: https://www.nasa.gov/mission_pages/tdm/green/overview.html. [Accessed 24 04 2020].

[10] N. Wingborg, "Heat of Formation of ADN-Based Liquid Monopropellants," *Propellants, Explosives, Pyrotechnics,* vol. 44, pp. 1090-1095, 2019.

[11] K. Anflo, T. Grönland and N. Wingborg, "Development and Testing of ADN-Based Monopropellants in Small Rocket Engines," in *36th AIAA/ASME/SAE/ASEE,* Cleveland,OH, 2000.

[12] K. Anflo and N. Wingborg, "Dinitramide Based Liquid Mono-Propellants". Sweden Patent WO0050363, 2000.

[13] M. Wilhelm, M. Negri, H. Ciezki and S. Schlechtriem, "Preliminary tests on thermal ignition of ADN-based liquid monopropellants," *Acta Astronautica*, vol. 158, pp. 388-396, 2019.

[14] k. Anflo and B. Crowe, "In-Space Demonstration of an ADN-based Propulsion System," in *47th AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit*, San Diego, California, 2011.

[15] A. Larsson, N. Wingborg, M. Elfsberg and P. Appelgren, "Characterization and electrical ignition of ADN-based liquid monopropellants - FOI-R--1639--SE," Weapns and Protection - FOI, 2005.

[16] S. Igarashi, Y. Matsuura, K. Hatai and H. Ikeda, "Safe 0.5N Green Monopropellant Thruster for Small Satellite Propulsion Systems," in *AIAA Propulsion and Energy Forum*, Indianapolis, 2019.

[17] A. Fukuchi, T. Inamoto, S. Miyazaki, H. Maruizumi and H. Kohono, "HAN/HN-based Monopropellant Thrusters," in *26th International Symposium on Space Technology and Science*, Hamamatsu, Japan, 2008.

[18] S. Igrashi, A. Fukuchi, N. Azuma, K. Hatai, H. Kagawa and H. Ikeda, "Development of a high-performance HAN/HN-based low-toxicity Monopropellant," in *Joint Conference ISTS/IEPC/NSAT*, Kobe Hyogo, Japan, 2015.

[19] S. Igarashi and Y. Matsuura, "Development Status of a Hyrazine Alternative and Low-cost Thruster Using HAN/HN-Based Green Propellant," in *53rd AIAA/SAE/ASEE Joint Propulsion Conference*, Atlanta, GA, 2017.

[20] G. P. Sutton, Rocket Propulsion Elements 9ed, WILEY, 2017.

[21] L. Ruby, C. Christian and E. A. Lehmann, "Autogenous Pressurization for Space Vehicle Propulsion Systems," in *AIAA 4th Propulsion Joint Specialist Conference*, Cleveland, Ohio, 1968.

[22] R. W. Humble, G. N. Henry and W. J. Larson, Space Propulsion Analysis and Design, McGraw-Hill Companies,Incorporated, 1995.

[23] J. C. Whitehead, "Hydrogen Peroxide Propulsion for Smaller Satellites," in *12th AIAA/USU Conference on Small Satellites*, Logan, UT, 1998.

[24] NASA Space Vehicle Design Criteria (Chemical Propulsion), "Pressurization Systems for Liquid Rockets - SP-8112," NASA, 1975.

[25] Flight Works, Inc., "Magnetic Drive Gear Pumps," Flight Works, Inc., 2014. [Online]. Available: https://products.flightworksinc.com/item/micro-gear-pumps/m-series-magnetic-drive-gear-pumps/2205-m03c40. [Accessed September 2020].

[26] B. L. Rhodes and P. D. Ronney, "Dynamics of a Small-Scale Hydrogen Peroxide Vapor Propulsion System," *Journal of Propulsion and Power*, vol. 35, no. 3, pp. 595 - 600, 2019.

[27] NanoAvionics, "CubeSat Propulsion System EPSS," NanoAvionics, 2019. [Online]. Available: https://nanoavionics.com/cubesat-components/cubesat-propulsion-system-epss/. [Accessed 29 June 2020].

[28] Busek Company, Inc., "datasheet - BGT-X5 Green Monopropellant Thruster," Busek Company, Inc., 2016. [Online]. Available: http://busek.com/index_htm_files/70008517E.pdf. [Accessed 29 June 2020].

[29] Aerojet Rocketdyne, "Modular Propulsion Systems datasheet," [Online]. Available: https://www.rocket.com/sites/default/files/documents/CubeSat%20Mod%20Prop-2sided.pdf. [Accessed 01 May 2020].

[30] D. Morris and R. Noble, "CubeSat Advanced Technology Propulsion System Concept," in *28th Annual AIAA/USU Conference on Small Satellites*, Logan UT, 2014.

[31] Tyvak, "Deployment Hardware," A Terran Orbital Corporation, 2020. [Online]. Available: https://www.tyvak.com/launch-services/. [Accessed August 2020].

[32] ISISPACE, "Deployers Datasheet," 2016. [Online]. Available: https://www.isispace.nl/wp-content/uploads/2016/02/CubeSat-deployers-Brochure-web-compressed.pdf. [Accessed August 2020].

[33] EXOLAUNCH, "EXOpod Technical Documentation," 2020. [Online]. Available: https://www.exolaunch.com/exopod.html. [Accessed August 2020].

[34] A. S. Gohardani, J. Stanojev, A. Demaire, K. Anflo, M. Persson, N. Wingborg and C. Nilsson, "Green space propulsion: Opportunities and Prospects," *Progress in*

Aerospace Sciences, vol. 71, pp. 128-149, 2014.

[35] R. Masse, R. A. Spores, S. Kimbrel, M. Allen, E. Lorimor and P. Myers, "GPIM AF-M315E Propulsion System," in *51st AIAA/SAE/ASEE Joint Propulsion Conference*, Orlando, FL, 2015.

[36] M. Negri, M. Wilhelm and C. Hendrich, "Technology development for ADN-based green monopropellant thrusters – an overview of the Rheform project," in *7th European Conference for Aeronautics and Space Sciences (EUCASS)*, Milano, IT, 2017.

[37] K. Hori, T. Katsumi, S. Sawai, N. Azuma, K. Hatai and J. Nakatsuka, "HAN-Based Green Propellant, SHP163 – Its R&D and Test in Space," *Propellants, Explosives, Pyrotechnics*, vol. 44, pp. 1080-1083, 2019.

[38] M. Wilhelm, M. Negri, H. Ciezki and S. Schlechtriem, "Preliminary tests on thermanl ignition of ADN-based liquid monopropellants," *Acta Astronautica*, vol. 158, pp. 388-396, 2019.

[39] S. Igarashi, K. Yamamoto and A. B. Fukuchi, "Development Status of a 0.5N-Class Low-Cost Thruster for Small Satellites," in *AIAA Propulsion and Energy Forum Joint Propulsion Conference*, Ohio, 2018.

[40] M. Tsay, J. Frongillo, D. Lafko and J. Zwahlen, "Development Status and 1U CubeSat Application of Busek's 0.5N Green Monopropellant Thruster," in *28th Anual AIAA/USU Conference on Small Satellites*, Logan, UT, 2014.

[41] M. Tsay and C. Feng, "Complete EM System Development for Busek's 1U CubeSat Green Propulsion Module," in *52nd AIAA;SAE;ASEE Joint Propulsion Conference*, Salt Lake City, UT, 2016.

[42] D. Freudenmann and H. K. Ciezki, "ADN and HAN-Based Monopropellants – A Minireview on Compatibility and Chemical Stability in Aqueous Media," *Propellants, Explosives, Polytechnics*, vol. 44, pp. 1084-1089, 2019.

[43] CP Lab Safety, "Acetal and Delrin® (Polyoxymethylene) Chemical Compatibility Chart," CP Lab Safety, 2018. [Online]. Available: https://www.calpaclab.com/acetal-polyoxymethylene-chemical-compatibility-chart/. [Accessed August 2020].

[44] D. N. Gorbunov, M. V. Nenasheva, N. A. Sinikova, Y. S. Kardasheva, A. L. Maksimov and E. A. Karakhanov, "Tandem Hydroformylation–Acetalization Using a Water-Soluble Catalytic System: a Promising Procedure for Preparing Valuable Oxygen-Containing Compounds from Olefi ns and Polyols," *Russian Journal of Applied Chemistry*, vol. 91, no. 6, pp. 990-995, 2018.

[45] PMD Tech., PMD Technology Low Gravity Fluid Dynamics, 2011. [Online]. Available: http://www.pmdtechnology.com/PMD%20Types/PMD%20Types%20-%20Sponges.html. [Accessed August 2020].

[46] J. W. Hartwig, "Propellant Management Devices for Low-Gravity Fluid Management: Past, Present, and Future Applications," *Journal of Spacecraft and Rockets*, vol. 54, no. 4, pp. 808 - 824, 2017.

[47] J. Thrasher, S. Williams, P. Takahashi and J. Sousa, "Pulsed Plasma Thruster Development Using A Novel HAN- Based Green Electric Monopropellant," in *AIAA Propulsion and Energy Forum*, Salt Lake City, UT, 2016.

[48] N. Wingborg, C. Eldsäter and H. Skifs, "Formulation and Characterization of ADN-based Liquid Monopropellants," in *2nd International Conference on Green Propellants for Space Propulsion*, Cagliari, Sardinia, IT, 2004.

[49] N. Wingborg, M. Johansson and L. Bodin, "Initial developmment of a laboratory rocket thruster for ADN-based liquid monopropellants - FOI-R--2123--SE," Weapons and Protection - FOI, 2006.