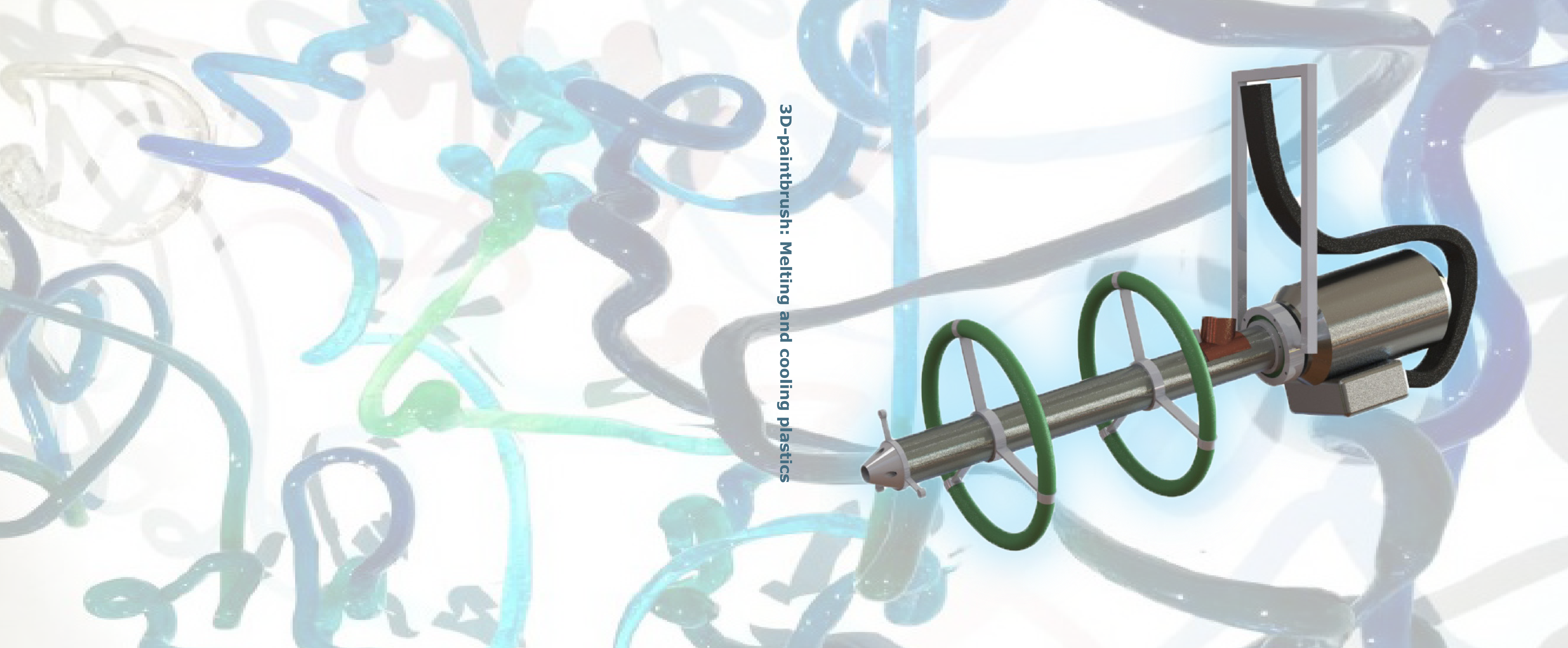

3D-paintbrush: Melting and cooling plastics

A graduation thesis by

Leander Hofman

3D PAINTBRUSH

MELTING AND COOLING PLASTICS

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INTRODUCTION

This project is done for Tiwánee van der Horst who is an artist. she creates 3D painting by replacing paint with plastic and brushes with the 3D-paintbrush.

This project is a follow up of J. Algra his graduation project. He developed the first few prototypes of the 3D paintbrush.

A 3D paintbrush is a manually controlled plastic extruder which translates human body movements into 3D works of art.

In this thesis research is done to optimize the extrusion speed by looking at both the melting and cooling of plastics.

futhermore the interaction between the human and the paintbrush has been analysed to improve the human machine interaction.

This thesis follows the progress from beginning to end, and the result is a new design. A mockup has been made from this design

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1 ANALYSIS

1.1 Starting point

This project is about designing an improved version of the 3D-paintbrush. In order to understand this 3D-paintbrush we have to look at how this idea started.

The 3D paintbrush started with the graduation project of Tiwánee van der Horst. In het project she wants to convert 2D paintings into 3D paintings by swapping paint for plastic. She investigated painting and 3D printing techniques and combined them.
The result is the idea to create a manually controllable extruder for plastic which translates body movements into 3D art sculptures. In order to do this a 3D-paintbrush had to be designed and created.

Tiwánee vander Horst initiated a graduation project at the TU Delft, Jelle Algra took this project and designed the first 3D-paintbrush. This tool converts granulates into extruded plastic much like a 3D printer would do. Only the 3D-paintbrush is manually controlled and has a bigger nozzle opening. With this 3D-paintbrush art objects of 3x 3x 3m can be created.

1.2 Assignment

The assignment is to build a large scale 3D-paintbrush, to craft at a human scale. This is a redesign of Jelle Algra's first 3D paintbrush. The original assignment (Figure 01) is focussed on material feed & extrusion process, nozzle design and body-machine interaction.

Research has been to to fully define the scope, mission and vision of this graduation project. This can be found in this chapter.

Fig. 01: Original assigment

1.3 What is a 3D paintbrush?

In order to fully understand what a 3D-paintbrush is and how it compares to other products we have to understand three different products. The 3D-paintbrush lies somewhere in between these products. These three products all have a material feed, the “in” of the system. They also have a way of melting the plastic, the “processing” part of the system. And lasty they all have an “out” the endproduct of the technique.

1.3.1 Comparison current techniques

First we have to look at the 3D printer, more specifically a Fuse Deposition Molding (FDM) printer. An FDM printer deposits material in single layers that fuse together to create a 3D object. In this printer filament of 1.75mm or 2.85mm is pushed through an heating block.. After the filament is melted it will be pushed through a nozzle of various sizes. The movement of the extruder is made by a slicer that translates a 3D object into layers and paths over cartesian axis shown in figure 2.

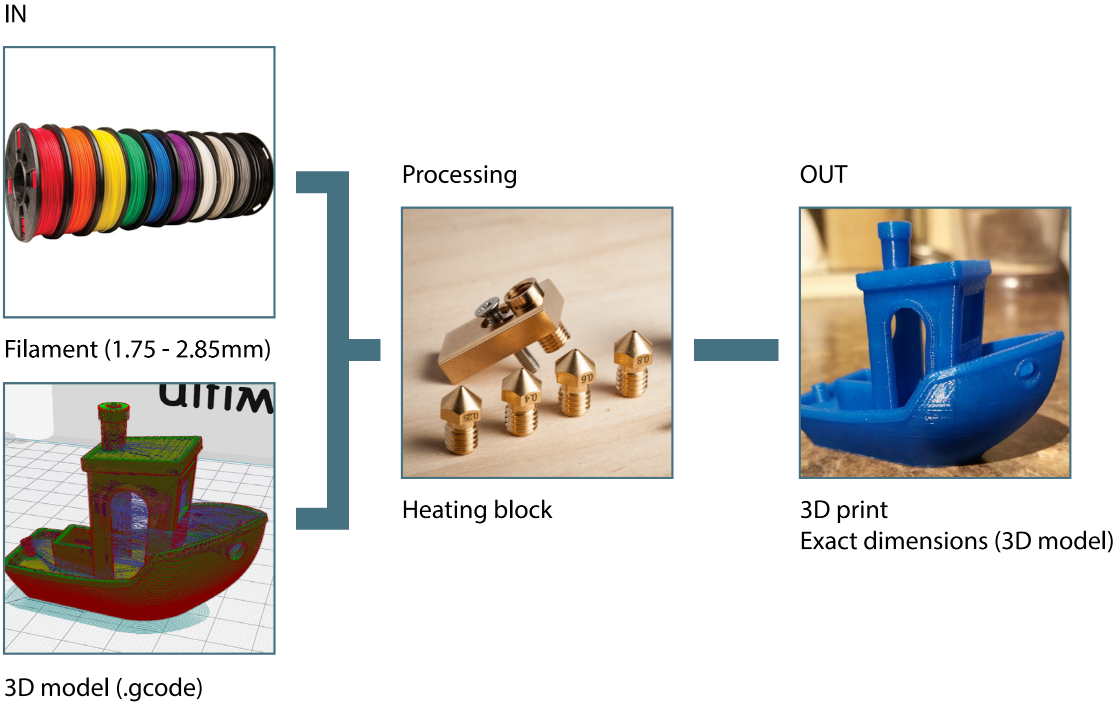


Fig 02:   FDM printing Process

Secondly we look at a 3D pen, shown in figure 3. This device heats up thin filament of 1.75 milimeter and pushes it through a nozzle much like a FDM 3D printer. However, the movement is not determined by a 3D model but is drawn by hand in 3D. This 3D pen can create freehand 3D products this way.

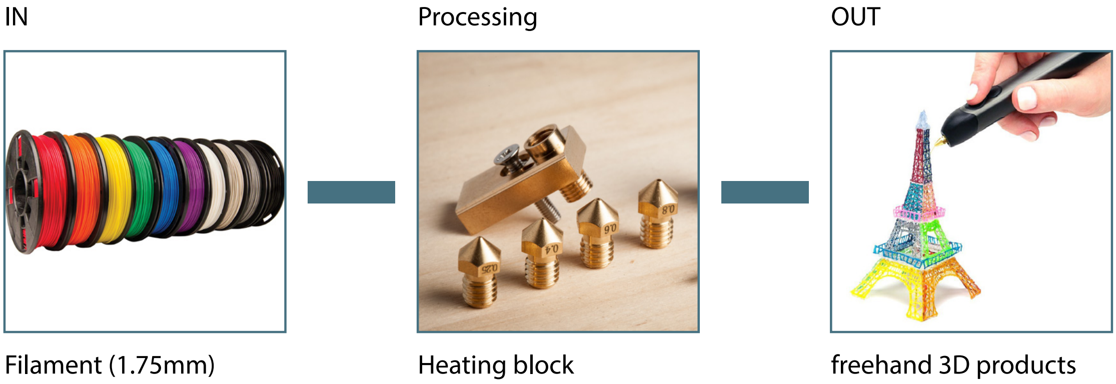


Fig 03:   Extrusion process

Lastly there is an injection molding machine, This machine moves and heats up granulates through a screw and barrel. Under pressure the molten granulate is pushed into a premade mold which has the negative shape of the desired object, shown in figure 4.

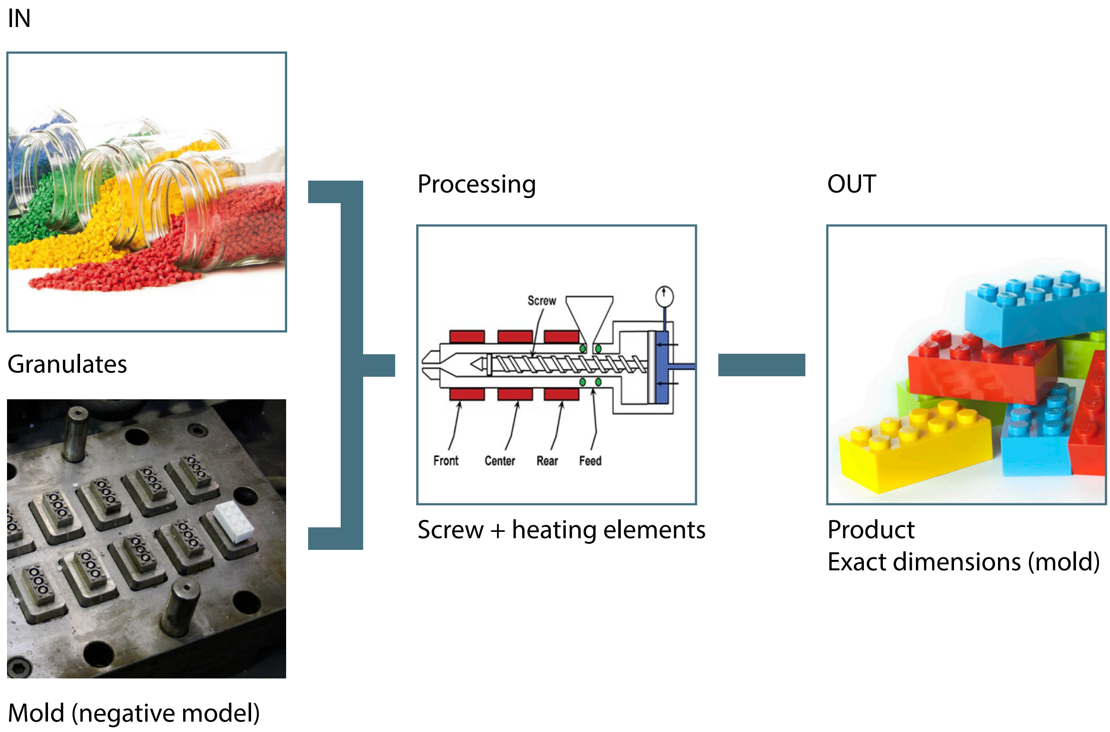


Fig 04: Extrusion process

Of these 3 basic production methods many hybrid methods are available, such as a granulate FDM printer.

1.3.2 Conclusions

The 3D-paintbrush is an unique product fitting somewhere in between. It has a screw and barrel and heats up granulates like an injection molding machine. But unlike with injection molding the shape of the actual product is human controlled by their movements much like a 3D pen only at a much larger scale and speed.

All printing devices melt plastic and thus use thermoplastic materials. Thermoplastic materials can be melted and extruded onto a spool for a 3D pen or printer. or can be made into granulates for injection moulding. The 3D paintbrush should also use thermoplastics for the same reasons. Typically 3D-printers or simulair devices use materials that melt before reaching 300 °C

1.3.3 Requirements

The 3D-paintbrush will use thermoplastic materials

The 3D paintbrush will heat up materials up to 300 °C

1.3.4 Wishes

The 3D-paintbrush projects should be recyclable.

The recycled projects should be able to be reused.

1.4 Current Setup

1. Motor
The function of the motor is to rotate the screw. The current motor is a 24V motor with a 120W output. It weighs about 3.4 kg.

2. Screw
The function of the screw is to move and melt granulate, up to 300°C. The current screw is a steel wood drill with a diameter of 18mm and a length of 320mm. more details about the current screw are in chapter 1.9.3

3&7. Insulation barriers
The barriers prevent heat to move through other areas, and directs heat into the right direction. It also decreases the heat flowing into the casing making the extruder safer for the user.

4. Barrel
The barrel help guide the granulate transfer to the right direction. Like the screw it should be able to withstand heat up to 300°C. Unlike the insulation the barrel needs to transfer the heat towards the nozzle.

5. Air cooler
The purpose of the air cooler is to cool the material as soon as it exits the nozzle. This is needed in order to create self supporting structures. Ideally no deformation happens after the material is cooled.

6. Nozzle
The nozzles function is to squeeze out material and decrease the area of the output to increase the material flow.

8. Temperature sensors
These sensors will measure the temperature in the barrel. It works with a chromel and alumel section and the voltage will change based on its temperature.

9. Heating elements
The heating elements will be wrapped around the barrel and heat the barrel locally.

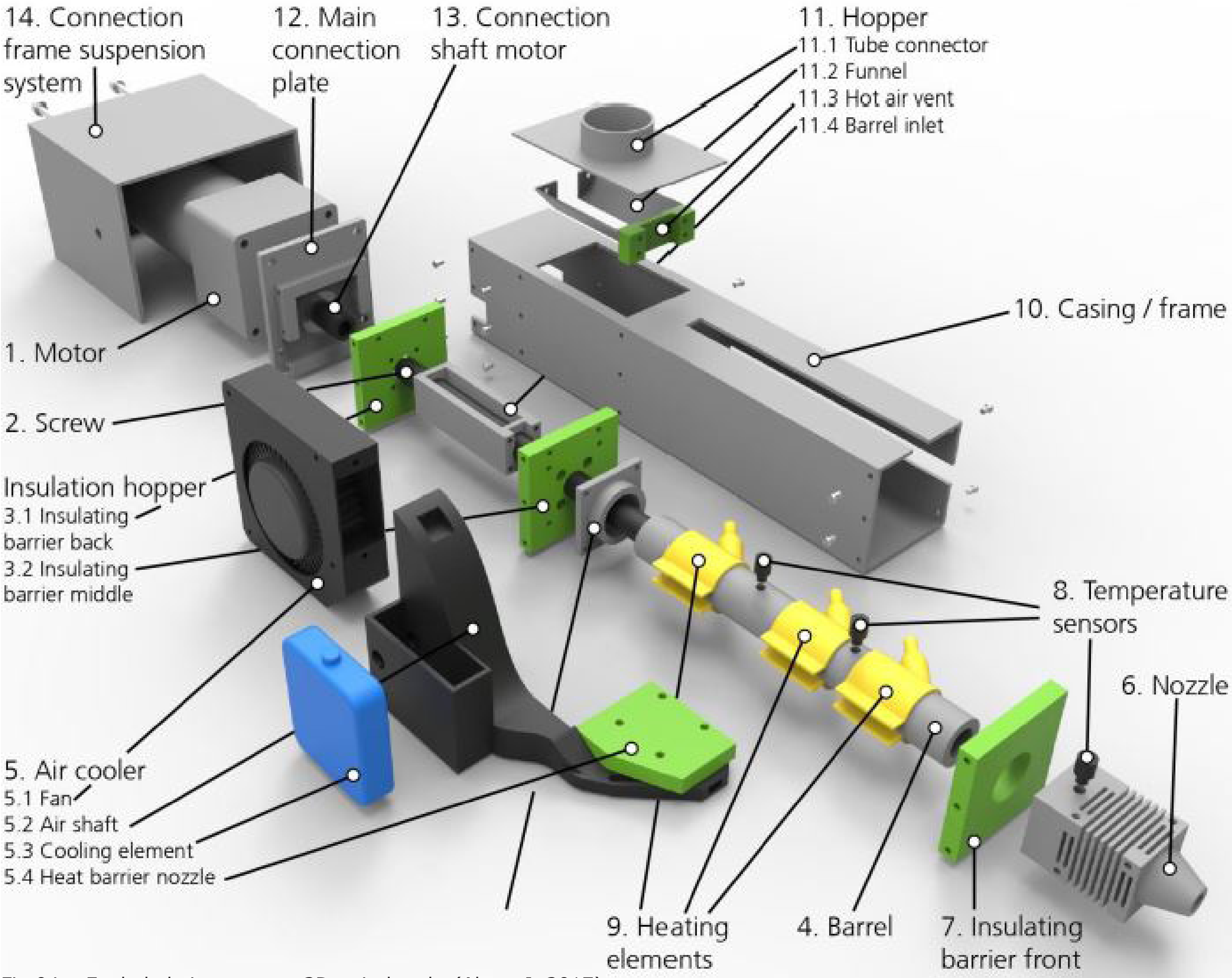


Fig 04: Exploded view current 3D-paintbrush. (Algra, J. 2017)

10. Casing / frame
The main objective of the casing is to shield the user from the heated parts of the extruder. It should fix all other parts in place and make the whole extruder rigid and strong

11. Hopper
The hopper should feed the granulate into the screw and barrel, it is the hoppers function to make sure a constant flow of granulate are added. The granulate in the hopper should not melt before it is fed into the barrel.

12. Main connection plate
This plate mounts to the casing.

13. Connection shaft-motor
This piece connects the motor and the screw and transfers the rotations of the motor to the screw.

14. Connection frame suspension
This frame covers the motor, houses some of the buttons and can be connected to the frame of the balance mechanics.

The frame keeps the paintbrush balanced with a counterweight and it is also where the control box is placed on.

Fig 05: Current 3D-paintbrush with frame. (Algra, J. 2017)

1.5 Using the 3D-paintbrush

1.5.1 General setup

The 3D-paintbrush is designed to make a sculpture of 3x 3x 3 meter. Because the current paintbrush is on a ridable platform it can make structures that are a lot wider and longer. The height of the structure is usually limited by the ceiling making the maximum heigth of the structure roughly 1.5m in a normal room.

The new paintbrush should atleast have the same range, possibly improving the height it can work in.

1.5.2 Setting up the paintbrush

The 3D-paintbrush is designed so that it can be moved for creating sculptures on location. This means that the paintbrush can be disassembled into several parts which all fit through a standard door. These parts are: The extruder, the top frame, the bottom platform, the counterweight and the electronics. The parts should be movable by one person.

The 3D-paintbrush is easy to setup and the electronic wired are color coded. The new 3D-paintbrush should have the same requirements and also fit through a standard door and should be easy to (dis)assemble.

1.5.3 Requirements

The 3D-paintbrush will make sculptures of 3x 3x 3m.

The 3D-paintbrush will be able to be (dis)assembled to make it transportable

The electronics must be easy to setup and it should be clear where each cable connects to

The 3D-paintbrush will fit a standard Dutch door size of 2015 x 830mm

The parts should be movable by 1 person

1.5.4 Wishes

The 3D-paintbrush should make structures higher then 2m even in spaces with a normal ceiling height

Each part should way less than 25kg

1.6 Working with the 3D-paintbrush

In order to understand the given assignment the current 3D-paintbrush needed to be analysed to do this current setup has been tested. This also showed how the 3D-paintbrush should be operated and what settings are used. The full test can be found in “Appendix B: Speed test and mass flow rate calculations.” This chapter will cover the most important details and findings of that test.

1.6.1 Speed test

A test has been done to determine the extrusion speed of the 3D-paintbrush. This test has been done with Polycarbonate (PC) and and Polypropylene (PP) which are the most used plastics by Tiwánee van der Horst at the beginning of this project.

In this test an extrusion length of 200mm has been timed ten times for both polypropylene and polycarbonate.

On average a 200mm extrusion length took 22.1 seconds for polypropylene and 24.3 seconds for polycarbonate.

1.6.2 Calculations

From the speed tests the extrusion speeds can be calculated. With these extrusion speeds the mass flow rate can then be calculated.

For this some some starting variables are needed, these are listed in a table with the mechanical properties of plastics. This table can be found in “Appendix A: Material properties”.

The following variables have been used:
Density of polypropylene and polycarbonate
ρPP = 945 [kg/m3]
ρPC = 1200 [kg/m3]

The radius of the nozzle
rNozzle= 4.0 [mm] = 0.0040 [m]

The extrusion speed based on the speed test.
vPP = 9.1 [mm/s] = 32.8 [m/h]
vPC = 8.3 [mm/s] = 29.9 [m/h]

From these variables the mass flow rate has been calculated. The mass flow rate for PP is 1.48 kg/h and PC is 1.69 kg/h as shown in the calculations in “Appendix B: Speed test and mass flow rate calculations.”

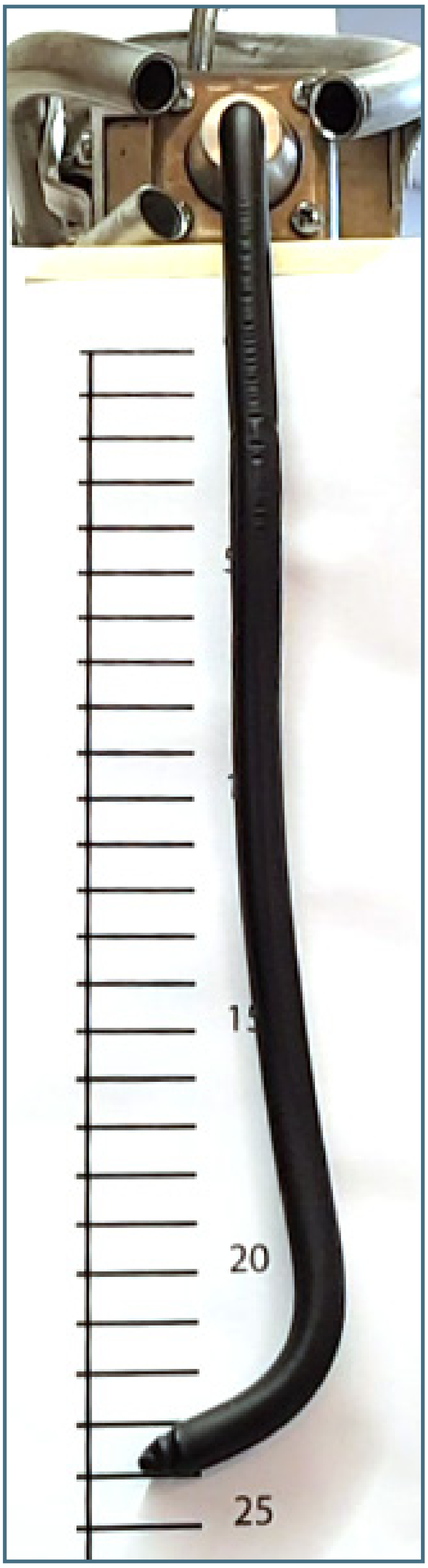


Fig 06: Photo of the test setup

1.6.3 Discussion

The results off this test are specific to the setup and the settings of the 3D-paintbrush. Doing this test another time with different settings, hardware or material batch can change the results of this test.

For example the 3D-paintbrush power supply has been replaced making it possible for the motor to turn faster before it staggers. Therefore the test results from the first test have been discarded and only the results of the second setup with the new power supply have been used.

Repeating this test also gives different results with small differences between the individual measurements. There are multiple reasons that can explain the differences in the measurements. The first explaination is human error, timing with a stopwatch has some variation because of the respond time of the tester.

The second explaination is when the extruded plastics curls up. This makes it visually hit the 200mm a fraction of a second later.
Lastly the material in the current screw could be fed unevenly leading into small differences in the results.

In order to even out these inconsistencies ten measurements are taken for both polypropylene and polycarbonate and from these ten results the average extrusion time has been taken and used for the calculations.

1.6.4 Recommendations

This is one of the first tests done with the extruder at the beginning of the project. For a more accurate measurements without the need to calculate the mass flow rate the mass flow rate can directly be measured by turning on the 3D-paintbrush for predetermined time and weigh the extruded plastic.

This method directly measures the massflow rate and eliminates the inconsistencies mentioned in the discussion.

1.6.5 Conclusion

With the current setup of the hardware and the current settings the 3D-paintbrush has been benchmarked. This has been done for both polypropylene and polycarbonate. The measured 9.1 milimeter per second and 8.3 milimeter per second extrusion speeds have been used to calculate the mass flow rate.
It can be concluded that the mass flow rate for polypropylene is 1.47 kilograms per hour with this setup and for polycarbonate it is 1.68 kilograms per hour

These mass flow rates can be used as a benchmark for later tests and comparing the current 3d-paintbrush to the redesign. The mass flow rate is also used for designing extrusion screws see chapter 4.3.2

1.6.6 Requirements

The extrusion speed should be increased

The mass flow rate should be increased to atleast 5kg/h

1.6.7 Wishes

The mass flow rate should be as high as possible considering the other criteria

1.7 Analysis -extruded work

In addition to working with the extruder the results of the 3D-paintbrush have been analysed. This was done by critically looking at the extruded plastic. Some discarded works have been given to be analysed

1.7.1 Delamination

Figure 7 shows a cross section of an extruded piece. This piece shows lamination by clearly having different layers. Probable causes are that the plastic was not heated enough to be fully melted this can be because the temperature was set to low or that the motor speed was too high.

The image also shows that there was still some residue of a different type of plastic left in the extruder, shown as clear plastic in the cross section.

Fig 07: Photo of lamination

Fig 08: Photo of improper color mixing and air bubbles

1.7.2 Color mixing

The image to the left (fig. 8) shows a piece where the pigments have not mixed properly. This is clearly visible in the yellow part at the bottom of the image. This could be temperature problem or a problem caused by the wood drill (screw).

1.7.3 Air bubbles

Some big and a lot of small air bubbles are formed in the plastic. The small inside air bubbles are not a problem, but the big surface bubbles reduce the visual quality of the artpiece. This is most likely cause by moist in the granulates. Even granulates left in a closed container absorbs moist over time. This granulate is about a year old at the time this piece was created.

Fig 09: Photo of hanging bridges

1.7.4 Slow cooling

Figure 9 shows how a structure made with the 3D paintbrush could be formed. The triangles should create a rigid structure. However in this case the extruded plastic is not cooled down fast enough. Bridges between two floating points will curve down by their own weight.

1.7.5 Discussion

As mentioned some of these problems relate to moisture in the pellets. Based on this Tiwánee van der Horst has been adviced to dry her pellets before using them. She tested this with pellets that were over a year old by putting them in a oven to make the pellets dry for several hours before extruding them.
This process significantly increased the quality of the extruded work. The biggest noticable improvement is that there are significantly less air bubbles in the pieces. (van der Horst, T. 2018)

1.7.6 Conclusion

From the time that the granulate enters the screw until it exits the nozzle the melting temperature of the plastic should be reached.
Failing to heat up till this temperature will lead into internal failure, structural failure or visually unpleasing extrusions. With the current setup, the wood drill, there is a clear trade off between extrusion speed and quality. increasing the speed reduces the quality because the granulates do not get enough time to fully melt before exiting the nozzle.

After the plastic is extruded through the nozzle it needs to cool fast to keep its shape and rigidity.

1.7.7 Requirements

The extruded material must be fully melted before it exits the nozzle

The pigments must be fully mixed into the resin before exiting the nozzle

There should be no air bubbles on the surface of an extruded artpiece

The extruded plastic must cool as fast as possible the avoid structures from collapsing

1.7. Wishes

The quality of the extruded plastic should be improved as much as possible.

1.8 Usertest: Tiwánee van der Horst

1.8.1 Introduction

In order to understand how this 3D-paintbrush works and what issues someone will encounter when using it, the owner and artist Tiwánee van der Horst has been observed. She is using the 3D paintbrush for one of her projects.

Fig 08: Photo of the hidden garden project

1.8.2 Context

This specific project is unique for Mrs. Van de Horst. The 3D paintbrush has been used in previous projects to build up a sculpture. In this project gravity will be used to create "branches" that are attached to the main sculpture. In addition, this is the first time where the flat nozzle will be used for a project and the power supply has been replaced with a more powerful one. The power supply should fit the motor better in order to increase the speed. She will be using recycled HDPE which has an opaque white color, to change the color pigments will be added in the granulate to have a blue/green color as output. These pigments are mixed into the batch before it will be loaded into the reservoir tube. Recycled materials have a preference for Tiwánee van der Horst and she plans to use HDPE a lot in the future.

1.8.3 Goal

The goal of this test is to observe how the 3D-paintbrush is being used and finding key moments during the process. These moments will show what the struggles and limitations are of the 3D-paintbrush in its current state and what are the things that work well.

1.8.4 Approach and method

This goal is achieved by observing how the 3D-paintbrush is being used this method is called shadowing. Sometimes when Tiwánee is waiting certain actions she took are being discussed. This combination will show both the needed improvements in the eye of the user as well as moments observed by the interviewer. During certain key moments the user will be asked why she is doing certain actions. This is done to optimize the whole process of painting with the 3D-paintbrush.

Tiwánee van der Horst her actions will also be timed. This is to track the time that is needed for certain actions to discover which actions are going well and which actions are time consuming or repetitive.

1.8.5 Observations

The actions have been timed in order to determine the amount of work and the difficulties of the process. This has been measured in minutes. 10-15 minutes prior to using the 3D-paintbrush it is turned on to heat up the barrel. the actions are numbered and repeated actions share the same number.

1.8.6 Settings

The current settings of the heaters and sensors are:
[T-heater 1=197] [T-sensor 1=197]
[T-heater 2=193] [T-sensor 2=212]
[T-heater 3=200] [T-sensor 3=198]

Fig 09: Photo of Tiwánee van der Horst working on the hidden garden project

1.8.7 Timetable

[1]	00:00 – 00:03	Getting granulate from the large storage box into a small container.
[2]	00:03 – 00:05	Adding pigment and mixing that in the container.
[3]	00:05 – 00:07	Filling the reservoir of the 3D-paintbrush from the container with a cup.
[4]	00:07 – 00:08	Turn on the motor of the 3D-paintbrush and put on a gas mask.
[5]	00:08 – 00:10	Balance the system by turning the nut at the end, lock the balance system with a rope to reduce the need to balance the system in between.
[6]	00:10 – 00:12	Attach the now extruded “branch” of +/- 1m to the rest of the work with the use of a screwdriver and plyers.
[7]	00:12 – 00:17	Waiting for the next “branch” to extrude.
[6]	00:17 – 00:19	Attach the now extruded “branch” of +/- 1m to the rest of the work.
[8]	00:19 – 00:23	Making a connection piece onto the artwork to support new “branches”.
[9]	00:23 – 00:28	Holding the extruder higher to make a longer “branch”.
[6]	00:28 – 00:31	Attach the now extruded “branch” of > 1m to the rest of the work.
[7]	00:31 – 00:36	Waiting for the next “branch” to extrude.
[6]	00:36 – 00:38	Attach the now extruded “branch” of +/- 1m to the rest of the work.
[8]	00:38 – 00:44	Fortify the last added branch to the artwork and make a connection piece onto the artwork to support new “branches”.
[7]	00:44 – 00:50	Waiting for new “branch” to extrude.
[6]	00:50 – 00:52	Attach the now extruded “branch” of +/- 1m to the rest of the work.
[7,1,2,3]	00:52 – 00:59	Waiting for new “branch” to extrude. Filling the reservoir of the 3D-paintbrush from the container with a cup. Filling up the small container from the storage box and mixing in pigment.
[6]	00:59 – 01:01	Attach the now extruded “branch” of +/- 1m to the rest of the work.

These actions are repeated until the work of art is finished.

1.8.8 Observations

Some of the issues were noticed during the observation. Also Tiwánee van der Horst addressed some other issues or lacking functions while she was using the 3D-paintbrush for her project.

These have been clustered together and assigned to different categories.

Optimize the speed, heating and cooling
The main functionality of the 3D-paintbrush is to make 3D object that are self-supporting. The successfulness of this product can be enhanced by optimizing the speed, the heating and the cooling of the extruded material.
A perfect balance needs to be found between these three settings. If these settings are not balanced it can result into loss of quality in various ways: Texture quality, forming of air bubbles, deformation after extrusion, improper adhesion to itself.

It is desired to optimize the following processes:
- Heating up the material to increase the extrusion speed.
- Cooling of material to created self-supporting structures with little deformation after extrusion.
- Optimize the speed without loss of quality.

User friendliness
When looking at user-friendliness of the product some actions were noticed. It is hard to grab and control the position of the 3D-paintbrush, there are no grips and some parts can be hot. There is a big reservoir to increase the time before refills, but there is no indication of how full this reservoir is.

Switching to a different material can be hard since the reservoir can be full with other material, and the reservoir can't be removed without emptying first at the moment. There is no track of how much material is in the reservoir or how much material is used, the amount of material used is valuable information for the artist.

The heater and temperature displays are currently located on the control box. This is usually placed on the feet of the 3D-paintbrush. At the current location someone can't easily get an overview of the current settings, or adjust the settings, without leaving the extruder, turn around and bend to the floor. There is no feedback of the speed settings other than a turnable knob with no indications.

The following things can be added or upgraded to improve the user friendliness of the 3D-Paintbrush
- Handles and grips to protect the user from touching warm parts.
- improve switching materials without having to empty the reservoir with the extruder.
- An indication of the material left in the reservoir and/or the material used (in Volume or weight).
- visible speed setting and temperature settings, placed at a convenient location.

Mixing pigment in granulates.
Mixing pigments is currently done by mixing a small amount of pigments in the granulate before putting it into the reservoir of the 3D-paintbrush. It is unpredictable when the pigments are coming out of the nozzle and mixing pigments to get a certain color is unreliable.

it is desired to optimize the following actions:
- control the amount of color pigments mixed into the granulate.
- control the consistency of mixing of pigments with the granulate.
- control combinations of pigment to create colors.

More functionality
Some other situations were noticed where improvements can add some extra functionality. Just like a painter has different brushes a 3D-painter could use different nozzles to differentiate shapes and strokes. This could be added to the 3D-paintbrush along with a system to change the nozzles in a user-friendly way.
The use of the balance system correctly is not perfect, ropes are added to prevent adjusting the balance system too regularly. The balance system of the extruder doesn't allow enough degrees of freedom (DoF's) for a complete motion. Which is noticeable when using nozzles that are not round.

To add more functionality these parts of the 3D-paintbrush can be added or upgraded.
- different nozzles and nozzle exchanging system, to increase the versatility.
- improve the balance mechanism so that it allows vertical extrusion and turning non-round nozzles
- more DoF's of the extruder and a better balance system that does not require regular tweaking.

1.8.9 Conclusions

Based on this usertest where Tiwánee van der Horst has been shadowed a lot of possible directions for the next 3D-paintbrush have been discovered. It was good to see her using the 3D-paintbrush while she is creating a piece of art and not during some test extrusions.

The findings from this test have lead to four different clusters: Speeding up the extrusion, user friendliness of the 3D-paintbrush, the mixing of colors and added functionality.

Optimizing the 3D-paintbrush should reduce the time Mrs. Van der Horst takes to create an art-piece based time of her timed actions during this art project.

1.8.10 Requirements

The paintbrush should use recycled plastics since it prefered by Tiwánee van der Horst

The 3D-paintbrush must have a higher extrusion speed, atleast twice as fast

The extruded material must be cooled faster to minimalize deformation

The reservoir must have an indication of when the material runs out

The reservoir must have an indication of the material used

The 3D-paintbrush must have handles to safely grab it

The handles should improve the controll of the movement with the 3D-paintbrush

The extruded plastic should be cooled enough to touch it with gloves or tools

1.8.11 Wishes

The extrusion speed should be as high as possible

The extruded plastic should be cooled so that it can be touched safely by hand

1.9 Understanding Plastics.

In order to understand how the 3D-paintbrush works we have to select certain types of plastics suited for extrusion.

Tiwánee van der Horst indicated that in the future she will mainly work with PE because she can buy recycled PE granulates. She also works with PC and PP. Any other plastic that melts and can theoretically be extruded. Taking into account that the message of the 3D Paintbrush is to use recycled plastics we can look into plastics that are biodegradable or that are commonly recycled.

1.9.1 Resin identification code

Most plastics are marked with a Resin Identification code (RIC). These codes are shown by three arrows circling in a triangle with a number in the middle, this number identifies one of seven different kinds of plastics, with 7 being other plastics. Since using recycled plastics is an important property of the 3D-paintbrush these RIC plastics have been looked at.

Low-density polyethylene LDPE<4>
LDPE is very similar as HDPE, but it has more branching than HDPE. making the intermolecular forces weaker, the tensile strength lower, its resilience higher and its density lower. (Wikipedia, 2018). LDPE is commonly used in trays and other containers, soft parts and snap on lids, packaging foam and plastic wraps.

Polypropylene PP<5>
PP is also a thermoplastic polymer with properties similar to polyethylene but it is slightly harder and more heat resistant. After PE is it the most widely produced commodity plastic often used for packaging and labelling.

Polystyrene PS<6>
PS is is mostly known as white Styrofoam™ but is can also be solid. Because of its low melting point PS is very suited for thermoforming. Plastic cups or milk containers are often made with PS by vacuum forming.

Acrylonitrile butadiene styrene ABS <7>
ABS is a common thermoplastic polymer also used a lot as 3D printing filament (Vialva, Jackson, Lai & Petch, 2018). It is known to be tough and impact resistant. The most known product made of ABS are Lego™ bricks(CES Edupack 2017, 2018). But also most household and consumer goods(CES Edupack 2017, 2018).

Polycarbonate PC <7>
PC are thermoplastic polymers containing carbonate. They are strong tough materials which can be optically transparent. PC is used in electric components, construction material and in automotive, aircraft and railway components.

Polylactic acid PLA <7>
PLA is a biodegradable plastic derived from renewable resources such as corn starch, cassava starch or sugarcane. PLA polymers range from amorphous glassy polymer to semi-crystalline and highly crystalline polymer with a glass transition of 60oC and melting points of 130-180oC (Lunt, 1998). PLA is commonly used in 3D printers, biodegradable cups and tea bags.

Polyethylene terephthalate PET <1>
PET is a thermoplastic commonly used for synthetic fibers, soft drink and water bottles and containers such as plastic jars. PET in its natural state is a colorless, semi-crystalline resin.

High Density Polyethylene HDPE <2>
HDPE is a polyethylene thermoplastic made from petroleum, it is has a high strength to density ratio (Peninsula Plastics Co., 2018) Because of these properties HDPE is used for many applications such as plastic bags, bottles and bottle caps, chemical resistant piping, water piping, food storage containers, fuel tanks and many other applications.

Polyvinyl chloride PVC <3>
PVC is a thermoplastic polymer. Commonly used in piping, electric cables and many other products. Processing PVC can be dangerous because PVC has phthalates. Phthalates are substances added to plastics to increase their properties. In PVC it is primarily used to soften the material. Governments in the US, Canada and the EU are gradually replacing many products made with these phthalates over health concerns. (U.S. Environmental Protection Agency, 2012). Because of this PVC should not be used in the 3D-paintbrush.

Fig 10: Anonymous (2007) Resin Index Codes

1.9.2 Mechanical properties

In order to work with these plastics the important mechanical properties have been listed in Appendix A. Most of this data is retrieved from CES selector unless specified otherwise.
The Mechanical properties listed are: Density, Thermal conductivity, Melting point (T_m), Glass temperature (T_g), Heat capacity or Specific heat (C_p) and Heat of fusion (ΔH_f)

1.9.2.1 Density
The denisity of a material is important to determine the weight based on the volume and vice versa. In this project it is used to calculate flow rates.

1.9.2.2 Glass and melting temperatures.
The glass transition temperature (T_g) and melting transition temperature (T_m) indicate when a plastics starts to melt.

The melting of a polymer crystal corresponds to the transformation of a solid material, having an ordered structure of alligned molecular chains, to a viscous liquid in which the structure is highly random. this occurs at the melting temperature (T_m) (Callister 2007).
The glass transition tempertature is the moment where a polymer experiences the transition from rigid to rubbery at the moment of heating up.

Glassy materials or in this case amorphous polymers become viscous at the T_g shown in figure 11. This figure als shows that a 100% crystalline solids need to be heated up till the T_m to fully melt. Some polymers are semicrystalline and have both a amorpheus part and a crystalline part

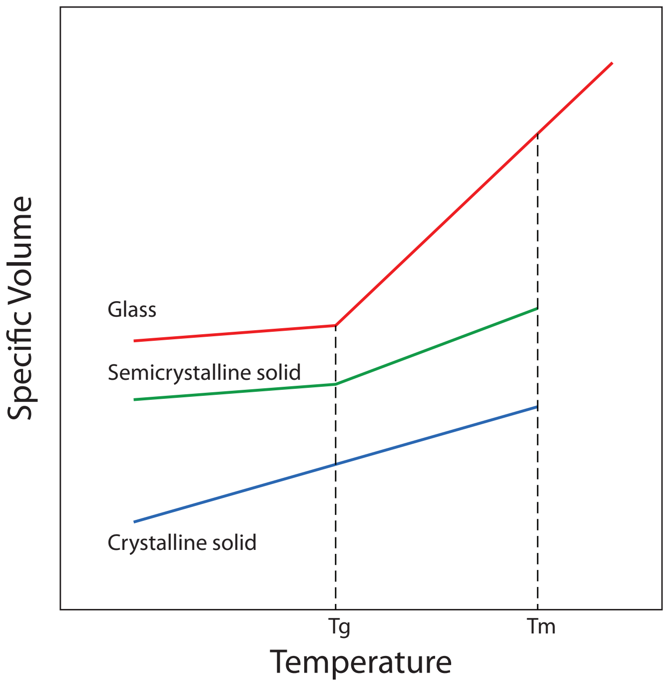


Fig 11: Specific volume versus temperature (Callister, 2007)

This means that the amorphous part will melt at the T_g and the crystalline part will melt at the T_m

The T_g and T_m of polymers help to understand the behaviour of the plastics. This is important when looking at the behaviour inside an extruder screw and at temperature settings of the 3D paintbrush.

Material	Glass Transition Temperature (°C)	Melting Temperature (°C)
LDPE	-110	115
HDPE	-90	137
PP	-18	175
PET	69	265
PVC	87	212
PS	100	240
PC	150	265

TABLE 1.1: Melting and glass transition temperatures for some of the more common polymeric materials (Callister, W.D. 2007)

1.9.2.3 Heat capacity.

In order to fully melt a plastic its temperature need to increase from room temperature, about 20 °C, to past its melting transition temperature around 140 °C for HDPE. Suppliers even suggest a higher temperature to fully melt the plastic and have a lower viscosity.

In order to calculate this we need to know how much energy is required to heat up a kg of material by 1 °C. This constant is called specific heat or heat capacity and is is written as C_p. These values can also be found in appendix A. Heat capacity is usually kcal/kg °C or J/kg °C.

1.9.2.4 Heat of fusion.

For melting of solid material extra energy in the form of heat must be added and break the crystal structure present. The amount of heat required to melt a crystalline solid without raising its temperature is called heat of fusion. the heat of fusion is written in kcal/kg or J/kg.

Material properties recyclable plastics		
Material	Heat Capacity (C_p)	Heat of fusion (ΔH_f)
	J/kg°C	kJ/kg
PET	1150 - 1250	0
HDPE	1750 - 1810	250
PVC	1000 - 1100	0
LDPE	1840 - 1920	130
PP	1870 - 1960	
PS	1200 - 1300	0
ABS	1390 - 1410	0
PC	1150 - 1250	0
PLA	1180 - 1210	

TABLE 1.2: Heat capacity and heat of fusion for recyclable plastics

1.9.3 Processing plastics

The current setup has a wood dril for an extruder screw, this wood drill works good for transferring the plastic to the nozzle through an heated barrel but is not very efficient at melting the plastic.

Granulates need energy to be heated up.
For example HDPE has to heat up from room temperature, about 20 °C, to past its melting transition temperature around 140 °C. Suppliers advice to heat HDPE up even further, up to 230°C

Plastics are good insulators this means that is takes a long time for a plastic to melt by conductive heating. The current screw has a diameter of 18mm (see figure 12) that means that with only conductive heating the heat need to reach 9mm inside the screw to fully heat all the granulates. The extrusion speed is limited by the melting time as noticed in the speedtest in chapter 1.6

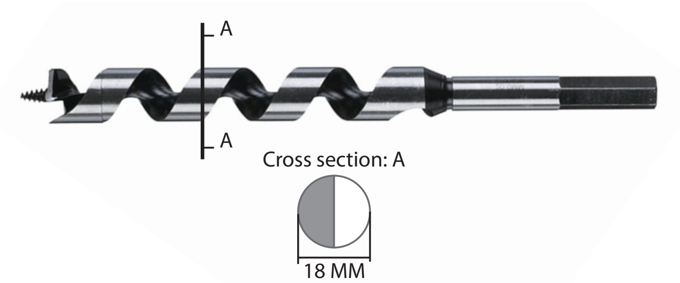


Figure 12: a wood drill with crossection

Replacing the wood drill with an actual extruder screw will imporve the efficiency of melting the plastics and increase the extrusion speed. When using an extruder screw 80% of the energy to melt the granulates comes from shear stress inside the barrel. The remaining 20% is from conductive heating with heater bands. (Reiley USA, 2015)

1.9.4 Conclusions

Most resins are suitable for recycling and suitable for the 3D paintbrush. Since recycling of plastics other than recycling discarded artworks is not done Tiwánee van der Horst uses HDPE. HDPE is a materials that can easily be bought from a supplier as recycled PE ganulates. Because of this all calculations will be done with PE, however this chapter shows alternative options for future projects.

Depending on the typ of plastic the glass transition temperature (T_g) and the melt transition temperature (T_m) are important for the heater bands and the settings.

Replacing the wood drill with an extruder will optimise the speed since most energy will come from the shear stress and not conductive heating.

1.10 Scope

Like many projects the 3D-paintbrush started with a broad scope. This was the whole machine including all its functions. During the project the scope had to be diverged into a smaller scope. The 3D-paintbrush turned out to be big project with many different subproblems. The complexity of most subproblems was quite high and could have been a project on their own. For this reason the frame and balance mechanism has been excluded from the scope.

Without including this subproblem more in depth focus can be given to the two main challenge areas. These areas are heating and cooling of the plastics. Having different heating and cooling can change the setup of the extruder and because of that the placement of the reservoir, adding pigment and human-machine interaction has been included into this scope. Overall the scope is everything in and on the extruder and anything external to make the extruder function. The frame and balance mechanism is completely excluded outside of the scope.

Fig 13: Image showing the scope of the project (Algra, J. 2017)

The 3D-paintbrush should be **safe and easy** to move, control and use. It should have an **improved extrusion speed** without the loss of quality.

The paintbrush should **cool** the extruded plastic **fast enough** so that 3D-structures can be formed.

1.12 Problem definition

The biggest improvement for the 3D paintbrush is to improve its extrusion speed. But just increasing the motor speed is not possible. There are a lot of parts in the extruder that work together for an optimal result.

For example when the motor turns faster the granulates have less time to melt because they pass faster through the barrel. Also a warmer temperature decreases the viscosity of the plastic.

Increasing the extrusion speed can mean that the extruded plastic needs more cooling because the temperature is higher and thus the viscosity lower. Extruding faster increases the 3D-paintbrush its granulate consumption. And the reservoir needs to be filled more often.

The 3D-paintbrush is a complicated system with different functions working together to create a good working product. Therefore the main problem is split up into different partial problems. Because this is a hand driven device the overall weight of the 3D paintbrush is important.

1.12.1 Partial problems

Melting of plastic

- Feeding the material through the barrel
Currently the granulates are fed through the barrel using a wood drill. The wood drill has the same channel depth throughout its whole length. Materials passes through the barrel fast without getting the proper time to fully melt

- Fast heating of the material
If the extrusion speed is increased the mass flow rate of the system will be higher this means the granulates have even less time to reach their melting point before it passes through the barrel and exits the nozzle.

The material needs to melt faster or the screw and barrel need to be longer to give the material more time to melt

Cooling of plastics

-Fast cooling of the material
Cooling is currently focussed on a small area after the plastic leaves the nozzle, if the speed is increased the extruded plastic spends less time in this cooling area. This means that the area needs to be increased or the cooling should be faster.

In mr. Algra's design cooling is focussed on one point, under the nozzle. Moving the 3D-paintbrush the opposite way makes the air from the fan blow before the extrusion.

Tiwánee van der Horst had adjustments made to the cooling setup splitting the air from the fan into three streams aiming just after the nozzle from three directions.

A future design could have the air stream more evenly spread around the nozzle

Human-machine interaction

- Material reservoir
Filling up the reservoir can be a repetitive task. A faster extrusion means more material will go through the system and thus more filling the reservoir. a bigger reservoir can compensate for this. In addition a clear reservoir can show the remaining granulates so that filling can be timed.

- Adding pigment
Adding pigment is done in batches, matching pigments of an old and a new batch is inaccurate. Also the pigments are randomly going through the system

- Changing nozzles
Having access to different nozzles increases the usefulness of the extruder. And much like a painter uses different brushes, multiple nozzle options can diverse the artists options.

- Holding the 3D-paintbrush
Where to hold the 3D-paintbrush when extruding is very important certain parts can be hot. Mainly only one user will use the 3D paintbrush, but Tiwánee has also done workshops with children and she sometimes has interns. The 3D-paintbrush should be controllable by both left and right handed people.

- Degrees of freedom
The degrees of freedom of the system can improve the 3D-paintbrush its functionality, especially with new designed nozzles.

Moving the 3D-paintbrush

- Multiple parts.

Moving the 3D paintbrush from one location to another happens ocasionally. Since the 3D paintbrush is a big machine it is important that it can be assembled and disassembled in various parts easily. Since the frame is not part of the scope of this project it is important that the 3D paintbrush connects to the current frame.

-Weight

Each part should be movable by one person. This means that the individual parts should be light enough to carry and do not exceed 25kg, the maximum carry weigth according to the ARBO (ARBO - Tillen en dragen, 2018).

- Size

The size of the individual parts are also limited. The parts should fit through an standard door of 0.8m wide.

1.12.2 Trade-offs

There are a lot of trade-offs in this project, or better formulated one change will result into a lot of other changes.

Faster extrusion speed	vs	time to melt
Faster extrusion speed	vs	smaller cooling time
A bigger reservoir for less filling time	vs	weight
A bigger motor to increase speed	vs	weight

1.12.3 Requirements

The 3D paintbrush should melt the material completely before passing through the extruder screw

The extruded material should melt faster to increase the extrusion speed

The granulates should melt evenly from all sides

The material reservoir should be transparent so that the remaining granulates can be seen

The amount of pigment being added to the granulates should be controlled so that the extrusion color is even

The nozzle should be replacable

1.12.4 Wishes

A set of different nozzles can increase the functionality of the 3D-paintbrush

1.13 Program of requirements and wishes

In this chapter all the previously mentioned requirements and wishes that are displayed in the dark green boxes have been listed and categorized. Together they form the program of requirements and wishes.

1.13.1 Requirements

A - General requirements

R-A1 The 3D-paintbrush will make sculptures of 3x 3x 3m.
(Ch 1.5.3)

R-A2 The 3D-paintbrush will be able to be (dis)assembled to make it transportable
(Ch 1.5.3)

R-A3 The electronics must be easy to setup and it should be clear where each cable connects to
(Ch 1.5.3)

R-A4 The 3D-paintbrush will fit a standard Dutch door size of 2015 x 830mm
(Ch 1.5.3)

R-A4 The parts of the 3D-paintbrush will be movable by one person and not weigh more than 25kg each
(Ch 1.5.3)

B - Material requirements

R-B1 The 3D-paintbrush will use thermoplastic materials
(Ch 1.3.3)

R-B2 The 3D-paintbrush will use recycled materials
(Ch 1.8.10)

R-B3 The 3D-paintbrush will use materials that fully melt below 300 °C
(Ch 1.3.3)

R-B4 There should be no air bubbles on the surface of the extruded artpiece
(Ch 1.7.3)

C - Extrusion speed requirements

R-C1 The extrusion speed should be atleast twice as fast
(Ch 1.6.4) - (Ch 1.8.10) - (Ch 1.12.3)

R-C2 The mass flow rate should be atleast 5kg/h
(Ch 1.6.4)

D - Heating requirements

R-D1 The extruded material must be fully melted before it exits the nozzle
(Ch 1.7.3) (Ch 1.12.3)

R-D2 The granulates will melt evenly from all sides.
(Ch 1.12.3)

E - Cooling requirements

R-E1 The extruded plastic must be cooled fast enough so that the structure does not collapse
(Ch 1.7.3) - (1.8.10)

F - Usability requirements

R-F1 The Pigments must be fully blended in the resin before exiting the nozzle
(Ch 1.7.3)

R-F2 The amount of pigment beind added to the granulates should be controlled so that the color is even
(Ch 1.12.3)

R-F3 The reservoir will have an indication of the material left inside the tube.
(Ch 1.8.10)

R-F4 The 3D-paintbrush must have handles to safely grab it.
(Ch 1.8.10)

R-F5 The handles should assist in controlling the movement with the 3D-paintbrush
(Ch 1.8.10)

R-F6 The 3D-paintbrush should be usable by left and right handed people
(Ch 1.12.1)

R-F6 The extruded plastic should be cooled enough to touch it with gloves or tools
(Ch 1.8.10)

R-F7 The nozzle should be replacable
(Ch 1.12.3)

1.13.2 Wishes

A - General Wishes
check

W-A1 The 3D-paintbrush should make structures higher then 2m even in spaces with a normal ceiling height
(Ch 1.5.4)

W-A2 Each part should weigh less than 10kg.

B - Material Wishes

W-B1 The 3D-paintbrush projects should be recyclable.
(Ch 1.3.4)

W-B2 The recycled projects should be able to be reused by the 3D-paintbrush
(Ch 1.3.4)

W-B3 The quality of the extruded plastic should be improved
(Ch 1.7.4)

C - Extrusion speed wishes

W-C1 The mass flow rate should be as high as possible considering the other criterea
(Ch 1.6.5)

F - Usability wishes

W-F1 The extruded plastic should be cooled enough so that it can be safely touched by hand.
(Ch 1.8.11)

W-F2 A set of different nozzles can improve the functionality of the 3D-paintbrush
(Ch 1.8.11)

2 IDEATION

2.1 Partial solutions

As mentioned in the analysis phase the problems have been split up into partial problems, in the ideation phase the solutions have been split up into the same categories.

2.1.1 Melting plastic

Heating up plastic is the main function of the 3D-paintbrush, to design a realistic extruder there are limited options to change current system of melting plastic

Drill (current)

The drill is a cheap option to move granulates to a heated barrel. Compared to other solutions it is very limited at what is can mean for the system. The only way the granulates melt is by the heating elements placed around the barrel. The heat transfer from the barrel onto the plastic is called conductive heating. Heating granulates only with conductive heating is very slow because the heat transfer of plastics is about 1/30th of that of the steel barrel. This means there can be large temperature differences between the barrel and the plastic and within the plastic itself (Paulson, 2018). Therefore it will take a lot of time to melt the granulate closest to the middle of the barrel through conductive heating only. It can be concluded that the extrusion speed is not limited by the speed of the drill but by the length of it. A longer drill gives the plastic more time to fully melt and this can be a possible solution.

Extrusion screw

An extrusion screw seems like a logical solution since it is what many extrusion production processes use in the plastic industry. It requires a die or nozzle and the extrusion has the same cross-section as the nozzle. Examples of extruded products are piping, tubing, window frames, filament and films (CES, 2018).

The great advantage of a screw over a wood drill is that a typical extrusion screw has three sections: A feed section, a transition section and a metering section.The feed section has a constant channel depth, its main purpose is to convey the plastic forward through the barrel.

In the transition section the channel depth decreases, the combination of compression and screw rotation causes shear friction, which generates shear heat. This heat in combination with the conductive heating from the barrel and heating elements melts the plastic.

Because the granulates are heating with but conductive heating and shear heating a screw is much more effective than just a wood drill. In an extrusion screw the 75% to 80% of the energy to melt the pellets comes from mechanical energy made by the shear stress. (Reiley USA, 2015)

Setting up a extruder screw is similar to the current setup, the wood drill. Just like the wood drill it has a barrel with heating elements around it. The barrel has a constant inner and outer diameter. It is the root diameter of the extrusion screw that changes causing the channel depth to decrease. Because of these similarities it is easy to implement this into the current 3D-paintbrush with minor adjustments.

Having the pellets melt by shear heating instead of conductive heating can speed up the motor and therefor speed up the extrusion.

The first predictions for the extruder screw have been done with the help of experts. They explained that extruder screws are classified by their mass flow rate, how many kilograms of plastic can be extruded into a hour. In order to compare the current setup the mass flow rate of the 3D-paintbrush has been calculated (see Ch.1.6. speed test). S. Bakker, extruder expert at Xtrution said that an extruder similar to the wood drill in size and weight can extrude between 7.5 kg/h (Bakker, 2018)

2.1.2 Cooling

Increasing the extrusion speed required a different more extreme version of cooling. More extruded plastic will extrude and it needs to cool in a shorter time.

Fan air (current system)

The current system of cooling is done with a computer fan, these come in various strengths and sizes. Professional computer fans are measured in airflow (in cfm or m3/h) an average high-end computer fan of 120x120x25mm delivers about 85m3/h or 50 cfm of air.

The air coming from a fan is directed into one direction. It needs another part to change the direction of the airflow on the extruded plastic. Jelle Algra's fan was only directed under the nozzle. Moving the nozzle sideways or downwards makes the airflow not hit the extruded plastic. In a later iteration 3 pipes are directed at the nozzle distributing the air more around the extruded plastic. With 3D printing the airflow can be directed better onto the nozzle thus improving the effectiveness of the airflow.

Water

Water cooling is also an option, it is commonly used into cars and PC's both having to cool several parts drastically. Watercooling is one of the most silent ways of cooling and that is the main reason why it is populair in PC's. Setting up water cooling requires a complicated extra system. There is no standard properties for watercooling so it is hard to compare various water coolers.

A basic setup for water cooling needs several parts and a basic system can be seen in fig XX

1: Water block, this is connected on the part that needs cooling.
2: Radiator and some fans, this cools the water inside the loop
3: Pump, that pumps the water through the tubing system to the waterblock, and pumps the hot water back to the radiator
4: Reservoir, to store access water
5: Tubes and fittings, to transfer the water
6: Coolant: distilled water for example, this runs through the system
7: Additives such as biocide to prevent algae from growing in your system
8: And anti corrosive to prevent metals from corroding (Lifehacker, 2012)

The biggest disadvantage for water cooling is having water close to electricity and the possibility of leaks. This can be a mayor safety hazard and unlike a PC the 3D-paintbrush moves around a lot making a water cooling setup more fragile because of repetitive strains on the system. Also having water close to the granulate can be bad. Having moist granulate will drastically affect the quality of the extrusion. As shown in the analysis of the extruded work (Chapter 1.7).

Maintaining your system can be complicated as it needs a good coolant as well as additives, bad maintenance can lead to clogs or leaks.

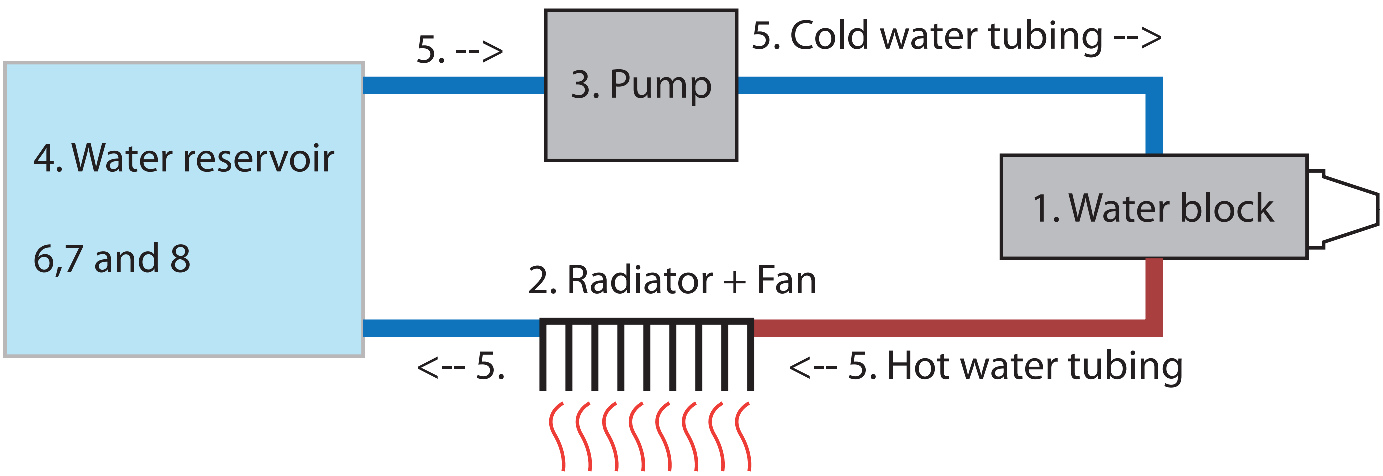


Fig 14: basic setup of a water cooling system

Vortex (air)

Vortex cooling is a promising alternative to fan cooling, just like a airfan it cools with air so there is no water involved. It does require an extra setup just like the water cooling since a vortex cooler works on compressed air. Compressed air can be easily transported to the nozzle of extruder without having a risk to affect the safety of the user or the quality of the work. A small compressor on the platform along with some tubing following the electricity cable to the extruder is a simple and minimal adjustment to make this solution work.

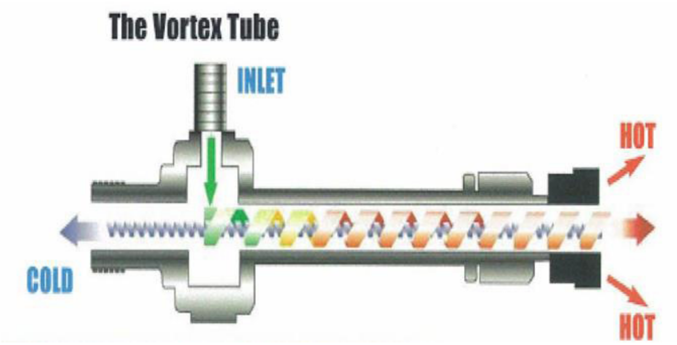


fig 15: Vortex cooler (universal-vortex.com. 2018)

Vortex cooling is done with a Ranque-Hilsch vortex tube. Compressed air enters in the inlet of the vortex tube, this air spin with over a million rotations per minute in the chamber. Because of the speed the air gets separated into hot and cold gas where the hot gas can reach temperatures of 200 °C and the cold gas down to -50 °C (Walker, 1975). The hot air is heavier and therefore will it rotate around the outside of the tube. at the end (right side in figure 15) are openings at the outer diamater of the tube, allowing the hot air on the outside to exit. The cold air does not have an exit and the direction is reverted to the left side. on this side a smaller opening allows the cold air to exit. The vortex tube is a simple and low maintenance solution since the vortex tube has no moving parts and setting up compressed air is relatively simple.

2.1.3 Degrees of freedom

To increase the movement of the 3D-paintbrush, also known and degrees of freedom (DOFs) several options have been explored. There are six degrees of freedom in total and currently the frame controls all the translation in the X,Y,Z Axis and one rotation around the Z-axis. The extruder can rotate around the Z-axis and limited movement around the X-axis. Overall the current system can move with five degrees of freedom with some limitations

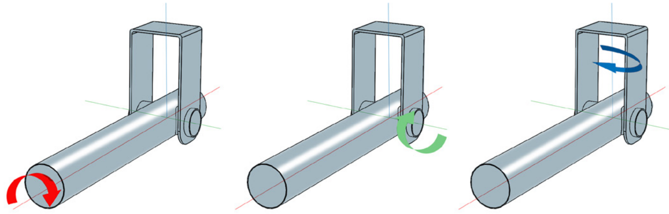


Fig 16: Movement around the X, Y and Z-axis

Various tests have been done with 3D printed parts, this because most of the parts are custom made, it is fast to prototype and it is cheap. It has been an iterative process where a fast prototype leads to a better version based on the discoveries of the previous iteration.

Y-axis
The rotation around the X-axis works well in the current 3D-paintbrush, the movement is limited by the small frame in which the extruder is hanging. The motor on the back hits the frame limiting the movement to roughly 60 degrees.

Changing the frame making it taller will make it possible for the motor to fit underneath increasing the range from 60 to about 300 degrees.

In addition to this the pivot axis can be increased from bolts to sliding bearings around a bigger pipe. The pipe then can be used to feed the granulates into the extruder.

X-axis
There are in the current 3d-paintbrush no options to rotate around the Y-axis. But since alternative nozzles have been added and these nozzles are not rotational symmetric turning the 3D-paintbrush around the Y-axis can have some added value.

For this several ideas have been made

Ball bearings

A large bearing has been designed that fits around the current extruder. This is 3D printed and has 3 parts (excluding the ball bearings). The ball bearing has been tested with various numbers of balls the minimum number of balls used is 4 where they are equally distributed into place by a socket into the outer ring. The middle ring had a groove all around so that the middle ring is free to rotate. The other versions had more balls, up to a bearing without sockets and all balls. This version showed the most promise and has the least resistance.

Fig 17: Ball bearing part

Figure 16 shows the prototype ball bearing, the square in the middle fits the current 3D-paintbrush allowing it to rotate in the X-direction (fig 15). Both sides have a bolt that fits in the cavity of the 3D print. On these bolts are sliding bearings. These bolts connect to the frame allowing the bearings to still rotate. This gives the new 3D-paintbrush rotation around the Y-axis.

Planetary gear

Another option to create the rotation in the Y-axis is with a planetary gear. A planetary gear has three types of gears: the middle gear called the sun, the surrounding gears called planets and the outer gear. By making the sun gear big enough it can be fitted around the extruder. With small planets this could still be a compact system. This can be seen in figure 17.

Fig 18: planetary gear

The teeth of the gear have been designed in a way they can not be disassembled. A Normal gear can be pushed out in the direction of the rotational axis. Giving the gear a helix prevents it to be pushed out, but they can be turned out. The final iteration of the gears have a double helix, clockwise to the middle of the gear then counter clockwise to the end.

The planetary gear is printed as one piece including the sun, planets and outer ring This saves in assambling time compared to the ball bearing.

Z-axis
The rotation is currently done at the point where the extruder is mounted to the frame, this is a strong good working system. No change is needed

Movement: Frame

As mentioned the frame has been put outside the scope of this project, however some work was done prior to this decision. Therefore the frame is mentioned in the ideation phase of the design as an advice to the client. It wont be mentioned in the concept- or embodiment-phase of this project. The frame is based on the Tertial, the famous ikea lamp with springs. Since the scale is bigger and the weight is higher the idea was to replace the metal springs with gas springs. These can withheld a lot of force and are commonly used for car trunks.

Upon further research a company that make these frames for tools has been found they offer a wide range of frames. It is recommended to look further into these frames.

An example frame has a range of 3800mm in diamter and 1400mm height which fits well in the requirements.

More information can be found in the folder added in Appendix D

Heating hose

An alternative idea for increasing the degrees of freedom is the use of a heating hose. This is a more expensive solution and will cost around 1800 for the hose alone (Hillesheim, 2018) but simplify the build and adds a lot of degrees of freedom.

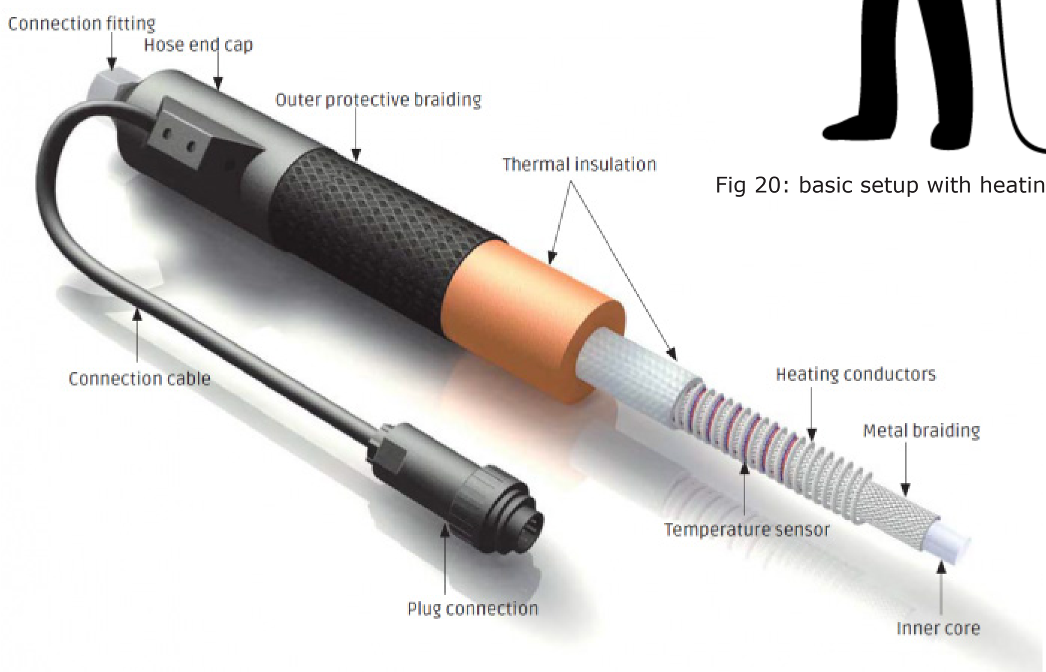


Fig 19: Heating hose (Hillesheim, n.d.)

The heating hose is a temperature and pressure controlled hose (figure 19). With this hose the extruder can be placed on the cart with the controllers. There is no need for a frame since everything will be controlled and placed on the cart and only the hose transports the plastic melt to the nozzle.
This gives the whole system 6 degrees of freedom with no limitations.

However apart from it being an big investment there are other downsides. Heating up the system before you start will take a long time since the remaining plastic in the hose needs to be melted through conductive heating. This also requires a lot of energy/electricity and is not sustainable.

When changing material or color it takes a long time before the new granulates or pigments reach the end of the nozzle. This will give a lot of waste material each time a color or material is switched.

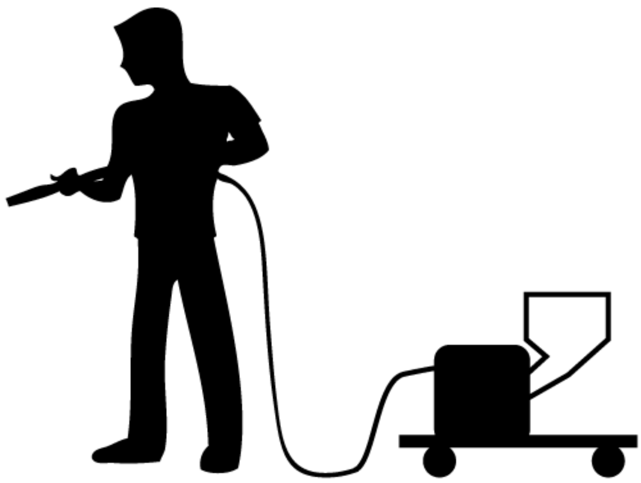


Fig 20: basic setup with heating hose

2.1.4 Usability

Various idea have been developped to further improve the usability and human-machine interaction

Reservoir

The current reservoir is a opaque black flexible hose. It lacks any indication of how full the hose is at any moment.

A transparent reservoir is the easiest way to improve the printer a scaling system on the reservoir can be added to determine how much volume of granulates have been used.
The size of the reservoir is highly dependent on the plastic consumption of the screw and barrel. However the weight of the reservoir including the granulates needs to be considered.

Pigment

Pigments should be added in a controllable way, it should be fed as close to the barrel as possible so it enters the feed fast. This reduced the time from the pigment being added to the pigment being extruded by the extruder.

The two variants for pigment controllers have been inspired by a gumball machine, where one gumball will be delivered by turning a wheel. And by a mint dispenser where pushing a button dispenses one mint each time.

Both solutions have been prototyped and tested this can be found in Appendix A: prototype log
In this phase the dispensers are unreliable and the dimensions need to be optimized. However the pigment dispenser where you push a button seems the most feasible choice.

Handles

There are many ways a user interacts with the 3D-paintbrush. From the usertest in Chapter 1.8 we learn that the two main interactions are holding and moving the 3D-paintbrush around and filling up the reservoir.

Currently there is no spot for holding the 3D-paintbrush, the idea is to have handles that can be placed on the extruder near the nozzle and one near the back of the extruder, this will be the easiest way to move and turn the 3D-paintbrush in the desired direction.

Fig 21: Grinder grip (amazon.co.uk, 2018)

Nozzle

The nozzle is very important for determining speed related to the extrusion length with a set flowrate doubling the surface of the nozzle halves the extrusion length during the same period. For Tiwánee van der Horst the extrusion length is important. a bigger nozzle means less movement to create a structure because more volume is extruded per length.

Because of this experiments on the current 3D-paintbrush have been made with a nozzle with a core, creating a hollow extrusion much like a pipe. With a nozzle with a core you can extrude a lot faster than the same outer diameter nozzle without a core.

A hollow nozzle also cools faster since there is less material and the cooling is done from the outside. this should decrease the risk of structures collapsing.

The creation and testing of the hollow nozzle can be found in embodiment phase in chapter 5.

Testing the cored nozzle shows that it has more advantages from an artistic perspective. because the extrusion is hollow it is easier to manipulate the extrusion. making it thinner by moving faster and thicker by moving slower. This increases the feeling of working with a brush because you have more control shown in figure 23.

furthermore a hollow extrusion adds to option to add light in your works.

During the tests the nozzle has been made out of aluminium and of steel. it was attached in the current "cooling block" which was made out of aluminum. An aluminium nozzle in an aluminium cooling block gets stuck after heating up the nozzle. There is a lot of friction between the two parts and the material wears out a lot.

A steel nozzle would be a better option, steel expands a lot less and also does not wear so easily. Therefore a second nozzle has been made out of steel this is shown in figure 22.

Fig 22: Steel nozzle with a core for hollow extrusion

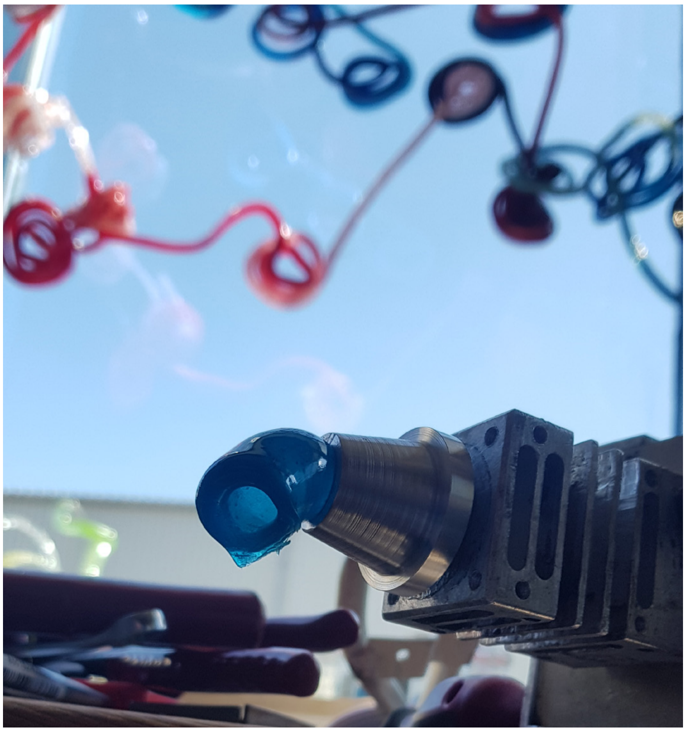


Fig 23: Extrusion with the nozzle with a core

3 CONCEPTUALIZATION

3.1 Introduction

The 3D-paintbrush is a one-of-a-kind product designed for one user. Having a production quantity of only one product can make the 3D-paintbrush expensive. Because the budget was not set at the start of this project and in the ideation phase the idea's can vary in a big range of prices the decision has been made to categorize the concepts based on costs.

With this in mind three concepts have been developed: The upgrade, a concept that upgrades the current 3D-paintbrush. The cylinder, a new 3D-paintbrush getting the most cost efficent solution and the Cart, the ideal concept with most benefits.

3.2 Morphological chart

In the ideation phase the ideas have been categorized based on the partial problems. For each of these partial problems multiple solutions have been found.
In the concept phase these solutions have been put together forming three concepts.
The best way to visualize and map the concept development is the use of a morphological chart. The morphological chart shows different sub-problems in different rows. And each row has the solutions in different squares shown in figure 24

The green line represents the current 3D-paintbrush. It uses a drill to feed the granulates, a fan for air cooling, a pipe as reservoir, batch mixing for pigmentation, removable nozzles, and limited DOFs with sliding bearings lastly the position can't be locked in place.

The blue line shows the upgrade concept. It has an extruder screw, fan cooling, a clear reservoir, dispenser mixing, threaded nozzles, three rotational degrees of freedom and the positions can be locked into place.

The purple line shows the cylinder concept.
It uses an extruder screw, with vortex cooling, a clear reservoir that feeds at the pivot point of the extruder, a dispenser for pigments, two rotational degrees of freedom and a locking mechanism.

The orange line shows the Cart.
This concept has an extruder screw, vortex cooling and a reservoir all located on the cart. It uses a heated hose to get the most degrees of freedom with a replaceable nozzle at the end of the hose.

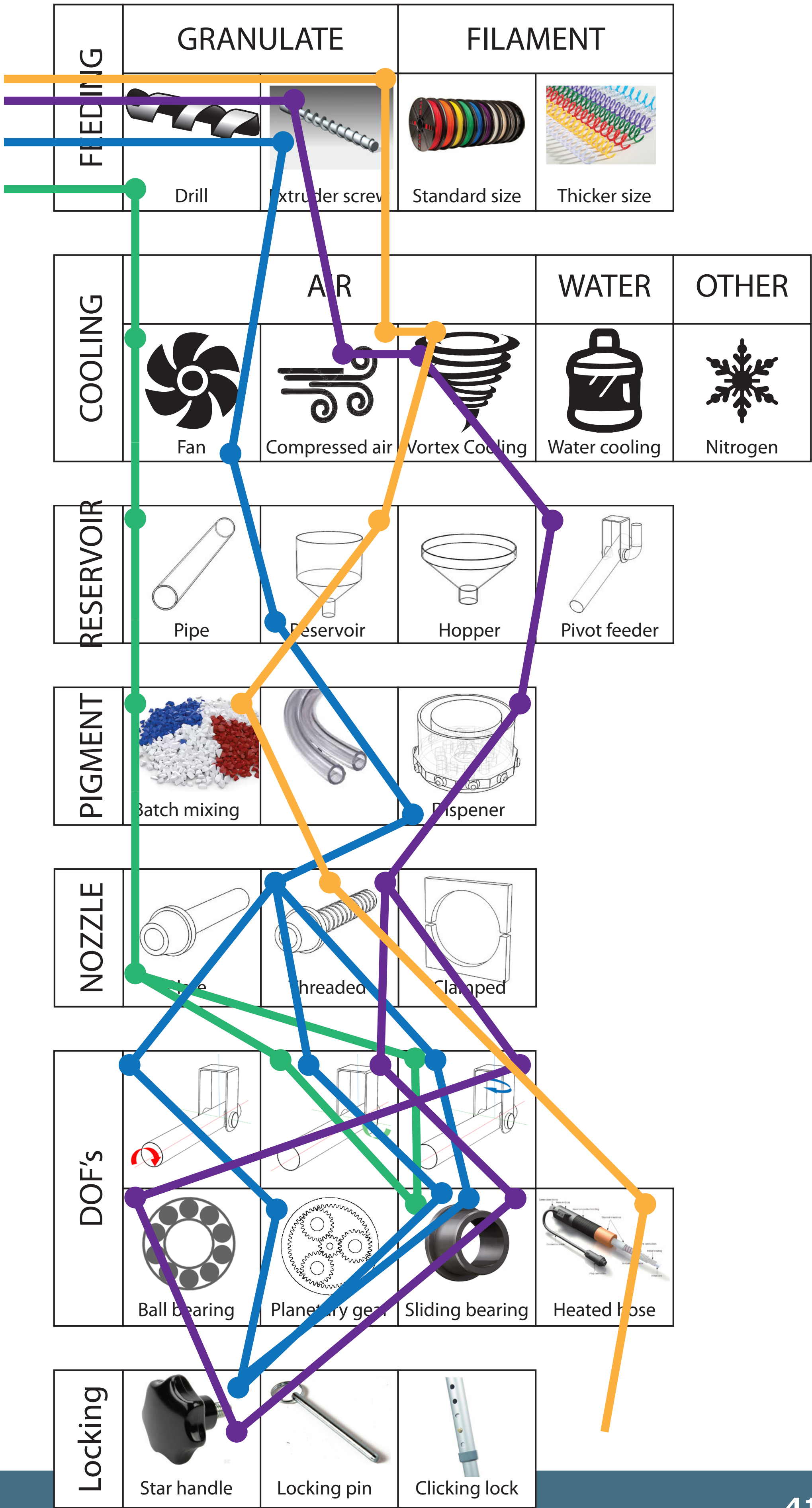


Fig 24: Morphological chart

3.3 Concept 1 - the Upgrade

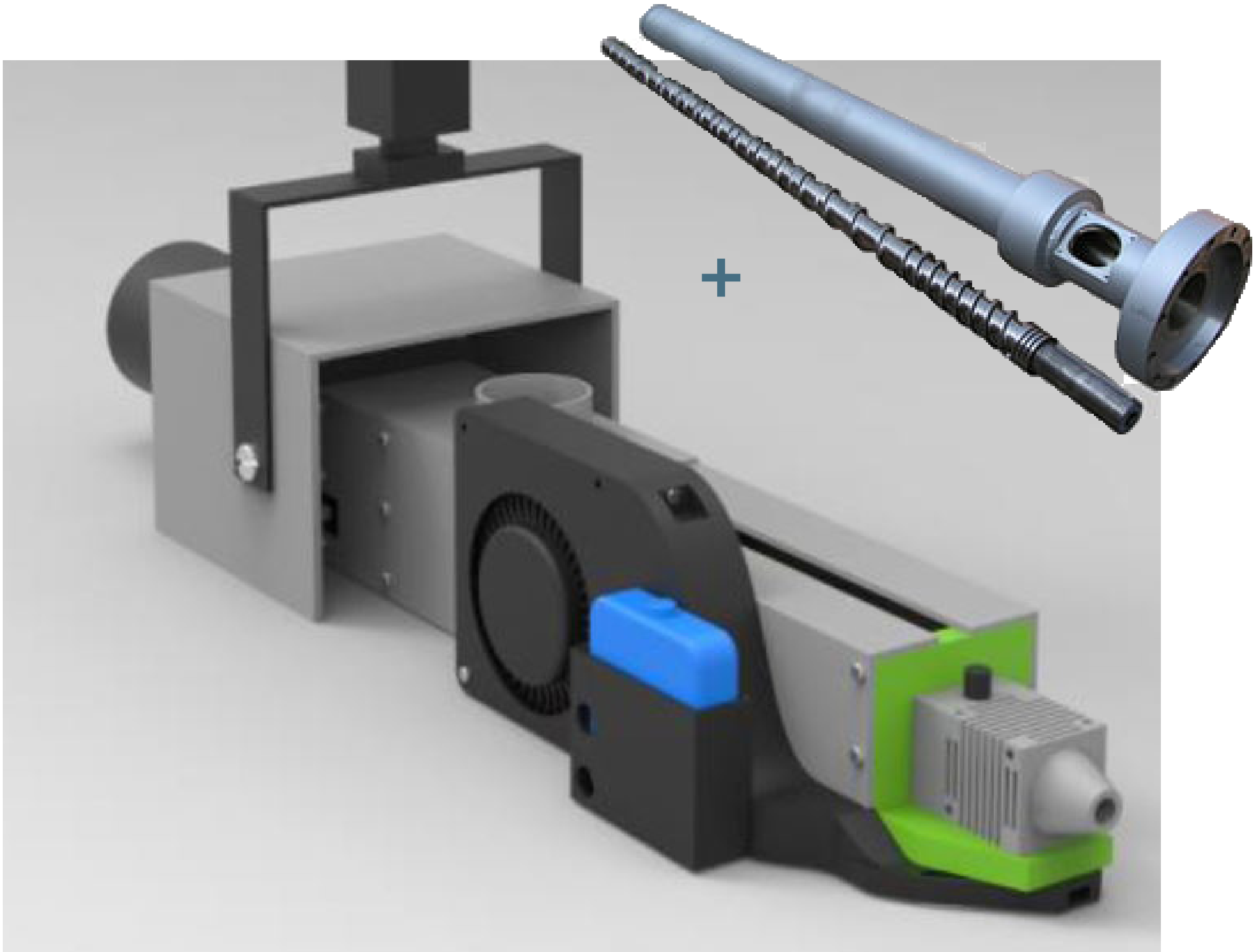


Fig 25: The original 3D-paintbrush with screw and barrel upgrade

3.3.1 Setup

The goal of this concept is to keep the costs low by using the existing 3D-paintbrush and most of the parts and make minor adjustments with big impacts.
The drill will be replaced with a extruder screw and a new barrel.
The air flowing from the fan will can be better redirected to the exit of the nozzle with a 3D printed part to further reduce the cost, however it is adviced to add the vortex cooling
A big clear reservoir will be added where the volume of the remaining granulates can be seen and can be measured
Three dispenser that will dispensing pigment into the barrel will be added, one red one blue and one yellow.
The cooling block at the end will be removed and a new block will be added allowing threaded nozzles to be easily mounted on the block.
A 3D-printed planetary gear will be added to increase the degrees of freedom of the extruder.
Grips will be added for better control and of the 3D-paintbrush.
Screws with grips will be added to lock a position of the extruder.

3.3.2 Costs estimation

This concept is the least expensive concept. but there are a lot of assumptions made. For example if you want to reuse the heater bands from the old barrel than the new barrel must have the same diameter. if the new barrel is much bigger the heating bands wont fit. This is true for any prt that will be reused.

The minimal parts needed to make this concept works are the screw and barrel. The electromotor needs to be replaced since the extruder screw melts the plastic with shear energy the motor must supply this power it will be a lot more power than the current motor can handle

Lastly a clear reservoir flexible tube will be added to so the user can keep track of the usage and sees when the reservoir is almost empty and needs refilling.

The total costs of this concept will be around €2000 euro, an overview of the costs can be seen in table 3.1

Concept 1: Upgrade	Number	Price per 1	Price total
Extruder screw + Barrel	1	1500	1500
Vortex cooler	1	200	200
Motor	1	225	225
reservoir hose	1	16	16
Cable carrier	1	30	30
		TOTAL	1971

Table 3.1: Costs for the upgrade concept

3.3.3 Advantages

- This concept requires the smallest investment.
- By only replacing the wood drill an extrusion screw the performance of the 3D-paintbrush will significantly increase.

3.3.4 Disadvantages

- You have a lot of leftover parts from the old extruder
- You only have one 3D-paintbrush compared to building a new one.
- The investment of the screw is significantly and it only required a small addition to the investment to build a new 3D paintbrush (concept 2, the cylinder)
-
- Instead of building the paintbrush around the extruder the extruder screw has to fit the current screw.

3.4 Concept 2- the Cylinder

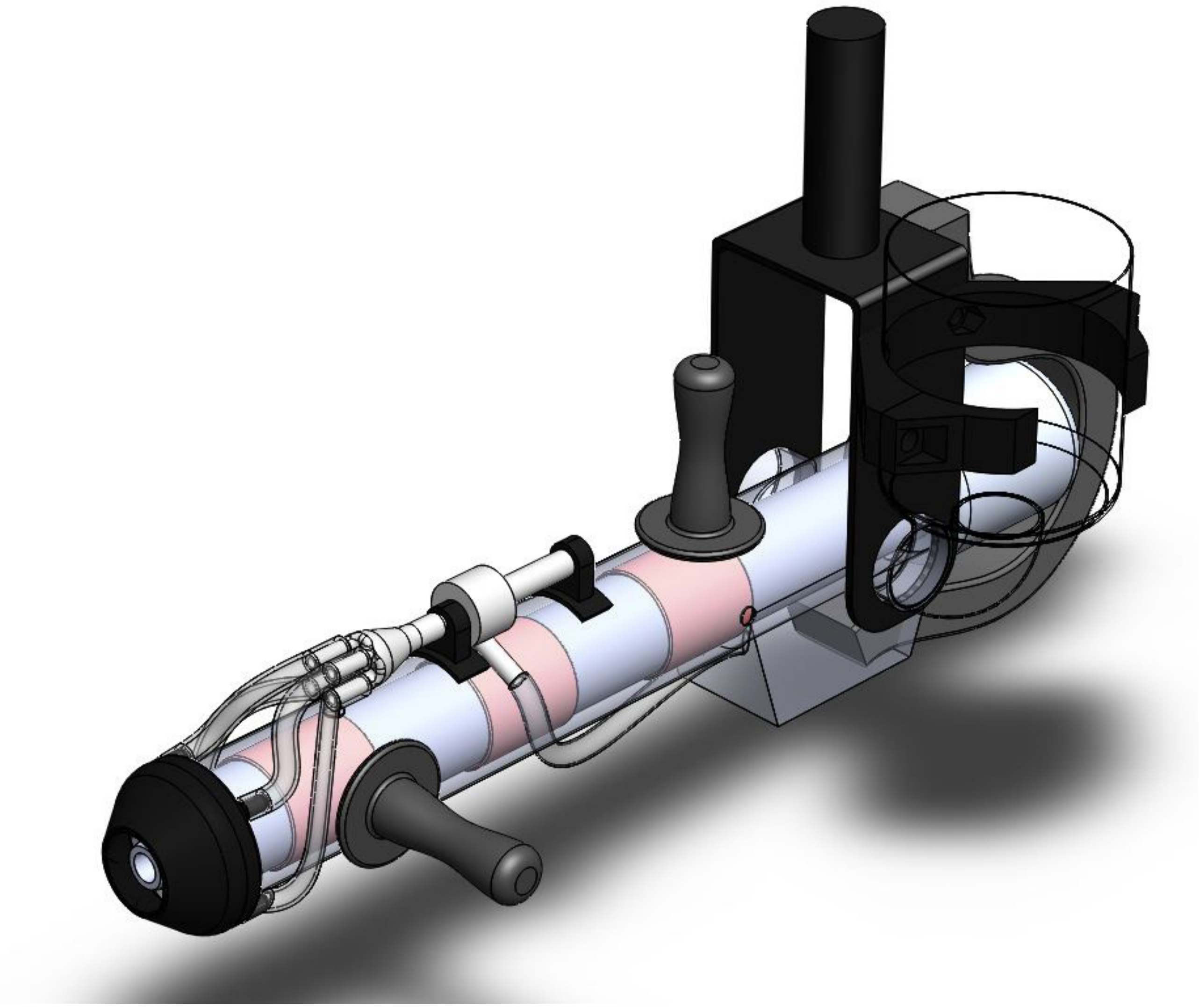


Fig 26: The cylinder concept

3.4.1 Setup

The Cylinder shown in figure 26will be a new and second 3D-paintbrush made from scratch
The goal of this concept is to build a new 3D-paintbrush learning from the first one and improving where possible. This solution keep the costs between the upgrade and the cart (concept 1 and 3)
A new extruder screw and barrel will form the base of the new cylinder.
Vortex cooling will be implemented to have a way to cool the extruded plastic fast.
A big clear reservoir will be added where the volume of the remaining granulates can be seen and can be measured
Three dispenser that will dispensing pigment into the barrel will be added, one red one blue and one yellow.
Nozzles should be threaded and replaceable
Grips will be added for better control and of the 3D-paintbrush.
Screws with grips will be added to lock a position of the extruder.

3.4.2 Estimated Costs

The Cylinder is priced between the other two concepts. The basis is the screw and barrel. But starting from scratch the frames and housing can be designed around the ideal barrel. This has an advantage over the upgrade concept because you are not limited by the dimensions of the current 3D-paintbrush

This concept needs a screw and barrel, aswell as three heating bands and all other electrical components. some bearings and 2 adjusting rings (stelringen).

The biggest costs however are the screw and barrel, the motor and the vortex cooler which are also in the upgrade concept.

the upgrade concept costed about €2000, but investing around €600 more will provide you with a second 3D-paintbrush specifically design for optimal extrusion with a lot more freedom of motion. the total costs for this concept are in table 3.2

Concept 2: Cylinder	Number	Price per 1	Price total
Extruder screw + Barrel	1	1500	1500
Heating bands	3	41	123
Pt100	3	20	60
insulating super wool	1	58	58
Vortex cooler	1	200	200
Motor	1	225	225
PID controllers	3	76	228
reservoir hose	1	16	16
bearing	1	61	61
Stelring	2	17	34
Cable carrier	1	30	30
ALuminium piping 80x5x800	1	29	29
		TOTAL	2564

Table 3.2: Costs for the Cylinder concept

3.4.3 Advantages

- It costs slightly more than the upgrade, but it will be a second 3D-paintbrush.
- Starting from scratch allows for a more efficient design, the extruder will be cylindrical and therefore thinner.
- Vortex cooling will be implemented to cool the extruded plastic faster.
- A 3D printed nozzle for the cooling will be added to spread the air around the nozzle and aim it just after the nozzle.

3.4.4 Disadvantages

- The frame is outside of the scope there need to be a second frame to have both 3D-paintbrushes operational.
- Vortex cooling requires a extra compressor and system to direct the compressed air to the vortex cooler, and thus also an extra outlet is needed.

3.5 Concept 3 - the Cart

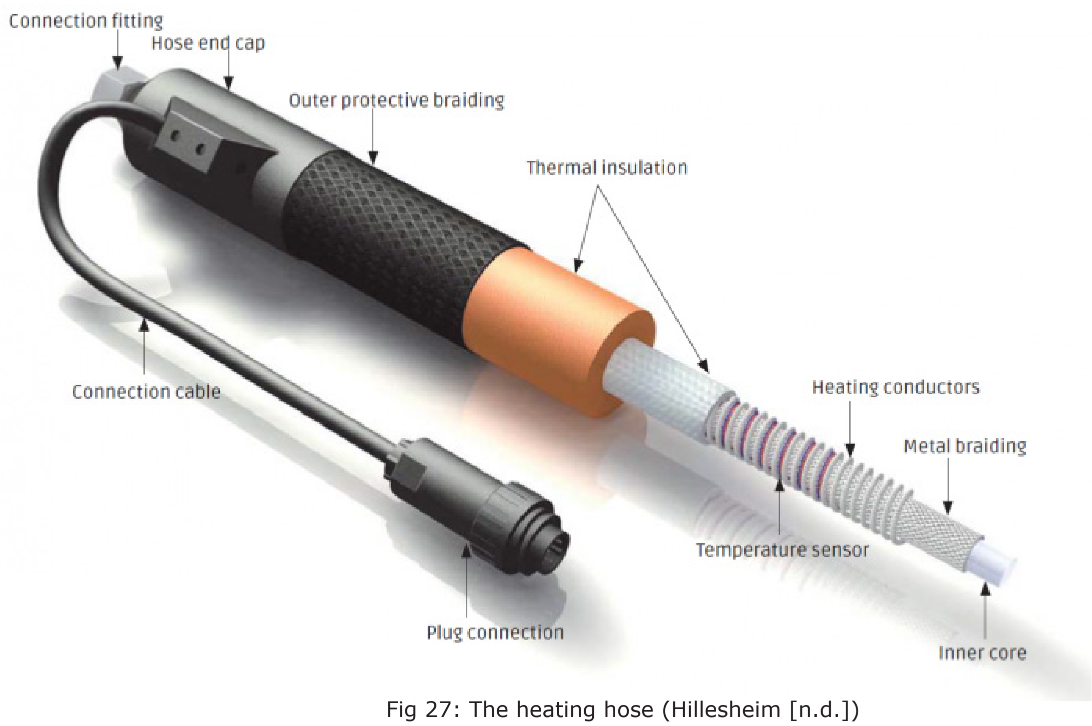


Fig 27: The heating hose (Hillesheim [n.d.])

Fig 28: Silhouette of the cart concept

3.5.1 Setup

The Cart is the "ideal" concept when it comes to movability of the nozzle. The need for a big frame with a balance mechanism is not needed. Instead the screw, barrel, motor and all electrical cables are mounted on a Cart. The compressor needed for vortex cooling is also mounted on the cart.

This leaves the user with a handheld device that only has the heating hose and air tubes leading up to it. Adding the heated hose to this concept adds a lot of freedom of movement in using the extruder, but adds a lot of costs.

A cart will form the basis of this design
The extruder screw and barrel will be mounted on the cart
The controllers and all electronics will be on the cart
A big clear reservoir will be added where the volume of the remaining granulates can be seen and can be measured. Since this is not being carried by the balans frame it can be a lot bigger.
Three dispenser that will dispensing pigment into the barrel will be added, one red one blue and one yellow.
The nozzle at the end of the heating hose will have thread and can be replaced1
The "gun" will have grips and will be designed for best control and comfort.

3.5.2 Estimated costs

The heating hose is a big investment. The price of this concept will be €1800 extra because of the heating hose. It will still be a new 3D-paintbrush so no parts willl be reused. this means that this concept needs most parts the cylinder concept used and adds the high extra cost of the heating hose.

This brings this concept up to almost €4400..

Concept 3: Cart	Number	Price per 1	Price total
Extruder screw +	1	1500	1500
Heating bands	3	41	123
Pt100	3	20	60
insulating super v	1	58	58
Vortex cooler	1	200	200
Motor	1	225	225
PID controllers	3	76	228
reservoir hose	1	16	16
Cable carrier	4m	30	120
ALuminium pipir	1	29	29
Heating Hose	1	1800	1800
		TOTAL	4359

Table 3.3: Costs for the Cart concept

3.5.3 Advantages

- A more compact setup because there is no frame needed and everything is mounted on the cart.
- The heated hose allows for the most accurate positioning and placement of the extruded plastic. With 6 degrees of freedom.

3.5.4 Disadvantages

- Adding the heated hose to the setup almost doubles the cost for this concept compared to the cylinder.
- Depending on the length of the hose it takes a long time for the plastic in the full length of the hose to be melted and this requires a lot of energy.
- Adding pigment or changing materials need to go through the whole hose before the effects can be seen, so controlling color will be a lot harder.

3.6 Harris profile

Based on all the advantages and disadvantages and together with the input from the concept meeting with Kaspar Jansen (chair of the project), Jo Gaerardts (mentor of the project) and Tiwánee van der Horst (company) a Harris profile has been made

A Harris profile looks at the program of requirements lists the most important requirements in order of significance. The more important the requirement is the higher it is on the list. The Harris profiles gives a quick and clear overview which concept should be further developed in the embodiment phase.

It is important to know that a good score for one criteria does not compensate for a bad score of another criteria, and scores can not be added to calculate the best concept (Roozenburg & Eekels, 2003)
The concept to further develop has been chosen based these results and also the discussion after the concept meeting.

3.6.1

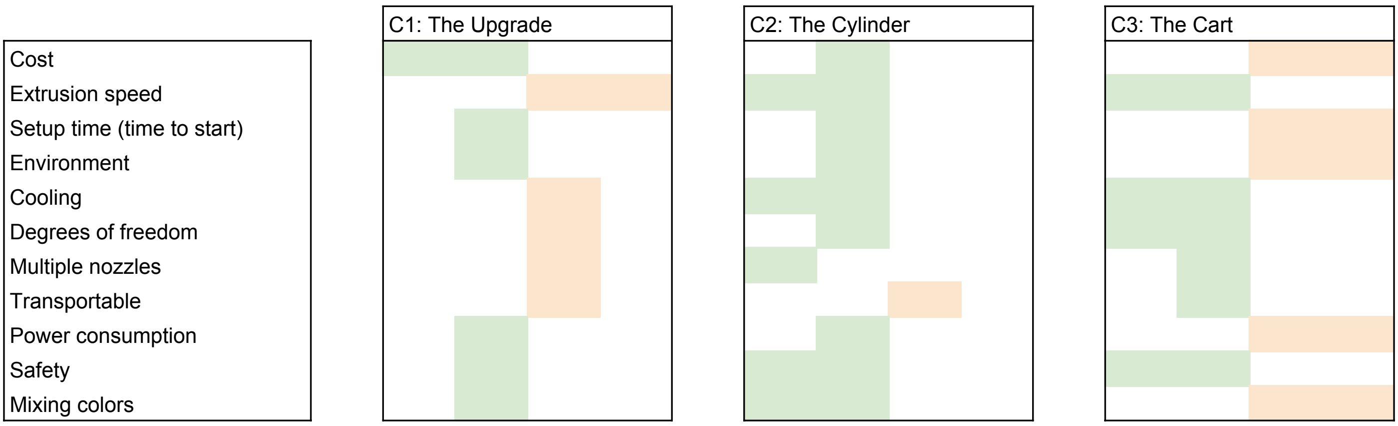


Table 3.4:a Harris profile comparing the concepts

3.6.2 Conclusion

To make an informed design decision on choosing a concept a Harris profile has been used. This method showed concept 2: the cylinder as best concept to further develop. This because it has a minimal investment to create a second 3D-paintbrush and does not have any of the big disadvantages that the cart has.

4 EMBODIMENT - THE CYLINDER

4.1 Introduction

The starting point of the embodiment phase is the second concept, the cylinder shown in figure 29. In order to validate the design a mock-up has been made. Based on the findings of the mock-up the final itterations have been done. The results of the embodiment and final itterations lead to the final design of the 3D-paintbrush shown in figure 30.

As mentioned in the ideation phase the balance frame has not been included in the design. But two versions of the frame will be presented, one version that fits the current frame, and another version for the frame mentioned in the ideation phase.

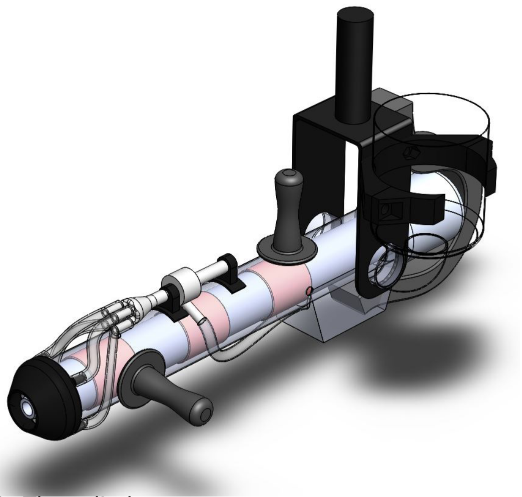


Fig 29: The cylinder concept

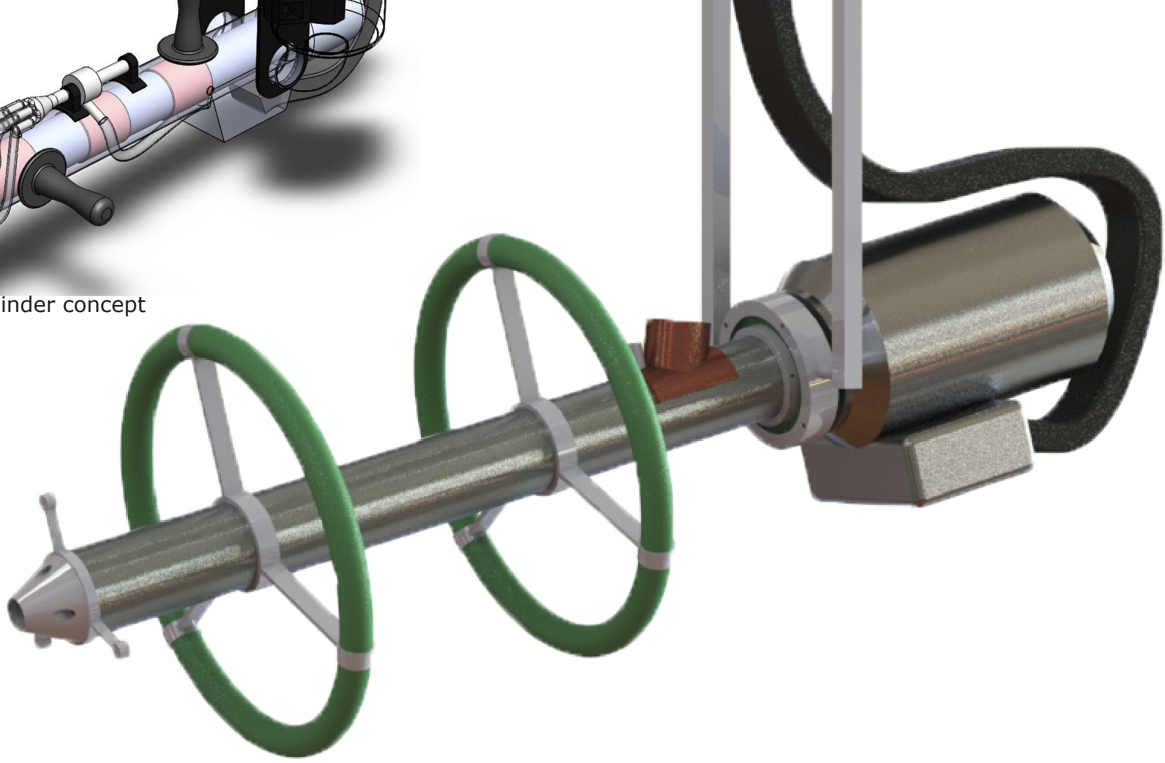


Fig 30: The cylinder final design

4.2 Part list:

The final design has the following parts they have been catergorized in six categories. All the parts can be found in the exploded view, figure 31.

Melting:
Extruder screw
Extruder barrel
Heater bands
Motor
Insulation
Nozzle

Cooling:
Cooling nozzles
Vortex cooler
splitter
tubing x3 (0.2m)
Tubing x1 (5m)
Vortex-housing connection pieces

Frame
Main Frame
Cylindrical Housing
Housing endcap
Hopper
Connection piece
Bearing holder

Connection pieces:
Reservoir Tube
Reservoir clamp
Motor/screw connection piece

Electronics
Heater band cables
Motor cables
On/off switches

Ergonomics
Handle ring small
Handle ring large
Chain cable

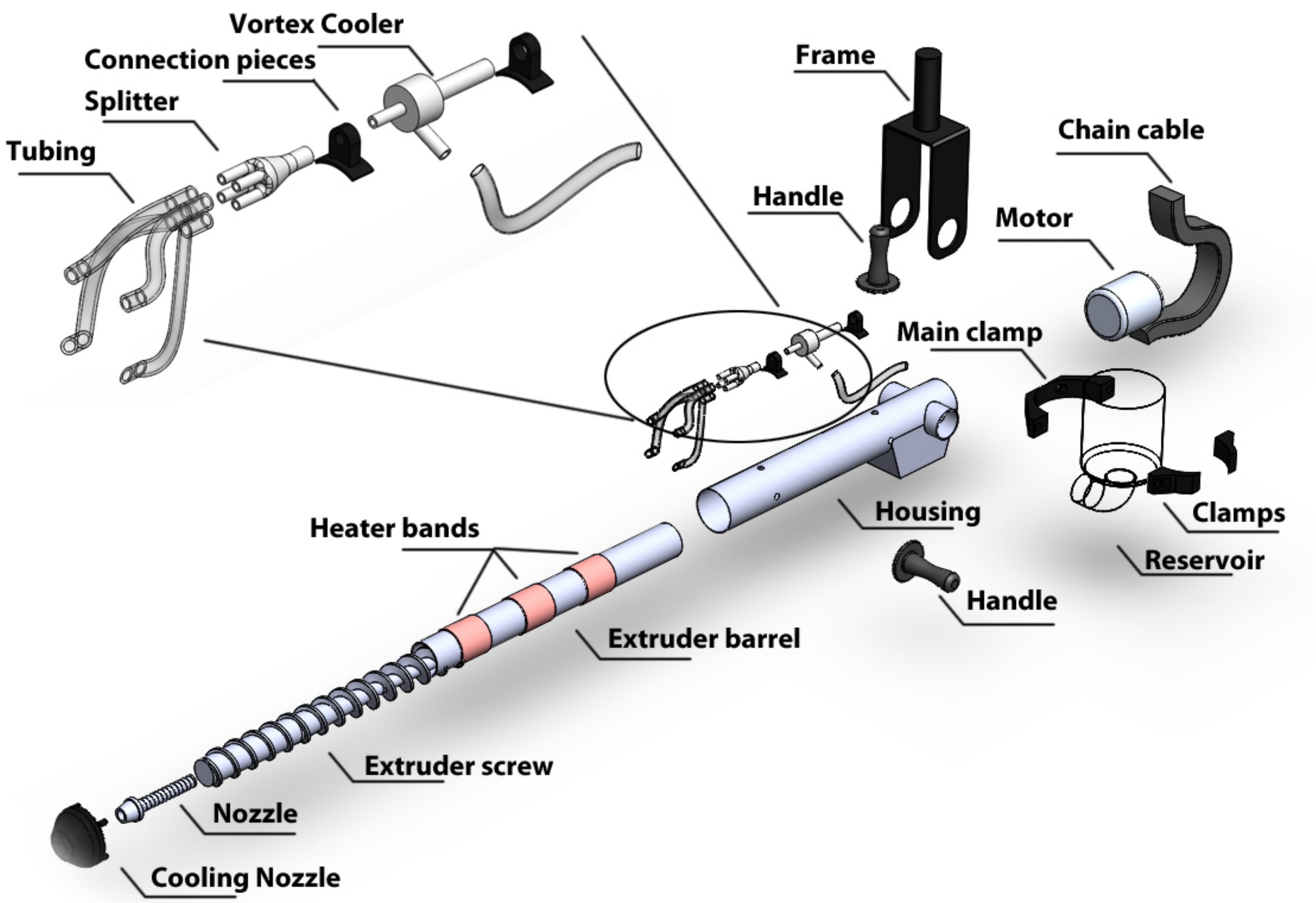


Fig 31: The cylinder Exploded view

4.3 Melting the plastic

4.3.1 Introduction

This chapter takes a deeper look into how the final design melts the plastic. It focusses on the "melting" parts of the part list mentioned in chapter 4.2. This includes the screw, the barrel, the heater bands, motor and insulation.

The design is slim and cylindrical, the dimension of this design start with the extrusion screw. The other parts are dependend on the screw.

4.3.2 The screw

As determined in Chapter 2.1 a 7,5 kg/h mass flow rate is ideal for this design. The screw as a significantly higher output, but is still small and compact enough for the 3D-paintbrush.

For a single screw there are some set design variables, starting with the diameter of the screw also known as D. The length of a extrusion screw is determined by a set length/diameter ratio (L/D ratio). Other variables are the screw profile, compression ratio and helix angle.,

To not overcomplicate things and make the screw too expensive the screw is kept as standard as possible, but is it good to understand what variables are part of an extruder screw design and what the effect of changing these variables mean.

Length/Diameter Ratio
The length / diamter ratio determines how much material can be handled at the time. A larger ratio allows more shear heat to generate uniformly in the plastic, it allows for better mixing and better homogeneity of the melt. (Reiloy USA, 2015)

Screw profile
The screw profile is the ratio between the zones. A typical screw has three zones: a feed zone, a transition or compression zone and a meter zone. Each zone in the screw has a specific function.

The feed zone feeds the pellets from the hopper into the screw, a longer feed zone creates a greater potential output. (Reiley USA, 2015)

After the feed zone the pellets enter the transition zone. This is where the pellets are compressed and melted and in this zone the channel depth will decrease. A longer transition zone gives the pellets more time to melt by convectional heating and require less shear heat, and vice versa.

The last zone is the metering zone, The plastic entering the zone should already be fully melted. The meter zone conveys the plastic to the nozzle along a constant channel depth to controll the output temperature and viscosity. a longer meter zone allows for more time to assure an isothermal and uniform melt quality (Reiley USA, 2015).

Compression ratio
As mentioned the transition zone compress and melt the pellets and the channel depth will decrease. The ratio between the channel depth at the start and the end of the transition zone is called the compression ratio. A typical compression ratio for an extruder screw is between 3.0:1 and 5.0:1 for extrusion screws. (Reiley USA, 2015)

A higher compression ratio increases the sheat heat on the pellets. Creates a higher heat uniformity of the melted plastic but can potentially create stress in some plastics.
(Reiley USA, 2015)

some typical compression ratios for PE and PP can be found in the theory about rheology (Single screw extrusion analysis, n.d.). The values are
HDPE (3.0-3.5)
LDPE (3.5-4.0)
PP (3.0-4.0)

For the design of the screw an average compression ratio of 3.5:1 has been chosen. This ratio is good for HDPE the most used material currently and also are suited for LDPE and PP.

Helix angle
The helix angle is the angle of a screw flight relative to a plane perpendicular to the screw axis. The standard helix angle is 17.6585° this makes the pitch, the distance between a flight to the same spot on the next flight, the same length as the diameter of the screw. This is called a scquare pitch.

Changing the helix angle is very uncommon. lowering the helix angle increases the turns per diameter. which allows for stiffer materials to convey with greater ease.(Reiley USA, 2015)

Chosen variables
The aim for this project is to increase the extrusion speed by five times. this requires a mass flow rate of 7.5-8.0 kg/h. As mentioned in Chapter 2.1, the partial solutions a extrusion screw of 7.5 kg/h fits the extrusion requirements and will not be too big or heavy. Based on the other dimensions of the extruder screw have been determined.

These first of the dimensions are taken from two standard screws currently available on the market that have an output between 7 and 9 kg/h. These two screws are: Neoplast (Neoplast, 2018) and Potop (Potop, 2018). From this it can be concluded that a extruder screw with an output of 7-9 kg/h has a screw diameter of 25mm. The two benchmarks from Neoplast (“Single Screw Extruder | neoplast”, 2018) and Potop (“Lab Small Single Screw Extruder”, 2018) can be found in Appendix E.

From the 25mm diameter screw the rest of the dimension can be established. Both Neoplast and Potop use a L/D ratio of 28. With a 25mm screw diameter this make the flighted length of the screw 0.7m.

From the 0.7m length of the screw we can determine the length of the feed-, compression- and metering zones with the 5-15-8 ratio.

Based on the variables and the benchmark examples of excisting screws the screw for the 3D paintbrush will have the following variables:

L/D ratio	= 28:1
Screw profile	= 5-15-8
- feed zone	= 0.125m,
- compression zone	= 0.375m
- metering zone	= 0.200m
compression ratio	= 3.5:1
- Channel depth	= 7.5mm
Helix angle = (square pitch)	= 17.66°

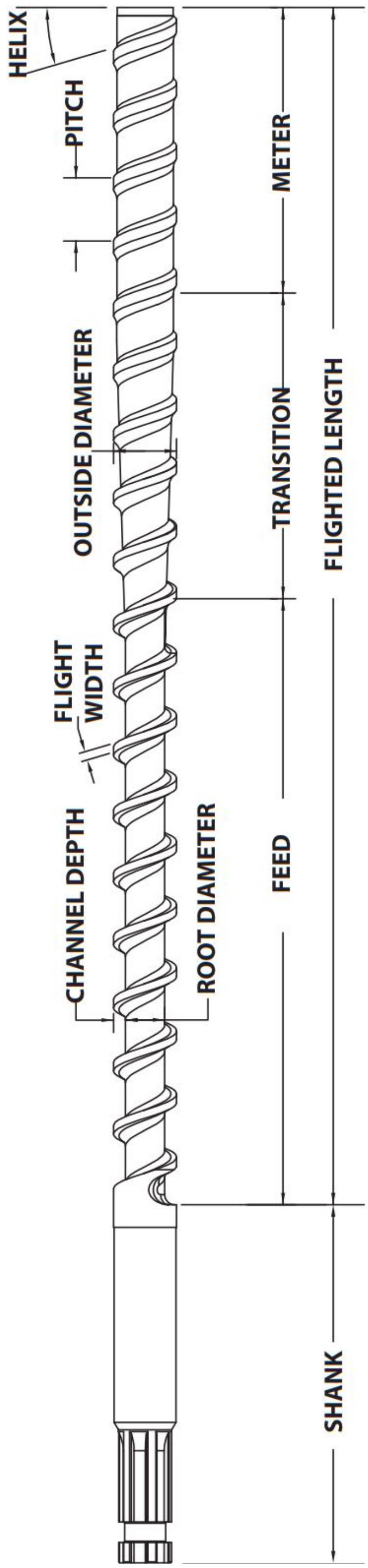


Fig 32: Extruder screw variables (Reiloy USA, 2015 (Edited))

Material screw
For this design the screw should be as standard as possible since a 3D-paintbrush is not used as much as a injection moulding machine that runs almost 24/7 and deals with a lot more pressure

Most screws are made from an 4000 series steel alloy, or nitriding steel (Reiley USA, 2015). however this material needs a heat treatement or an attitional coat to increase the wear resistance. Table 4.1 shows other possible materials a screw can be made of. The further down the table the harder the material gets and the more resistant it is to various wear conditions.

It is important to keep in mind that even a alloy steel screw needs somekind of treatment. the barrel and screw handbook (Reiley USA, 2015) states that the thickness of the treatment is important when it comes to extruder screws.

BASE SCREW MATERIALS				ACCEPTABILITY FOR RESIN WEAR CONDITIONS				
MATERIAL DESIGNATION	TREATMENT (1)	Rc (2)	FH (3)	ABRASIVE			CORROSIVE (7)	
				NORMAL (4)	AVERAGE (5)	SEVERE (6)	MODERATE	SEVERE
ALLOY STEELS:								
4140	Flame-hardened	48-55	no	Acceptable	Poor	Unacceptable	Unacceptable	Unacceptable
4140	Chrome-plated	60-65	Optional	Good	Acceptable	Unacceptable	Good	Unacceptable
Nitralloy 135-M	Nitrided	63-70	Optional	Good	Acceptable	Unacceptable	Poor	Unacceptable
TOOL STEELS:								
PM 9V	Heat-treated	54-56	no	Excellent	Excellent	Good	Acceptable	Unacceptable
PMM4	Heat-treated	62-64	no	Excellent	Good	Acceptable	Poor	Unacceptable
PM Stainless Tool Steel	Heat-treated	54-56	no	Excellent	Excellent	Good	Excellent	Good
SPECIAL ALLOYS:								
Hastelloy C-276	Age hardened	RB 87	Optional	Acceptable	Unacceptable	Unacceptable	Excellent	Good
Nickel 718	Age hardened	43-45	Optional	Acceptable	Unacceptable	Unacceptable	Excellent	Good
XC4000	Carbide Encapsulated	70+	Optional	Excellent	Excellent	Good	Excellent	Good
XC1000	Carbide Encapsulated	70+	Optional	Excellent	Excellent	Good	Excellent	Poor

(1) Includes chrome-plating to .003"-.005" and gas or ion nitriding for 24+ hour cycle.
(2) Rockwell C hardness
(3) Flight hardsurfacing required
(4) Thermoplastics with no reinforcements
(5) Thermoplastics with up to 30% reinforcement.
(6) Thermoplastics with more than 30% reinforcement.
(7) Moderate includes cellulosics, acetals and others containing corrosive additives.

Table 4.1: Screw material guidelines (Reiley USA, 2015)

Pressure in the screw
An extruder screw has three zones, in each of these zones the pressure changes.

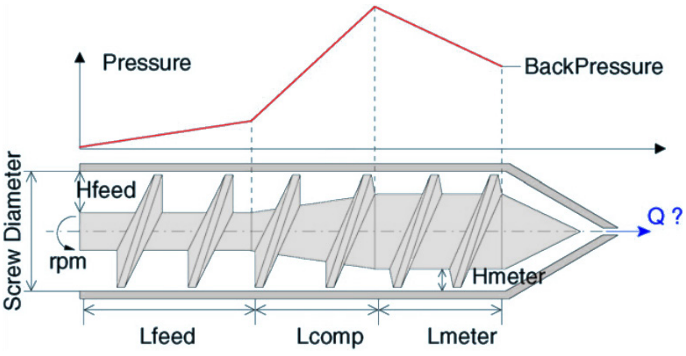


Fig 33: Pressure in a three zone screw. (Bereaux, Y. 2009)

Figure 33 shows the pressure gradient in an extruder screw.

In the first zone, the feed zone the pressure increases along the length of the screw. Most if this pressure generated comes from atmospheric pressure created by the rotation of the screw

The barrel has a smooth interior surface therefor the pressure can not reach high values. This is because the pellets touching the barrel will start to melt and thus releasing any pressure. at the end of this zone a thick film of molten plastic has formed. (Béreaux, Charmeau & Moguedet, 2009)

The rest of the melting occurs in the transition or compression zone. The melted film against the barrel wall will increase, penetrating the solid bed and creating a melt pool (Béreaux, Charmeau & Moguedet, 2009)). This is shown in Figure 34

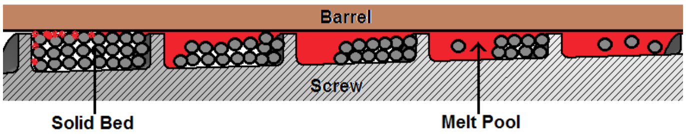


Fig 34: Forming of the melt pool in the compression zone. (Macro Engineering & Technology, 2015)

Because this occurs in the compression zone where the volume ratio at the end of the zone is 3.5 times smaller than the beginning of the zone the pressure will rise to reach a maximum at the end of the zone.

Nearing the end of the compression zone an entering the metering zone the solid bed is completely melted and the melt is only being conveyed past this point.

Ideally the pressure drops in the metering zone. A drop in pressure in this zone promotes the drag flow while an increase in pressure hinders the drag flow (Béreaux, Charmeau & Moguedet, 2009).

figure 35 shows the flow between two plates of infinite length, with one plate in motion. This plate has a speed of V0. the velocity profiles V change depends on the pressure P

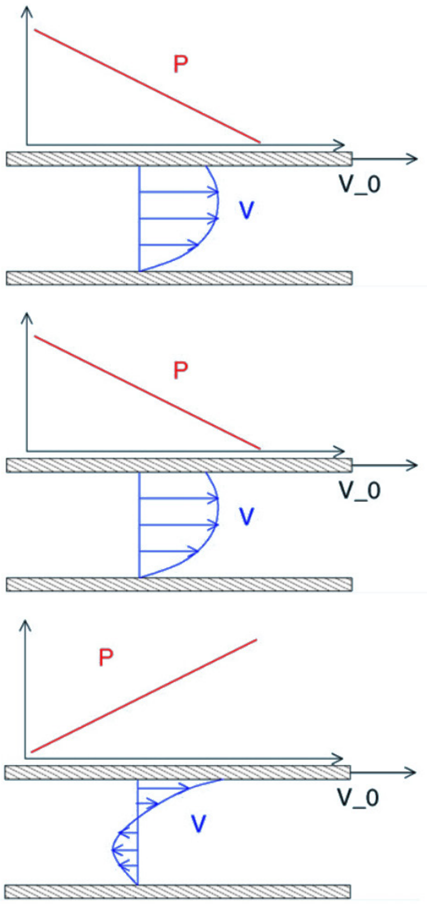


Fig 35: Velocity profiles according to the pressure gradient. (Béreaux, Charmeau & Moguedet, 2009)

4.3.3 Motor

The electromotor is a important part of melting the plastic because the drill has been replaced by a screw the motor has to deliver the energy to partly melt the pellets.

According to the Barrel and screw handbook 75% to 80% of the energy to melt the pellets in an extruder screw is mechanical energy and comes from shear heating inside the barrel (Reiley USA, 2015)

now that the dimension and variables of the extruder screw are know we can calculate how much energy needs to come from the motor.

Power requirements
The power of the motor must be high enough to melt the plastic and pump the molten plastic to the nozzle. For these calculations we take the mechanical properties described in chapter 1.9. A table of the values can be found in Appendix A.

The energy needed to melt a plastic can be calculated by the folowing equation (Single screw extrusion analysis, n.d.).

$$P = (P_{heat} + P_{HF}) \times 0.75 + P_{pressure} \qquad (1)$$

Equation 1 can be split up into three part to better understand where the energy is used for.

The first part is the energy needed to heat up the material from room temperature to a desired temperature past the T_g and T_m of a plastic. Usually the temperature settings of a plastic supplier are leading and overrule the technical properties. The power needed to heat up the plastic is calculated by equation 2

$$P_{heat} = \dot{m} \times Cp \times \Delta T \qquad (2)$$

where :

$\dot{m}$ = massflowrate in kg/h
C_p = heat capacity in J/kg°C
ΔT = temperature rise in °C

The second part is the energy needed to break the crystalline bonds. This is called heat of fusion (H_f). For a amorphous plastic the H_f is 0 since they do not have crystalline bonds. It is calculated by equation 3.

$$P_{Hf} = \dot{m} \times Hf \qquad (3)$$

Where :

$\dot{m}$ = massflowrate in kg/h
H_f = heat of fusion in J/kg

It is mentioned that only about 75% comes from the motor so we multiple the outcome of formula 2 and 3 by 0.75 as can bee seen in equation 1.

The last part is the of the motor power compensates for the head pressure inside the screw.

this is calculated by equation 4

$$P_{head} = \dot{m} / \rho \times \Delta P \qquad (4)$$

Where:

$\dot{m}$ = massflowrate in kg/h
ρ = density of the material in kg/m^3
ΔP = head pressure

With these formulas the power requirements have been calculated. HDPE has been used because it is the preferred material and the material being used the most used at this moment.

$\dot{m}$ = 7.5 kg/h
C_p = 2500 J/kg°C
ΔT = (230-20) 210 °C
H_f = 250000 J/kg
ρ = 965 kg/m^3

Head pressure is a different variable it is the pressure build up in the form of back pressure resulting from the screens, breaker plate and die as can bee seen in figure 36.

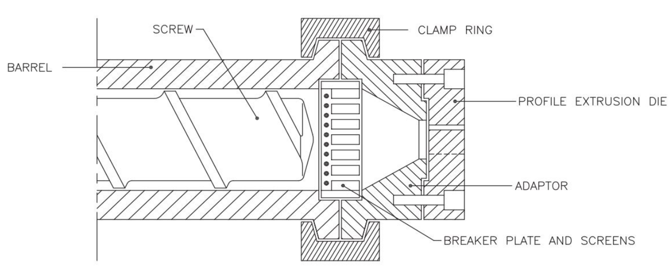


Fig 36: Extruder head components (Reiloy USA, 2015)

The screens are wires meshes that filter unpurities in the material. the breaker plate is a plate with holes it distributes the forces in the meshes so that they are pushed against the breaker plate and will not break.
These parts are commonly used in professional extruder screws but are not needed in the 3D-paintbrush. Ofcourse the 3D-paintbrush has a die which is the nozzle.

According to the single screw extrusion analysis n average head pressure is between 10 and 50 MPa (Single screw extrusion analysis, n.d.).
Since the 3D-paintbrush has no screens or breaker plate we assume the head pressure is at the lower end, so for this calculation we assume that 10 MPa will be enough back pressure.

The power requirements for each of the three parts of equations have been made the calculations can be found in appendix G: "Power requirementes calculations for the motor of the 3D-paintbrush".

It can be concluded from these calculations that most of the energy goes into heating up the plastic from room temperature to its desired extrusion temperature, in this case 0.82 kW. And 0.39kW is used to break the crystalline bonds. Only 0.02kW is used to pump the plastic to the system.

The calculated power requirements are 1.23kW
The actual electromotor needs to supply more power considering electromotors do not have an efficiency of 100%. In appendix H2: Technical data electromotor it shows that an electromotor of that size have an efficiency of 79%.
The chosen motor should atleast supply 1.64 kW of power in order to melt the plastic at 7.5 kg/h.

Chosen electromotor

Knowing that the motor needs to supply 1.62kW of power we can select the motor for the 3D-paintbrush.

A motor with 2.2kW has been selected. This motor has enough power to melt and pump the plastic.

The motor is 315mm long and 185 mm wide. these dimension are shown in figure 37. This motor also have been selected because of the power supply, it can run on 230V and does not need a higher current.

The full list of dimension and specification can be found in appendix G2

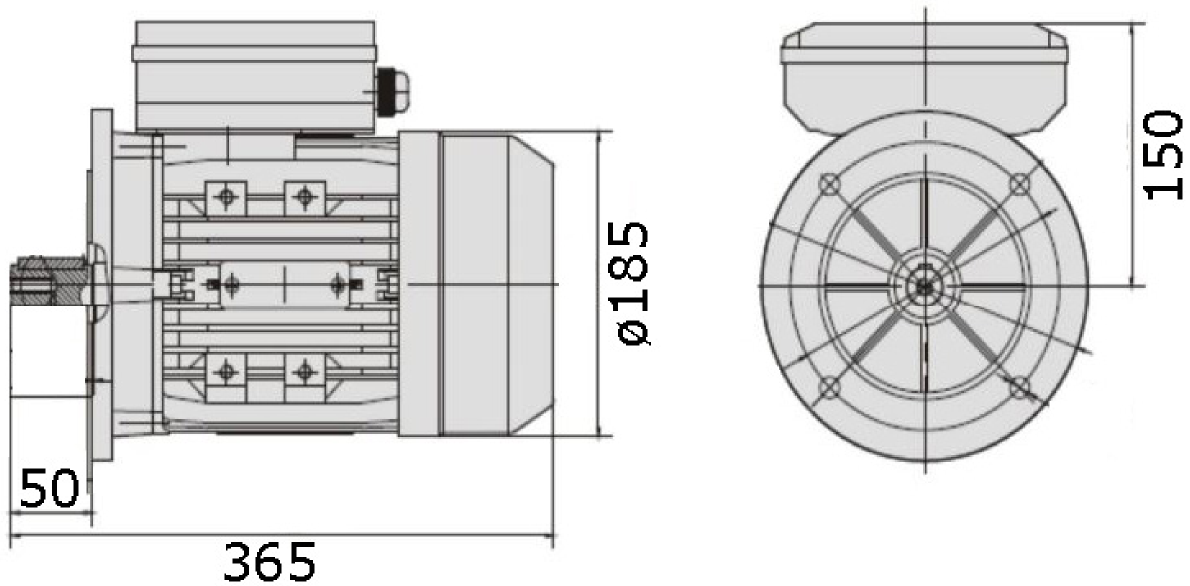


Fig 37: Motor dimensions (Electramo.com; edited)

4.3.4 Barrel

The barrel should fit the screw thightly. and should be a bit longer than the screw to fit the nozzle and the connection with the electromotor. The outer diameter of the barrel is important for the size of the heating bands.

Just like the extruder screw the barrel should be as basic as possible.

Material

The materials are most of the time determined by the machine supplier but based on the theory we can determine what options are possible for the 3D paintbrush.

The most common material for the external portion of the barrel, called the shell, is 4100 series alloy steal (reiley USA, 2015). From the screw calculations we already know that there is not a lot of head pressure and therefor the internal pressures are low enough to make 4100 series alloy steel suitable for the barrel.

Other material options for the barrel are tool steels or special alloys. They improve the wear resistance but will make the barrel more expensive. Considering the barrel is used in the 3D-paintbrush and not a production machine that runs 24/7 investing in a better barrel is not adviced. All possible material options can be found in the screw material guideline (Reiley USA, p.41, 2015) and in table 4.2

In chapter 1.7 we learned that moist in the pellets can affect the quality of the work, but moist can also corrode the barrel. A chrome plated treasment is adviced to improve the corrosive resistance and also improves the wear resistance of the barrel.

Size

Based on the screw the barrel should have the following dimensions, it should be 750mm long with an outer diameter of 30mm and a wall thickness of 2.5mm.

BARREL MATERIAL GUIDELINES

BARREL LINING MATERIAL	HARDNESS RANGE Rc	ACCEPTABILITY FOR RESIN WEAR CONDITIONS				
		ABRASIVE			CORROSIVE	
		NORMAL(1)	MODERATE(2)	SEVERE(3)	MODERATE(4)	SEVERE(5)
NITRIDE: (Gas or Ion)						
4140 or equivalent	63-70	Acceptable	Poor	Not acceptable	Poor	Not acceptable
Nitralloy 135 M or equivalent	63-70	Acceptable	Poor	Not acceptable	Poor	Not acceptable
CAST BIMETALLICS:						
Reiloy R121	N/A (6)	Good	Acceptable	Poor	Poor	Not acceptable
Reiloy R216	N/A (6)	Excellent	Excellent	Good	Good	Good
TOOL STEELS:						
D-2	58-60	Good	Acceptable	Poor	Acceptable	Not acceptable
PM10V	62-64	Excellent	Excellent	Good	Acceptable	Not acceptable
PM Stainless Tool Steel	58-60	Good	Acceptable	Acceptable	Excellent	Good
SPECIAL ALLOYS:						
Nickel 718 (Inconel or Pyromet)	43-45	Acceptable	Not acceptable	Not acceptable	Excellent	Excellent
Monel K-500	37-39	Acceptable	Not acceptable	Not acceptable	Excellent	Excellent
Hasstelloy C-276	RB 87	Acceptable	Not acceptable	Not acceptable	Excellent	Excellent
C-2 Tungston Carbide	79-81	Excellent	Excellent	Excellent	Excellent	Good

(1) All thermoplastics without reinforcement or abrasive fillers.
(2) Thermoplastics with abrasive reinforcement or fillers up to 30%.
(3) Thermoplastics with 30% or more reinforcements or abrasive fillers and thermosets.
(4) Cellulosics, Ionomers, Acetals and others containing corrosive additives.
(5) Fluoropolymers.
(6) Standard HRc unmeasureable due to the extreme hardness of the carbides in this matrix.

Figure 4.2: Barrel material guidelines (Reiley USA, 2015)

4.3.5 Heating bands

With the outer diameter of the barrel known the heating bands can be specified. The inner diameter of the heating bands must be 30mm. nl.rs-online.com offers suitable heating bands.

The requirement from chapter 1.3.3 determine that the 3D-paintbrush can use materials that heat up to 300°C, the heater bands must be able to heat up to 300°C too.

In chapter 4.3.3 the power calculations for the motor have been made. In that chapter was stated that 75% to 80% of the energy to melt the pellets is mechanical energy and comes from shear heating inside the barrel (Reiley USA, 2015) This means that the other 20% to 25% must come from conductive heating of the heater bands.

With the same equations for the electromotor power requirements the power requirements for the heating bands can be calculated. This can be found in Appendix G.

These equations show that the heater bands need to have a power of 0.404 kW in order to provide enough energy to heat up the pellets.

The chosen heater bands have a diameter of 30mm and a width of 30mm all the dimension are shown in figure 38. It can be heated up to 340°C and have a power of 0.135 kW. Three heating bands will together provide 0.405kW which will be enough. The full specifications can of the heater bands be found in appendix G2

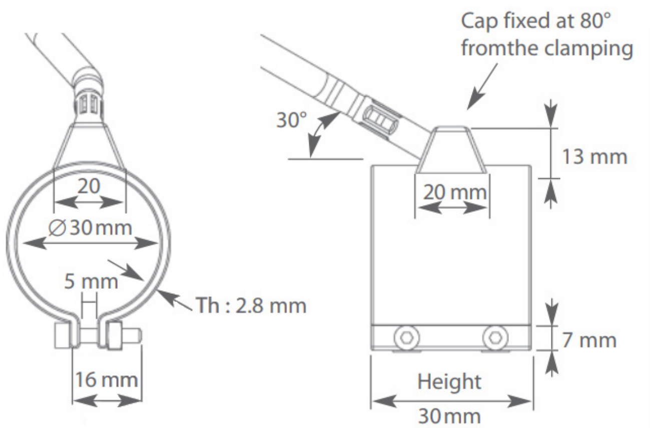


Figure 38: Dimensions heater bands (Acim Jouanin, 2018 (edited))

Bands placement
In chapter 4.3.2 the pressure gradient along the three zones of the screweds have been showed. these profiles are important for the placement of the heater bands.

Given the extruder screw has a length of 700m with a 5-15-8 ratio the lengths of the zones are known. The feeding zone is 125mm, the compression zone is 375mm and the metering zone is 200mm

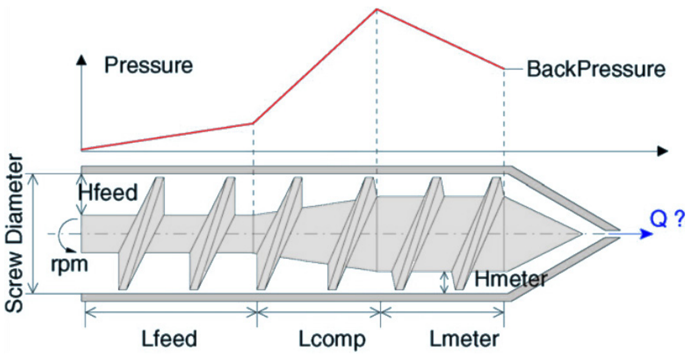


Fig 39: Pressure in a three zone screw. (Bereaux, Y. 2009)

knowing that three heater bands are needed to supply the power to assist on melting the plastic and knowing the pressure gradient as described in 4.3.2 and shown in figure 39

The first heater band will be placed at the end of the end of the feed zone this will help the pellets eat up a bit and start the thin film of melted plastic against the barrel wall.
The second heater band will be placed at the end of the compression zone. This band will assist melting the plastic and controll the temperature output at the end of the compression zone.
The last heater band will be placed at the end of the metering zone. This band will controll the tet

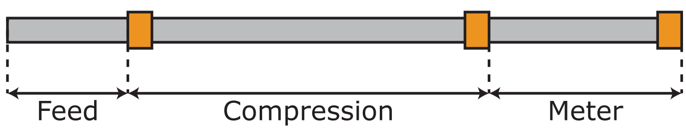


Figure 40: Heater bands placement

Temperature sensors
The temperature will be measured with PT100 RTD sensor. PT100RTD stands for platinum 100 resistance temperature detector. it is a platinum thin film sensing element encased in a ceramic housing.

The temperature difference of the platinum increases or decreased the resistance of the sensor. The 100 in PT100 means that the sensor has 100 Ω resistance at 0°C.

These sensors have a temperature coefficient. This is a ratio the resistance changed per °C increase or decrease. This coefficient is based on the material for platunum is it 0.385 Ω/100°C

using Ohm's law R=V/I we can calculate the resistance and therefor the temperature change by measureing the voltage.

The selected PT100's have a diameter of 2.8mm and a length of 25mm all specifications for the Pt100's can be found in Appendix G3.

The temperature sensors should be mounted close to the heating bands in order to create the best feedback loop to the system.

Insulation
Insulation is needed around the barrel this keeps the heat around the barrel and prevents it from dissipating into the surroundings. In addition it prevents the outside of the 3D-paintbrush from becoming too hot.

In order to understand insulation we have to understand two kinds of mechanical properties.

Thermal conductivity
Thermal conductivity measures the rate at which heat can pass through. A lower Themal conductivity means it takes longer for heat to pass through. It is measured in W/m°K

Heat capacity
The heat capacity is how much heat the material can store. It is measured in J/kg°C

A material with a low thermal conductivity and a high heat capacity is the best insulation.

The selected product is a Calcium-Magnesium Silicate Thermal Insulation (nl.rs-online.com, 2018) more imformation about this material can be found in Appendix G4

Figure 41: Pt100 sensor (nl.rs-online.com, 2018)

Figure 42: Calcium-Magnesion Silicate Thermal Insulation (nl.rs-online.com, 2018)

Insulation heat loss calculation
Conductive heat loss through the wall of a cylinder or pipe can be expressed calcuted. For this calculating the assumption is made that the insulation is a pipe. The pipe has the dimensions as the space between the barrel and the frame. The inside temperature of the pipe is 230°C and the outside is room temperature 20°C. Here the metal of the barrel and the frame are ignored.

The equation for heat loss is based on Fouriers law and according to the theory (Cylinders and Pipes - Conductive Heat Losses, 2018) heat loss for pipes can be expressed with the following equation.

$$Q = (2 \times \pi \times L \times \Delta T) / (\ln (r_0/r_i) /k) \qquad (1)$$

With the information of the 3D paintbrush and the insulation material we can calculate how much heat loss occurs. For this the following variables have been used

Thermal conductivity at 400°C of the insulation according to the datasheet (Appendix H4)

k= 0.10 W/m°K

The length of the barrel

L= 0.750 m

The temperature difference between the barrel and the outside. HDPE will be heated up to 230°C and the outside temperature is room temperature of 20°C

ΔT= 210 °K

The outer and inner diameter of the insulation.

r_o= 0.07 m
r_i = 0.03 m

By using these variables in equation 1 the conductive heat loss is calculated. The rate of heat loss 117W or 117 J/s

<u>*Nozzle*</u>
A design has been made for the nozzle to be replacable. It can be screwed into the housing end cap with M30 thread (see 4.5.2). By screwing in the nozzle has a perfect fit that wont leak. In addition the nozzle wont be pushed out under pressure.

50mm of the nozzle can be inserted into the housing end cap allowing for new shapes of nozzles such as a flat nozzle or a nozzle with a core (see chapter 5.4 validation).

Two nozzles with a core, for hollow extrusion, have been made and tested, one out of aluminium and one out of steel. The aluminium wears a lot when trying to remove the nozzle and the steel one is more durable.
Although aluminium is a better heat conductor it is adviced to use steel nozzles in a system where the nozzle will be changed a lot.

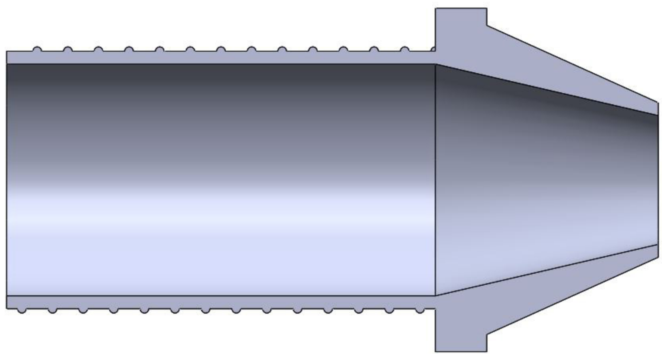


Figure 43: A 15mm outlet nozzle with 50mm M30 thread

4.4 Cooling the plastic, the vortex cooler.

4.4.1 Introduction

This chapter takes a deeper look into how the final design cools the plastic after it exits the nozzle. It focusses on the “cooling” parts of the part list mentioned in chapter 4.2. This includes the vortex cooler, the cooling nozzle, the splitter, the tubing and the vortex-housing connections.

4.4.2 Vortex cooler

The vortex cooler is an important new feature of this design. It is a new and effective way to cool plastics. Vortex cooling has briefly been described in chapter 2.1.2 of the Ideation phase.

In this phase vortex cooling has been explored by testing an actual vortex cooler as shown in figure 44
The model to test with is the ITW Vortec personal air cooler (PAC) This model is design to cool down a vest. This model has a temperature regulator which can be controlled by turning a lever (1).

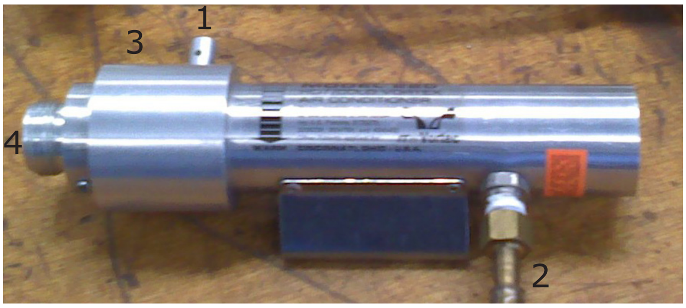


Figure 44: ITW Vortec PAC

At first the vortex cooler was tested as is, this is shown in figure X. This vortex cooler has an inlet for compressed air at he bottom right (2). a hot air outlet at the top left (3), and a cold air outlet at the left (4).

This setup has been tested with a FLIR Camera, which captures thermal images The same spots have been marked into the FLIR images. For this test the lever has been turned so that the vortex cooler supllies the coldest possible air with this setup.

A movie of the temperature changes have been captured. The two images, figure XX and figure xx are stills taken from the beginning and the end of the recording.

At the beginning the whole cooling system has a temperature around 25 °C. Within in a minute the temperature changes and the cold air coming out of the cold outlet falls to 17°C. The hot outlet reaches a temperature up to 35°C

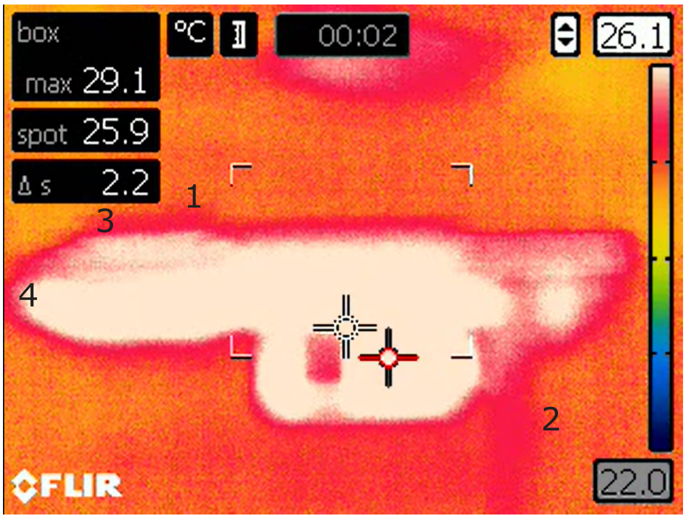


Figure 45: FLIR image beginning of the recording

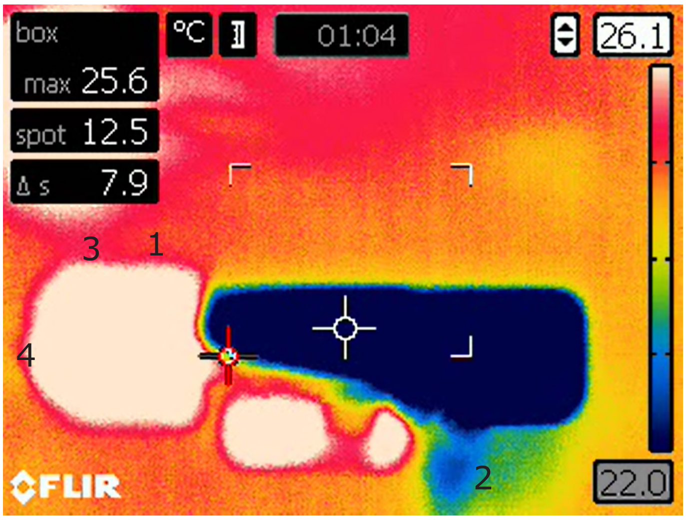


Figure 46: FLIR image end of the recording

By removing the air regulator the vortex cooler itself is exposed. This vortex cooler is a lot smaller and more compact as can be seen in figure 47. Unlike the the cooler with the temperature regulator this has the outlets on opposite sides.

In figure 47 the compressed air enters at the inlet (A). The cold air exits at the right outlet (B). The warm air exits at the left outlet (C)

The temperatures coming out the vortex cooler have been measured. This time it has been measured with temperature sensors instead of the thermal camera to get more accurate measurements.

The vortex cooler has been placed between some metal blocks so that it does not move. Then a digital temperature has been used to measure the minimum and maximum temperatures of the hot and cold airstream.

as shown in figure 48 and 49 the minimum temperature reached is -15°C at the cold outlet. The warm outlet reached a maximum of 39°C.

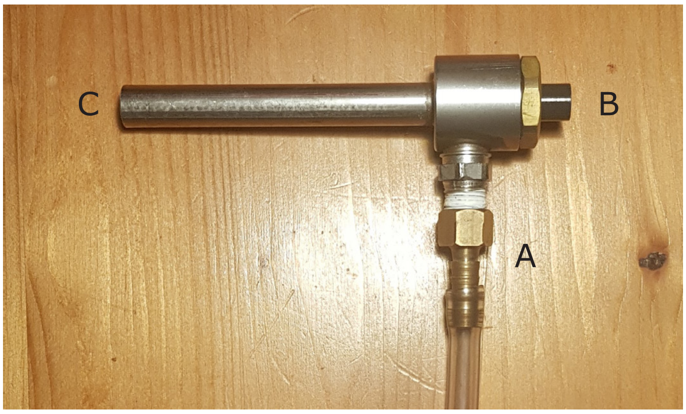


Figure 47: Minimum measured temperature

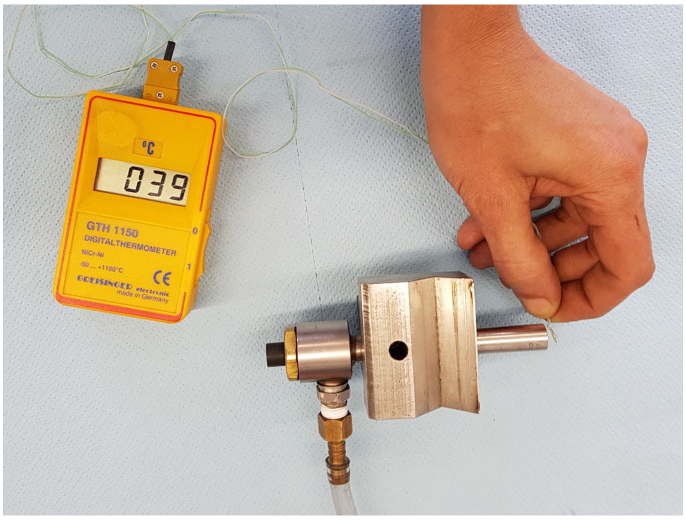


Figure 48: Maximum measured temperature

Figure 49: Minimum measured temperature

4.4.3 Cooling Nozzle

For the 3D-paintbrush a nozzle has been designed to direct the air onto the extruded work just after it is extruded. this nozzle has four equal cavities that direct the air from the vortex cooler through a splitter into a conical airstream surrounding the nozzle. This is shown in figure 50. After the mockup the nozzle has been replaced this is described in Chapter 5

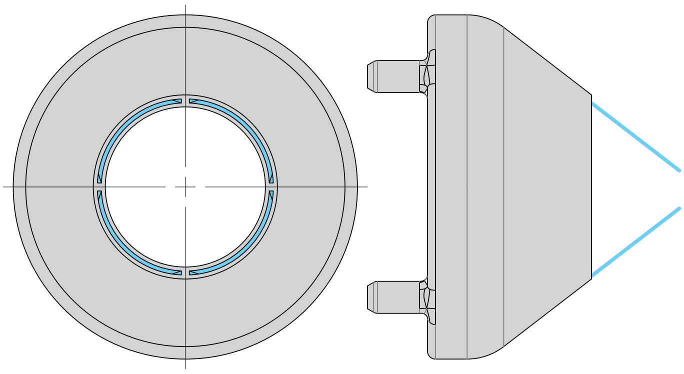


Figure 50: Cooling nozzle with airflow direction

The vortex cooler, with tubing splitter and cooling nozzle has been tested. The vortex cooling reaches temperatures of -5°C (figure 51) with all the parts connected. from this it can be concluded that the extra tubining, splitter and cooling nozzle create a loss of 10°C cool air.

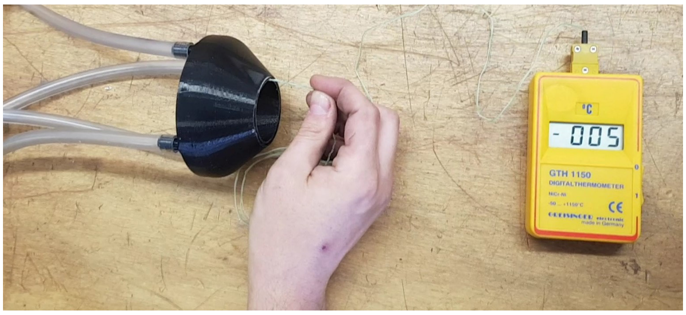


Figure 51: Temperature after the cooling Nozzle

4.4.4 Splitter.

The splitter is a custom designed part. The goal of the splitter is to divide the airstream from the vortex cooler in four equal streams of air. It is attached to the vortex cooler so that the cold airstream immediatly gets split into four. Two itterations can be seen in figure XX the splitter is screwed on the vortex cooler with temperature regulation. In figure 52 the splitter is integrated with one of the connection pieces.

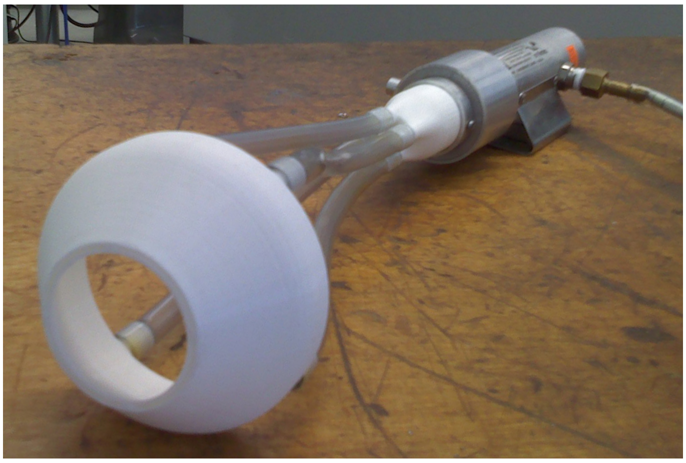


Figure 52: Vortex cooler with splitter, tubing and Cooling nozzle

4.4.5 Tubing

The tubing directs the four airstreams at the splitter to the cooling nozzle. It is important that these tubes are not too long to minimize heat loss. Insulated tubing after the vortex cooler is considered but by keeping the tubes short the temperature loss will be minimized.

In addition the amount of air flowing past the extruded material is more important than the temperature.

The air nozzle, splitter and tubing has been tested on the vortex cooler with temperature regulator. with this setup the heat loss from the vortex cooler (at 17°C) to the end of the air nozzle (at 19°C) was only 2°C.

4.4.6 Vortex-housing connections

Some small part have been design to mount the vortex cooler on top of the frame without the vortex cooler touching the frame itself.
the goal is to keep the vortex cooler in place at the bottom of the 3D-paintbrush.

Figure 53 shows the vortex cooler mounted on the frame with the two connection pieces. The splitter is integrated with the left connection piece.

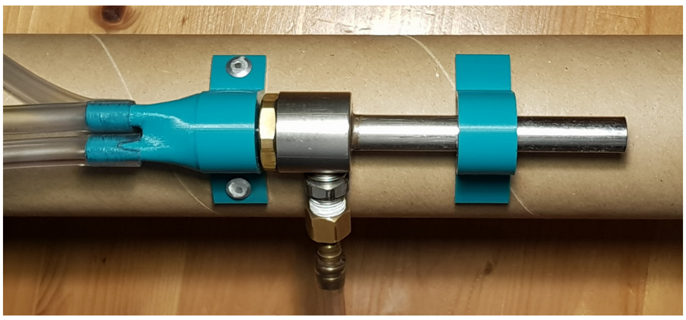


Figure 53: Vortex cooler is mounted on the frame

4.5 Housing and frame.

4.5.1 The housing

The housing cylinder is main body of the 3D-paintbrush is fixes all the parts together, prevents the user from touching the heated parts and keeps the whole extruder rigid.

The housing cylinder is made from aluminium, a lightweight but strong material. The housing should be ø 80mm with a thickness of 5mm and a length of 850 mm.

At the end of the housing is a hole for the hopper. There is a hopper inside the housing and a connection piece on top of the housing. this is shown in the cross-section views in figure 54 and 55.

The connection piece (1) is attached to the housing, it is angled at 20°. When the extruder is held vertically the connection piece is not horizontal and gravity still helps the pellets fall into the hopper.

A small pipe (2) is inserted past the connection piece into the hopper. Pigment will enter through this pipe, entering the hopper just before it enters the screw.

The internal hopper (3) covers the slot in the barrel of the extruder. The pellets will fall through the hopper and enter that barrel in the feeding zone. There the screw can convey the pellets to the nozzle.

both the conection piece and the small pipe fit a Flexible PVC pipe that acts as a reservoir.

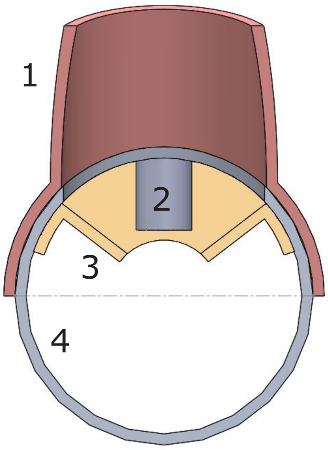


Figure 54: Vortex cooler is

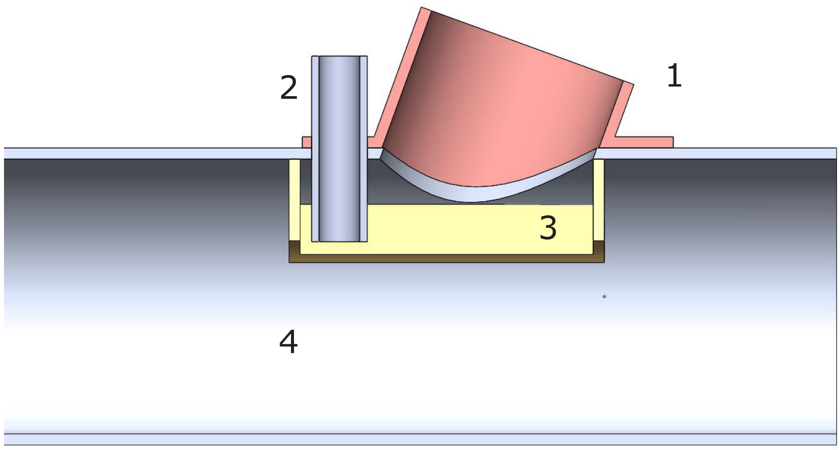


Figure 55: Vortex cooler is mounted on the frame

4.5.2 Frame

The frame carries the housing and is connected to the balance mechanism. it can already rotate in the Z-axis. The frame makes rotating in the X and Y-axis possible. (see figure 56)

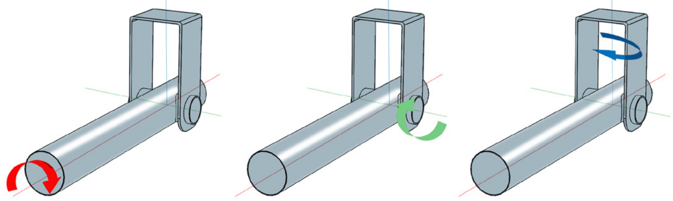


Fig 56: Movement around the X, Y and Z-axis

The Frame has two parts. The main frame and the bearing holder.

The main frame
The main frame is the connecting piece between the old balance mechanism and the 3D-paintbrush. It is made of 20 x 20 x 2 piping making a U-shape. it is about 500mm high so that the motor of the 3D-paintbrush fits through it without touching.

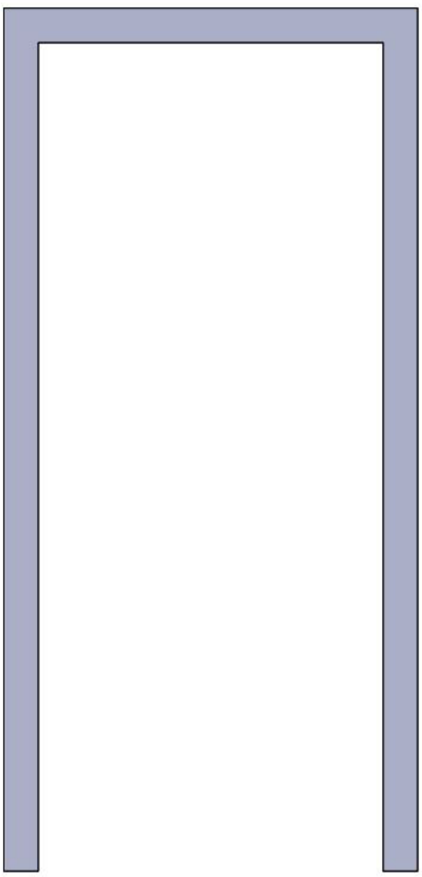


Fig 57: The U-shaped mainframe

The bearing holder
THe bearing holder consists of multiple parts, its main goal is to keep the bearing in place but not prevent the rotational movement.

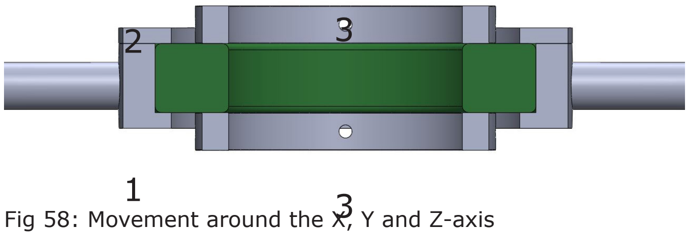


Fig 58: Movement around the X, Y and Z-axis

A cross-section of the bearing holder can be seen in figure 58. This shows that is made out of three different parts and how they are placed. The bearing is shown in green and is not part of the bearing holder. The bearing is a standard part and can be found in appendix G5.

Part 1 is the bearing holder ring. it is a milled part that fits the around the outter diameter of the bearing and has a 5mm flange to prevent the bearing from sliding out. Two 15mm rods are attached to opposite ends. These rods are mounted in the mainframe and with four sliding bearings it allows the movement in the Y-axis.

Part 2 is a ring shaped cap. this can be screwed on the bearing holder ring so that the bearing is locked in the holder.

Part 3 are two adjusting rings on placed on opposite sides of the bearing. A small screw can be used in the holes to tighten the djusting rings to the housing cylinder. With this method the bearing is locked in place on the the housing cylinder and it can not move. By untightening the adjusting rings the bearing can be moved along the length of the cylinder in order to find a good balancing spot. This placement can balance out the motor and the extruder in order to keep the 3D-paintbrush level. the technical data for the adjusting ring can be found in appendix G6

4.5.3 Barrel endcap

The endcap is a conical piece that is screwed to the flange of the barrel. the conical allows for better visual acces to the nozzle, giving the user a clear view and thus better controll over the extruded plastic.

The endcap is placed on the flange of the barrel by four M5 screws (figure 59). The last heating band is located just after the flange. This way the barrel endcap stays enough heat to keep the plastic melted before it exits the nozzle.

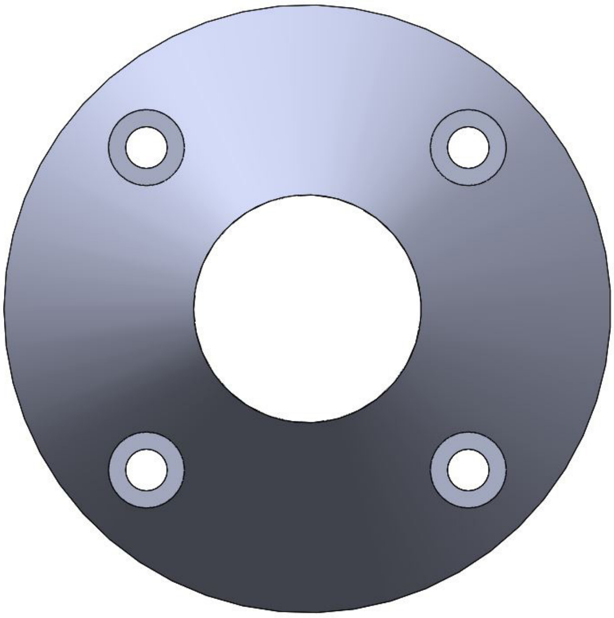


Fig 59: Conical endcap

The inside of the endcap has a M30 thread. The endcap is a simple design and can be easily replaced if the part is broken or worn. by making the endcap out of a softer aluminium it will protect the steel barrel and steel nozzle.

4.6 Ergonomics

4.6.1 Grips

The handle grips as shown in the cylinder concept chapter 3.4 have been replaced by rings these rings allow both left and right handed users easily control the 3D-paintbrush and the user has the choice to stand on either side without changing the position of the grip. They also shield off and protect the cylindrical housing which can become warm over time.

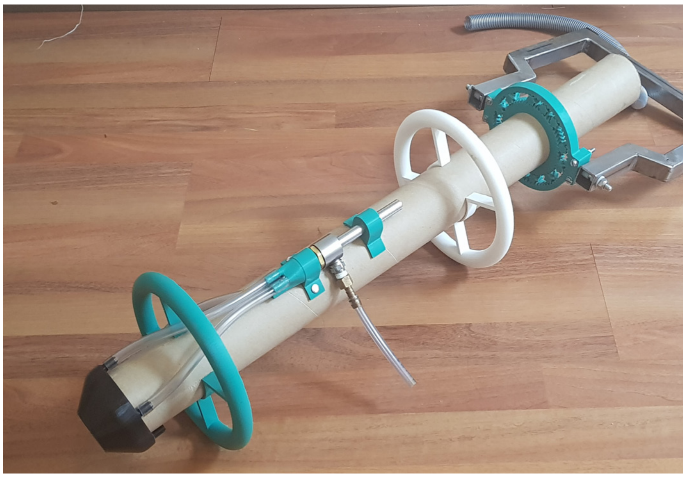


Fig 60: Grips on the mockup

4.6.2 Cable carrier

With all the electrical cable and the extra air piping for this design cable management is important.

In addition the new 3D-paintbrush has more degrees of freedom so it is important that the cables do not get entangled by the machine.

A cable carrier will be mounted on the back of the 3D-paintbrush allowing the cables to be neatly packed together and leading them up to the balance mechanism. The cable carrier folds so that the 3D-paintbrush can still be used vertically

Fig 61: Cable Carrier

5 FINAL DESIGN - THE CYLINDER

5.1 Mockup

At the end of the embodiment phase a mockup has been made. The purpose of the mockup is to test all the sizes determined in the embodiment phase. In addition the mockup shows the degrees of freedom of the 3D-paintbrush and the how all the features work

Based on this mockup some final changes have been suggested and made. these are listed here in chapter 5.

Fig 62: Muckup of the 3D Cylinder.

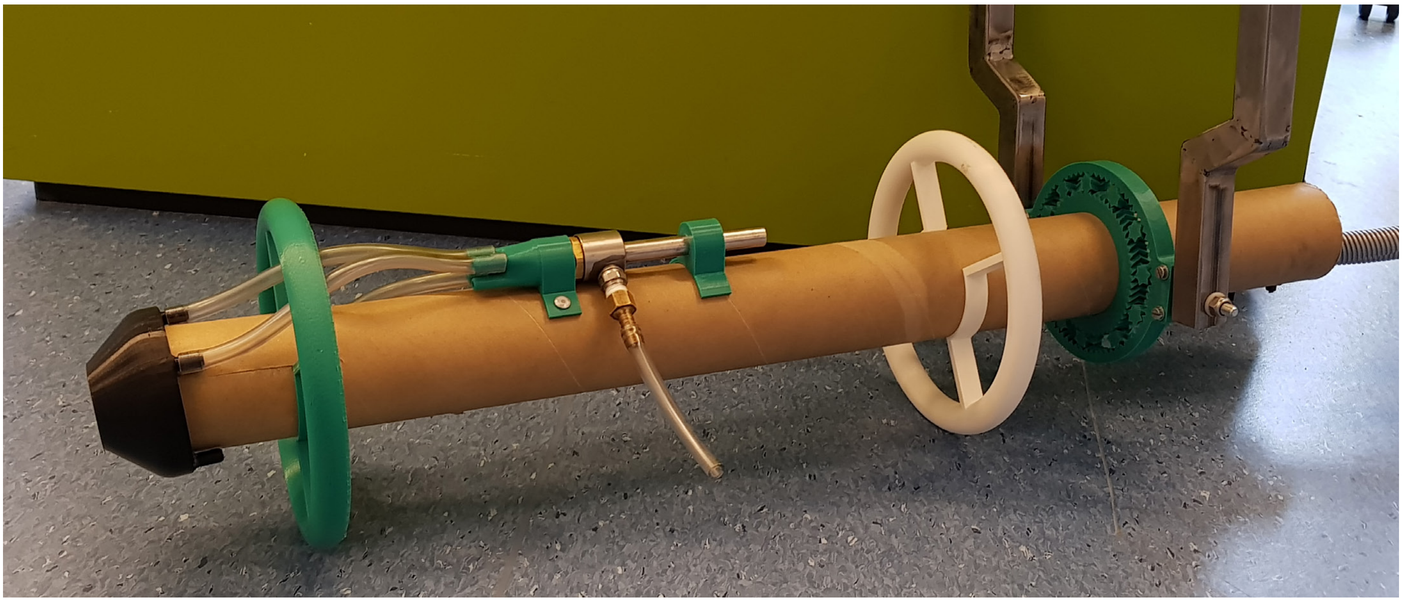


Fig 63: Muckup of the 3D Cylinder.

5.1.1 Cooling nozzle and splitter

The cooling nozzle from chapter 4.4.3 has been replaced. This nozzle could only be produced with 3D printing and having a plastic cooling nozzle so close to the nozzle would melt and clog the cooling nozzle.

as an alternative a simulair system as the current 3D-paintbrush has been used. the current has 3 aluminium tubes bend and directed at the nozzle.

Fig 64: flexible tube

In the revised design the cold air will be directed through three flexible tubes as shown in figure 64 these can be positioned so that the air can be directed to the correct spot and if they are in the way they can be directed elsewhere.

In addition the decision has been made to make the splitter split the airstream from the vortex cooler into three streams instread of four.

This means that there are only three outlets around the 3D-paintbrush and the view of the nozzle is less obstructed.

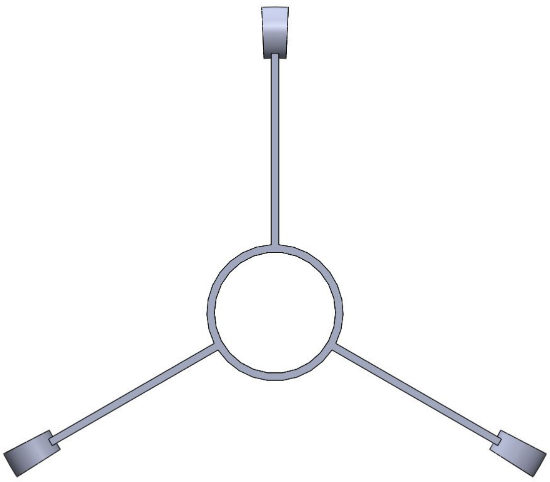


Fig 65: Aluminium frame without grips

5.1.3 The grips

The grips were also revised. The second iteration has bigger round grips that are further away from the 3D-paintbrush. This allows for more control and keeps your hands away from the possibe hot 3D-paintbrush parts

The grips are now a aluminium frame (figure 65) that is mounted on the cylindrical housing. This way no plastic parts are touching the 3D-paintbrush and possibly melt over time. This aluminium frame will hold the grips that are printed in four parts, shown in figure 66
The frame will be mounted on the cylindracal houses simular as the bearing is blocked as described in chapter 5.4.3 the frame acts as an adjusting ringand can be placed anywhere along the length of the cylindrical housing.

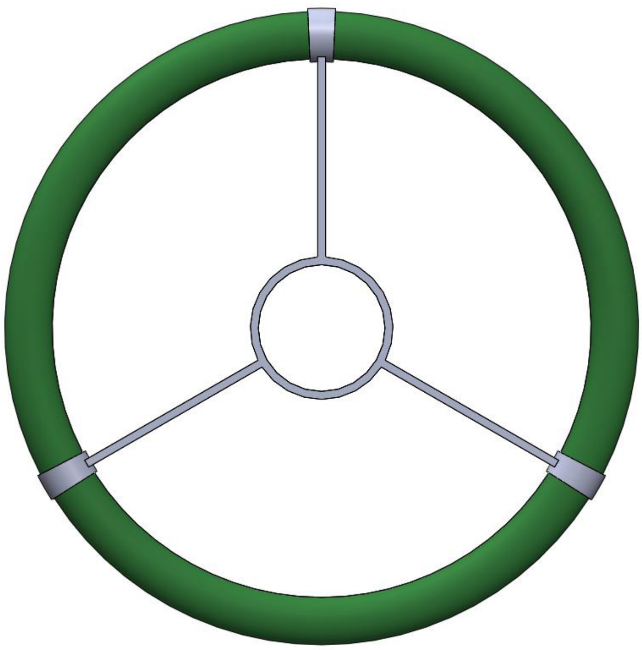
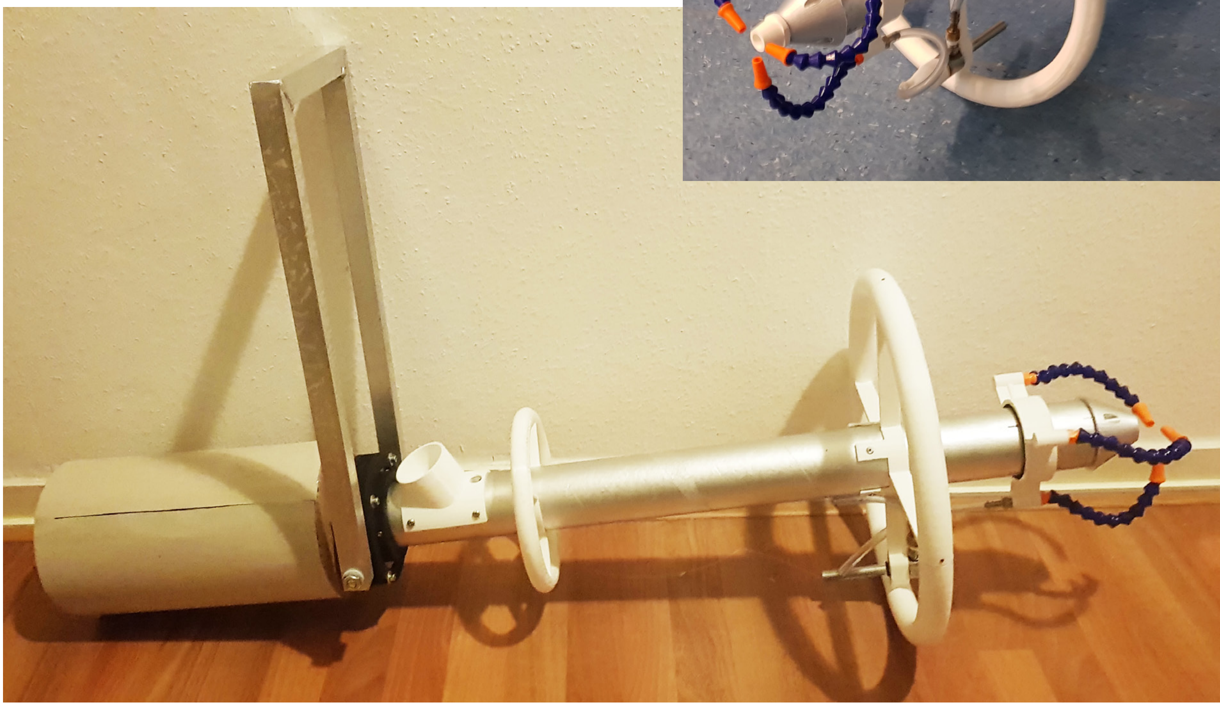


Fig 66: Aluminium frame with grips

5.2 Final mockup



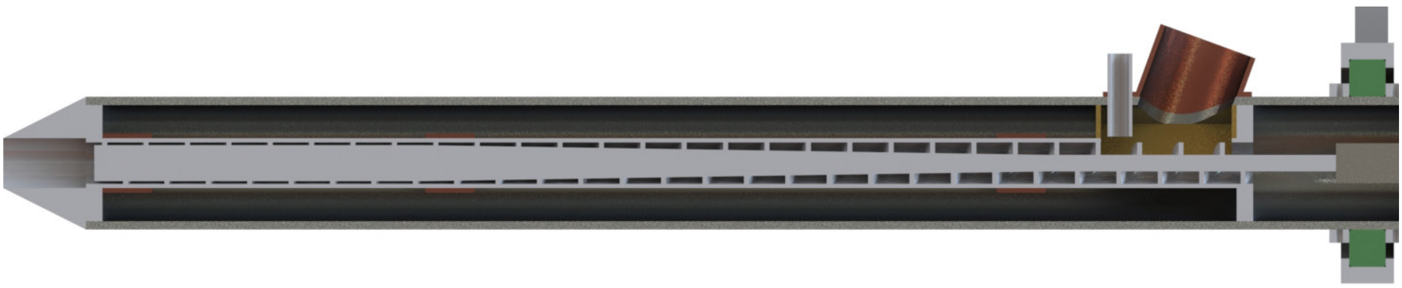


Fig 67: Crossection of the 3D extruder

5.3 costs

It is important to get an insight of the cost for the final design. it can be concluded that the prices vary a lot depending on if the expensive parts are ordered from China or locally.
For example with the extruder screw and barrel, contacting a company in the Netherlands or Germany will have benefits over buying from China. When buying locally the companies give a lot of advice and they have a lot of experience with extruders for different materials and purposes.
When ordering from China they only want the technical drawing and that is exactly what they will deliver.

Vortex coolers come locally with specific specifications and strengths. While a vortex cooler from aliexpress is unclear about the specifications and the capabilities of the device.

For this reason both a low and a high end cost calculation has been made. Where the low end budget is based on getting a lot of parts from China where the costs are lower but the specifications might be unclear and there is no advice from professionals in the field.

in the cost list most big electronic parts have been added, but some assumptions have been made regaring the other electronics. Estimates have been made for the wireing and other electronics such as connectors and relays.

Part	number	Cost pp	Cost Low	Cost High	Resource
Extrution Screw barrel (estimate)	1	1500		1500	Extrution
Screw + Barrel	1	500	500		Aliexpress
Heating band	3	41	123	123	RS-online
PT100	3	20	60	60	RS-online
Insulating super wool	1	58	58	58	RS-online
Vortex cooler	1	200		200	Exair
Vortex cooler (aliexpress)	1	39	39		Aliexpress
Motor	1	225	225	225	Electromotor.nl
end rod	3	18	54	54	RS-online
PID controllers SSR	3	76	228	228	TC direct
Electric Wiring	1	48	48	48	Hornbach
Other electronics	1	150	150		
TRICOFLEX CRISTAL 60-70 MM PER MTR	1	16	16	16	witway.nl
6016-2RS1 Bearing	1	61	61	61	Ebele
Adjusting ring	2	17	34	34	Zamro.nl
Cable carrier	1	30	30	30	Aliexpress
Aluminium piping 80x5x825mm	1	29	29	29	Aluminiumopmaat
		TOTAL	1655	2666	
Nuts, bolts and other small build materials (10%)			1821	2933	

Table 5.1: Final costs for the 3D-paintbrush

6.2 Validation

In chapter 1.11 the vision for this project is mentioned. The vision for this project is.

The 3D-paintbrush should be **safe and easy** to move, control and use. It should have an **improved extrusion speed** without the loss of quality.

The paintbrush should **cool** the extruded plastic **fast enough** so that 3D-structures can be formed.

the key points mentioned here are safety, controllability of the 3D-paintbrush, movement and ease of use, improved extrusion speed and fast cooling.

6.1.1 safety

It is hard to validate safety based on what is learned so far. unfortunately this project didnt have the time to build the new 3D-paintbrush, this means safety has to be adressed based on the mockup and insight.

Compared to the old design of the 3D paintbrush the new version has big grips. These grips are user cues and motivate the user to grab the 3D-paintbrush by the grips and not on any hot parts.

6.1.2 Controllability

Controllability refers to the movement of the 3D-paintbrush. Based on the mockup we can determine what the range of movement is.

This design has more freedom than the old 3D-paintbrush. The bearing and its housing make the 3D-paintbrush move 90° around the X-axis shown in figure 67 and slo 90° around the Y-axis shown in figure 68

There are no limits or stops preventing from moving the 3D-paintbrush further but it is adviced not to move past these angles.

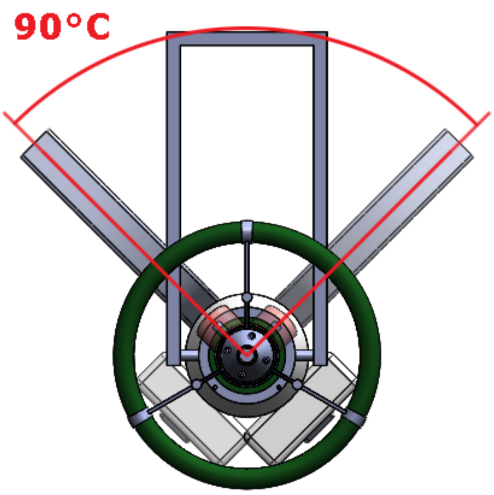


Fig 68: D-paintbrush, movement in the X-axis

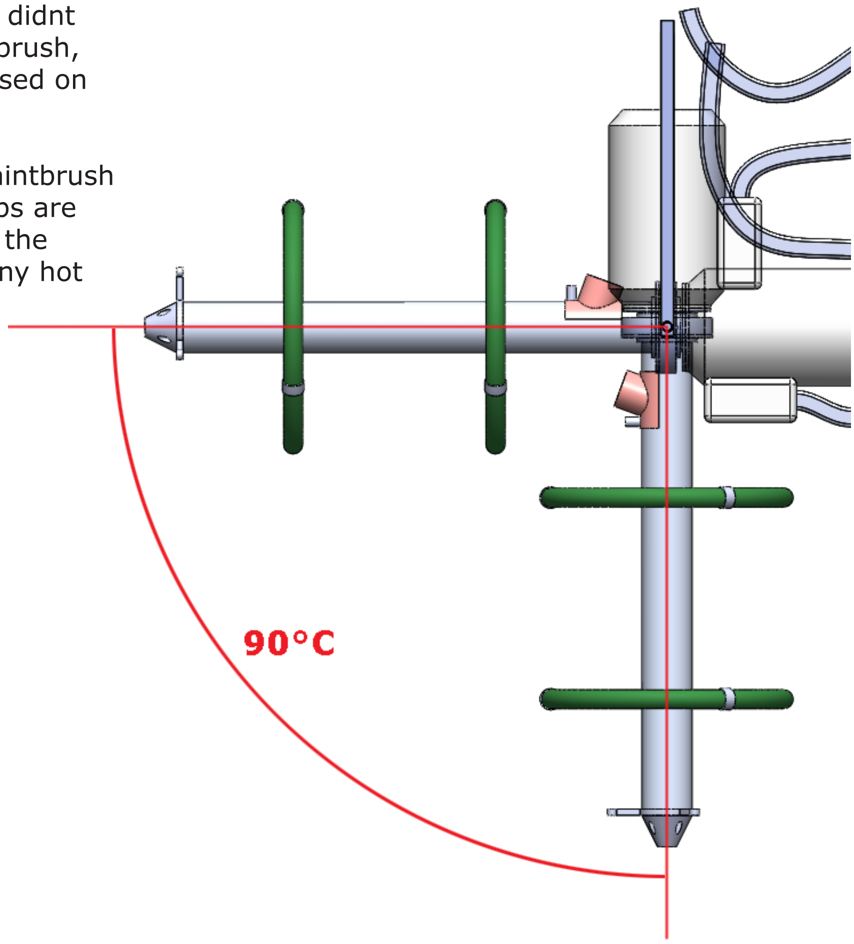


Fig 69: 3D paintbrush, movement in the Y-axis

6.1.3 Extrusion speed

During this project various nozzles have been tested . The initial benchmark of the old 3D-paintbrush has been done with a 8mm round nozzle (Chapter 1.6) And later in this project a nozzle with a core has been made to try hollow extrusion.

in chapter 1.6 working with the 3D paintbrush we learned that the 8mm nozzle extruded roughly 9mm per second.

knowing the new 3D-paintbrush has a optimal mass flow rate of 7.5kg/h the extrusion speed with various nozzles can be calculated.

if you divide the massflow rate by the density you get the volumetric flow rate. The volumetric flow rate divided by the surface area of the nozzle is the extrusion speed.

The extrusion speed is calculated for various nozzle sizes this can be seen in table 5.1.

we can read from the table that theoretically the new extruder screw would extrude 44 mm/s with a nozzle size of mm. comparing this to the benchmark we can conclude that the new 3D paintbrush extrudes 4.9 times faster.

These calculations are also made of nozzles with cores, creating hollow extrusions.

Nozzle size (mm)	Extrusion m/s
5.0	0.113
6.0	0.078
7.0	0.058
8.0	0.044
9.0	0.035
10.0	0.028
11.0	0.023
12.0	0.020
13.0	0.017
14.0	0.014
15.0	0.013
16.0	0.011
17.0	0.010
18.0	0.009
19.0	0.008
20.0	0.007

Table 5.1: Extrusion length in mm/s

The surface area of the core is substracted from the nozzle surface area. to calculate the extrusion speed of hollow extrusion. The assumption is made that there is neglectable resistance from the plastic against the wall of the core.

Table 5.2 shows the extrusion speeds for various nozzle and core sizes. For example a 10mm nozzle with a 6mm core extrudes just as fast as a 8mm nozzle.

Extrusion length in meter per second

Nozzle size (mm)	Core size (mm)																
	0.0	4.0	5.0	6.0	7.0	8.0	9.0	10.0	11.0	12.0	13.0	14.0	15.0	16.0	17.0	18.0	19.0
5.0	0.113	0.314															
6.0	0.078	0.141	0.257														
7.0	0.058	0.086	0.118	0.217													
8.0	0.044	0.059	0.072	0.101	0.188												
9.0	0.035	0.043	0.050	0.063	0.088	0.166											
10.0	0.028	0.034	0.038	0.044	0.055	0.078	0.149										
11.0	0.023	0.027	0.029	0.033	0.039	0.050	0.071	0.134									
12.0	0.020	0.022	0.024	0.026	0.030	0.035	0.045	0.064	0.123								
13.0	0.017	0.018	0.020	0.021	0.024	0.027	0.032	0.041	0.059	0.113							
14.0	0.014	0.016	0.017	0.018	0.019	0.021	0.025	0.029	0.038	0.054	0.105						
15.0	0.013	0.014	0.014	0.015	0.016	0.018	0.020	0.023	0.027	0.035	0.050	0.097					
16.0	0.011	0.012	0.012	0.013	0.014	0.015	0.016	0.018	0.021	0.025	0.032	0.047	0.091				
17.0	0.010	0.010	0.011	0.011	0.012	0.013	0.014	0.015	0.017	0.019	0.024	0.030	0.044	0.086			
18.0	0.009	0.009	0.009	0.010	0.010	0.011	0.012	0.013	0.014	0.016	0.018	0.022	0.029	0.041	0.081		
19.0	0.008	0.008	0.008	0.009	0.009	0.010	0.010	0.011	0.012	0.013	0.015	0.017	0.021	0.027	0.039	0.076	
20.0	0.007	0.007	0.008	0.008	0.008	0.008	0.009	0.009	0.010	0.011	0.012	0.014	0.016	0.020	0.025	0.037	0.072

6.1.4 Cooling

Cooling the extruded plastic is an important task for the 3D paintbrush. The tests done with the vortex cooler look promising. a lot of cold air can flow past the extruded plastic releasing the heat. Flexible tubing can help direct the airstream and adjust it if necessary.

If the temperature in the 3D-paintbrush is ideal the plastic will exit the nozzle just above the Tg or Tm in case of semi crystalline plastics. The vortex cooler only needs to transfer a bit of heat from the plastic for it to solidify.

Based on the design and the tests during this thesis it can be concluded that it is possible to blow air at a below 0°C temperature to the extruded plastic

6.2 Recommendations

6.2.1 Extruders

In this project a standard extruder screw has been dimensioned. The basis for this extruder are two examples found as professional machines. From the mass flow rate and the diameter of the screw has been found.

With the help of papers and handbooks the other dimensions have been determined. They are all based on this theory. However This screw has been specifically designed with HDPE in mind.

Chapter 4.3.2 describes what changing the variables will do for the extruder. However there are many variables . For someone without experience or acces to expensive calculation software to find the optimum between all these dimensions can be very challenging.

It is recommended to find an expert to take a critical look at the final screw design. Some contact was made with Xtrution in Haarlem (NL) it is advised to find them or a simular company that can ake the final screw design a reality

6.2.2 Vortex cooling

In this graduation project vortex cooling has been explored as a valid option to cool plastic fast. Most of the conclusions come from the basic theory about vortex coolers and testing at the faculty.

The faculty however has an endless supply of compressed air. some more research needs to be done to determine how big of an air supply is needed for Vortex cooler.

6.3 Evaluation

when I look back at the beginning of the project I had different expectations.Although this project had many oppurtunities to do some 3D modelling and quick prototyping as part of an iterative process. I wished that the actual 3D-paintbrush could have been build during my graduation.

I could have looked deeper into extruder screws at the beginning of the analysis phase. Ofcourse it was only clear around the concept meeting that the extruder screw way the direction the project was headed, I felt like I had to catch up on a lot of knowledge.

At the moment I feel like I know a lot about extruder screw variables and how a extruder screw works, and I wish ould put this theory in practice

My design process could get better if I have a more structured planning. I find it very hard to plan for the whole graduation period at the beginning of the projects. And when my planning strays I should adapt it faster.

Ive learned that I need to invest more time in research so I can make better design desicions. I think that investing more time in research and analysis in the beginning of the project could help speed up later in the process.

At the end of the project I still feel that a lot of progress is made for the 3D-paintbrush although some ideas are at concept level and the new 3D-paintbrush to be build before they can be tested.

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APPENDICES

Appendix A: Material properties.

Material properties recyclable plastics					
Material	CES	RIC	Density	Glass temp (T_g)	Melting point (T_m)
	(level 3 polymer)		kg/m³	°C	°C
PET	Unfilled > Amorphous	1	1290 - 1390	60 - 84	
HDPE	Unfilled > General purpose	2	952 - 965		130 - 137
PVC	Unfilled > Rigid, molding	3	1300 - 1490	80 - 88	
LDPE	PE-LD	4	917 - 932		98 - 115
PP	Level 2	5	890 - 910		150 - 175
PS	Unfilled > General purpose	6	1040 - 1050	90 - 100	
ABS	Unfilled > Extrusion	7	1020 - 1080	88 - 120	
PC	Unfilled > Low viscosity	7	1040 - 1210	142 - 158	
PLA	Unfilled > General purpose	7	1240 - 1270	52 - 60	145 - 175

Material properties recyclable plastics			
Material	Thermal conductivity	Heat Capacity (C_P)	Heat of fusion (ΔH_f)
	W/m °C	J/kg°C	kJ/kg
PET	0.138 - 0.151	1150 - 1250	0
HDPE	0.461 - 0.502	1750 - 1810	250
PVC	0.147 - 0.209	1000 - 1100	0
LDPE	0.322 - 0.348	1840 - 1920	130
PP	0.113 - 0.167	1870 - 1960	
PS	0.120 - 0.140	1200 - 1300	0
ABS	0.226 - 0.235	1390 - 1410	0
PC	0.193 - 0.218	1150 - 1250	0
PLA	0.130 - 0.160	1180 - 1210	

Appendix B: Speed test and mass flow rate calculations.

Introduction

This appendix decribes in detail how the current 3D-paintbrush has been benchmarked. This has been done by testing the speed and from this calculating the mass flow rate.

Goal

The goal is to have a benchmark of the current 3D-paintbrush. For extruders the speed of the extrusion is expressing by mass flowrate in kg/h
By knowing the mass flow rate the extrusion speeds of different nozzles can be calculated. Since the current 3D-paintbrush does not have

Setup

The 3D-paintbrush has been put on a table so that it is not moving see figure B01. The temperature have been determined by Tiwánee van der Horst's experience. These settings have been fine tuned to find the optimal speed without the loss of quality of the extrusion. This test has been done with two materials, Polycarbonate (PC) and Polypropylene (PP).

There are three heating bands around the barrel. The settings for the heating bands were [200°C - 220°C - 220°C] for polypropylene and [220°C - 240°C - 240°C] for polycarbonate both starting with the heating band closest to the nozzle.

The 3D-paintbrush has been tested with a 8mm nozzle and the cooling fan has been turned on. the extrusion is pulled down by its own weight. A ruler has been printed and hung on the edge of the table, as shown in figure B02.

The length from 0mm to 200mm has been timed 10 times with a stopwatch for each material. Considering the reaction speed with the stopwatch the times have been rounded to 1/10th of a second.

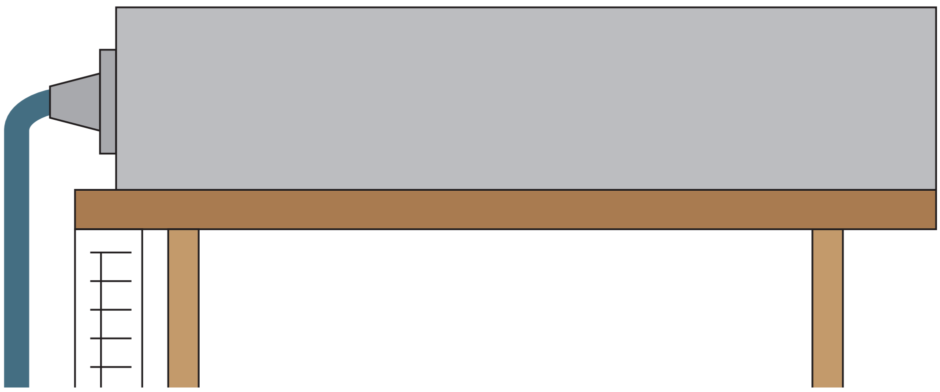


Fig B01: 3D-paintbrush placement

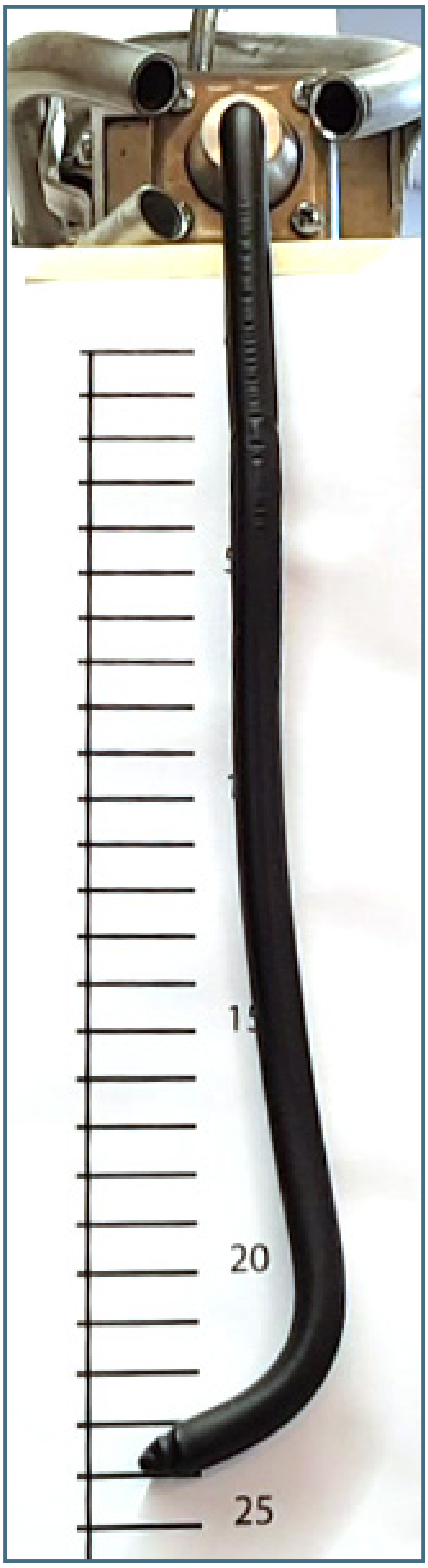


Fig B02: Photo of the test setup

Test results

The test results can be found in table B1, this table shows the measured times for ten tests with PP and PC

X	200mm Polyproylene extrusion (s)	200mm Polycarbonate extrusion (s)
1	21.6	23.9
2	22.3	24.1
3	22.0	25.2
4	22.1	24.3
5	21.4	23.9
6	22.6	24.2
7	22.2	24.8
8	22.1	24.3
9	21.7	24.3
10	23.0	23.8

Table B01: Hofman, W.L. (2018) measures extrusion times

from this data we can conclude that the average time 200mm is extruded is 22.1 seconds for polypropylene and 24.3 seconds for polycarbonate.

By dividing the length by the extrusion time we can calculated the extrusion speed for polypropylene and polycarbonate this is done in equasion 1 and 2.

$$v_{PP} := \frac{200\text{mm}}{22.1\text{s}}$$

$$9.05\ \frac{\text{mm}}{\text{s}} \qquad (1)$$

$$v_{PC} := \frac{200\text{mm}}{24.3\text{s}}$$

$$8.23\ \frac{\text{mm}}{\text{s}} \qquad (2)$$

The results of this test have been put into Maple. With the data from these test the volumetric flow rate and the mass flow rate have been calculated.

Mass flow calctulations

Density of polypropylene and polycarbonate have been selected with the averages of the density as shown in the cambridge engineering selector database. This data is also summerized in appendix A: Material properties of plastics. The average density of polypropylene is 900kg/m3 and for polycarbonate is 1125 kg/m3

$$\rho_{PP} := 900\ \frac{\text{kg}}{\text{m}^3}:$$

$$\rho_{PC} := 1125\ \frac{\text{kg}}{\text{m}^3}:$$

The nozzle sized used for this setup has a 8mm diameter and thus a 4mm radius,
in maple the nozzle size is measured in meters. This is shown in equasion 3.
From the radius of the nozzle the nozzle surface area can be calculated with the formula used in equasion 4

$$r_{nozzle} := 4.0\text{mm}$$

$$4.00 \times 10^{-3}\ \text{m} \qquad (3)$$

$$A_{nozzle} := r_{nozzle} \cdot r_{nozzle} \cdot \text{Pi}$$

$$5.03 \times 10^{-5}\ \text{m}^2 \qquad (4)$$

To calculate the flow rates the extrusion speeds from polyproylene, equasion 1 and polycarbonate, equasion 2 need to be converted to SI units. The conversion from milimeters per second to kilograms per hour has been done in equasion 5 and 6.

$$v_{PP}$$

$$3.26 \times 10^{1}\ \frac{\text{m}}{\text{h}} \qquad (5)$$

$$v_{PC}$$

$$2.96 \times 10^{1}\ \frac{\text{m}}{\text{h}} \qquad (6)$$

With the surface of the nozzle, equasion 4 and the extrusion speed of polypropylene, equasion 5 set we can calculate the volumetric flow rate for propylene

$$\dot{V}_{PP} := A_{nozzle} \cdot v_{PP}$$

$$1.64 \times 10^{-3}\ \frac{\text{m}^3}{\text{h}} \qquad (7)$$

The volumetric flow rate from equasion 7 can be calculated to the mass flow rate by multiplying it by the density of polypropylene. This is done in equasion 8.

$$\dot{m}_{PP} := \dot{V}_{PP} \cdot \rho_{PP}$$

$$1.47 \times 10^{0}\ \frac{\text{kg}}{\text{h}} \qquad (8)$$

Now the volumetric flow rate for polycarbonate can be calculated in the same way: with the nozzle surface, equasion 4 and the extrusion speed of polycarbonate, equasion 6

$$\dot{V}_{PC} := A_{nozzle} \cdot v_{PC}$$

$$1.49 \times 10^{-3} \ \frac{m^3}{h} \qquad (9)$$

With the density of polycarbonate the mass flow rate for polycarbonate can be calculated.

$$\dot{V}_{PC} := A_{nozzle} \cdot v_{PC} \cdot \rho_{PC}$$

$$1.68 \times 10^{0} \ \frac{kg}{h} \qquad (10)$$

Discussion

The results off this test are specific to the setup and the settings of the 3D-paintbrush. Doing this test another time with different settings, hardware or material batch can change the results of this test.

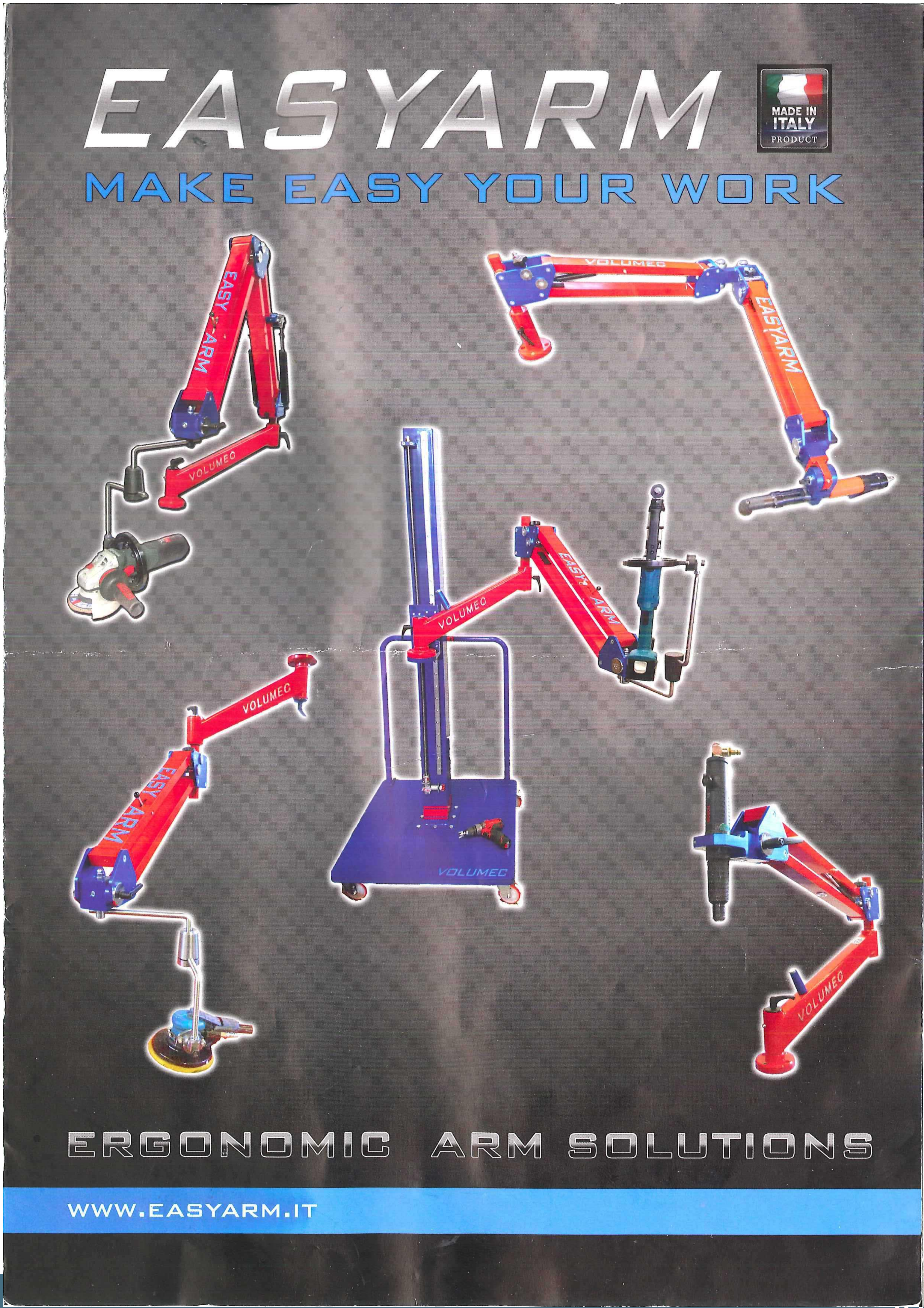
For example the 3D-paintbrush power supply has been replaced making it possible for the motor to turn faster before it staggers. Therefore the test results from the first test have been discarded and only the results of the second setup with the new power supply have been used.
Repeating this test also gives different results with small differences between the individual measurements. There are multiple reasons that can explain the differences in the measurements.
The first explaination is human error, timing with a stopwatch has some variation because of the respond time of the tester.
The second explaination is when the extruded plastics curls up. This makes it visually hit the 200mm a fraction of a second later.
Lastly the material in the current screw could be fed unevenly leading into small differences in the results.

In order to even out these inconsistencies ten measurements are taken for both polypropylene and polycarbonate and from these ten results the average extrusion time has been taken and used for the calculations.

Conclusion

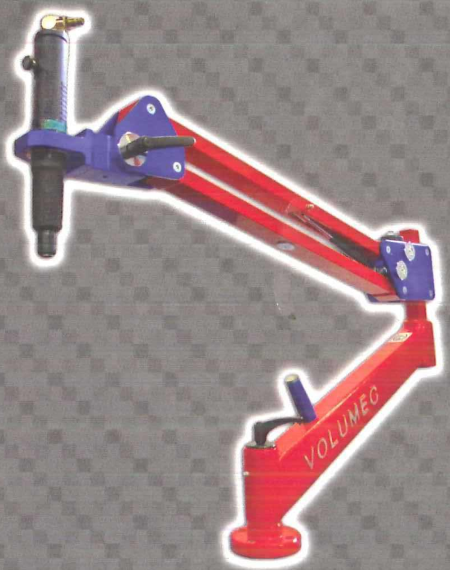
With the current setup of the hardware and the current settings the 3D-paintbrush has been benchmarked. This has been done for both polypropylene and polycarbonate. The measured 9.1 milimeter per second and 8.3 milimeter per second extrusion speeds have been used to calculate the mass flow rate.
It can be concluded that the mass flow rate for polypropylene is 1.47 kilograms per hour and for polycarbonate it is 1.68 kilograms per hour

Appendix C: Frame folder

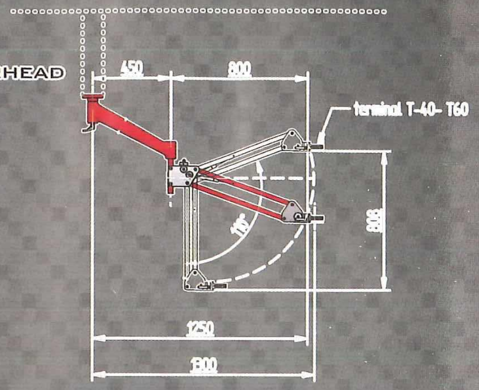


EA 2

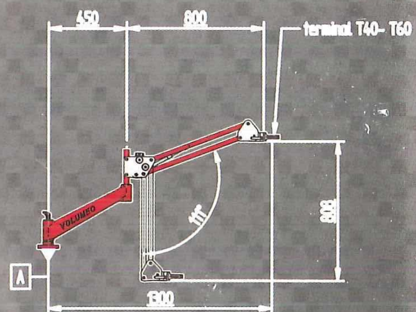
WEIGHT RANGE 1-30 KG/ 66 LBS.
MAX REACH 1300 MM/ 50 "



FIXING OVERHEAD (S)



FIXING BENCH



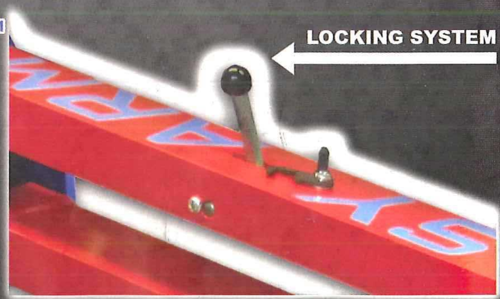
EA2 STANDARD DOUBLE ARTICULATED ARM

THE ARTICULATED ARM EA2 BALANCES THE WEIGHT OF THE TOOL OR EQUIPMENT IN ALL WORKING AREA, GUARANTEEING FAST AND PRECISE MOVEMENTS WITHOUT EFFORT. **ZERO GRAVITY**

Model	Work area	Structure	Max torque	Weight tool/equipment
EA135003	1290 mm	Double arm	120 Nm	1,5 – 3 kg
EA135006	1290 mm	Double arm	120 Nm	3,5 – 6 kg
EA136010	1290 mm	Double arm	150 Nm	6,5 – 10 kg
EA136015	1290 mm	Double arm	150 Nm	11 – 14 kg
EAT136010	1290 mm	Double arm	200 Nm	7 – 10 kg
EAT136014	1290 mm	Double arm	200 Nm	10 – 14 kg
EAT136019	1290 mm	Double arm	200 Nm	15 - 19 kg
EAT138030	1290 mm	Double arm	200 Nm	20 - 30 kg

EAB2 DOUBLE ARTICULATED ARM WITH LOCKING SYSTEM

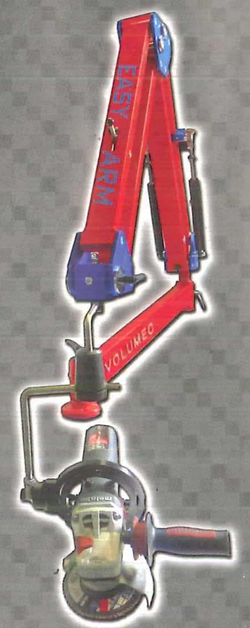
THE EAB SERIES CAN BE USED AS STANDARD BALANCED ARM WITH THE OPTION OF LOCK THE TOOL TO A DESIRED HEIGHT AND MAINTAINED OVER THE ENTIRE WORK AREA.

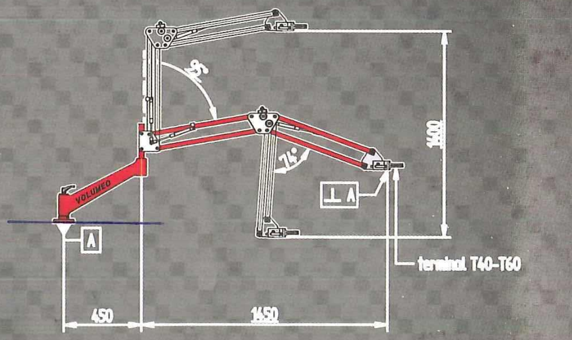


Model	Work area	Structure	Max torque	Weight tool/equipment
EAB136003	1290 mm	Double arm	150 Nm	1,5 – 3 kg
EAB136006	1290 mm	Double arm	150 Nm	3,5 – 6 kg
EAB136010	1290 mm	Double arm	200 Nm	6,5 – 10 kg
EAB138014	1290 mm	Double arm	200 Nm	11 – 14 kg
EAB138020	1290 mm	Double arm	200 Nm	15 - 18 kg
EAB138025	1290 mm	Double arm	200 Nm	19 - 25 kg

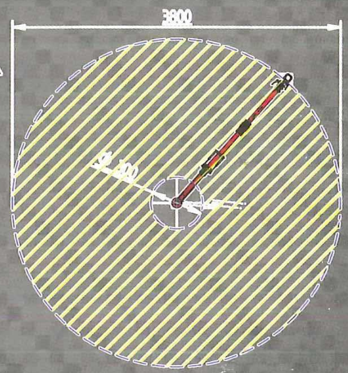
EA 3

WEIGHT RANGE 1-20 KG/ 44 LBS.
MAX REACH 1900 MM/ 75 "





WORK AREA



EA3 STANDARD TRIPLE ARTICULATED ARM

THE PANTOGRAPH STRUCTURE MAINTAINS THE BALANCE AND AT THE SAME TIME CONTRASTS THE TORQUE TOOL. BY THE TILTING ARM IS POSSIBLE TO OPTIMIZE THE BEST WORKING POSITION. ZERO GRAVITY

Model	Work area	Structure	Max torque	Weight tool/equipment
EA195002	1900 mm	Triple arm	120 Nm	1,5 – 2,5 kg
EA195004	1900 mm	Triple arm	120 Nm	3– 5 kg
EA195010	1900 mm	Triple arm	180 Nm	5,5 – 8 kg
EA196010	1900 mm	Triple arm	300 Nm	8,5 – 11 kg
EA196015	1900 mm	Triple arm	300 Nm	11,5 – 15 kg
EAT198010	1900 mm	Triple arm	500 Nm	16 - 20 kg

EAB3 TRIPLE ARTICULATED ARM WITH LOCKING SYSTEM

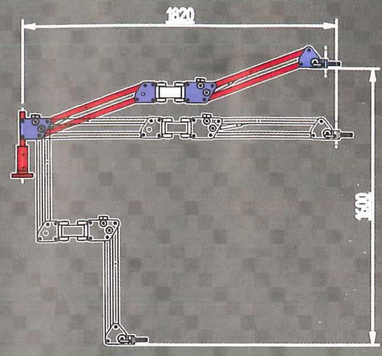
THE EAB SERIES CAN BE USED AS STANDARD BALANCED ARM WITH THE OPTION OF LOCK THE TOOL TO A DESIRED HEIGHT AND MAINTAINED OVER THE ENTIRE WORK AREA.

LOCKING SYSTEM

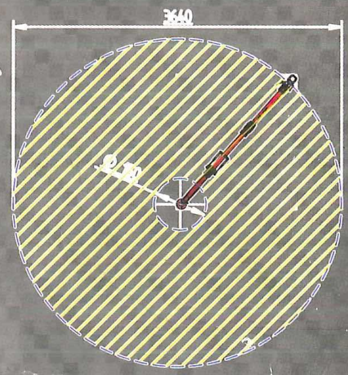
Model	Work area	Structure	Max torque	Weight tool/equipment
EAB196002	1900 mm	Triple arm	150 Nm	1,5 – 2 kg
EAB196004	1900 mm	Triple arm	150 Nm	2,5 – 5 kg
EAB196008	1900 mm	Triple arm	180 Nm	5,5 – 8 kg
EAB196010	1900 mm	Triple arm	300 Nm	8,5 - 11 kg
EAB196015	1900 mm	Triple arm	300 Nm	11,5 – 15 kg

EA 4

WEIGHT RANGE 1-10 KG/ 22 lbs.
MAX REACH 1800 MM/ 71 "



WORK AREA



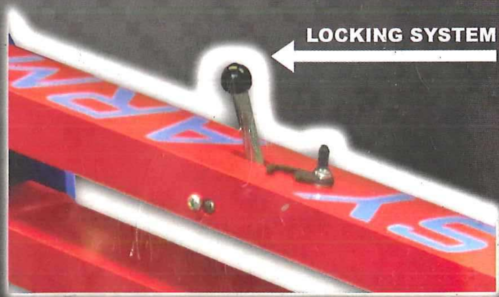
EA4 MULTI ARTICULATED ARM

THE SPECIAL ARTICULATION FOR MAXIMUM FLEXIBILITY AND MOVEMENTS, DOUBLE BALANCE ADJUSTMENT AND LARGE WORK AREA ALSO IN HEIGHT. POSSIBILITY TO WORKING ALSO NEAR THE FIXING BASE. ZERO GRAVITY

Model	Work area	Structure	Max torque	Weight tool/equipment
EA186002	1820 mm	Multi arm	150 Nm	1,5 – 2 kg
EA186004	1820 mm	Multi arm	150 Nm	2,5 – 5 kg
EA186008	1820 mm	Multi arm	150 Nm	5,5 – 8 kg
EA186010	1820 mm	Multi arm	150 Nm	8,5 – 10 kg

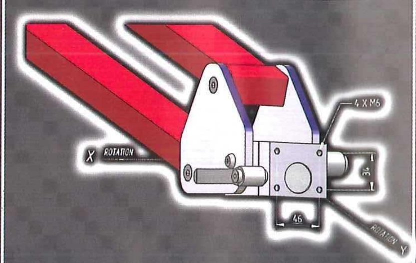
EAB4 MULTI ARTICULATED ARM WITH LOCKING SYSTEM

THE EAB SERIES CAN BE USED AS STANDARD BALANCED ARM WITH THE OPTION OF LOCK THE TOOL TO A DESIRED HEIGHT AND MAINTAINED OVER THE ENTIRE WORK AREA.

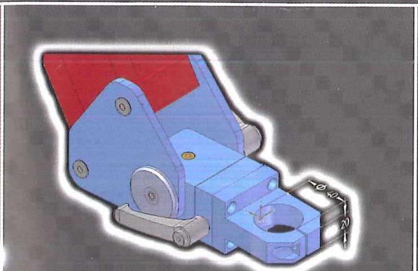


Model	Work area	Structure	Max torque	Weight tool/equipment
EAB186002	1820 mm	Multi arm	150 Nm	1,5 – 2 kg
EAB186004	1820 mm	Multi arm	150 Nm	2,5 – 5 kg
EAB186008	1820 mm	Multi arm	150 Nm	5,5 – 8 kg

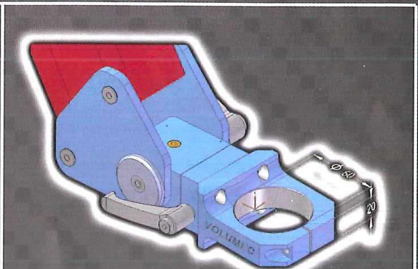
HEADS AND ACCESSORIES



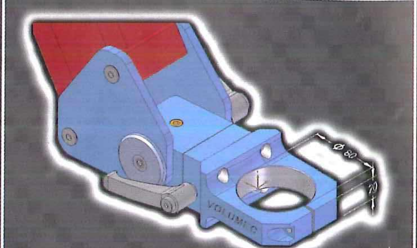
M
MULTIDIRECTIONAL HEAD



T40
TERMINAL FIXING TOOL DIAMETER 40 MM

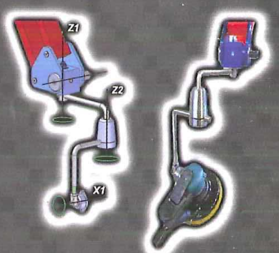


T60
TERMINAL FIXING TOOL DIAMETER 60 MM



T80
TERMINAL FIXING TOOL DIAMETER 80 MM

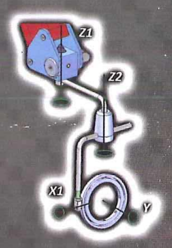
A40-A60 -A80
ADAPTER FOR DIAMETERS SMALLER THAN 40 MM, 60 MM, 80 MM



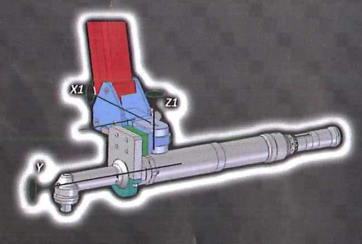
ORBITAL ATTACHMENT A

ORBITAL ATTACHMENT B

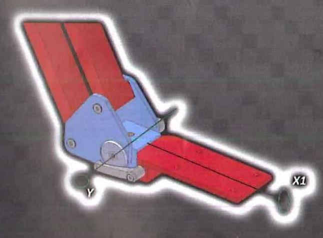
ORBITAL ATTACHMENT C



ORBITAL ATTACHMENT D



ORBITAL ATTACHMENT E



ATTACHMENT F

EXAMPLE

EA196010

(M)
MULTI DIRECTIONAL HEAD TO WORK WITH DIFFERENT ANGLES

(T40 - T60)
TERMINAL FIXING TOOL DIAMETER 40MM /60MM

(A40 - A60)
ADAPTER FOR DIAMETER SMALLER THAN 40MM OR 60 MM

TOOL NOT INCLUDED

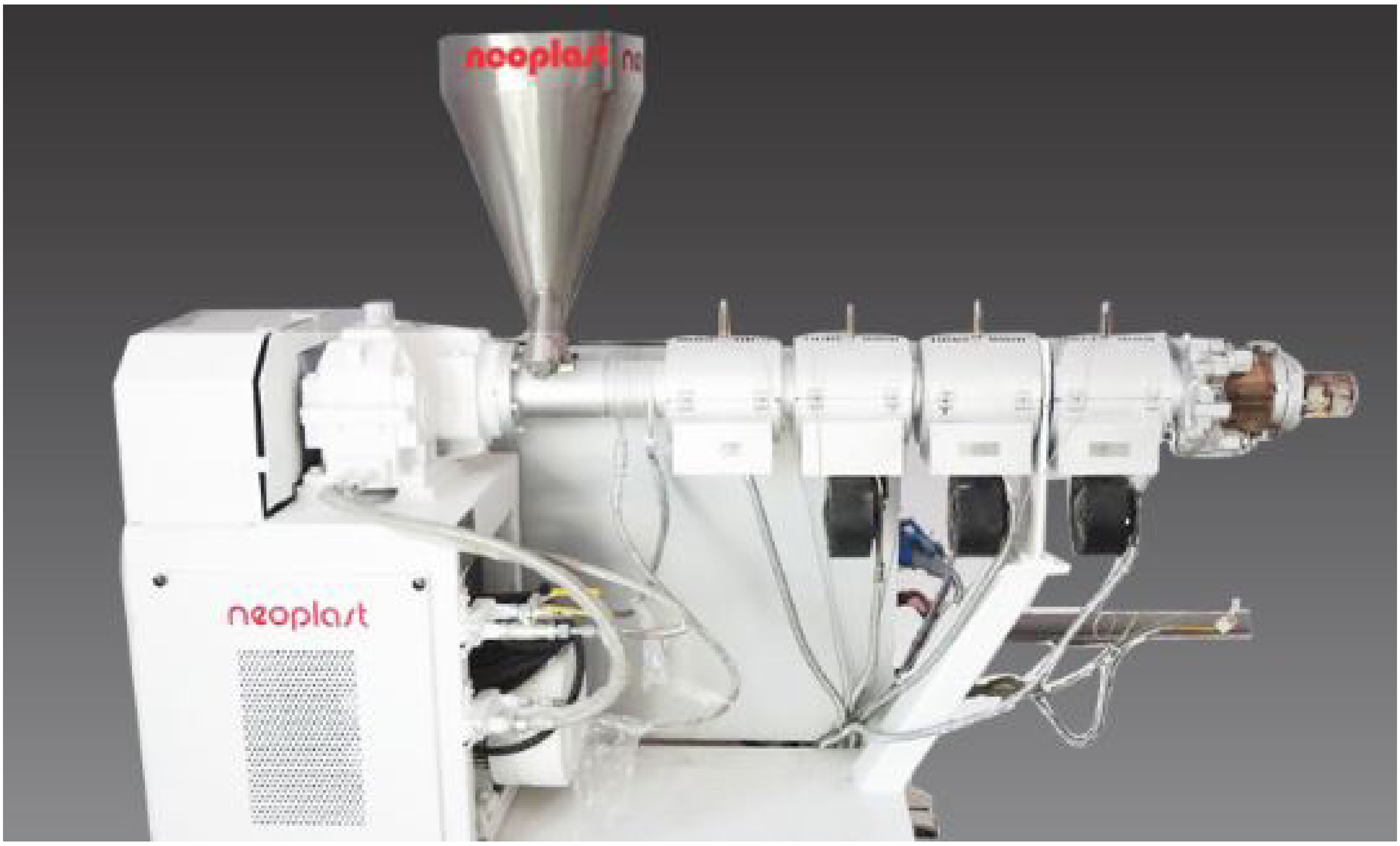
ACCESSORIES

WORK-TABLE
WORK-TABLE WITH T-SLOT 800 X 600 MM H = 830 MM
THICKNESS OF THE WORKING PLANE 30 MM
WEIGHT 150KG

TROLLEY FOR ARTICULATED ARM WITH A SHELVE
4 WHEELS (2 WITH BRAKES)
SIZE: 850X750X870H
WEIGHT: 65KG

Appendix D: Single Screw suppliers

Neoplast



Single Screw Extruders – SSE Series

Sr.No.	Model	Screw Dia (mm)	Screw Length(L/D)	Main Motor(kW)	Output Capacity(Kg/Hr)
1	SSE-25	25	20 / 25 / 28	2.2 / 3.7 / 7.5	9
2	SSE-45	45	20 / 25 / 28	5.5 / 7.5 / 11	35
3	SSE-65	65	20 / 25 / 28	11 / 15 /18	70
4	SSE-75	75	20 / 25 / 28	18 / 22 / 30	100
5	SSE-90	90	20 / 25 / 28	30 / 37 / 45	200
6	SSE-110	110	20 / 25 / 28	30 / 37 / 45	250
7	SSE-150	150	20 / 25 / 28	45 / 55 / 75	350

Potop

Item	Unit	MESI-20/28	MESI-25/28	MESI-30/30	MESI-35/32
Screw diameter	mm	20	25	30	35
L/D ratio	L/D	28		30	32
Rated revolution speed	rpm	120			
Max. temp.	℃	350			
Temp. control accuracy	℃	±1			
Heating/cooling method		Electrical heating / Air cooling			
Max. throughput	kg/h	3.5	7	13	25
Total power	kW	10		14	
Total weight	kg	300		350	400
Size (L×W×H)	mm	1970×690×1660		2070×690×1660	

Appendix E: PE Supplier technical data

Technical Data Sheet

QUALITY
CIRCULAR
POLYMERS

QCP™ PE 5404EX - 0216

Product Characteristics
QCP™ PE 5404EX - 0216 is a circular high density polyethylene grade supplied in pellet form for extrusion applications.

Sustainability
QCP™ PE 5404EX - 0216 contains at least 95% of post-consumer material from pre-sorted plastic packaging waste.

Recommended Applications
QCP™ PE 5404EX - 0216 is a general purpose grade that can be used for non-pressure (corrugated) pipe and sheet extrusion applications.

This product is in particular not tested and therefore not validated for use in food, pharmaceutical, medical or potable water applications.

Properties	Units	Nominal Value[1]	Test method
Physical			
Density	kg/m^3	956	ISO 1183
Melt mass-Flow Rate (MFR)			
190 °C, 2.16 kg	g/10 min	0.30	ISO 1133
Melt Volume-flow Rate (MVR)			
230 °C, 2.16 kg	cc/10 min	0.52	ISO 1133
Colour		RAL 9018[2]	CIELlab
Bulk density	kg/m^3	580	ISO 60
Ash content	%	< 2	ISO 3451-1/A/600°C
Filtration level	µm	150	-
Volatiles	%	< 0.2	ASTM D6980 @ 120°C
Recycled content	%	> 95	EN 15343
Mechanical[3]			
Tensile modulus	MPa	830	ISO 527-2/1A/1
Tensile strength	MPa	23	ISO 527-2/1A/50
Tensile strain at break	%	85	ISO 527-2/1A/50
Flexural modulus	MPa	870	ISO 178/2
Impact			
Notched Charpy Impact Strength			
23 °C, injection moulded	kJ/m^2	15	ISO 179-1/1eA

[1]) The nominal values are typical values
*[2]) closest RAL colour based on CIELab L*a*b* values*
[3]) Properties were determined on injection moulded specimens prepared in accordance with ISO 1872-2

95%

Regulatory Information

For further information send an e-mail to tds@qcpolymers.com

Storage and Handling
The material shoud be stored in a dry and dust free environment at a temperature below 50°C avoiding direct exposure to sunlight, heat and weather conditions to avoid qaulity deterioration. High humidity, heat, exhaust fumes (e.g. forklift) or combinations thereof can influence the performance of the material in a negative way.

Health and Safety Information
The material related health and safety information is available in th Material Safety Data Sheet (MSDS) which can be downloaded from www.QCPolymers.com. Before using the material you are advised to consult the MSDS for the applicable procedures for handling and use

Disclaimer
"No warranty is given and no representation is made by Seller, whether express or implied, as to the usefulness, sufficiency, merchantability or fitness for any purpose whatsoever of the goods supplied, unless explicitly given respectively made in writing. The correctness of information provided by Seller regarding the quality, composition or possible applications of the goods is warranted only if such warranty is explicitly stated in the sales agreement. Seller's liability shall not exceed the net sales price of the goods concerned. In no event shall Seller's liability include indirect or consequential damages."

Appendix F: Power requirementes calculations for the and heating bands of the 3D-paintbrush

F.1 Requirements

In order to determine the power of the motor and the heating bands we have to take into acount what the purpose is of both the motor and the heating bands.
The motor must be melt the plastic by mechanical energy in this case heating from shear stress. And the motor also must pump the plastic to the nozzle.
The heating bands assist in melting the plastic by conductive heating. and the heating bands controll the temperature at specific points in the barrel.

F.2 Variables

To calculate we need certain variables, for these calculations we take the mechanical properties described in chapter 1.9.
A table of the values can be found in Appendix A. These calculations are done for HDPE currently the most used and preferred plastic of the 3D-paintbrush.

To calculate the power the following variables are needed.

The massflow rate of the screw

$$\dot{m} := 7.5 \frac{\text{kg}}{\text{h}} \;:$$

The heat capacity of HDPE

$$C_p := 2500 \frac{\text{J}}{\text{kg}} \,{}^\circ\text{C}:$$

The temperature difference between room temperature (20°C) and desired temperature (230°C for HDPE)

$$\Delta T := 230 - 20\,{}^\circ\text{C}:$$

Semi-crystalline plastics need extra energy to break the crystalline bonds in the plastic this is called heat of fusion.
This extra energy results in no temperature change. Amorphous plastics do not need this energy because they do not have these crytalline bonds therefor the heat of fusion is for amorphous plastics is 0. Here the heat of fusion for HDPE is used a semi-crytalline plastic. the Heat of fusion is 250 kJ/kg for HDPE.

$$H_f := 250 \frac{\text{kJ}}{\text{kg}} \;:$$

the density is used to calculate the volumetric flow rate from the mass flow rate. the density of HDPE is:

$$\rho_{PE} := 965 \frac{\text{kg}}{\text{m}^3} \;:$$

Head pressure is a different variable it is the pressure build up in the form of back pressure resulting from the screens, breaker plate and die as can bee seen in figure 1.

The screens are wired meshes that filter unpurities in the material. the breaker plate is a plate with holes that distributes the forces in the meshes. This way the screens are pushed against the breaker plate and will not break. These parts are commonly used in professional extruder screws but are not needed in the 3D-paintbrush. Ofcourse the 3D-paintbrush has a die which is the nozzle.

According to the single screw extrusion analysis the head pressure is between 10 and 50 MPa (Single screw extrusion analysis, n.d.).
Since the 3D-paintbrush has no screens or breaker plate we assume the head pressure is at the low end, so for this calculation we use 10 MPa.

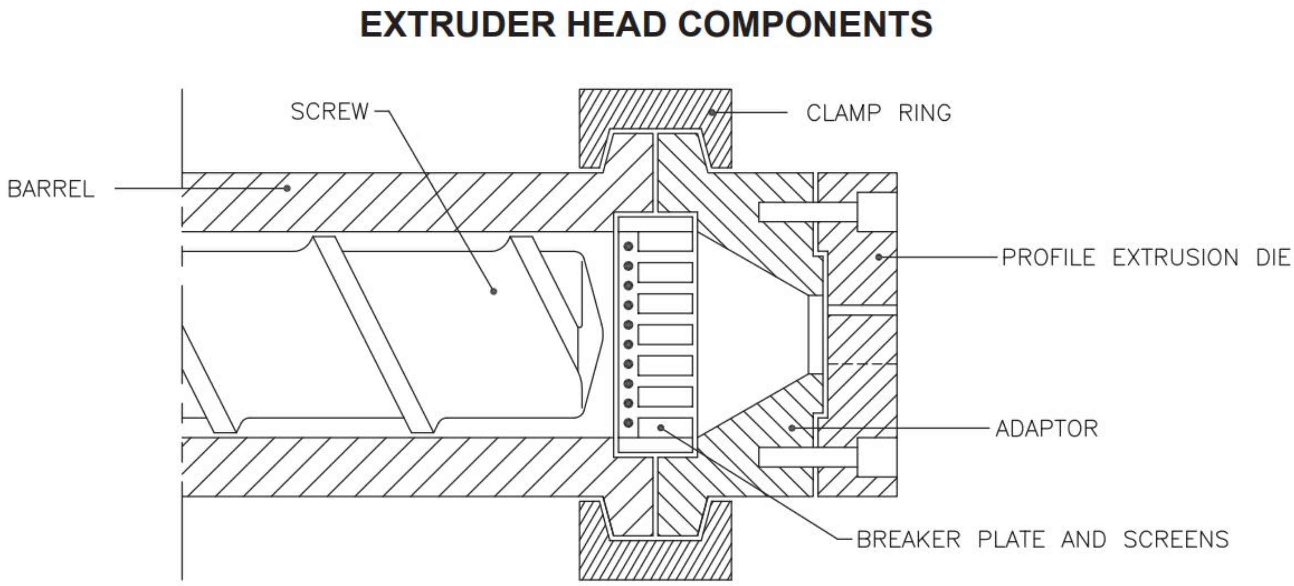


Fig 1:Extruder head components (Reiley USA, 2015)

$\Delta P := 10\ \text{MPa}$:

F.3 Motor calculations

$$P_{motor} := \left(\dot{m}\cdot C_p\cdot \Delta T + \dot{m}\cdot H_f\right)\cdot 0.75 + \frac{\dot{m}}{\rho_{PE}}\cdot \Delta P$$

1.23 kW **(1)**

Splitting this formula up into three parts, the power needed for the temperature difference, the power needed to break the crystalline bonds and the energy needed to pump the material through the screw gives insight where the highest power demands come from.

$$P_{head} := \left(\dot{m}\cdot C_p\cdot \Delta T\right)\cdot 0.75$$

0.82 kW **(2)**

$$P_{Hf} := \left(\dot{m}\cdot H_f\right)\cdot 0.75$$

0.39 kW **(3)**

$$P_{head} := \frac{\dot{m}}{\rho_{PE}}\cdot \Delta P$$

0.02 kW **(4)**

we can conclude that most energy goes into heating the material and only 2% of the energy is for pumping the material.

The efficiency of the motor has te taken into acount. The effeciency for an electro motor for this size motor is about 79% with that we can calculate the power requirement of the electromotor.

$$P_{Emotor} := \frac{P_{motor}}{0.79}$$

1.56 kW **(5)**

F.4 Heating band calculations

As mentioned the heating band only have to assist in melting the plastic and they do not help pump thematerial through the barrel.
Therefor we only need equation 2 and 3 to determine the power requirements of the heating bands.

Since we assumed the electromotor only privides 75% of the energy needed to melt the plastic the other 25% comes from the heating bands.
Equasion 6 is the total power needed from the heating bands to assist in melting the plastic.

$$P_{Band} := \left(\dot{m}\cdot C_p\cdot \Delta T\right)\cdot 0.25 + \left(\dot{m}\cdot H_f\right)\cdot 0.25$$

0.404 kW **(6)**

Appendix G: Technical data standard parts

G.1: Technical data electromotor

IEC MOTOR
GOST MOTOR
NEMA MOTOR
PUMP
GENERATOR
D.C. MOTOR

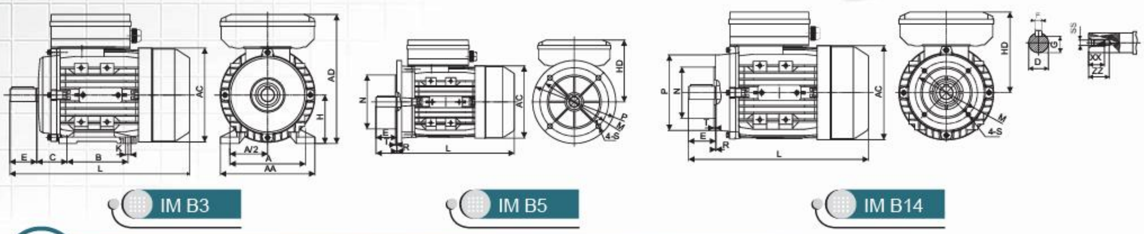
ELEKTROMOTOR.NL

ML Series

Single-Phase Capacitor Start and Capacitor Run Asynchronous Motors

Aluminum Housing

ML series aluminum housing single-phase dual-capacitor asynchronous motors,with latest design in entirety, are made of selected quality materials and conform to the IEC standard.
ML motors have good performance,safety and reliable operation, the multiple of starting torque is up to 2.5.
These series motors are suitable for the occasion where the requirements of big starting torque and high over load, such as air-compressors, pumps, and many other small machines.



Overall & Installation Dimensions

Frame Size	Mounting Dimensions																					Overall Dimensions					Shaft End Screw Dimensions		
	A	B	C	D	E	F	G	H	K	IM B14						IM B5													
										M	N	P	R	S	T	M	N	P	R	S	T	AA	AC	AD	HD	L	SS	XX	ZZ
63	100	80	40	11	23	4	8.5	63	7X10	75	60	90	0	M5	2.5	115	95	140	0	ф10	3.0	120	130	179	116	212	M4	10	15
71	112	90	45	14	30	5	11	71	7X10	85	70	105	0	M6	2.5	130	110	160	0	ф10	3.5	132	145	194	123	255	M5	12	18
80	125	100	50	19	40	6	15.5	80	10X13	100	80	120	0	M6	3.0	165	130	200	0	ф12	3.5	157	165	223	143	290	M6	16	22
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
90L	140	125	56	24	50	8	20	90	10X13	115	95	140	0	M8	3.0							172	185	240	150	365	M8	20	25
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
112M	190	140	70	28	60	8	24	112	12X15	130	110	160	0	M8	3.5	215	180	250	0	ф15	4.0	222	230	295	183	416	M10	22	28

Technical Data (at 230V/50Hz)

Model	Power (KW)	Current (A)	Speed (r/min)	Eff. (%)	Power Factor (CosΦ)	Rate Torque (N.M)	T_{st}/T_n (Times)	T_{max}/T_n (Times)	Starting Current (A)	Run Capacitor (μF/V)	Start Capacitor (μF/V)	Noise dB (A)	W.T (Kg)
ML631-2	0.18	1.38	2710	63	0.9	0.63	2.5	1.6	8	10μF/450V	30μF/250V	70	3.9
ML632-2	0.25	1.89	2710	64	0.9	0.88	2.5	1.6	10	12μF/450V	40μf/250V	73	4.4
ML711-2	0.37	2.66	2780	65	0.93	1.27	2.5	1.8	15	12μF/450V	75μF/250V	75	6.1
ML712-2	0.55	3.78	2790	68	0.93	1.88	2.5	1.8	20	16μF/450V	100μF/250V	76	7
ML801-2	0.75	4.87	2800	72	0.93	2.56	2.5	1.8	30	20μF/450V	100μF/250V	76	9
ML802-2	1.1	7.04	2810	73	0.93	3.74	2.5	1.8	40	30μF/450V	150μF/250V	79	10.3
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
ML90L-2	2.2	13.57	2810	75	0.94	7.48	2.5	1.8	75	50μF/450V	250μF/300V	84	16.7
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
ML112M1-2	3.7	21.48	2850	78	0.96	12.40	2.5	1.7	140	60μF/450V	600μF/300V	90	33
ML112M2-2	4.0	22.18	2850	80	0.98	13.41	2.5	1.7	150	60μF/450V	600μF/300V	90	34.2
ML631-4	0.12	1.05	1350	55	0.9	0.85	2.5	1.6	6	10μF/450V	30μF/250V	64	4.1
ML632-4	0.18	1.55	1350	56	0.9	1.27	2.5	1.6	8.5	12μF/450V	40μF/250V	64	4.5
ML711-4	0.25	2.01	1380	60	0.9	1.73	2.5	1.7	10	12μF/450V	50μF/250V	66	5.9
ML712-4	0.37	2.84	1380	63	0.9	2.56	2.5	1.7	15	16μF/450V	75μF/250V	68	6.9
ML801-4	0.55	4.03	1400	66	0.9	3.75	2.5	1.8	20	20μF/450V	100μF/250V	71	9.6
ML802-4	0.75	5.25	1410	69	0.9	5.08	2.5	1.8	30	25μF/450V	100μF/250V	71	10.9
ML90S-4	1.1	7.24	1410	71	0.93	7.45	2.5	1.8	40	35μF/450V	150μF/250V	74	13.8
ML90L-4	1.5	9.61	1400	73	0.93	10.24	2.5	1.8	55	40μF/450V	200μF/300V	79	16.7
ML100L1-4	2.2	13.90	1430	74	0.93	14.70	2.5	1.8	75	50μF/450V	300μF/300V	79	22.8
ML100L2-4	3	18.70	1440	75	0.93	19.91	2.5	1.8	110	60μF/450V	500μF/300V	83	28.7
ML112M1-4	3.7	21.99	1440	77	0.95	24.55	2.5	1.7	140	60μF/450V	600μF/300V	86	31
ML112M2-4	4.0	22.41	1440	80	0.97	26.54	2.5	1.7	150	60μF/450V	600μF/300V	86	32.8

Data Sheet

Electramo NV
Industrieweg 14
B-2390 Malle
Belgium
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info@electramo.com
www.electramo.com
BE 0414.941.452

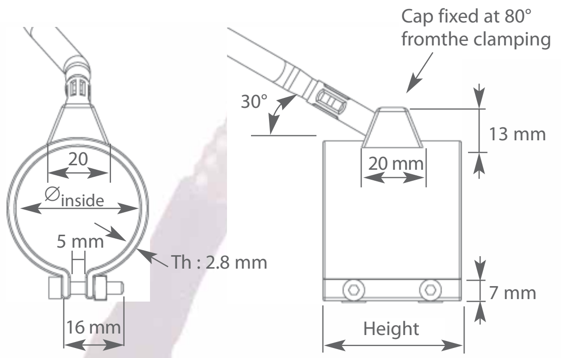
Electric motor Type		**ML90L-2 - 2,2kW - 2810 rpm - 230V**				
Efficiencies		IEC60034-30		single phase		
Insulation class		F / B				
Temperatures		-20°C / +40°C				
Connection - Phases		L+N				
Tension	**V**	230				
Frequency	**Hz**	50		Start Cap:	250 µf	300 V
Output	**kW**	2,20		Run Cap:	50 µf	450 V
Speed	**min⁻¹**	2.810				
Current	**A**	12,50				
Efficiency	**%**	**100%**				
		79,00				
Cos ф		**100%**				
		0,97				
Starting Current	**A**	6,00	Ia/In			
Nominal Torque	**Nm**	7,48	Nm			
Starting Torque	**Nm**	2,20	Ms/Mn			
Maximum Torque	**Nm**	1,80	Mmax/Mn			
Construction		Aluminum				
Mounting position		B3 - IM1001 - feet - horizontal				
Protection		IP 55				
Cooling method		IC 411				
Duty type		S1				
Tropical treatment		95%				
Max. altitude A.S.L.		1000 m				
Paint (body / fan cover)		RAL 5010				
Terminal Box Position		Top - A1				
Cable entries		1 x M20x1,5				
Direction of rotation		← / →				
Drain hole(s)		Lowest point - with plug				
Bearing DE		6205 2RS C3				
Bearing NDE		6205 2RS C3				
Shaft dimensions	**mm**	24 x 50				
Oilseals DE / NDE	**mm**	25 x 37 x 7		25 x 37 x 7		
Balancing (Class)		Half Key		A (IEC 60034-14)		
Sound level - L(p)A	**dB(A)**	84,0	50Hz - at 1m - no load			
Weight	**Kg**	17,0				

G.2: Technical data heating bands

STANDARD ENCAPSULATED SEALED NOZZLE HEATERS

- Max. watt density over the surface of the heater: 6.5 W/cm²
- Max. operating temperature over the surface of the heater: 340°C, depending on working conditions.
- Diameter : 25 to 100 mm
  Height : 20 to 80 mm
  Wattage : 65 to 970 W, 230 V single phase
  For other dimensions, not kept in stock, see p 5
- Sealed band heater in brass, with folded ends. Band heater connection, waterproof technology.
- Electric insulation by mica plate.
- Connection : nickel core, fiberglass insulated + earth wire; protected by a galvanized steel braid.
- Connection cap : axial 30°, centred on the height of the band heater, up to 38 mm height. Over 38 mm height, it is placed at 20 mm from the edge. (See sketch). (Except L2570C26G10*)
- Square angle flange clamping, screw BTR M4, self-locking square nuts.
- Our products are in accordance with EN 60335-1
  Wattage tolerance: +5% -10%
  Leakage current < 0.75 mA/kW
- Special manufactures :
  - Sealed stainless steel nozzle heater (see picture on next page).
  - Max. watt density : 5 W/cm².
  - Specific sealed nozzle heaters not kept in stock, see p 5.
  - Accessories and options, see p 12.
  - How to define a special band heater: see p 18.

- Dimensions of a standard insulated mica nozzle heater :



To each diameter of band heater corresponds a clamping capacity. For instance, a band heater with a diameter of 30 mm can be fitted on a nozzle of 30 mm to 31 mm.
In charts below, the diameter of a band heater is written in green and below it, its clamping capacity is written in black between brackets.

Diameter Ø (mm)	Height H (mm)	Power P (W)	Braid L (mm)	Part number
25 (25 to 26)	20	65	500	L2520C6A5
	25	85	500	L2525C8A5
	30	105	500	L2530C10A5
	35	125	500	L2535C12A5
	38	145	500	L2538C14A5
	70	260	1000	L2570C26G10*
26 (26 to 27)	30	115	500	L2630C11A5
	35	135	500	L2635C13A5
28 (28 to 29)	20	75	500	L2820C7A5
		75	1000	L2820C7A10
		75	2000	L2820C7A20
	25	100	500	L2825C10A5
	30	125	500	L2830C12A5
	35	150	500	L2835C15A5
	38	170	500	L2838C17A5
	50	220	500	L2850C22A5
30 (30 to 31)	20	85	500	L3020C8A5
	25	110	500	L3025C11A5
		110	1500	L3025C11A15
	30	135	500	L3030C13A5
		135	1000	L3030C13A10
		135	1500	L3030C13A15
	35	160	500	L3035C16A5
		160	1000	L3035C16A10
	38	185	500	L3038C18A5
	38	185	1000	L3038C18A10
	50	235	500	L3050C23A5

Diameter Ø (mm)	Height H (mm)	Power P (W)	Braid L (mm)	Part number
30 (30 to 31)	50	235	1000	L3050C23A10
	60	285	500	L3060C28A5
		285	1000	L3060C28A10
	65	310	500	L3065C31A5
32 (31 to 32)	20	90	500	L3220C9A5
	25	115	500	L3225C11A5
	30	145	500	L3230C14A5
		145	1000	L3230C14A10
		200	2000	L3230C20A20
	35	170	500	L3235C17A5
	38	195	500	L3238C19A5
		195	1000	L3238C19A10
		195	2000	L3238C19A20
	50	250	500	L3250C25A5
	60	300	500	L3260C30A5
		300	2000	L3260C30A20
34 (34 to 35)	20	95	500	L3420C9A5
	25	125	500	L3425C12A5
		125	1000	L3525C12A10
		125	1500	L3425C12A15
	30	155	500	L3430C15A5
		155	1000	L3430C15A10
	35	180	500	L3435C18A5
		180	2000	L3435C18A20
	38	185	2000	L3438C18A20
		210	500	L3438C21A5
	50	265	500	L3450C26A5
	60	325	1000	L3460C32A10

Diameter Ø (mm	Height (mm)	Watt. W (W)	Braid L (mm)	Part number
38 (38 to 39)	25	140	500	L3825C14A5
	30	170	500	L3830C17A5
	35	200	500	L3835C20A5
	38	235	500	L3838C23A5
40 (40 to 41)	20	125	500	L4020C12A5
		125	1000	L4020C12A10
		125	2000	L4020C12A20
	25	160	500	L4025C16A5
		160	1000	L4025C16A10
	30	200	500	L4030C20A5
		200	1000	L4030C20A10
		200	2000	L4030C20A20
	35	235	500	L4035C23A5
		235	2000	L4035C23A20
	38	200	500	L4038C20A5
		270	500	L4038C27A5
		270	1000	L4038C27A10
		270	1500	L4038C27A15
		270	2000	L4038C27A20
	45	305	500	L4045C30A5
		305	1000	L4045C30A10
		305	2000	L4045C30A20
	50	345	500	L4050C34A5
		345	1000	L4050C34A10
		345	2000	L4050C34A20
	55	380	1000	L4055C38A10
	60	415	500	L4060C41A5
		415	1000	L4060C41A10
		415	1500	L4060C41A15

* Cap off center at 0 mm from the edge of the band heater. One end of the clamping tab is bevel-edged at 45°

STANDARD ENCAPSULATED SEALED NOZZLE HEATERS

Diameter ∅ (mm)	Height H (mm)	Watt. W (W)	Braid L (mm)	Part number
40 (40 to 41)	60	415	2000	L4060C41A20
	65	430	500	L4065C43A5
	70	450	500	L4070C45A5
		450	2000	L4070C45A20
42 (42 to 43)	25	155	500	L4225C15A5
	30	190	500	L4230C19A5
	38	260	500	L4238C26A5
	50	330	500	L4250C33A5
		330	2000	L4250C33A20
44 (44 to 45)	20	125	500	L4420C12A5
	25	160	500	L4425C16A5
	30	200	500	L4430C20A5
		200	1000	L4430C20A10
		200	1500	L4430C20A15
	35	235	500	L4435C23A5
	38	270	1000	L4438C27A10
		300	500	L4438C30A5
	45	310	500	L4445C31A5
		310	1000	L4445C31A10
	50	345	500	L4450C34A5
		345	1000	L4450C34A10
	55	385	500	L4455C38A5
	60	420	500	L4460C42A5
48 (48 to 49)	20	135	1000	L4820C13A10
	25	180	500	L4825C18A5
	30	220	1000	L4830C22A10
	38	300	2000	L4838C30A20
50 (50 to 51)	20	140	500	L5020C14A5
	25	185	500	L5025C18A5
		185	1000	L5025C18A10
	30	225	500	L5030C22A5
		225	1000	L5030C22A10
	35	270	500	L5035C27A5
		270	1000	L5035C27A10
	38	310	500	L5038C31A5
		310	1000	L5038C31A10
		310	1500	L5038C31A15
		310	2000	L5038C31A20
	45	350	500	L5045C35A5
	50	390	500	L5050C39A5
		390	1000	L5050C39A10
	60	475	500	L5060C47A5
		475	1000	L5060C47A10

Diameter ∅ (mm)	Height H (mm)	Watt. W (W)	Braid L (mm)	Part number
50 (50 to 51)	60	475	2000	L5060C47A20
	65	510	500	L5065C51A5
	70	560	500	L5070C56A5
	75	600	2000	L5075C60A20
54 (54 to 55)	25	200	500	L5425C20A5
		200	1000	L5425C20A10
	30	245	500	L5430C24A5
	38	335	500	L5438C33A5
		335	2000	L5438C33A20
	45	380	500	L5445C38A5
56 (56 to 57)	38	350	500	L5638C35A5
58 (58 to 59)	38	360	500	L5838C36A5
60 (60 to 61)	20	170	1000	L6020C17A10
		250	500	L6020C25A5
	25	220	500	L6025C22A5
	30	275	500	L6030C27A5
		275	1000	L6030C27A10
		325	2000	L6030C32A20
	35	325	500	L6035C32A5
		325	1500	L6035C32A15
	38	375	500	L6038C37A5
		375	1000	L6038C37A10
		375	1500	L6038C37A15
	45	425	500	L6045C42A5
		425	2000	L6045C42A20
	50	475	500	L6050C47A5
		475	1000	L6050C47A10
	55	525	500	L6055C52A5
	60	575	500	L6060C57A5
	65	625	500	L6065C62A5
	80	780	500	L6080C78A5
64 (64 to 65)	20	185	500	L6420C18A5
	25	240	500	L6425C24A5
	38	400	1500	L6438C40A15
	45	455	500	L6445C45A5
68 (68 to 69)	30	310	500	L6830C31A5

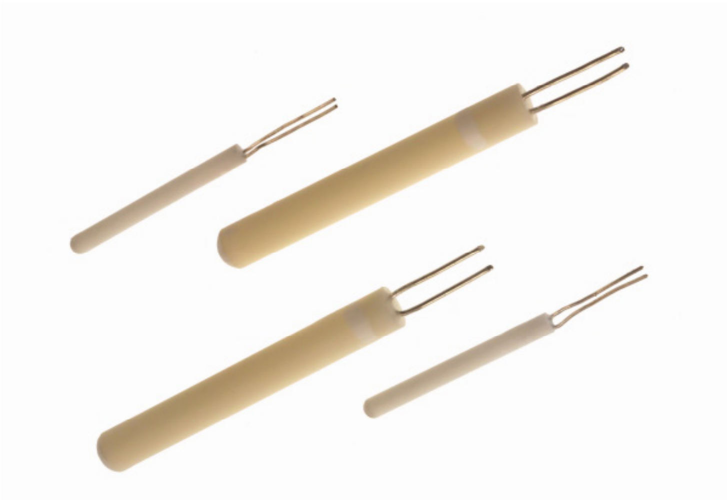
Diameter ∅ (mm)	Height H (mm)	Watt. W (W)	Braid L (mm)	Part number
70 (70 to 71)	30	320	500	L7030C32A5
		320	1000	L7030C32A10
	35	380	500	L7035C38A5
	38	440	500	L7038C44A5
		440	1000	L7038C44A10
		440	1500	L7038C44A15
		550	1500	L7038C55A15
	45	500	500	L7045C50A5
	50	560	500	L7050C56A5
	65	730	500	L7065C73A5
	70	785	500	L7070C78A5
72 (72 to 73)	30	330	1000	L7230C33A10
74 (74 to 75)	30	340	1000	L7430C34A10
	50	590	500	L7450C59A5
80 (80 to 81)	30	365	500	L8030C36A5
	35	435	2000	L8035C43A20
	38	500	500	L8038C50A5
		500	1000	L8038C50A10
	45	570	500	L8045C57A5
	50	630	500	L8050C63A5
		630	1000	L8050C63A10
90 (90 to 91)	30	415	1000	L9030C41A10
	45	645	1000	L9045C64A10
	60	875	500	L9060C87A5
94 (94 to 95)	55	830	1000	L9455C83A10
100 (100 to 101)	30	460	500	L10030C46A5
	60	970	500	L10060C97A5
		970	1000	L10060C97A10

Stainless steel sealed nozzle heater
(Special manufacture)

Sealed nozzle heater, in
brass.

Resistance Pt100 Wire-Wound Detector Elements

Pt100 platinum resistance thermometer elements in a choice of sizes – single & dual element



- Pt100 elements to IEC 60751 Class A or B
- 100Ω Ohms @ 0°C
- Single or dual element
- Platinum coil wire-wound construction sealed inside a high purity alumina ceramic body
- Optimum performance & stability
- Temperature range –200°C to +650°C

Specifications:

Sensor type:	Pt100 (100 Ohms @ 0°C)
Construction:	Wire-Wound, 10mm tails
Temperature range:	-200°C to +650°C
Ice point resistance:	100Ω
Fundamental interval (0°C to 100°C):	38.5Ω (nominal)
Self-heating:	0.02 to 0.3°C/mW
Thermal response:	<0.4s (secs. to 63% of final value – in water @ 1m/s)
Measuring current:	1mA
Tolerance Class:	In accordance with IEC 60751
	W0.15 (Class A) -100°C to +450°C
	W0.3 (Class B) -196°C to +660°C

Continued:

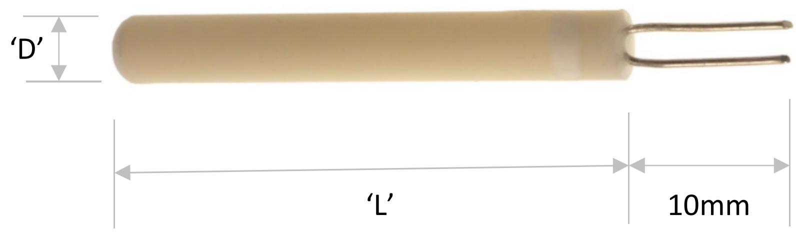
RS135/0816

Single element:

Resistance	Tolerance Class	Diameter ('D')	Length ('L')	Allied code	RS order code
Pt100	Class B	1.5mm	8mm	70646153	**611-7851**
Pt100	Class A	1.5mm	8mm	70646155	**611-7873**
Pt100	Class B	1.5mm	15mm	70646154	**611-7867**
Pt100	Class A	1.5mm	15mm	70646151	**611-7839**
Pt100	Class B	2.8mm	15mm	70646150	**611-7823**
Pt100	Class A	2.8mm	15mm	70646152	**611-7845**
Pt100	Class B	2.8mm	25mm	70646147	**611-7794**
Pt100	Class A	2.8mm	25mm	70646149	**611-7817**

Dual element:

Resistance	Tolerance Class	Diameter ('D')	Length ('L')	Allied code	RS order code
Pt100 (x2)	Class A	1.5mm	15mm	70643873	**397-1595**



ENGLISH

Datasheet

Calcium-Magnesium Silicate Thermal Insulation Sheet 5m x 0.61 x 6mm

RS Stock No: 724-8903

Description:

Superwool 607 HT Blanket is made of Superwool 607 HT long fibres. It exhibits outstanding insulating properties at elevated temperatures, has an excellent thermal stability and retains its original soft fibrous structure up to maximum continuous use temperature. Blanket contains neither binder nor lubricant and does not emit any fume or smell during the first firing. It is flexible, easy to cut and shape and easy to install.

- Excellent thermal insulating properties
- Thermal stability
- Low heat storage
- Flexible and resilient
- Immune to thermal shock
- No reaction with alumina based bricks in application in the range of the typical use temperature
- Exonerated from any carcinogenic classification under nota Q of directive 97/69 EC

Specifications:

Type:	Blanket made from high temperature insulation wool	
Classification Temperature:	1300°C (ENV 1094-3)	
Continuous use Temperature:	1150°C. The maximum continuous use temperature depends on the application	
Colour:	white	
Density:	kg/m^3	64, 96, 128, 160
Tensile Strength (ENV 1094-7)	64 kg/m^3	30 kPa
	96 kg/m^3	50 kPa
	128 kg/m^3	75 kPa
	160 kg/m^3	95 kPa

Permanent Linear Shrinkage (ENV 1094-7) <2%
after 24 hours isothermal heating at 1260°C

Thermal Conductivity (ASTM C-201)
at mean temperature of:

		96 kg/m^3	128 kg/m^3
200°C	W/m.k	0.05	0.04
400°C	W/m.k	0.10	0.08
600°C	W/m.k	0.19	0.14
800°C	W/m.k	0.32	0.23
1000°C	W/m.k	0.48	0.34
1200°C	W/m.k	0.69	0.48

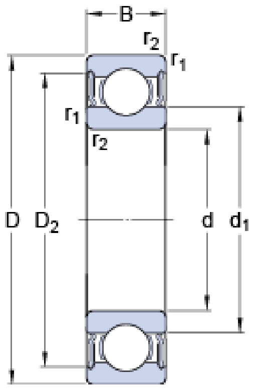
Chemical Composition:

SiO_2	70-80%
CaO + MgO	18-25%
Others	<3%

6016-2RS1

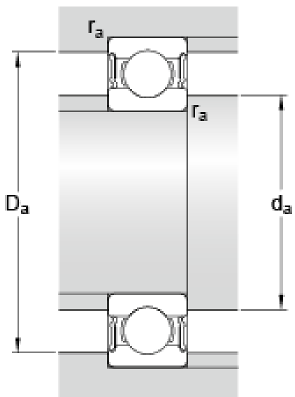
Popular item
SKF Explorer

Dimensions



d		80	mm
D		125	mm
B		22	mm
d_1	≈	94.4	mm
D_2	≈	114.1	mm
$r_{1,2}$	min.	1.1	mm

Abutment dimensions



d_a	min.	86	mm
d_a	max.	94.3	mm
D_a	max.	119	mm
r_a	max.	1	mm

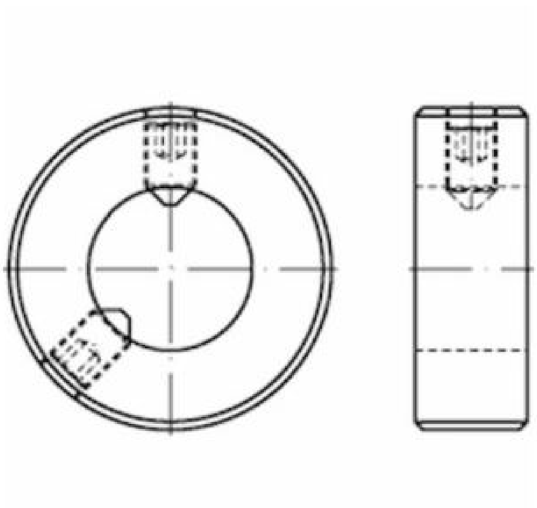
Calculation data

Basic dynamic load rating	C	49.4	kN
Basic static load rating	C_0	40	kN
Fatigue load limit	P_u	1.66	kN
Limiting speed		3200	r/min
Calculation factor	k_r	0.025	
Calculation factor	f_0	15.6	

Mass

Mass bearing	0.88	kg

G.6: Technical data Adjusting ring



FAST-X DIN705a staal 80 /1 asring (met 1 borgschroef din553)

Artikelnummer: C0CA0
EAN: 4043952139233

Breedte (mm)	22.0
Binnendiameter (mm)	80.0
Materiaal	Staal
Uitwendige diameter (mm)	110.0