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ESCUELA DE INGENIERÍAS INDUSTRIALES

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DESIGN A SMALL EXTRUSION HEAD FOR 3D PRINTER USING PLASTICS GRANULATES

Autor:

ANDRÉS SACRISTÁN, ARTURO

Responsable de Intercambio en la Uva:

SANCHEZ BASCONES, ISABEL

Universidad de destino:

VIVES UNIVERSITY, KORTRIJK

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TÍTULO: DESIGN A SMALL EXTRUSION HEAD FOR 3D PRINTER USING PLASTICS GRANULATES

ALUMNO: ANDRÉS SACRISTÁN, ARTURO

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CENTRO: VIVES UNIVERSITY, KORTRIJK

TUTOR: VANDERSICKEL, KAROLIEN

RESUMEN Y PALABRAS CLAVE

El proyecto aquí descrito consiste en el planteamiento de un nuevo diseño de cabeza de impresora 3D que sea capaz de imprimir utilizando, como materia prima, plástico granulado. Hoy en día la tecnología de impresión 3D ha adquirido una gran importancia, debido sobre todo a su uso en creación de prototipos. Gracias al desarrollo de esta tecnología en los últimos años, es posible realizar prototipos, e incluso piezas finales y útiles, de manera rápida y con un coste mínimo. Sin embargo, aún existen muchas limitaciones y campos de mejora. Este proyecto trata de abordar una de estas limitaciones.

La gran mayoría de impresoras 3D utilizan la tecnología Fuse Deposition Modeling (FDM), para imprimir las piezas a partir de un filamento o cable de plástico. Con este nuevo diseño se pretende eliminar el paso intermedio de la elaboración del filamento a partir del plástico granulado. Se ha planteado el diseño para utilizar el plástico PLA, ya que es uno de los más usados, aunque el principio seria el mismo para cualquier otro plástico de los que se utilizan en impresión 3D, como el ABS.

Para diseñar y dimensionar la nueva cabeza, se han basado muchos cálculos en la maquina DeltaRocket, una de las impresoras 3D más usadas debido a su sencillez.

El nuevo diseño, aunque se asimile en muchos parámetros a la DeltaRocket, imprimirá a partir de la extrusión del plástico granulado lo que permite realizar un proceso continuo de impresión, al tiempo que se pueden usar cualquier tipo de plástico y mezclas de los mismos.

PALABRAS CLAVE:

- Impresión 3D
- Cabezal
- PLA
- Extrusión plástico
- Diseño

INDEX

1. INTRODUCTION

Due to the large scope of 3D printing this technology has experienced in the recent decades a great development. The access to 3D printers is becoming easier as the prizes are going down. Nowadays both companies and regular users can develop their own parts in a relatively simple and quickly way. That is why there is more and more interest in evolving this technology which has already revolutionized manufacturing processes.

Today there are plenty options when choosing a printer and a lot of different companies that manufacture and sell these printers. However, there are still many things to improve and a lot of research that needs to be done. Indeed, this project is raised as the beginning of one of these lines of research. We are trying to give rise to a new type of 3D printer heads, a field which can be widely developed.

This memory contains the information and researches done to propose a design of a new head for the 3D printers. This design must allow to print using plastic granulate instead of the wire commonly used. The aim of the project is to propose a new design of a functional 3D printer head that overcome some limitations of the filament based process. For example, the need for a thermoplastic filament as feed material or especially the limited range of commercially available materials which can be processed. In addition, it will be studied the feasibility of this new head comparing with the existing ones, how expensive can it be and which are the benefits and disadvantages of it.

This project will study the world of 3D printing, explaining what is the 3D printing and the additive manufacturing and its applications. Which is the technology that already exist and which are the fields where this technology can be improved. In the end we will try to propose a new design for a 3D printer head. It has to be mentioned that this project is only a starting point for the design of a new head. After it requires many test and experimental data to came up with the optimal design. Especially when it comes to plastic extrusion which is still more practical than theoretical.

We will try to provide the drawings and the material information needed to produce the head so in the future it will be possible to continue with the project by producing the head, testing it and improving it.

2. GOAL

The main goal of the project is to design a new head for 3D printer starting from plastic granulate instead of using the plastic wire. The objective is to overcome with the limitations that this wire technology has. From the information and knowledge gained on the research part we try to propose a design for the new head so in the future projects it can be manufactured and tested.

In addition to this main goal the project has a few others goals. For example, to introduce to the reader into the 3D printing world. We will explain the most commonly used processes, technology and materials in 3D printing. Other important goal is to make a quick overview on all the things that hadn't been developed yet. In this way we will try to encourage new projects and researches in this world.

The last goal of the project is to find a cheaper way 3D print. 3D printing is much cheaper than many other existing techniques, but we will try to find a way to reduce the cost that nowadays exists. This is the reason why we are using plastic granulate instead of the plastic wire. The granulates are largely cheaper, which helps to reduce the cost of the process.

3. LITERATURE STUDY

As said this project will try to provide an overview of 3D printing world. The first step in the project is to make a research of all the different processes, the existing technology and the theoretical knowledge from previous researches. It is also necessary to make some research on plastic extrusion technology as it is the main principle in a 3D printer head.

3.1 ADDITIVE MANUFACTURING

3D printing or additive manufacturing is a process of making three dimensional solid objects from a digital file by adding material layer by layer. Here it will be explained the different ways to obtain a 3d part to show the possibilities. Also to enter the world of 3D printing in order to understand why has this technology become so important.

Not all the 3D printers use the same technology. There are several ways to print although all of them differ mainly in the way layers are built. Some methods use melting or softening material to produce the layers. Selective laser sintering (SLS) and fused deposition modelling (FDM) are the most common technologies that use this way of printing. Another method of printing is curing a photo-reactive resin with a UV laser, the most common technology using this method is called Stereolithography (SLA).

Despite the different ways of 3D printing it always starts with making a virtual design of the object you want to create. This virtual design is made in a CAD (Computer Aided Design) file using a 3D modeling program. Then this file is sent to a different program that slices the model into layers generating a g-code needed for the printer.

Nowadays 3D printing is a well-known technology mostly used in the processes of prototyping due to the simplicity and the speed of the process. Thanks to the increasing interest and technological evolution, 3D printers are starting also to be used for the production of single or small series of functional products.

Broadly speaking, there are three categories of additive manufacturing: selective binding, selective solidification and selective deposition.

- Selective binding technologies make a 3D printed object from powder (metal and gypsum usually) by applying binding agents or heat to fuse the powder's particles together.
- Selective solidification makes a solid object from a vat of liquid by applying energy to solidify the liquid a layer at each time. The most commonly used technology in this process is Stereolithography (SLA). Typically, a first layer is created on some sort of platform, which then moves down into the liquid. In some cases, the platform pulls up out of the liquid.
- Selective deposition techniques only place material where you want it. Fused deposition modelling (FDM) is the most common technology. During printing, the plastic filament is fed through a hot extruder where the plastic gets soft enough that it can be precisely placed by the print head. These are the most popular machines and the cheapest ones.

However, the American Society for Testing and Materials (ASTM) group has developed a set of standards that classify the additive manufacturing processes into 7 categories:

- Binder Jetting
- Directed Energy Deposition
- Material Extrusion
- Material Jetting
- Powder Bed Fusion
- Sheet Lamination
- Vat Photopolymerisation

3.1.1 BINDER JETTING

This technology was first developed at the Massachusetts Institute of Technology in 1993 and in 1995 Z Corporation obtained an exclusive license. Binder jetting use materials powder as base material and an adhesive binder which is usually liquid. The powder is spread in the chamber creating a powder bed and the binder is injected by a print head which moves horizontally along the X and Y axes. After each layer, the object is lowered and another layer of powder is spread over the platform using a roller.

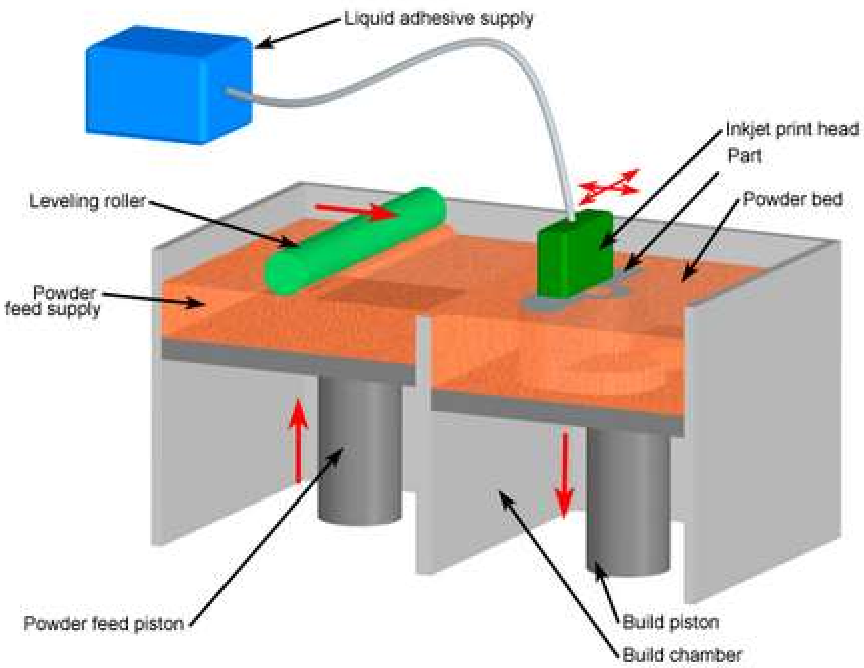


Figure 1. Binder Jetting process.

The process allows metal, polymers and ceramics as base materials. It is generally faster than others because it is easy to increase the number of holes in the head that deposit the binder material. The two material approach allows for a large number of different binder-powder combinations. Also various mechanical properties options of the final model can be achieved by changing the ratio and individual properties of the two materials.

However, this process is not always suitable for structural parts because of the binder material. In addition, post processing is often required to make the part stronger and give the binder-material better mechanical and structural properties. So this can increase a lot the time of the process.

3.1.2 DIRECTED ENERGY DEPOSITION

Directed Energy Deposition (DED) is a more complex process. It is usually used with metals but it can also be used with polymers or ceramics.

A DED machine consists on a nozzle mounted on a multi axis arm, which deposits melted material onto the specified surface. The process, as shown in the figure, uses wire or powder as feed material. This feed material is melted and deposited onto the specific surface as the nozzle moves. Usually they are 4 or 5 axis machines so the material can be deposited from any angle. The method of melting varies between a laser, an electron beam or plasma arc.

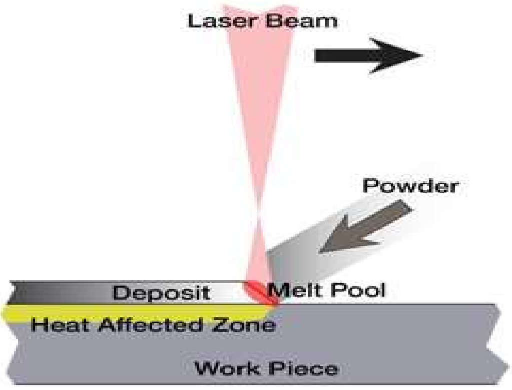


Figure 2. Directed energy Deposition principle.

As it is usually used to repair or add additional material the part is usually fixed and the nozzle moves around the part. However, it is also possible to do it the other way round.

The main advantages of this process is the possibility to control the grain structure so it makes high quality pair work. In the other hand, post processing is usually required to achieve the desire finishes in the parts.

3.1.3 MATERIAL EXTRUSION

Material extrusion is a selective deposition process usually associate to the Fused deposition modelling (FDM) technology. The principle of Selective deposition is as simple as building up a piece by adding melted plastic on a flat surface and erect the part layer by layer. It is a common technique used in many domestic 3D printers.

The feed material is always polymer or plastic in a wire form, which is drawn through a nozzle in a continuous process and under constant pressure. The nozzle is heated in order to melt the plastic before it is deposited layer by layer.

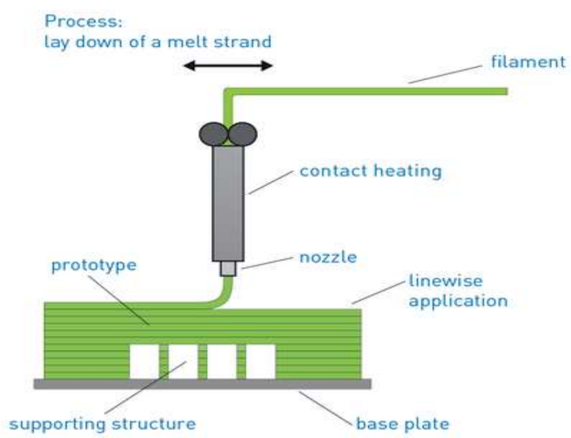


Figure 3. Extrusion Material process.

The nozzle can move horizontally in X and Y axis and up and down in the Z axis, nevertheless is also possible that the nozzle is fixed and is the base plate the motion piece. After a layer is deposited, the nozzle moves up, or the platform moves down.

The process is quite inexpensive and it allows a wide range of materials as feed material (ABS, PLA, Nylon, PC, PC, AB). It is also a quick process and it is used in fast prototyping. The disadvantages of FDM are that the accuracy of the final model is low comparing with other processes and also the nozzle radius limits and reduces the final quality. The project will focus on this process so it will be further explained later.

3.1.4 MATERIAL JETTING

Material Jetting, also known as Multijet modelling or Drop on Demand (DOD), creates objects by jetting material onto a build platform.

Material jetting machines utilize inkjet print heads to jet droplets of melted materials, which then cool and solidify. Droplets are dispensed only when needed. The material layers are then cured or hardened using ultraviolet (UV) light. By adding layer on layer, the part is built.

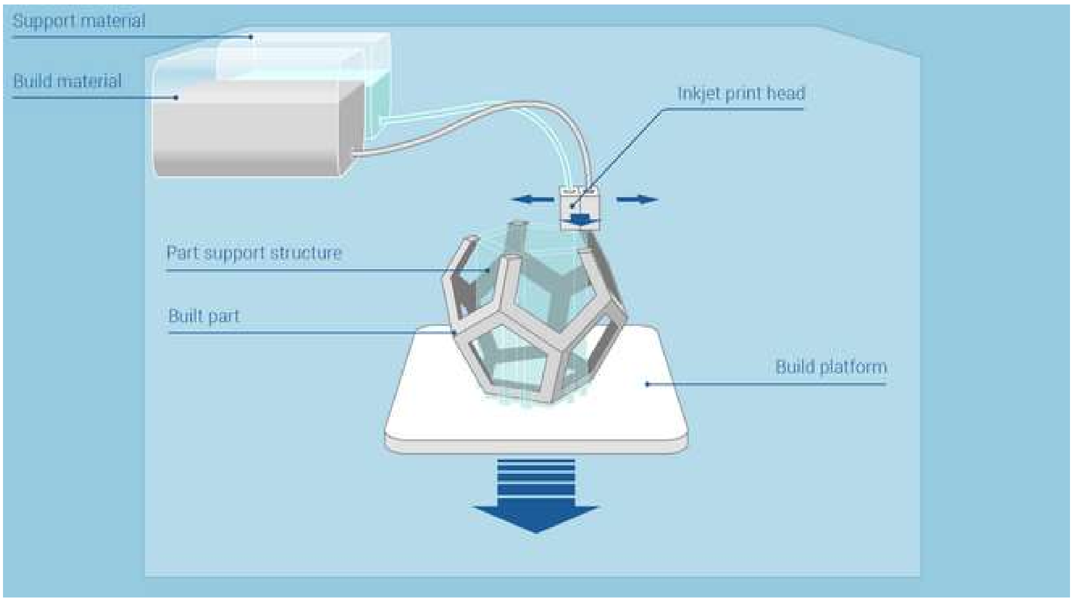


Figure 4. Material Jetting process.

This technology can achieve very good accuracy and surface finishes, however, using droplets, limits the number of materials that can be used. Polymers and waxes are often used due to their viscous nature and ability to form drops. Viscosity is the main determinant in the process. In addition, there is a need to refill the reservoir quickly and this in turn affects print speed.

The process also allows multiple materials and colours due to the multiple jet head.

3.1.5 POWDER BED FUSION

The Powder Bed Fusion process includes several printing techniques: Direct metal laser sintering (DMLS), Electron beam melting (EBM), Selective heat sintering (SHS), Selective laser melting (SLM) and Selective laser sintering (SLS). All of these techniques may be similar to binder jetting process but using either a laser or electron beam, instead of a binder, to melt and fuse material powder together. Only Selective Heat Sintering (SHS) uses a heated thermal printhead to fuse the powder material together.

The process sinters the powder, layer by layer. After a layer is fused by the laser a new layer of powder is spread over the previous one using a roller. This process continuous until the part is finished, then the unfused powder is removed.

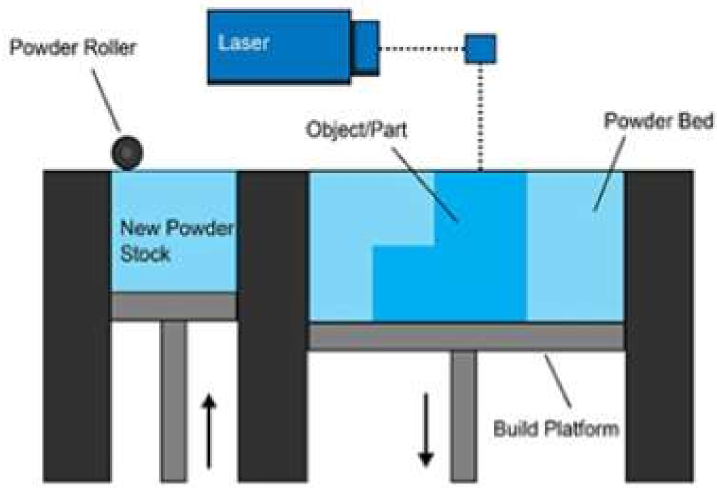


Figure 5. Powder Bed Fusion process.

This process is suitable for creating prototypes as it is relatively inexpensive. In addition, large range of materials, both metals and plastics, can be used. Also the powder bed acts as an integrated support material, which reduced the waste of material.

In the other hand, the speed of the process is quite slow. Furthermore, high power is required and the finishes of the pieces depend on the powder grain size.

3.1.6 SHEET LAMINATION

Sheet lamination processes include Ultrasonic Additive Manufacturing (UAM) and Laminated Object Manufacturing (LOM).

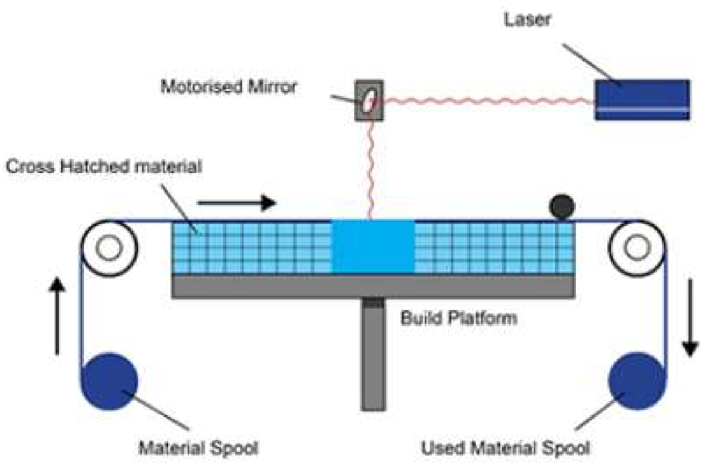


Figure 6. Sheet Lamination process.

UAM uses sheets of metals, such as aluminium, copper, stainless steel and titanium, which are bound together using ultrasonic welding. The material is placed and bonded to the previous layer, then it is cut in the required shape. The process repeats this steps building layer by layer the part. LOM uses a similar process but using paper and adhesive instead of metal and welding.

The process occurs at low temperature and allows internal geometries to be created. Also, as the metal is not melted requires relatively little energy. However, laminated objects are often used for aesthetic and visual models and are not suitable for structural use.

In addition, the main feed material for LOM techniques is paper which greatly reduces the cost.

3.1.7 VAT PHOTOPOLYMERISATION

Vat Polymerisation is a method in 3D printing to print 3D plastic and polymer objects by using a vat of liquid photopolymer resin, out of which the model is constructed by photo polymerisation.

A platform is lowered from the top of the resin. The UV light cures the resin layer by layer. After one layer is done the platform moves downwards so the next layer remains over the solid material. Once the object is finished the vat is drained of resin and the part can be removed.

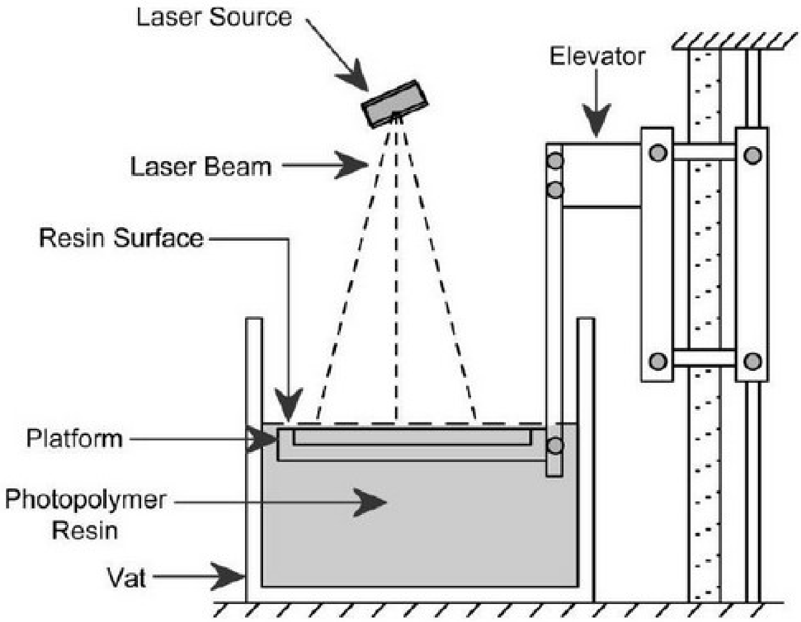


Figure 7. Vat Photopolymerisation process

Because the process uses liquid to form objects, support structures will often need to be added as there is no structural support from the material. Unlike powder based methods, where support is given from the unbound material.

The advantages of this process is that it is a relatively quick process with a high level of accuracy and finish. Also it is possible to have large built areas. Nevertheless, it is an expensive process because often requires support structures and post processing. In addition, limited material can be used, only those affected by photo polymerisation.

3.2 EXTRUSION MATERIAL EXISTING TECHNOLOGY

The principle of Selective deposition in additive manufacturing is as simple as building up a piece by adding melted plastic on a flat surface and erect it layer by layer. Of course for building up a 3D piece it is necessary to have a 3D printer and also a model in the computer, 3D printers start with a computer model of an object and then use that model to control a robotic device. A 3D printer is a gadget or device that can apply melted plastic in all three dimensions: right and left on a surface and up and down vertically. The head normally moves by stepper motors or servomotors. It is also possible that is the base surface which has movement and the head stays motionless.

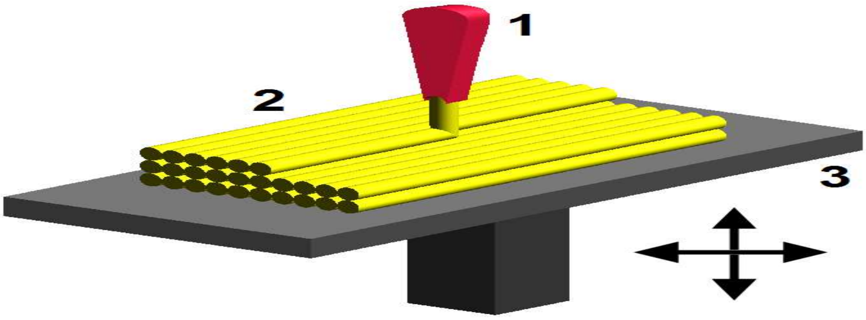


Figure 8. Additive manufacturing process.

So thanks to the additive manufacturing technology we are capable now to print up from a flat surface, adding melted plastic layer by layer creating our 3D output. This means that we can let down ink jet printers which can only print an image or a view of an object and we can now create that object.

As we said we are going to focus in Selective deposition techniques only but there is a lot of different ways for doing the process of 3D printing. The key part on our project is the process of melting the plastic from the granulate so we can deposit it on the platform and solidifies after. Here we are going to describe the existing techniques for melting the plastic.

Extrusion based 3D printing processes fabricate objects through the deposition of material using a print head. In this case objects are produced by heating the thermoplastic material into a visco-elastic melt that is extruded and deposited layer upon layer. There are different ways to get the plastic melted. Here is an overview of the presented extrusion principles:

a) the well-known FDM principle.
b) syringe based extrusion.
c) the screw based extrusion.

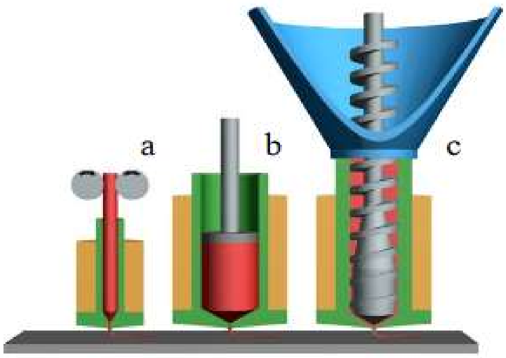


Figure 9. Extrusion principles

3.2.1 FILAMENT BASED 3D PRINTING (FDM)

Fused Deposition Modeling (FDM) was developed by S. Scott Crump in the late 1980s and was commercialized in 1990. It is the most famous technique of Selective deposition techniques. FDM is an additive manufacturing technology commonly used for modeling, prototyping, and production applications.

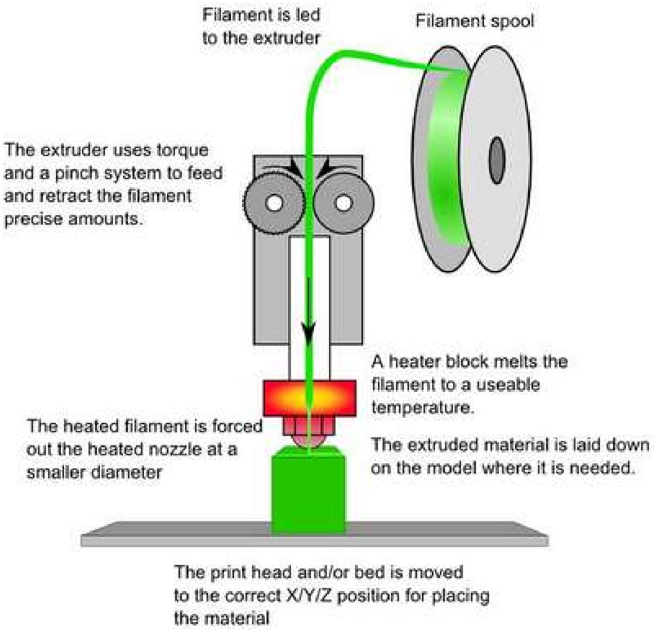


Figure 10. Example of the filament extrusion 3d printing.

A plastic wire is forced to pass through the extruder where it is heated and melted into a liquefied polymer. Then that melted plastic is forced to come out through the nozzle as the extruder keeps going. The incoming solid filament acts as a plunger to push and extrude the liquefied polymer through the nozzle. The plastic is deposited on the platform following the pattern to create the piece. Once a layer is processed, the head is raised or the building platform is lowered a layer thickness and a new layer can be deposited.

FDM systems are capable of producing parts from the largest range of thermoplastic materials, feature detail, surface finish, accuracy. FDM uses production-grade thermoplastics, such as acrylonitrile butadiene styrene (ABS), PPSF (Polyphenylsulfone), PC (Polycarbonate), and PC-ABS which improves mechanical properties of ABS. Because of the material properties, FDM parts typically withstand functional testing and have high heat resistance. Some companies have sterilized PPSF for medical applications. Some producers can deliver machines able to process polylactic acid (PLA) a biodegradable polymer.

Nevertheless, a big problem remains with this process which is the limited availability of commercial polymer fed materials. It is therefore seen as a major shortcoming of the filament based 3D printing process.

That is one of the main reasons to develop a 3D printer capable of working with granulate plastic. Our project is focused on designing an extruder which works with PLA plastic granulate so we can overcome with the limit of material that can be used in 3D printing. After it will be possible to work with all the different commercial polymer.

3.2.2 SYRINGE BASED 3D PRINTING

This is a different extrusion process which overcomes the limitations of the filament based extrusion described in the previous point. Especially in terms of the range of the materials that can be processed. In addition, you can use the granular shape of the plastic which is the common shape for thermoplastics.

This configuration makes typically use of materials that solidify due to a chemical solidification. A deposit is filled with the material and heated to the processing temperature. A force is applied to the feed material by the displacement controlled plunger that pushes the material out of the deposit according to the generated path from the 3D model.

Despite of its simplicity and the advantages of the process, there are some important disadvantages also:

- If the object is too large, it can be necessary to refill repetitively the syringe causing interruptions in the building process. Also it cools down of the printed product and syringe, resulting in a poor adhesion between the layers.
- The material is heated all along the syringe so the higher material after a time at elevated temperature will suffer thermal degradation, resulting in poor material properties.
- It is possible that the syringe contains air which will interrupt the process and also air encapsulations in the material of the piece.

3.2.3 SCREW BASED 3D PRINTING

A third option could solve the mentioned problems of the FDM and the syringe process, especially the limited range of available materials. A three-section screw based extrusion process. This technique is commonly used in the plastic processing industry to create continuous profiles.

In this kind of extrusion, the feed material, which is the granulate plastic, is added into a hopper and melted thanks to the heat applied all along the three-section screw. The heat applied along the extruder and the pressure build up by the screw melt the polymer granules.

The main advantages of this way of extrusion are:

- Possibility of using commercial granules as fed material.
- Continuous process can be realized.
- The screw creates and homogenous melting and the material suffers less degradation.
- Lots of different polymer can be used as polypropylene (PP), polyethylene (PE), polystyrene (PS), polylactic (PLA), polycaprolactone (PCL), …

As we have said before the main object of the project is to design this kind of screw based head for a 3D printer. The reason this technique is not commonly used is because of the complex design of the three-section screw. However, this type of screw is required to prevent interruption of the extrusion avoiding trapped air in the melt.

3.3 THE EXTRUSION PROCESS

The extrusion is a process used to create objects with defined cross section. Extrusion involves passing under the action of pressure a material through an orifice in such a way that the material acquires an equal section as the orifice. Extrusion may be continuous or semicontinuous and also the process may be done with warm or cold material.

Plastic extrusion typically uses plastic granulate or pellets as feed material. They are usually dry in a feed tank or hopper before going to the feed hopper. Polymer resin is heated to melt by resistance found in the barrel of the extruder and the heat from friction screw extruder. The screw forces the resin to pass through the head into the desired shape and then the plastic is cooled and solidified. In some cases, after the extrusion, the material is passed through a long die in a process called pultrusion.

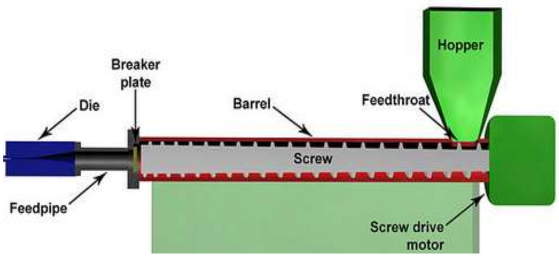


Figure 11. Example of an extruder, with the main components.

Extrusion has high productivity and is the most important process of obtaining plastic forms. Its operation is the simplest, because once the operating conditions are established the production continues without problems as long as there is no greater disturbance. In addition, the cost of extrusion machinery is moderate compared to other processes such as injection, blow molding or calendaring. It also has a good flexibility for product changes without making major investments.

The general classification of the different types of polymer extrusion techniques are:

- Single screw extruders:
  - Conventional extruders
  - Co-mixers extruders
  - Venting extruders or degasification
- Without screw extruders
  - Pumps
  - Disc extruders
- Multi-screw extruders
  - Twin screw extruders
  - Intermeshing screws
  - Not intermesh Screws
- Extruders with more than two screws
  - Planetary roller
  - 4 screw extruders

We are going to focus on the single screw extruder which is what we are trying to design for our 3D printing.

3.3.1 SINGLE SCREW BASED EXTRUSION

All types of extrusion have similar characteristics and components. Here we are going to give an equipment description of a single screw extrusion in order to show its main functions. We also will try to detect where are we going to find the main problems while designing.

Basically, an extruder consists of a central metal shaft with helical blades called spindle or screw installed inside a metal cylinder. This cylinder is coated with an electrical heating jacket. At one end of the cylinder there is a hole where a feed hopper is installed, generally with conical shape, for the feed material. At that end is also allocated the spindle drive system, compound of a motor and a speed reduction system. At the other end of the screw, the material outlet is located and so the die which defines the final form of the plastic.

3.3.1.1 EQUIPMENT DESCRIPTION

- Hopper cylinder: the hopper is the tank where the pellets of plastic material are placed for feeding the extruder. It must have the right dimensions to be fully functional. If the design is not correct, mainly in the angles of descent of material, it may has deadlocks in material and the extrusion will be forced to stop. Sometimes a hopper with vibrating system can solve the problem and avoid the deadlocks. It is also possible to use a hopper with a screw inside to achieve the feeding.

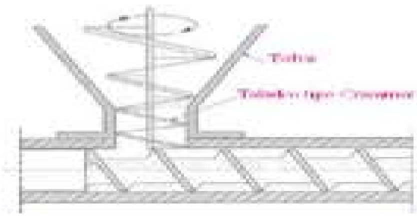


Figure 12. Example of a hopper with screw.

It is also important to know that there are some type of hoppers, the drying hoppers, which are used to remove the moisture from the material.

- The feed throat: is the feed opening through where the plastic material is introduced to the extruder. It is usually necessary to cool down the feed throat to keep the plastic particles from sticking to the wall.

- Cylinder: it is a metal cylinder that houses the screw and constitutes the main body of the extruder. It forms, with the screw, the melting chamber and the pumping of the extruder.
  It must have a compatibility and resistance with the material which is going to process. For this reason, different methods of surface hardening are applied to the inner walls, in order to minimize any wear. Due to those are exposed to the effects of abrasion and corrosion during the process.
  The cylinder has electrical resistors that provide the heat energy required to melt the material. For the best conservation along the cylinder and preventing changes in production quality because of variations in the temperature, it is usually used a material with low thermal conductivity. In addition, glass fiber or filter can be added, to isolate the body of the cylinder.
  Although it may look contradictory, each heating zone of the extruder screw is accompanied in most commercial equipment, by a fan. These fans allow the temperature control by airflow over the surface required.
  The extrusion temperature can only be controlled precisely by the combined action of the electrical heating bands and fans for each zone.

  Therefore, the key points in the design of the cylinder are that it has:
  1. Maximun durability.
  2. High heat transfer.
  3. Minimum dimensional change with temperature.

  To facilitate processing materials with low friction coefficient sometimes is necessary to use an extrusion cylinder which has channels, on its inner surface. To be carried forward, the material should not rotate together with the screw, or at least must rotate at a lower speed than the screw. The drag force is the only force that prevents the material turns with the screw. The higher friction the lower rotation of the material with the screw and, therefore, more forward movement.

  Grooved feed zones help to control the coefficient of friction polymer-cylinder by geometry reducing the sensitivity to temperature and the thermodynamic properties of the resins. Moreover, grooved feed zones allow to increase the volume of the feed section, accelerating the merger and thereby they increase the extrusion rate.

- Barrel Heating and Cooling: Heating is usually done with electrical band heater along the length of the extruder. It is necessary to help the screw to melt the plastic.
  Sometimes it is also necessary to cool the barrel if the internal heat generation rises the barrel temperature above the set point. This is likely to occur with high viscosity plastics and high screw speeds. Cooling is usually done with air but water can be used as well.

- Spindle or screw: It is the most complicated piece for design and the most important because it largely determines the quality of the extrusion process. Its functions are to melt and transport the plastic. It performs three basic functions: solid conveying function, melting function and metering function or pumping function. The three screw functions occur simultaneously over most of the screw length and they are strongly interdependent. In every screw there are three different zones, which are: the feed section, the transition section and the metering section.

  The geometric name of a screw section such as feeding section, does not necessarily indicate the only function of the screw section. For example, the feeding section not only performs solid conveying function, but also melting and metering functions.

  The screw extruder has one or two spiral "wires" of constant width along its axis to form a helical channel. The measured diameter to the outside of the helix is the same throughout the length. However, in general, the channel depth decreases from the feed end to the end of the dice.

  The dimensions for the screw usually follow a L/D ratio between 24:1 and 32:1, but there are also special applications where extruders are built as short as 10:1 L/D and as long as 50:1. The proper dimensions are determined by the process and applications that the screw is going to be used in.

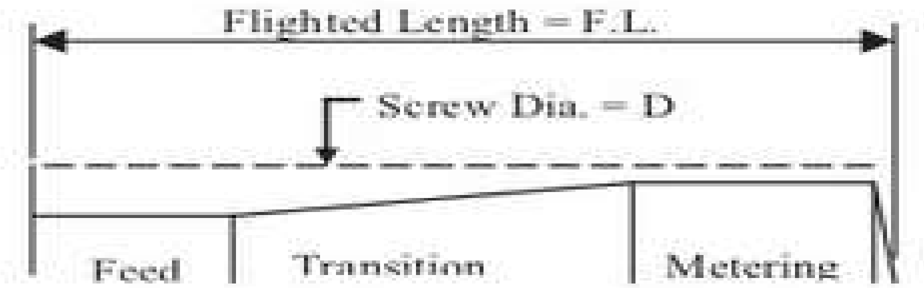


Figure 13. Illustrative image of the main areas of the screw

- Breaker plate: Breaker plates are a thick metal puck with many holes drilled through it, which acts as a screen, filtering contaminates from the final product. The breaker plate also serves to create back pressure in the cylinder. Back pressure is required for uniform melting and proper mixing of the polymer.
  It also does the function of converting "rotational memory" of the molten plastic into longitudinal flow.

- Nozzle or die: after passing through the breaker plate the melted plastics enters the die. The die is the part responsible for giving the final shape to the plastic. The flow channel of the die should be designed such that the plastic melt achieves a uniform velocity across the die exit. The shape of the land region, which is the end of the die, determines the shape of the extruded product.
  However, the size of the final product is not exactly the same as the land region. It is difficult to predict how the die should be designed, because of the several variables affecting the size and the shape of the final product. For example, the drawn down, cooling, swelling or relaxation.
  Nowadays die design is still based on experience and on trial and error process rather than on engineering calculations.

3.4 MATERIAL: POLYLACTIC ACID (PLA)

The polylactic acid, commonly named as PLA, is a biodegradable thermoplastic polyester of low molecular weight, that comes from renewable resources. It was discovered by the scientist Wallace Carothers in 1932 while working for Dupont companies. It is one of the plastics more researched and developed due to its multiple applications on the market. Nowadays it is the most used plastic for 3D printing.

This interesting polymer originated in starch from plants such as corn, cassava, wheat, beets or sugar cane, facilitates extraction source away from the transformation processes of hydrocarbons characterizing obtaining other polymers. It was included in the list of plastics FDA (Food and Drug Administration) for its applications in the field of biomedicine and food. In 2010 it has the second highest comsuption volume of any bioplastic in the world.

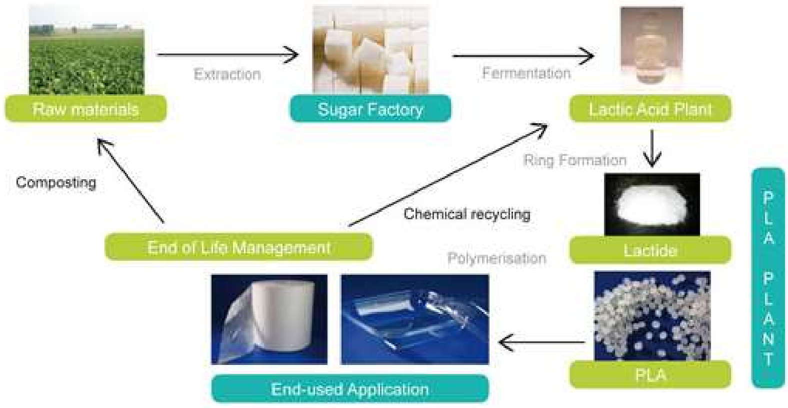


Figure 14. Summary of the gathering process and life cycle of PLA.

3.4.1 PROPERTIES

To show up the properties and advantages of PLA we are going to compare it with ABS (Acrylomitrile butadiene styrene) which is also one of the most used materials for 3D printing. ABS is a tough hard plastic, which allows to be sanded polished, drilled, etc. These features make it ideal for printing mechanical parts or pieces that need to be handled or machined after printing. However, PLA has similar properties:

1. PLA has a density between 1.2 and 1.4 g / cc, making it heavier than ABS material.
2. Shore hardness (scale measures hardness of plastics) is 63.5 degree, being higher than ABS. What makes it a harder plastic than the previous one.
3. It is more rigid than the ABS, having a modulus of elasticity 3.63 GPa, making it difficult to deformation under load and makes it a less elastic material.
4. Less impact resistance than ABS. It has mechanical properties similar to PET.
5. PLA melting temperature: 173-178 ° C.
6. PLA Glass transition temperature: 60-65 ° C.
7. PLA extrusion temperature between 180 and 220 ° C.
8. PLA printing temperature between 190 and 210 ° C.
9. Good adhesion to a large variety of surfaces.
10. Insoluble in water.

3.4.2 APPLICATIONS

PLA is processed by extrusion in 3D printing, injection molding, film and sheet casting, providing access to a wide range of materials.

PLA is used as a feed material in 3D printers in additive technology process to conform prototypes as well as final products. Because it is able to degrade into innocuous lactic acid, it is used for medical purpose. Nowadays it has more and more applications as medical implants in the form of anchors, screws, plates, pins, rods and as a mesh.

In addition, PLA is also used in packaging, which is by far its main function. It is the perfect material for packaging, as it is biodegradable. It is useful for producing loose-fill packaging, compost bags, food packaging and disposable tableware.

3.4.3 PLA PRINTING

As feed material for 3D printing PLA is used to create functional products as well as medical pieces and for packaging food.

When printing PLA, we can see that is easier to print it than others. We can print with a temperature between 190 and 210 ° C. For the configuration of the printer base plate there are several options:

3.4.3.1 COLD PRINTING

One of the options when printing this material is to use a configuration without adding temperature in the printer base plate. This causes the printer consumes less electrical power as we do not have to heat the surface on which the workpiece is supported.

In this configuration a fixer which adheres the part to the base is needed. Also ensure through calibration as fixing the first layer to the base printing is critical.

However, the possibility of printing cold with this material, is dismissed when you want to print pieces of long prints, large geometries and medium-high speeds. It is likely that areas of the workpiece can completely come off the base along printing.

3.4.3.2 HOT PRINTING

The most commonly option used by 3D printing users who consume this type of material is to use a heated base. Placing the base temperature higher than PLA´s glass transition temperature.

it has to ensure that tensions near the printer base are minimal, because, with low tensions the piece could came off or warp. Despite we need to heat the base, we cannot set a temperature much higher than the glass transition temperature, since they could give different creep phenomena in the material. Various printing defects may also appear on the walls and face fixed to the base.

In order to avoid these problems a fixer can be used to ensure a good adhesion of the part to the base plate.

3.4.4 PREDRYING

The PLA is a thermoplastic material, and as such absorbs moisture from the atmosphere. This moisture makes PLA processing more complex. When it is heated this moisture can turn to steam bubbles which can interfere with printing. PLA is required to be properly dried before processing.

Because we will extrude the PLA with a single screw extruder, the material must be pretreated to remove the moisture it may hold. The drying must be done in a dehumidifying (desiccant) dryer, to reduce the moisture in PLA at least below 250 PPM level. However, under 200 PPM is better because viscosity is more stable. PLA needs different degrees of drying depending on the grade and how it will be used. Usually PLA needs to be dried between 60 and 80 degrees for 4 hours.

This should be taken into account as for the proper functioning of our printer. It would be necessary to have a drying hopper.

3.4.5 PLA SUPPLIER

Normally the plastic can be obtained in pellets of 3 mm diameter and 3 mm high, and there are plenty of supplier where you can find this pellets. However, because the size of our printer will be very small cavities inside the cylinder will also be small. This means that we can’t use this 3mm pellets as feed material, we need a smaller size for our feed material. For that reason, we surveyed the market and found a company, B&J PARR, which allows us to obtain the filler material in powder form. This company is located in Mansfield, Nottinghamshire, and is specialised in recycling polythene. However, they also offer a service where they transform into powder any plastic. We can order the PLA to them of let them transform our own plastic. Having powder as feed material allows us to reduce the dimensions of the extruder.

In the bibliography below we have attached the link to the website of the company.

4. OPTIONS OF DESIGN

Before choosing the final design for the 3D printing head, it's necessary to think in all the possible options that could fix in our project. Here we are going to explain the different option we have thought about for the printer head, and the advantages and disadvantages for each one.

As it has been said before, this project is a first study and it shouldn't be taken as an ended work. For this reason, the options we explain here are going to be judged in order to achieve our aim in this project. However, in the future, a review of this options might come into a different decision.

4.1.1 OPTION 1

Most 3D printers use a wire as feed material, so the first option is to add an extruder that permits the manufacture of the wire. This allows us to start the process of printing from plastic granulate. This option also allows us to maintain the current head thus it would not be necessary to change anything of the printer. We will just need to add the extruder.

The process starts feeding the hopper with the plastic. The screw drags and breaks the granulates. The extrusion process continues until the material comes out of the nozzle creating he wire which will be guide by a plastic tube into the printer´s head.

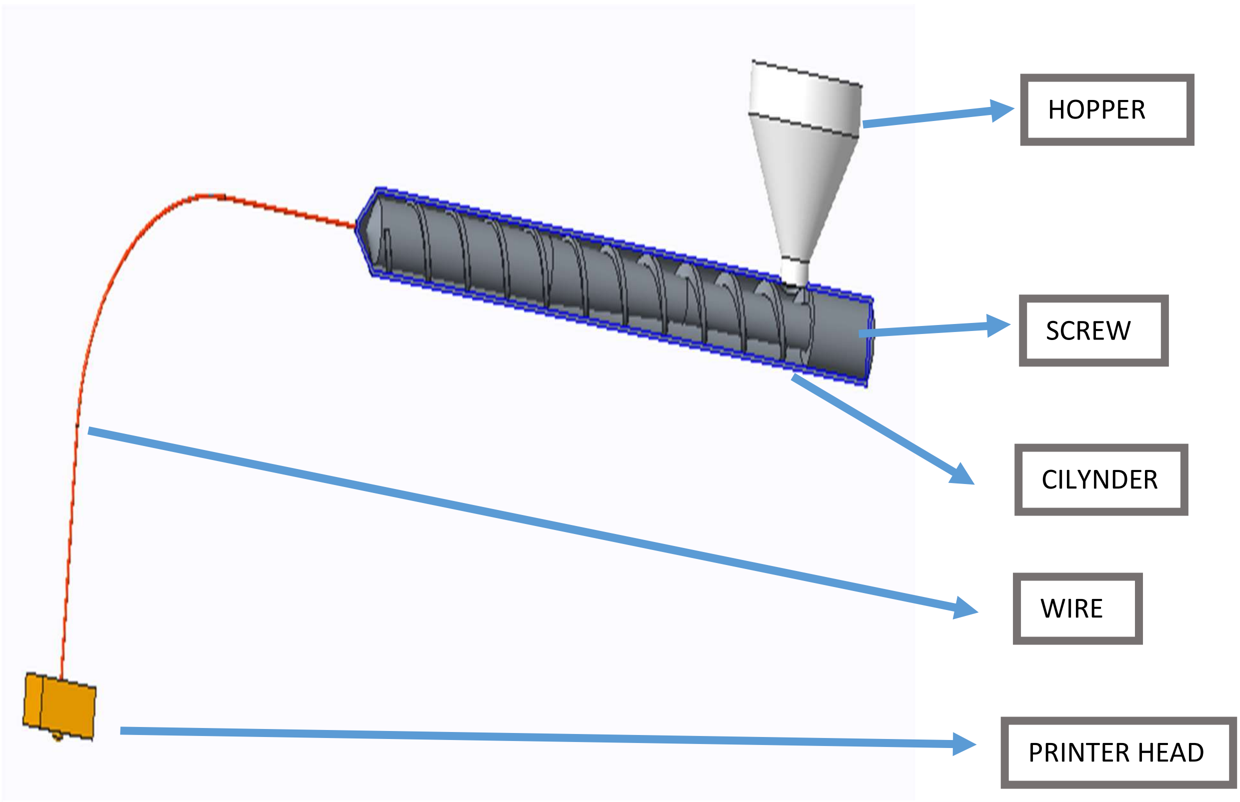


Figure 15. Model assembly of the extruder without the structure that holds the extruder.

Apparently this option is the simplest one but there are some problems to be solved. The biggest problem is when the 3D printing stops working all the plastic inside the canal lowers its temperature and solidify. So is not possible to start the process again. Furthermore, as the wire comes out with a high temperature and in a melted way, the material gets stuck into the tubes walls and the printing process is not uniform and it can block the tube.

- **Advantages:**
  - The printer's head is already made.
  - Easy design.
- **Problems/disadvantages:**
  - When the printing process is stopped, the plastic in the tube that connects the extruder to the head is solidified. This makes impossible to start another impression.
  - As the plastic comes out at a very high temperature of the extruder, it could stay stuck in the tube walls.

As each time the machine stops the process would be blocked, this option is not possible and therefore we reject it.

4.1.2 OPTION 2

In this second option we have thought about creating an extruder, which would be the printer´s head, and fix it on the top of the machine. The base will have the movement needed to print the piece, while the head remains motionless.

The process is also based in an extruder which melts the granulates plastics into a fluid state. After the extruder there is another screw that guides the plastic vertically into the nozzle. The particularity of this option is that the cylinder and all its components are fixed and is the base the one which has the triaxial movement.

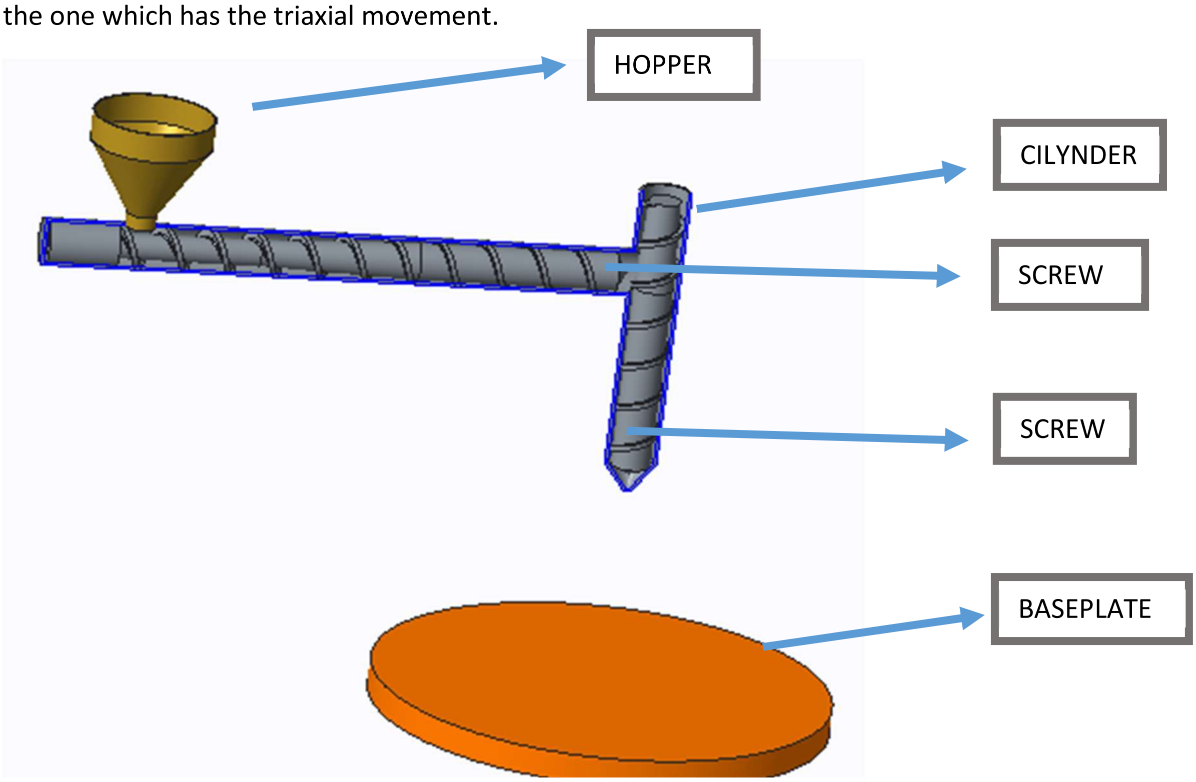


Figure 16.Model assembly with both extruder and the base platform.

The main problem of this option is that is not easy to achieve the base movement. The base must be able to move up and down, left and right and front and back, so the system to achieve it is difficult to design. In addition, the base can be very heavy because of the heating system, making it difficult to move.

- **Advantages:**
  - It allows a larger extruder and it avoids the limitation in weight and size.

- It avoids the problem of the granulates size.
- Cable is not necessary.

- **Problems/disadvantages:**
  - A new and complex movement system has to be designed.
  - The plate could be very heavy to be moved.
  - Two extruders will be needed.

This option does not fit for us either, because besides having to design the extruder it is also necessary to solve the problems with the base platform. So we also discard this option.

4.1.3 OPTION 3

This option considers the possibility of melting pellet by pellet one after each other.

Due to the small flow rate of plastic needed may be possible to create a device, which introduce pellet by pellet in the cylinder. Then the heater would melt the pellets one by one.

The nozzle and the hot end would be the same as the common filament 3D printers. However, the energy used in the heater would be lower because it has to melt less material.

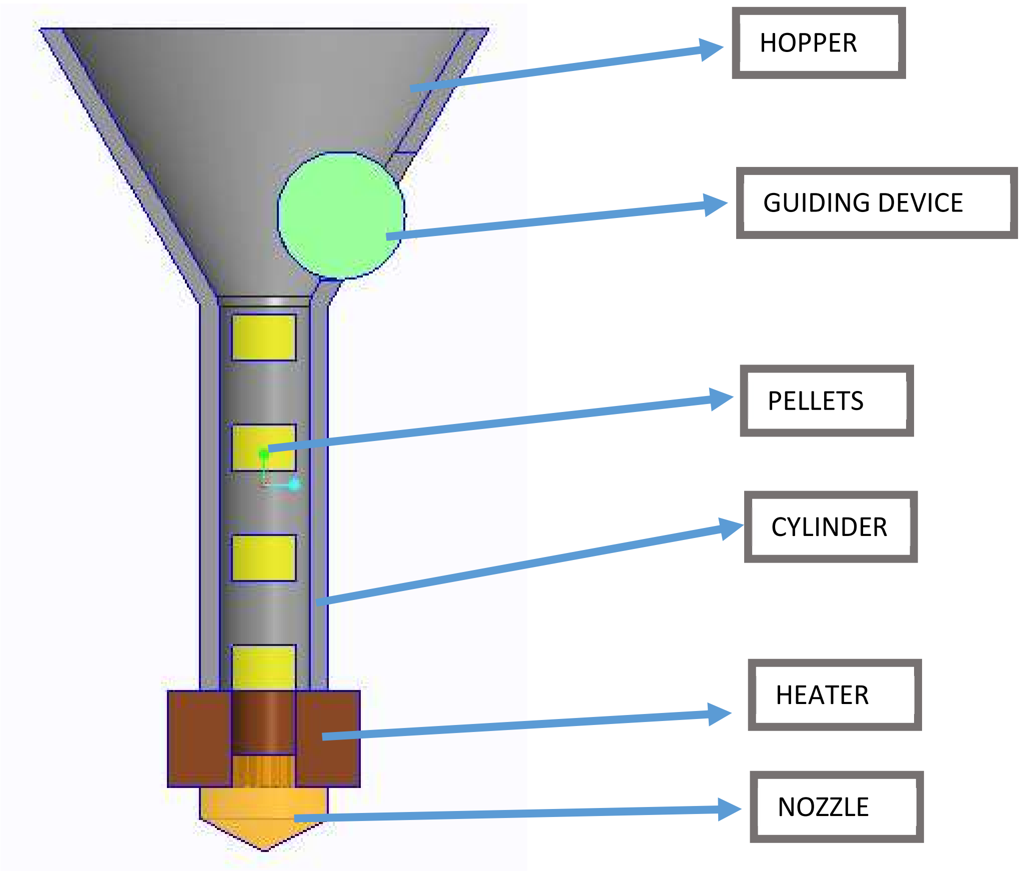


Figure 17.Assembly where it is possible to see how the pellets would be melted one by one.

The main issue of this option is that despite it is easy to melt the pellet, the melted plastic won't drop by itself. The 0.4 mm end of the nozzle makes it necessary to apply pressure to make the plastic come out of the extruder and this is not easy.

One option to solve the problem is to add vacuums at the end to vacuum out the plastic once is melted. The design of this head is probably the most difficult one because there is nothing similar so there is no previous information. In addition, the design of the guiding device is also inventing a new part with no example to base on. Basically this design should be made through try and failure, making experiments to collect experimental data.

- **Advantages:**
- It avoids designing and creating the extruder.
- Low energy is used because is easy to melt one pellet.
- Small size and low weight.
- **Problems/disadvantages:**
- It is difficult to achieve a continuous flow.
- Pressure will be needed over the plastic, otherwise the melted plastic won't come out through the nozzle.
- A device that divides the pellets one by one has to be designed.
- Based in experimental data.

For this reasons we dismiss this option for our head, as it is not possible to come up with a functional design with the means available to us.

4.1.4 OPTION 4

The last option that we have considered is to design a small extruder which would form the main part of the head of the 3D printer. This extruder should be feeded with the plastic through a hopper placed on top of the machine. The head should move over the base plate in three space directions to be able to create the 3D parts.

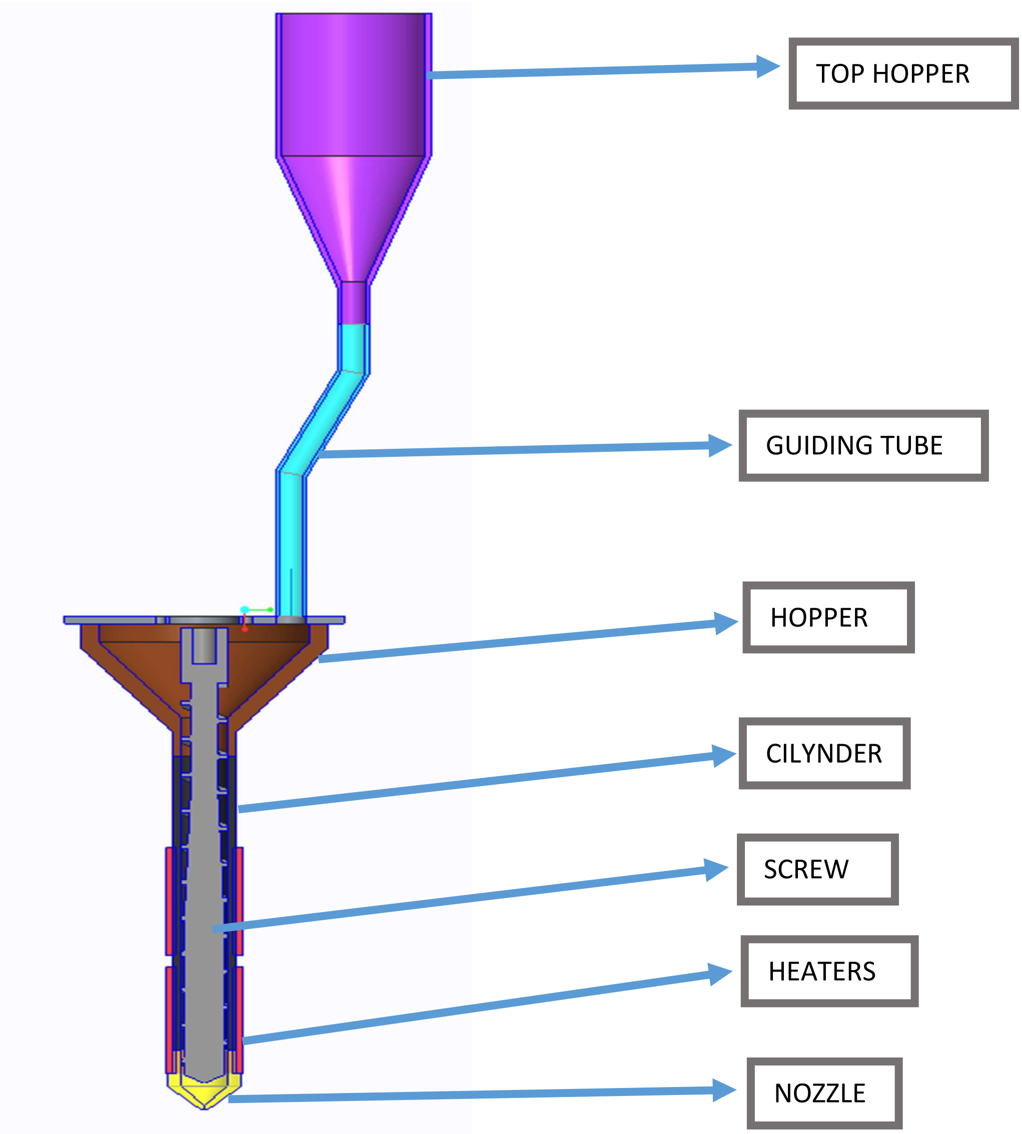


Figure 18. Model assembly with the extruder head and the top hopper.

This option allows a continuous process due to the top hopper which is fixed on top of the machine and can be refilled at any moment, even when the printer is printing. From the top of the machine the granulates will be guided through a tube to the extruder. Then the screw would force the plastic granulates to enter in the cylinder. Thanks to the heaters on the cylinder and the friction the extruder will melt the plastic generating the liquid plastic that will drop to create the parts. The screw itself will act as the pump, due to the high pressure generated in the interior of the cylinder.

This provision for the printer head allows the machine to use plastic granulate as feed material, instead of the commonly used wire. This will allow to print a large range of materials that cannot be printed nowadays. The extruder will melt the granulates and create the plastic flow needed to print. In addition, the way it would be fed allows a continuous feed to the hopper of the extruder even when the head is moving.

Having a screw extruder gives the possibility to regulate all the process of extrusion, which means that we can control the speed of the screw and the temperature of extrusion. Also this extruder head allows different temperatures for the extrusion, as the heaters can be regulated.

- **Advantages:**
  - Print in a continuous process.
  - Print large range of plastic, due to the use of granulate.
  - Avoiding the wire, it can print with any mix we want to do at any moment.
- **Problems/disadvantages:**
  - The dimensions of the head have to be very small; otherwise the printer's head would be very heavy to be moved.
  - As a result of the extruder's size, the granulates diameter has to be very small before entering to it.
  - Expensive to fabricate the small pieces.

This option provides a feasible solution, since the design of an extruder can be based on theoretical equations, and we believe it is the best option for our project.

5. PRINTER ELEMETS DESIGN

Once we have chosen the distribution we want to have in our printer, we started with the design of it. However, instead of doing it blindly is better to look to one of the existing machine. Thus can be set clear objectives like trying to get the same flow or print speed.

5.1 DELTA ROCKET 3D PRINTER

When printing plastic there is a lot of different machine with lots of different speeds, flow rate, diameter, etc. Instead of choosing random values for our extruder it's better to have a previous value for the parameters that we want to achieve. We must choose and existing 3D printing and try to repeat its parameters.

Our design for the new head for the 3D printer is going to be based in the DELTAROCKET PRO 3D printer in order to have a point from which we can start. For design our head we will try to achieve the same flow rate, temperatures and speed of the existing delta rocket.

The reason for taken this Delta Rocket as the example is because is an easy 3D printer which we can use on the lab and make some test with it. Furthermore, this give us some parameters which we can compere our extruder with, to conclude if the design is correct or not.

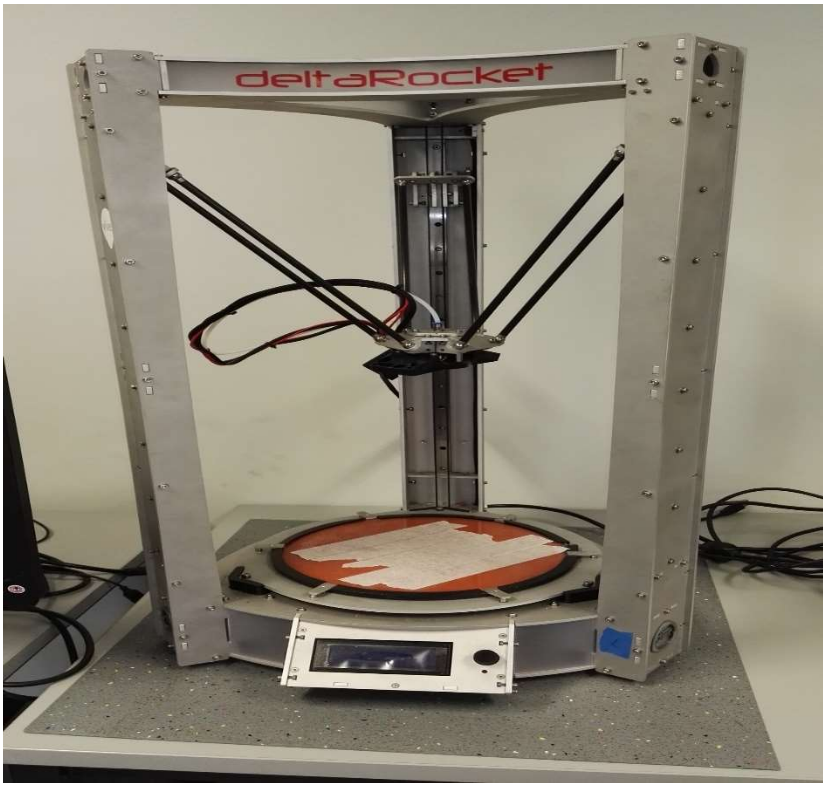


Figure 19.Picture of the Delta Rocket where you can see the head, the wire connexion and the base platform.

The aluminium head is hold by 6 metal bars that are held in place by ball-shaped magnets that allows the movement. The wire is guided into the head with a plastic tube which connects on top of the head. It also has a piece that holds the layer fans.

The main specifications of the Delta Rocket are:

- Nozzle diameter: 0.4 mm.
- Nozzle temperature: up to 250ºC.
- Filament diameter: 1.75mm.
- Supported materials: PLA, ABS, HIPS.

It uses an open source software, Repetier Host-slicer. Our head will be designed in order to be used with the same software, but we are not going to raise the electronic of the head. Further information about the machine can be found on the internet.

The most important parameter we need from the Delta Rocket is the flow rate. We want our extruder to achieve the same flow rate that the Delta Rocket has. To know the flow rate, we perform the following experiment.

We set the printer and print a piece of 20x20x1 mm to print a volume of 400mm^3. We control also the time while printing so with the volume, the density and the time we can obtain the flow rate. We made this process a few times and take the average of the results.

$\rho = 1.3 * 10^{-6}\ {}^{kg}/_{mm^3}$ $\quad V = 400\ mm^3$ $\quad t = 107.183\ seg$

$$\text{Volume flow rate: } Q = Vx\frac{1}{t} = 3.732\frac{mm^3}{seg}$$

$$\dot{m} = \rho\, x\, V\, x\, \frac{1}{t} = 4.852 * 10^{-6}\ {}^{kg}/_{s} = 2.911 * 10^{-4}\frac{kg}{min}$$

We are going to use this flow rate to design our extruder. The new extruder must be able to achieve this flow rate, therefore, this parameter will guide us while designing the rest of the parameters.

5.2 DESCRIPTION OF THE EXISTING MACHINE

As the head should be a useful piece in a real printer and in order to make the design easier we are going to base our design in an existing machine. The reason for doing this is to have a direct use of the head where it can be tested. In addition, this avoids us to design a whole machine from zero, which will be a longer job.

The chosen machine, from VIVES maak lab, is a machine with three axis movement. The head moves in the x and y axis and the base plate is moved in the z direction. The extruder´s head and the rest of the components are placed in the x axis, which is moved by a motor. At the same time, the x axis is set in two y axis, which each of them are also shifted by a motor with the same characteristics as the one located in the x axis. It has a track of 800 mm for the x axis and 990 mm for the y axis.

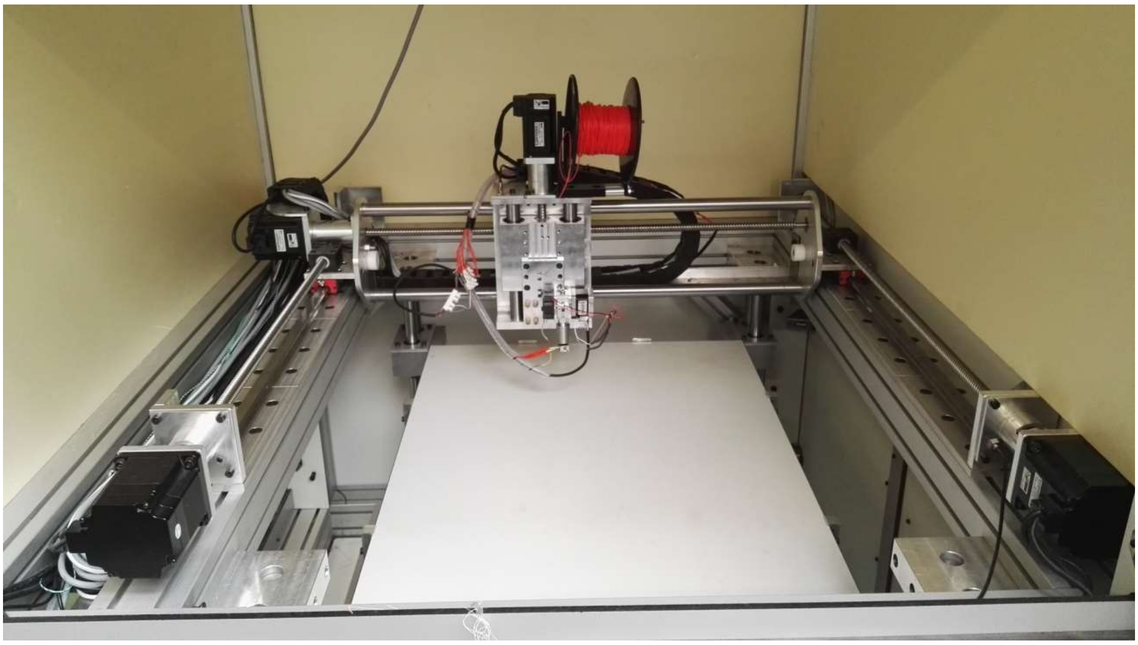


Figure 20. Overview of the existing machine.

The plate is holded by 4 axes, one in each corner, all of them connected by a transmission band which is moved by a motor. Its track total measure is 510 mm. The plate has a rectangular shape and its dimensions are 660x915 mm. So the printing area's size available is 603900 mm2.

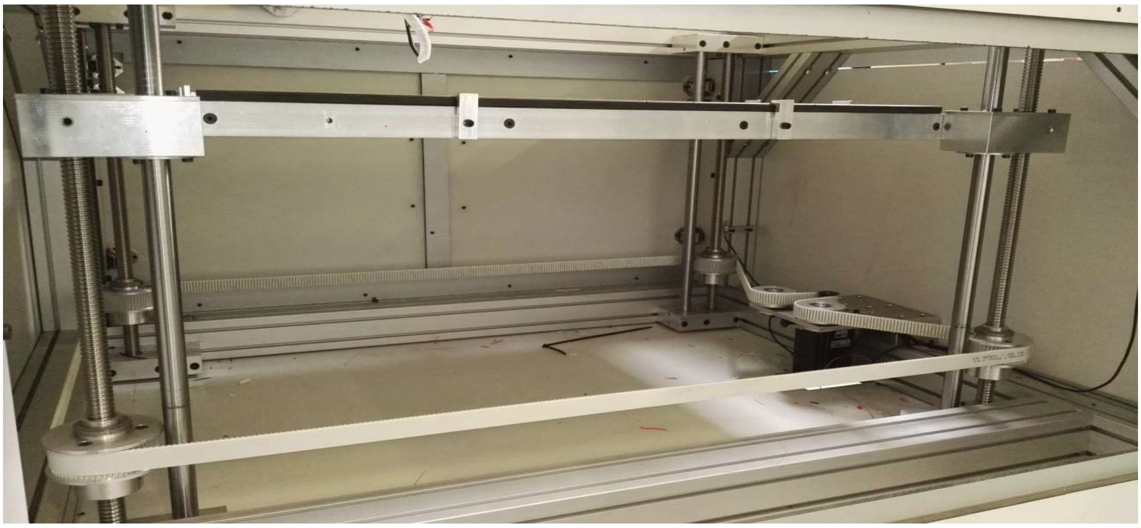


Figure 21. Picture with the 4 axis that support the base platform.

The head, in which the extruder will be placed on, has a dimensions of 175x110x245 mm. It also has a motor, connected to the plate to set the high of the extruder in the position that we want.

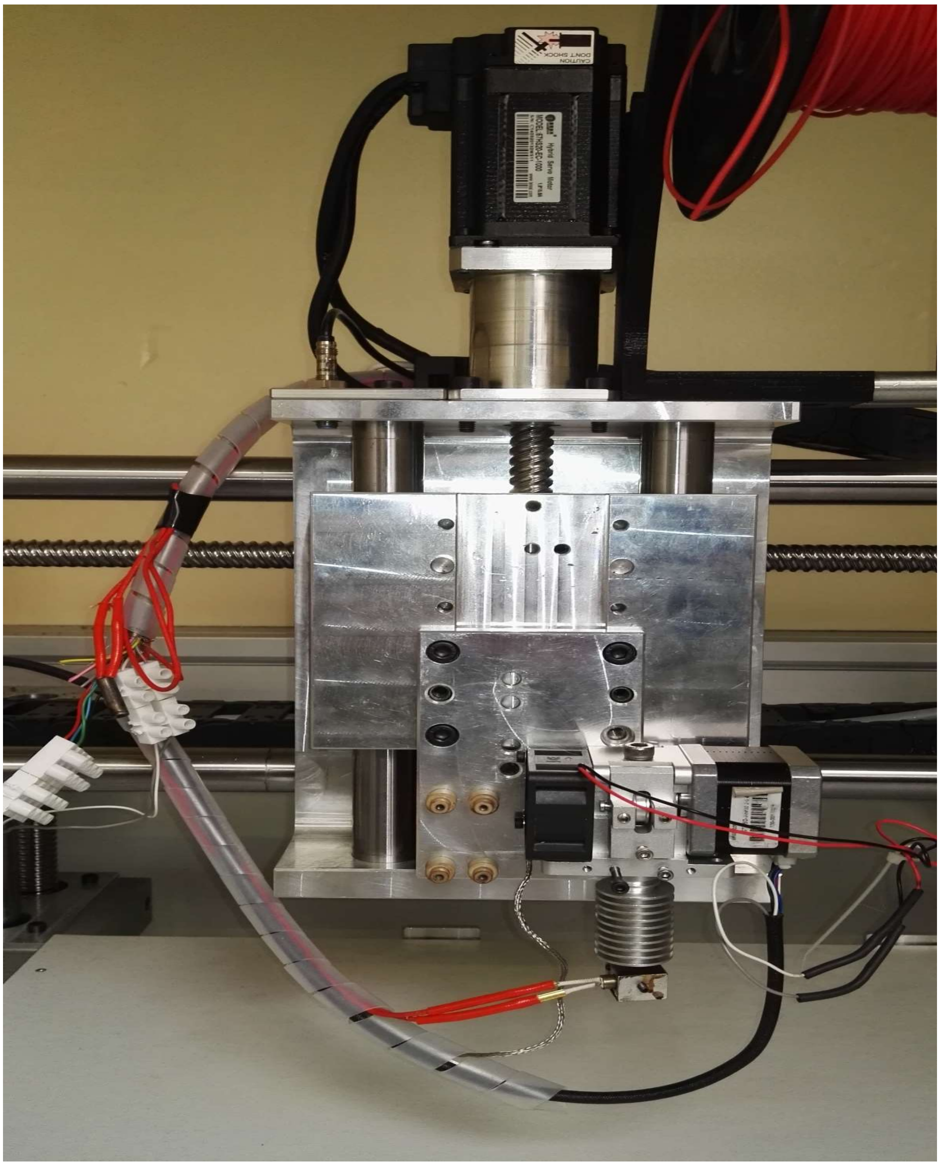


Figure 22. Head of the existing machine.

The main reason for choosing this machine is that the head is big enough to support our extruder. Also the axis are strong enough to support all the weigh. In addition, the fact that is the baseplate which moves up and down, gives more stability to the head.

5.3 EXTRUDER PARAMETERS DESIGN

Once we have chosen our references, it is time to start with the design of our new head. The first step in the design of the 3d printer´s head, is designing the screw for the extruder. This point is key since it will largely condition the final size of the head and the speeds of the printer. The size of the screw, and therefore the extruder, will determinate the flow rate, the spinning speed of itself and the movement speed of the printer. When designing the screw, we must take into account several factors. For example, we must take into account the type of polymer with which it will work, its glass transition temperature and melting temperature.

Both the application and production of the extruder depend on the diameter of it, the ratio of length and the speed of the screw. Likewise, is very important the gap between the thread crest and the inner surface of the cylinder. When the gap is large the material is mixed better but production decreases because it increases the reverse flow.

The screw has to be very small in order not to be very heavy to make the printing movements. In general, we are very limited for this reason so the first step is to decide the measures of the screw. That will delimit how much is going to occupy the screw in terms of volume and, by extension, mass.

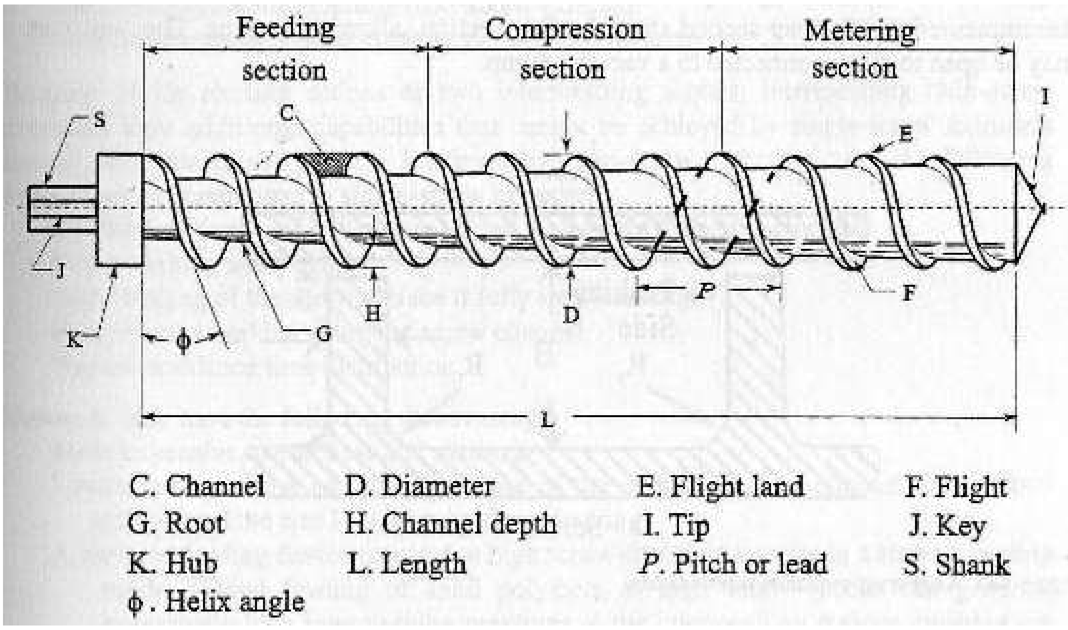


Figure 23. Summary of parameters to be determinate for the screw.

The diameter we decide to work with is 15 mm and for the relation between the length and the diameter we choose, 10/1. The reasons to take these measures and not any others are based basically on the fact that the screw has to be the smallest size possible without increasing very much the price. So we consider 15 mm to be the smallest diameter with reasonable price and with precise usefulness. In addition, we choose 10/1 for the relation L/D because we consider 150 mm the maximum length keeping a light screw in terms of weight, taking into account that if the relation L/D is bigger, the price will be lower.

Therefore, we have defined the first parameters of our screw $D = 15mm$ and $L = 150mm$. Also they have been taken into account other options of diameters and length and the calculations are shown in annex 10.1. There it is possible to see the differences between our extruder and the other possibilities.

The other parameters depend on the value chosen for these two or can be calculated gradually from the above.

5.3.1 NUMBER OF CHANNELS

The first step to be taken in the process of design a screw is deciding the number of channels on it, that is, deciding the number of threads. In applications where a large flow is required, screws can be used with two or more threads, but in our case the flow is very small so we will use a screw with a single thread.

So the number of channels for our extruder m=1.

5.3.2 HELIX ANGLE

Also one of the first things we can determine of our extruder is the helix angle of the screw. For general purpose screws, the gap between 2 crests or the pitch (t) usually coincides with the diameter. So: $t = D = 15mm$.

When this happens the helix angle is:

$$\varphi = \tan^{-1}\frac{t}{\pi \cdot D} = \tan^{-1}\frac{15}{\pi \cdot 15} = 17{,}65º$$

5.3.3 RIDGE WIDTH

The width of the ridge is defined by the diameter of the screw as it exists a relation between them, $e = 0.12 * D$.

So: $e = 0.12 * 15 = 1.8mm$.

5.3.4 SCREW LENGTHS

We based our decision of the zones lengths on the percentage from the total length that normally has each zone. For the feeding zone is between 20% and 25% of the screw length, for the compression zone between 32% and 38% and for the metering zone between 40% and 45%.

Feeding zone length: $L_1 = 0.217 * 150 = 33mm$

Compression zone length: $L_2 = 0.348 * 150 = 52mm$

Metering zone length: $L_3 = 0.435 * 150 = 65mm$

The percentages used in each zone are obtained as follows:

$$\% = \frac{\%}{\%_1 + \%_2 + \%_3}$$

$$L_1\% = \frac{20}{20 + 32 + 40} = 0.217$$

$$L_2\% = \frac{32}{20 + 32 + 40} = 0.348$$

$$L_3\% = \frac{40}{20 + 32 + 40} = 0.435$$

5.3.5 CHANNEL DEPTH AND SCREW CLEARANCES

The clearances inside the screw and with the cylinder are also defined by the diameter we have chosen.

The initial channel depth h_1, is the space between the cylinder and the soul of the screw. It is related with the screw diameter with the equation:

$$h_1 = 0.2 * D.$$

The filet clearance is the space between the thread and the interior surface of the cylinder. It should be small enough to avoid the plastic to come back while extruding. The equation to calculate it is:

$$\delta = 0.002 * D.$$

The depth of the channel at the end of the screw is defined by the compression ratio (Z). The compression ratio relates the depth of the channel at the beginning and at the end of the screw. Usually this compression rate takes a value between 2-4. We have chosen $Z = 3$.

$$Z = \frac{h_1}{h_2} = 3$$

Replacing the value of the diameter we obtain:

$$h_1 = 0.2 * 15 = 3mm$$

$$\delta = 0.002 * 15 = 0.03mm$$

$$Z = \frac{h_1}{h_2} \rightarrow h_2 = \frac{h_1}{Z} = \frac{3}{3} = 1mm$$

Dimensioning these parameters, we have also defined the diameters of the screw root, due to the diameters are related with the channels depth.

To the feeding zone the radio of the root of the screw is:

$$r = \frac{D}{2} - h_1 = \frac{15}{2} - 3 = 4.5mm$$

To the metering zone the radio of the root of the screw is:

$$R = \frac{D}{2} - h_2 = \frac{15}{2} - 1 = 6.5mm$$

5.3.6 NOZZLE DIMENSIONS

It is necessary to think about the dimensions of the die in order to be able to calculate the flow in the extruder, for this reason we are going to decide now the dimensions of our nozzle. However, the real design of the nozzle will come after.

The entrance diameter is related with the metering zone diameter and the clearance in this part. In addition, we want a printing diameter of 0,4 mm, which will be the diameter at the end of the nozzle. So we have these dimensions already decided:

$$d_0 = D - 2 * h_2 = 13mm$$

$$d_1 = 0.4mm$$

For the length of the nozzle it will be divided in two different zones, one conical and other one cylindrical, but the whole length will be 10mm. The length for cylindrical zone will be L_1=8 mm, and the length for the cylindrical part L_2=2 mm. More detail of the dimensions and the shape can be found below, on the annex 10.4.

5.3.7 EXTRUDER PRODUCTION

Production expressed as volumetric flow, Q, is the result of three different types of flow. Drag flow a), is the largest component caused by turning the screw. Pressure flow b), is the component that opposes the flow system. Flow filtration is produced by the loss of material between the clearances of the screw cylinder.

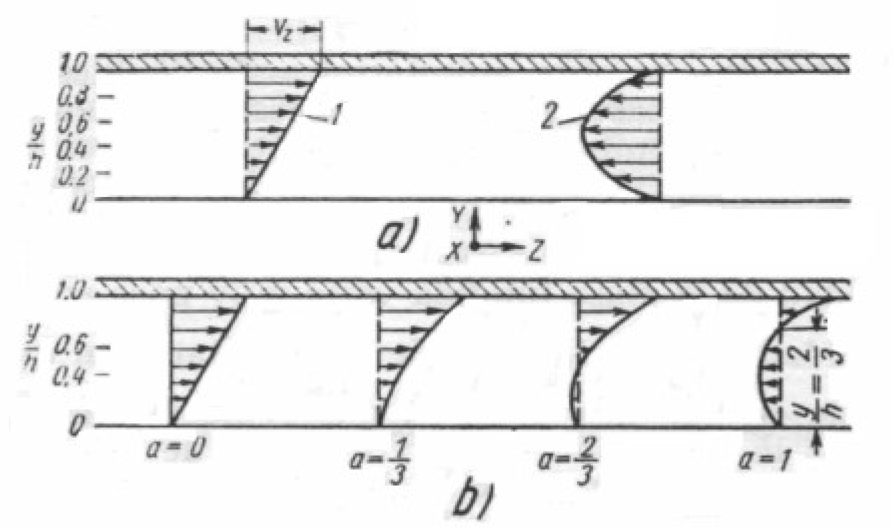


Figure 24.Flow distribution inside the channel. a) is the drag flow distribution and b) is the pressure flow distribution.

The volumetric flow Q can be calculated with this equation:

$$Q = \left(\frac{\alpha K}{K + \gamma + \beta}\right)\eta$$

Where:

Drag flow coefficient: α.

Pressure flow coefficient: β.

Filtration flow coefficient: γ.

Head geometrical constant: K.

Spindle speed: η.

5.3.7.1 DRAG FLOW COEFFICIENT

The Drag flow is the component caused by the turning screw. The plastic enclosed between the spindle and the cylinder is forced to advance in axial direction. It can be calculated with this equation:

$$\alpha = \frac{\pi * m * D * h * \left(\frac{t}{m} - e\right) * cos^2\varphi}{2}$$

Where:

Screw diameter: D=15mm.

Pitch: t=15mm.

Initial channel depth: h_1=1mm.

Helix angle: φ=17.65.

Ridge width: e=1.8.

Number of channels m= 1.

Thereupon the drag flow we will have:

$$\alpha = \frac{\pi * 1 * 15 * 1\left(\frac{15}{1} - 1.8\right) * cos^2 17.65}{2} = 847.276\, mm^3$$

5.3.7.2 PRESSURE FLOW COEFFCIENT

Pressure flows appears against the main flow. It is very important to design properly the screw so the pressure flow is lower that the drag flow, otherwise the extruder won't have any production flow.

$$\beta = \frac{\pi * h^m * \left(\frac{t}{m} - e\right) * sen\varphi * cos\varphi}{12 * L}$$

Where:

Screw length: L= 150mm.

The rest of the parameters are the same that the ones we used to calculate the drag flow coefficient.

Introducing our data, we obtain the following value for the pressure flow coefficient:

$$\beta = \frac{\pi * 1^1 * \left(\frac{15}{1} - 1.8\right) * se\ \ 17.65 * cos 17.65}{12 * 150} = 0.057\, mm^3$$

5.3.7.3 FILTRATION FLOW COEFFICIENT

The filtration flow coefficient represents the portion of fluid that seeps between the crest of the screw and the cylinder wall.

$$\gamma = \frac{\pi^2 * D^2 * \delta^3 * tan\varphi}{10 * e * L}$$

Where:

Filet clearance: δ=0.03mm.

The rest of the parameters are the same as the previous ones.

As a result, we obtain:

$$\gamma = \frac{\pi^2 * 15^2 * 0.03^3 * tan 17.65}{10 * 1.8 * 150} = 7.066 * 10^{-6} mm^3$$

5.3.7.4 HEAD GEOMETRICAL CONSTANT

To determine the constant K, the head is divided into successive zones of different settings, setting for each of these areas a different constant k_i. Our head is divide in two different zones, one conical and the other one cylindrical.

To the conical section:

$$k_1 = \frac{3 * \pi * d_0^3 * d_1^3}{128 * L * (d_1^2 + d_1 * d_0 + d_0^2)}$$

Where:

Length of the section: L.

Initial diameter of the section: d_0.

End diameter of the section: d_1.

To the cylindrical section:

$$k_2 = \frac{\pi * d^4}{128 * L}$$

Where:

Diameter of the channel: D_2.

Length of the section: L_2.

The real geometrical constant of the head is calculated in the next way:

$$K = \frac{1}{\sum \frac{1}{k_1} + \sum \frac{1}{k_2} + \cdots + \sum \frac{1}{k_i}}$$

The data for our nozzle are:

d_0=15.06 mm.

d_1=0.4 mm.

L_1=8 mm.

d_2=0.4 mm.

L_2=2 mm.

In our case the geometrical constant will have a value of:

$$k_1 = \frac{3\pi * 15.06^3 * 0.4^3}{128 * 8 * (15.06^3 + 15.06 * 0.4 + 0.4^2)} = 0.008635$$

$$k_2 = \frac{\pi * 0.4^4}{128 * 2} = 0.0003142$$

$$K = \frac{1}{\frac{1}{0.008635} + \frac{1}{0.0003142}} = 0.000303$$

5.3.7.5 SCREW TURNING SPEED

We have calculated all the necessary parameters to determine the production of our extruder. We only need to determine the speed of rotation of the screw. We use the flow experimentally obtained and the flow equation to determine the rotational speed. However, the calculated flow will be multiplied by a safety factor of 1.25 to ensure that production is greater than or equal to the desired.

$$Q = \left(\frac{\alpha * K}{K + \gamma + \beta}\right)\eta \rightarrow \eta = \frac{Q}{\left(\frac{\alpha * K}{K+\gamma+\beta}\right)}$$

Where:

Flow rate: $Q = 1.25 * 3.732 = 4.665 \frac{mm^3}{seg}$

Drag flow coefficient: $\alpha = 847.276\, mm^3$

Pressure flow coefficient: $\beta = 0.057\, mm^3$

Filtration flow coefficient: $\gamma = 7.066 * 10^{-6} mm^3$

Head geometrical constant: $K = 0.000303$

So the turning speed we must work with is:

$$\eta = \frac{4.665}{\left(\frac{847.276 * 0.000303}{0.000303 + 0.057 + 7.066 * 10^{-6}}\right)} * \frac{60\, seg}{1 min} = 62.68\, rpm$$

5.3.8 REQUIRED POWER

The power required symbolizes the speed with which a job is carried out. This is an approximation to the power we need to add to the extruder so it can melt the plastic. It can be calculated using the following energy balance:

$$N = \rho * Q * C * (T_m - T_0)$$

Where:

Density: $\rho = 1.3 * 10^{-6} \frac{Kg}{mm^3}$

Flow rate: $Q = 1.25 * 3.732 = 4.665 \frac{mm^3}{seg}$

Heat capacity of the material: C= 1386 J/Kg*K.

Outlet temperature: T_m=200ºC.

Inlet temperature: T_0=20ºC.

In our case the material is PLA, whose heat capacity is C= 1386 J/Kg*K. The working temperatures will be T_0=20 ºC at the entrance of the screw and T_m =200 ºC to the output.

Thereof:

$$N = 1.3 * 10^{-6} * 4.665 * 1386 * (200 - 20) = 1.513\, W$$

5.3.9 MAXIMUN MACHINE PRESSURE

The pressure in the extruders is generated in the metering zone and it plays an important role in the process and in the material surface finish. In addition, it is important because different calculations for the design of the machine are derived from the pressure.

To calculate the maximum pressure, we consider zero flow $Q = 0$, so the drag flow becomes also zero. We use the next formula:

$$Pmáx = \frac{6 * \pi * D * L * \eta * \mu}{{h_1}^2 * \tan \varphi}$$

Where:

Diameter of the screw: D.

Length: L.

Turning speed: η.

Initial channel depth: h_1.

Viscosity: μ .

Helix angle: φ.

5.3.9.1 SHEAR RATE AND VISCOSITY

Experiments have limited the value of the shear rate of plastic between the range 100 to 1000 for extrusion processes. The next figure shows up the interval of share rate depending on the process.

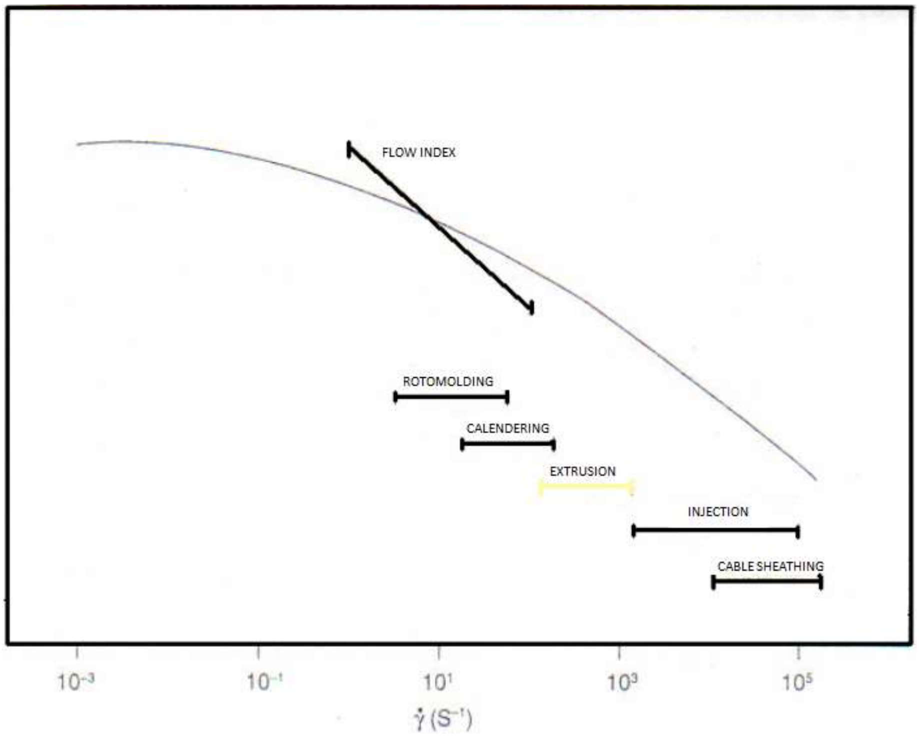


Figure 25. Graph showing the ranges of the shear rate expected for each type of process.

We choose the value of 100 s^{-1} as the limit for calculating the minimum working conditions. With this value we can now obtain the viscosity oh the polymer, which depends as well on the temperature.

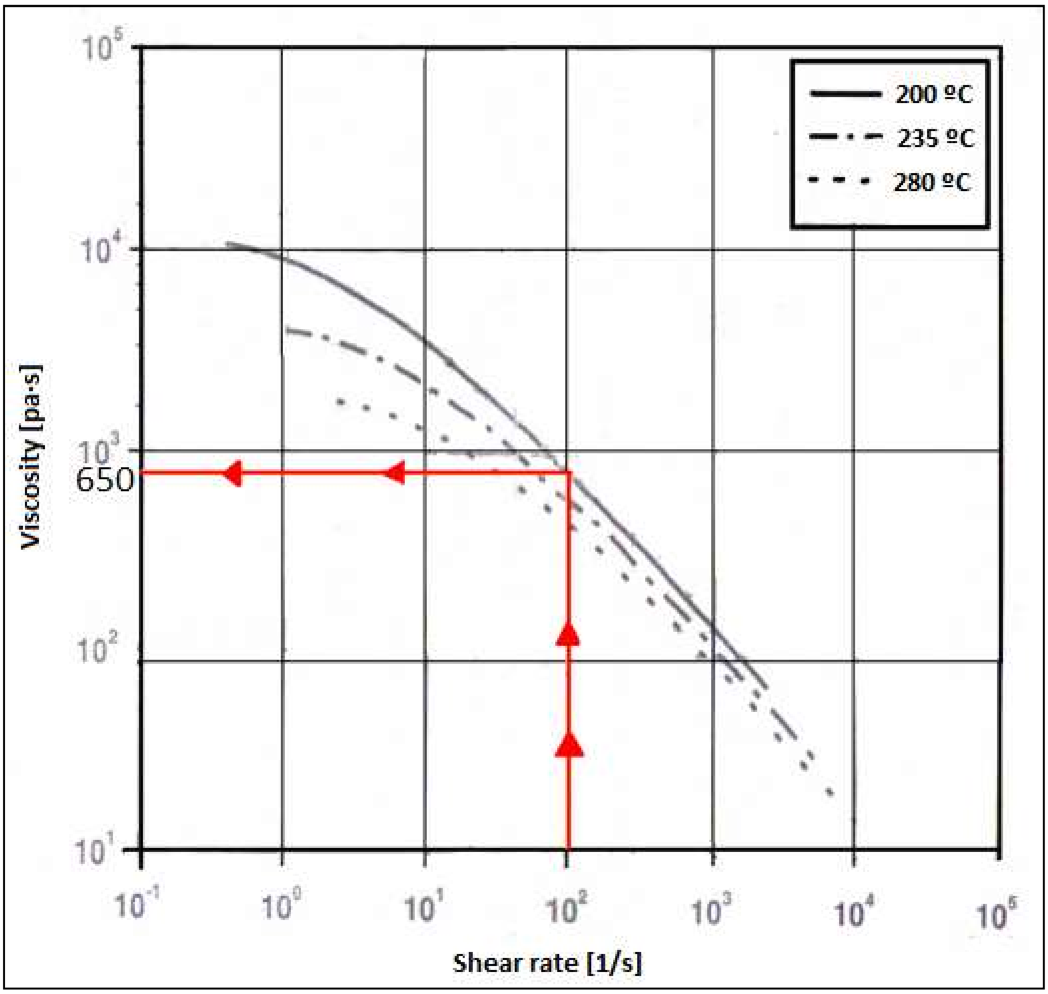


Figure 26. Graph with the relation between the share rate and the viscosity of plastics.

As we have said before, the temperature for the extrusion process would be around 200ºC. Looking into the graph in the figure 26, we obtain a viscosity of 650 Pa·s.

So replacing the data in the previous equation:

Diameter of the screw: $D = 15\ mm.$

Length: $L = 150mm.$

Turning speed: $\eta = 62.68\ rpm = 1.045rps.$

Initial channel depth: $h_1 = 3\ mm.$

Viscosity: $\mu = 650\ \mathrm{Pa \cdot s}$.

Helix angle: $\varphi = 17.65$ º.

$$Pmáx = \frac{6 * \pi * 15 * 150 * 1.045 * 650}{3^2 * \tan 17.65} = 10027926.8\ Pa = 98.97\ bar$$

5.4 PRINTERS SPEED

All the parameters calculated above allow us to define our extruder. But our goal is not to create an extruder but a printer that is functional. We have defined the speed and flow rate of the extruder, but we have to relate them to the speed at which the printer will move. For this we will approach the layer printed as a rectangle, although we know that due to the shape of the nozzle and the action of gravity the plastic tends to form rounded shapes in the corners.

While printing, the printer is laying down a long thin line of plastic every one second. It's easy to see that the volume being extruded in one second, which correspond with the flow rate, is the product of the width of the layer being printed, the layer height, and the distance that the head moves in one second. This speed corresponds with the printers one.

$$Q = w * h * V_p$$

Where:

Flow rate: Q.

Layer width: w.

Layer height: h.

Printer speed: V_p.

Thus we can relate the flow produced by the extruder with the speed at which the printer must move, defining the height we want to get in the layers. The width of the layer is determined by the end diameter of the nozzle, $w = 0.4mm$. The layer height we want to achieve is $h = 0.2mm$, which is the same value on the Delta Rocket. The flow rate is $Q = 4.67\ \frac{mm^3}{s}$ as we have calculated before.

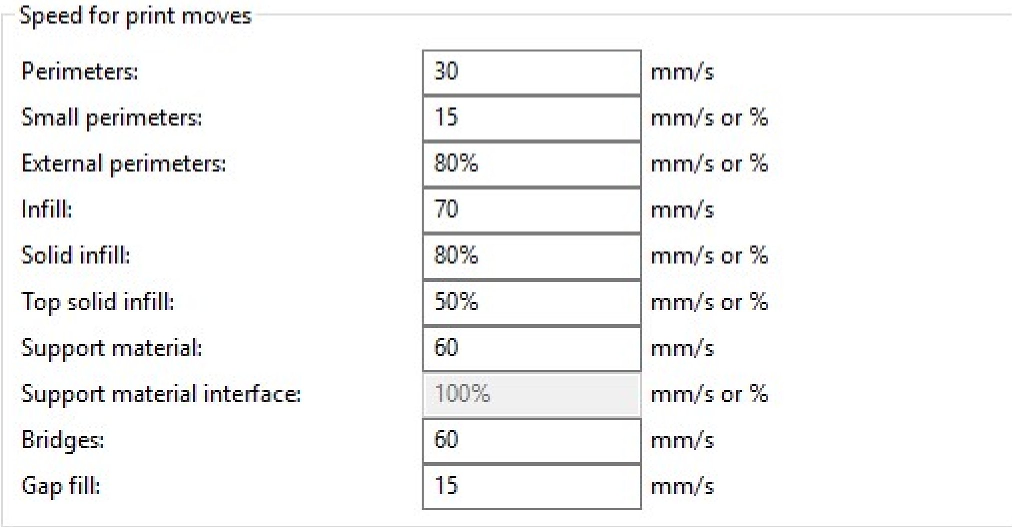
So:

$$Q = w * h * V_p \rightarrow V_p = \frac{Q}{w * h} = \frac{4.67}{0.4 * 0.2} = 58.375 \frac{mm}{s}$$

This would be the speed necessary for the intermediate layer. However, at the beginning of printing the layers are usually higher to ensure a good base to the piece. For example, in the Delta Rocket the initial height of the layers is $h_i = 0.25\ mm$. So the required speed for the first layers is:

$$V_p = \frac{Q}{w * h} = \frac{4.67}{0.4 * 0.25} = 46.7 \frac{mm}{s}$$

If we compare these speeds with those set for the Delta Rocket we can see that they are between the minimum, for the first layers, and the maximum for the infilling.



Speed for print moves

Perimeters:	30	mm/s
Small perimeters:	15	mm/s or %
External perimeters:	80%	mm/s or %
Infill:	70	mm/s
Solid infill:	80%	mm/s or %
Top solid infill:	50%	mm/s or %
Support material:	60	mm/s
Support material interface:	100%	mm/s or %
Bridges:	60	mm/s
Gap fill:	15	mm/s

Figure 27.Data speeds of DeltaRocket defined in the slicer.

Nevertheless, these speeds, that we have calculated, can be changed easily by modifying the extrusion process. As we explained, screw speed was defined for achieving the flow rate $Q = 4.67\ \frac{mm^3}{s}$,calculated before. If we take a look in the flow equation, we see that it is directly proportional to the rotational speed of the screw.

$$Q = \left(\frac{\alpha * K}{K + \gamma + \beta}\right) \eta$$

This means that if we increase the speed of rotation of the screw it would increase the flow rate of the extruder.

Similarly, if we look in the equation used to calculate the printer speed, we see that it is directly proportional to the flow rate.

$$V_p = \frac{Q}{w * h}$$

Therefore, we can increase the speed of movement of the printer by increasing the speed of rotation of the screw, as it increases the flow rate. This means that we can build up our pieces faster. Likewise, we can also modify the layer's height by changing the speeds.

6. PARTS DESIGN

6.1 SCREW DESIGN

As already said screw is one of the most important parts of our printer, as it determines the flow rate that can be obtained. It is the part responsible for melting, mixing and pushing the plastic through the cylinder to the nozzle. In the previous section it has been necessary to define the majority of the screw parameters, to calculate the flow and speed of the printer, so we will not repeat the process and calculations again. In the annex 10.2 enclosed below there is a table as a summary with all the parameters.

However, there are some data of the screw that need more explanations.

6.1.1 CONECTION WITH THE ENGINE

The screw is hooked in its upper part with the engine and is suspended inside the cylinder. For this reason, we have to design an extra element in the screw. This connection between the screw and the engine will be allocated inside the hopper. How is the assembly of this parts will be explained below.

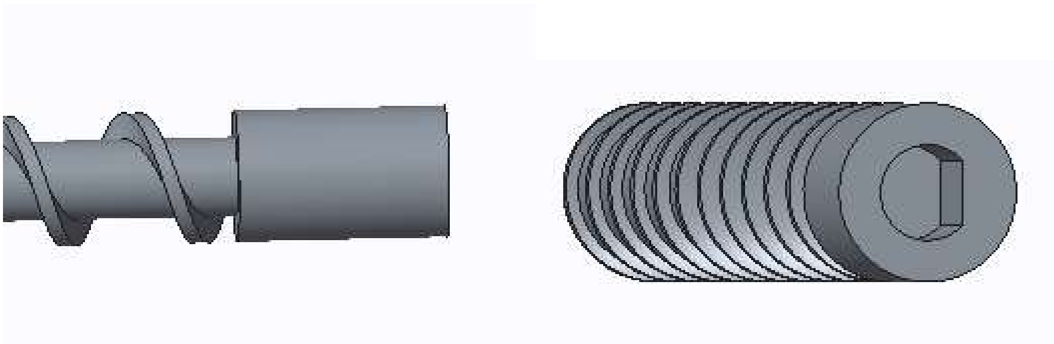


Figure 28. View of the conection of the screw.

The hitch has been designed to fit with the motor shaft, so that no fastenings elements are needed between. It has to be as tight as possible in order not to have a gap between both elements. With this premise the movement will be given directly from the engine to the screw, so controlling the engine's angular velocity we can adjust the exact angular velocity that we want for the screw.

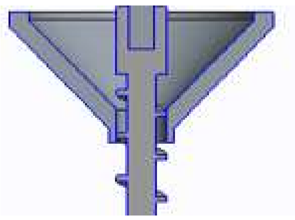


Figure 29. 3D model where you can see how the screw gets into the hopper.

In addition, it has taken advantage of the disposition of the screw using the screw itself as filler material aid. For it the length of the feed zone of the screw, previously calculated, has been extended. So it gets into the hopper and forces the plastic powder to get into the extruder.

Below the whole assembly will be explain and this part will be more clear. In addition, in the annex 10.4 are the drawings with more information and details of the screw itself.

6.1.2 VOLUME AND WEIGHT

There are two basic characteristics that the screw should satisfy in order to perform his function correctly. It has to be hard enough to bear with the possible erosion and to be able to handle with high temperatures. The high temperatures will be caused by the movement that the screw has, the friction against the cylinder and the heating system.

The material chosen for the screw is steel F-174, which is a nitriding steel. This material is typically used in extruders screws and cylinders and reaches a vickers hardness of 1048-1064 HV. In addition, it is able to handle with the high temperatures reached inside the extruder, which will be around 200ºC. Steel pieces which has been treated with a nitriding process are usually prepare to stand temperatures up to 500ºC. Also the nitriding process gives the piece an extra layer of protection against the corrosion.

This piece is the most difficult to manufacture and must be machined with special attention to the surface finish throughout. For the properly development of the extrusion process it is necessary that the screw surface is as smooth as possible, to avoid friction and to allow the plastic slide on it.

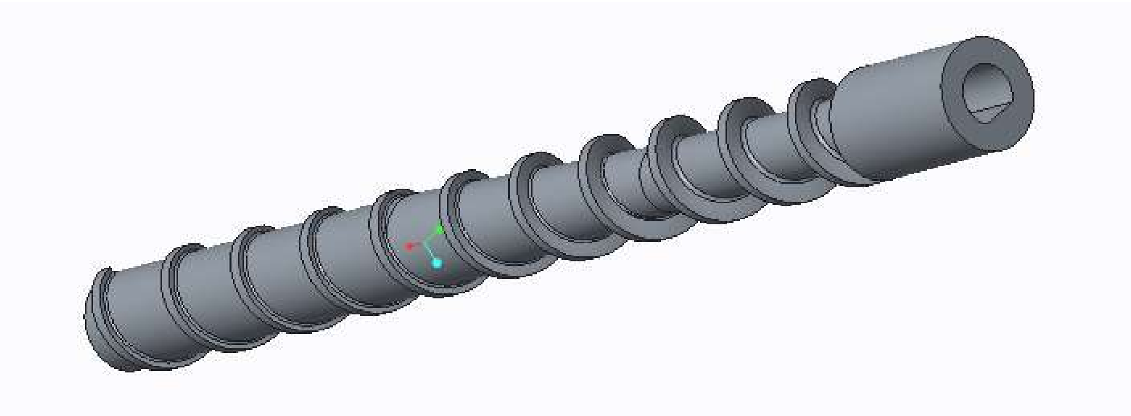


Figure 30. 3D model of the screw. It is visible on it the shape of the connection with the engine.

We can calculate the weight of screw using the program we have used to design it, Creo Parametrics 3.0. Entering the value of the density of the material, in this case steel $\rho = 7700\frac{Kg}{m^3}$.

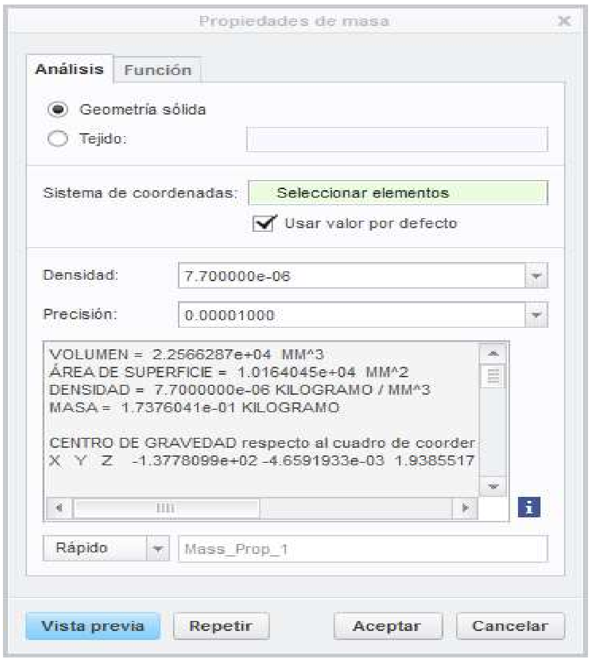


Figure 31. Results of the values obtained by CreoParametrics 3.0.

The program itself calculates the volume and the mass of the piece. It shows a table with the results with other parameters that may be of interest as the center of gravity or the inertia momentum.

The results are:

$$V = 2.257 * 10^4 mm^3$$

$$m = 1.737 * 10^{-1} Kg$$

As the total weight is below 200 g, we can consider the screw dimensions valid. We tried to minimize the weight of the extruder's head and all its components. Finally, we reach these dimensions, that are between the limits we wanted in terms of volume and weight.

6.2 NOZZLE DESIGN

As explained above the nozzle is the final element of the 3D printer and shapes the extruded plastic. In the previous section we have determined the diameters and lengths inside the nozzle necessary to calculate the geometrical constant that we used in the sizing of the screw of the extruder. However, we still have to design the outside to be fully defined.

The data for our nozzle are:

d_0=15.06 mm.

d_1=0.4 mm.

L_1=8 mm.

d_2=0.4 mm.

L_2=2 mm.

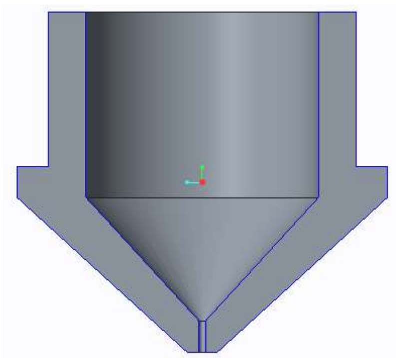


Figure 32. Section where the inside of the nozzle is visible.

Figure 33. Final shape of the nozzle.

This piece is threaded on its cylindrical outer surface as it is designed to screw inside one of the heaters, so that it bonds with the cylinder. Thus the extruders channel continuous with the hole inside the nozzle. In the annex 10.4 are the drawings with more information and details of the nozzle dimensions.

The conical shape is inspired by most of nozzles in the market. It is made on purpose to prevent the plastic from sticking on the nozzle so the plastic comes out of the printer cleanly. A very common problem when printing is precisely that the plastic sticks to the head rather than deposite on the base.

The material most commonly used for nozzles is brass because it has to withstand high temperatures. Likewise, is a good conductor of heat, quality that is needed to heat fast and uniform the nozzle as the printing material needs to be printed around 200ºC. Brass is one of the material with best characteristics and this is why we are choosing it for the nozzle. The nozzle is also one of the most important elements of a 3D printer, as it defines the final shape of the plastic. Between its characteristics we are going to remark its hardness and the fact that it perfectly keeps its conditions for a long period of time. Also, it doesn't get affected by the external conditions. Its characteristics make it one of the best materials in the market but with a lower price.

6.3 CYLINDER DESIGN

The cylinder is the part in charge of keeping the material inside while going throughout the screw. For this reason, its inner diameter is the sum of the screw diameter and the clearance calculated above, to a total of 15,06 mm. Its total length to be able to cover all the screw is 140 mm. In the annex 10.4 are the drawings with more information and details of the cylinder dimensions.

Just as for the screw, the material chosen for the cylinder is steel F-174, for the same reasons. The cylinder must also be able to handle with high temperatures and be hard enough to resist degradation due to the friction generated between the inner face of the cylinder and the plastic flow.

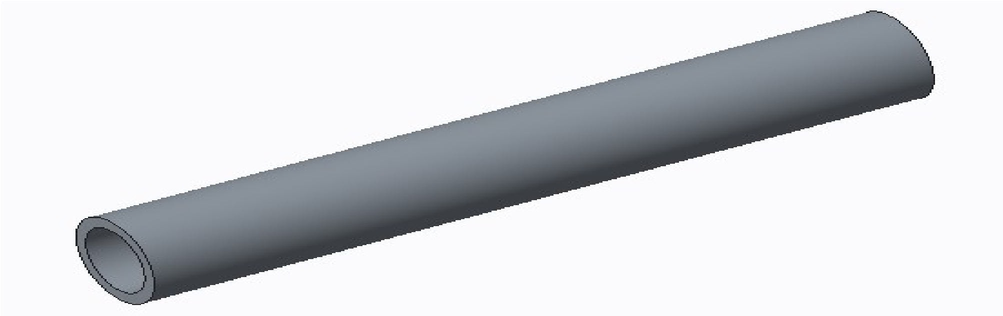


Figure 34. Preview of the cylinder designed in CreoParametrics 3.0.

The cylinder is threaded on its outside surface. It will be threaded in the heaters so it gets fixed and joined to the nozzle. On the inner surface a very slick finish is not necessary, since the fact that a certain roughness improves the flow of the plastic and the mixture inside the extruder. On the top part of the cylinder a teflon joint will be engaged on the cylinder.

6.4 TEFLON JOINT

The purpose of this joint is to prevent the heat from the cylinder, due to the temperature at which the cylinder is heated during the process, reaches the hopper. Thereby we keep the feeding zone cold, preventing the plastic powder from sticking in the throat of the hopper.

For this reason, teflon has been chosen as the joint material, since it is a great insulator capable of withstanding temperatures up to 260 degrees without degrading.

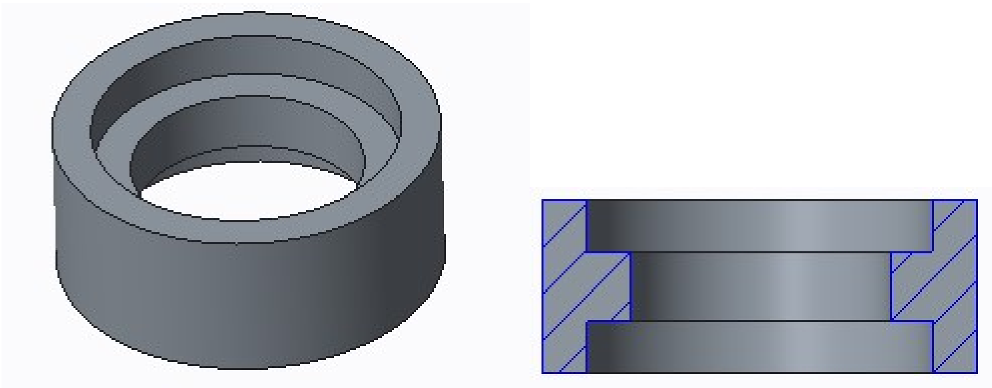


Figure 35. Teflon joint shape and section.

The joint will be embedded between the hopper and the cylinder isolating thermally both pieces. It will be threaded at top of cylinder and the hopper will be threaded as well to the joint. In this way, we managed to join the hopper and the cylinder, while the hopper is isolated from the heat.

In the annex 10.4 are the drawings with more information and details of the joint dimensions.

6.5 HOOPERS AND FEED SYSTEM DESIGN

The hopper is the part responsible for storing the feed material and leading it to feeding zone of the extruder. Typically, only one big hopper is placed at the beginning of the extruder. However, in this case we will have 2 hoppers connected instead of one. This is because if we want to reduce the maximum size of the 3D printer head our hopper cannot be very large.

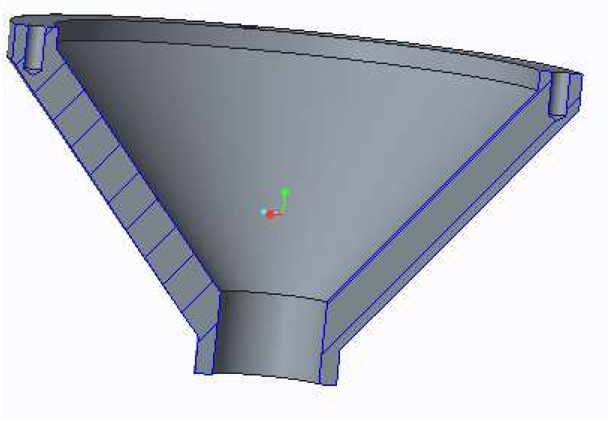


Figure 36. Section where you can see the inner geometry of the hopper of the extruder.

In the figure 36 you can see the geometry of the extruder´s hopper. It is fixed to the cylinder by the joint of teflon, which as we have said makes insulation preventing the hopper to warm up.

This hopper is continuously fed from the top, thanks to the connection through a flexible plastic tube with the upper hopper. Unlike the large hoppers of the common extruders, this hopper is not capable of holding large amounts of material. Even so, it will not be necessary to stop the printer every little time to fulfill this hopper. The flexible connection between the two hoppers allows the upper hopper feed the extruder´s hopper even when in motion. Thus we managed to print performing a continuous process, because we only have to fill the upper hopper. This can be done at any time while printing. As it has been said before, the hopper houses inside the connection between the engine and screw, which reduce the volume available to the feed material, making more necessary the second hopper. In the next figure you can see how the hopper will be feed. The plastic tube, which guides the material into the hopper, will be attached to a plate placed over the hopper.

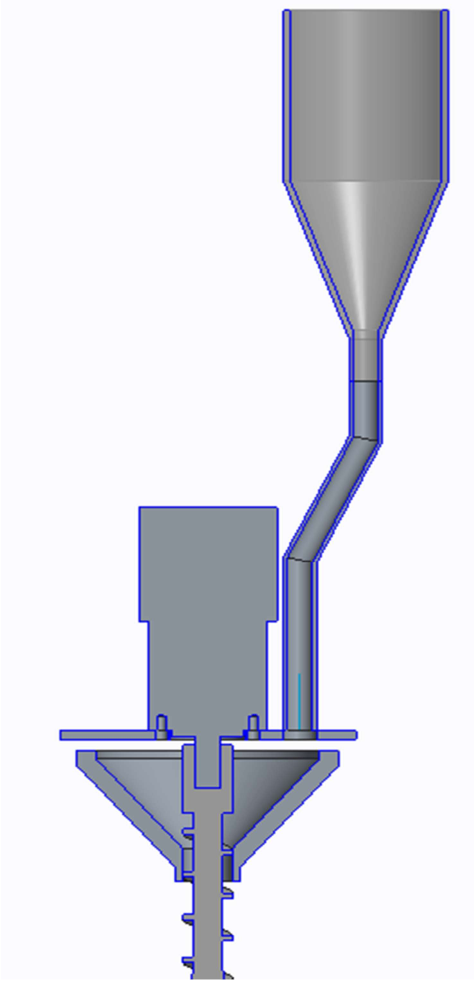


Figure 37. Feed system and engine support to the hopper.
It is also visible the connection of the screw with the engine.

The extruder´s hopper will be made in Corzan (CPVC), because it is resistant to corrosion and temperature and easy to manufacture. In addition, it is also used sometimes as an isolate material, which helps to keep the feed throat of the extruder cold. The other hopper, located on the top of the machine, will be fabricated in Polypropylene (PP), because it is a cheap material and also lighter. However, as we have said before, because the PLA needs a predrying process, this upper hopper can be replaced by a drying hopper.

Moreover, the hopper will also serve as support for the engine that will turn the screw. As shown in the previous figure an aluminum plate fixed on the hopper will support the engine and fix it to the printer head. The plate is fixed to the hopper with screws, and the engine is also fixed to the plate with screws.

6.5.1 UPPER HOPPER VOLUME

One of the characteristics that our printer must have is to be able to print performing a continuous process. This means that the upper hopper should contain enough material to avoid being constantly refilled. The design of the upper hopper is done trying to achieve this goal.

To calculate the volume, we have approached the inner cavity of the hopper dividing it into two zones, one cylindrical and one conical. So that the total volume will be the sum of these two areas:

$$V = \left(\pi * \left(\frac{D}{2}\right)^2 * h\right) + \left(\frac{1}{3} * \pi * \left(\frac{D}{2}\right)^2 * tg(60)\right)$$

Where:

Diameter: D=100 mm.

Height: h=50 mm.

So:

$$V = \left(\pi * \left(\frac{100}{2}\right)^2 * 5\right) + \left(\frac{1}{3} * \pi * \left(\frac{100}{2}\right)^2 * tg(60)\right) = 619424\ mm^3$$

Considering that the flow rate of the extruder is $Q = 4.67\ \frac{mm^3}{s}$ we can calculate the time, in hours, that the printer can be working without being refilled.

$$T = \frac{V}{Q * 3600} = \frac{619424}{4.67 * 3600} = 36.84\ hours$$

HOPPER VOLUME		
Diameter (D)	100	mm
Height (h)	50	mm
Volume (V)	619424,002	mm^3/s
Time (t)	36,8441591	h

This means that our printer with a small hopper of 100 mm diameter, can work without stopping for something more than day and a half.

6.6 ENGINE

The engine is the device responsible for giving movement to the screw and provide the energy required for the extrusion. For the engine we wanted to choose an existing product in the market, so we don't have to design it ourselves. We were looking for the simplest and cheapest engine on the market that has the needed specifications. After a market study, we found out some useful conclusions. Most of the 3D printers use NEMA motors, which are step by step engines with quality guarantee. We also found that mostly of the 3D printers has 1.8º as the step of the engine. Only the very precise 3D printer has 0.9º as step. Due to our printer doesn't have to be very precise we have chosen 1.8º for our step motor. In addition, a logical intensity for our case is 1,7 A, as it is the most used one in common printers. In addition, the operating torque depends on the load needed. In our case we considered a light-weighted load, so the torque has to be between 0,28 N·m and 0,4 N·m.

We have chosen an existing NEMA17 engine consisting of a Motor: 42HS40-1704Z and Gearbox: 36PLGB2-xxZ. The datasheet of the engine with the gearbox can be found in the annex 10.3 below.

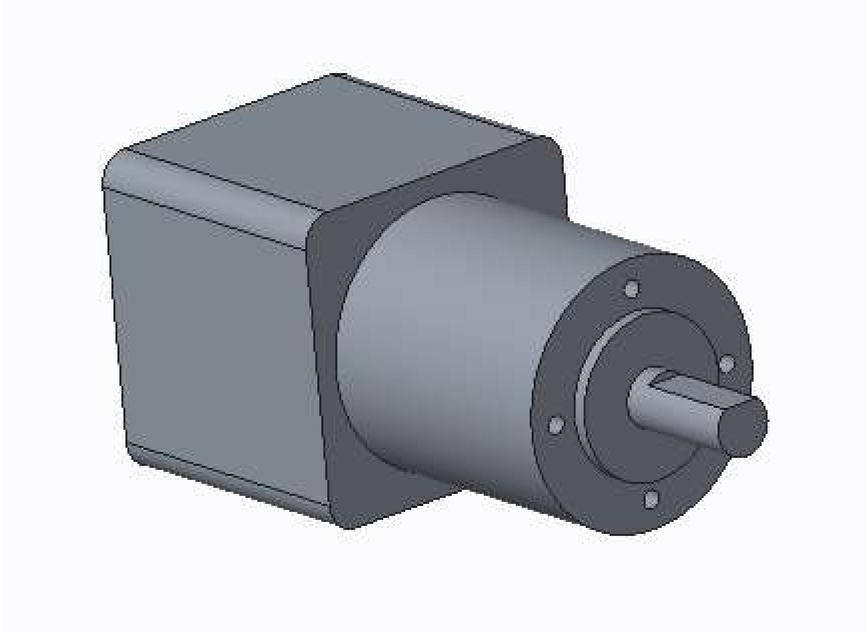


Figure 38. 3D engine with gearbox model.

Previously it has been already explained how the motor is fixed to the head of the extruder. In the figure you can see the holes which accommodate the screws to fix it to the plate as mentioned above. It is also visible the shape of the edge that will connect with the screw. The screw itself, has been designed so this edge can enter into the hole on the top of the screw.

The reason for choosing this engine instead of any other is because it is small enough, so it doesn't increase too much the weight of the head, but still provides the power we need. In addition, the fact that it comes together with the gearbox allows the electronic system of the printer to control the rotation of the motor and therefore the screw. This is necessary because during the printing process its speed changes. For example, speed is not the same while printing the outer profiles of the layers than when filling them.

6.7 HEATER SYSTEM DESIGN

In the beginning of the extrusion process it is necessary to provide heat to the cylinder so that the enclosed plastic warms up too until it melts. Only in this way it is possible to restart the extruder. If the plastic enclosed inside does not melt, the screw is blocked and the extruder cannot be turned on and begin the process. For that reason, we had to include a system of heaters to provide the heat necessary, to melt the plastic. In addition, after turning on the extruder and the screw begins to rotate, the friction generated between the plastic and the cylinder generates additional heat which increases the temperature of the cylinder a lot. For that reason, in the extruders it is also necessary to add a cooling system that allows to control the temperature in the cylinder despite the heat generated by friction.

For this reason, the design of this heating system and temperature control is one of the most difficult parts of the project. In addition, the traditionally used systems for heating and cooling the cylinder in common extruders are too big and they will increase the size of our printer head a lot. Therefore, we had to think in a new system that could fix in our project.

For the system´s design the first thing we have done is think about how we heat the cylinder so it can have different temperatures in each zone of the extruder. For example, during the extrusion process the temperature in the compression zone is not the same as in the transition zone. In extruders, heaters rings with electrical resistances are normally used, placed in each area in which a certain temperature is required. Together with one of these rings is also placed a fan which will cool down the zone and perform as the temperature control once friction begins to raise the temperature. However, these rings and fans are usually very big and we cannot include them in our design.

Figure 39. Example of rings heaters used in traditional extruders.

For our printer we have relied on both, the Delta Rocket HotEnd and the information collected in the book Printing in Plastic, where they explain how to build your own 3D printer. In the book it is explained how to mount our own HotEnd, including the necessary materials and the process to follow. The system consists on electric resistors coupled to an aluminium part, which will be the heater, in which the cylinder is inserted. The electrical heating elements heat up the aluminium piece and therefore the cylinder. Thus it is achieved the heating and melting of the plastic inside the cylinder. In addition, the nozzle is also threaded into this aluminium piece, so it gets attached to the cylinder and heated, preventing the plastic from getting stuck in the end of the extruder. Besides the resistances, a thermal sensor is attached to the heater that enables reading the temperature in the heater, and so control the temperature.

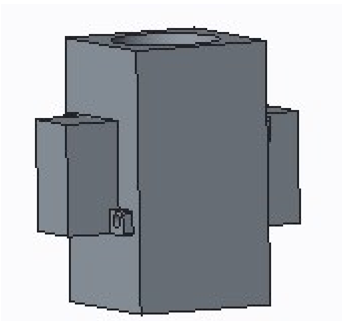


Figure 40. Heater system with the resistances attached to the heater piece.

In the figure 40, you can see the arrangement of the resistors in the heater piece. Positioning the resistances on opposite sides, it helps the heating of the workpiece to be more uniform and easier to control. In one of the free sides the temperature sensor will be placed. It will enable the electronic system to control the temperature switching on or off the heating system when it is necessary. The resistances chosen are RH10 RE65G which gives us the energy necessary because they can work at temperatures up to 250 degrees and the process for PLA develops around 200ºC. The information datasheet of the resistance can be found on the annex 10.3.

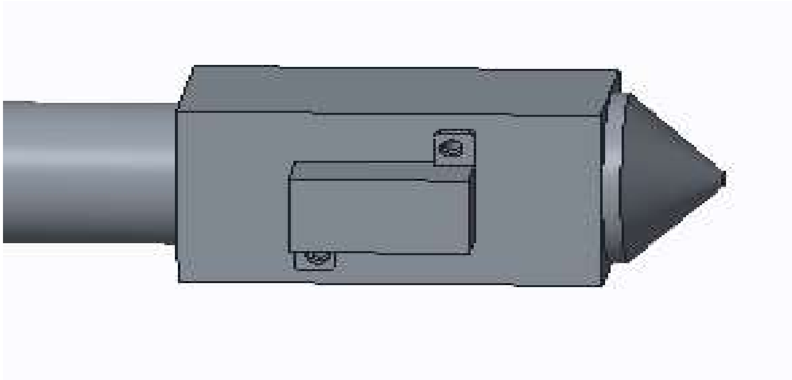


Figure 41. 3D model of the assembly where you can see the heater attached with the cylinder and the nozzle.

In our project, because the size is very small we believe that it will only be necessary to control the temperature in 2 zones, so we will add only two of these heaters, one for the compression zone and one for the metering zone.

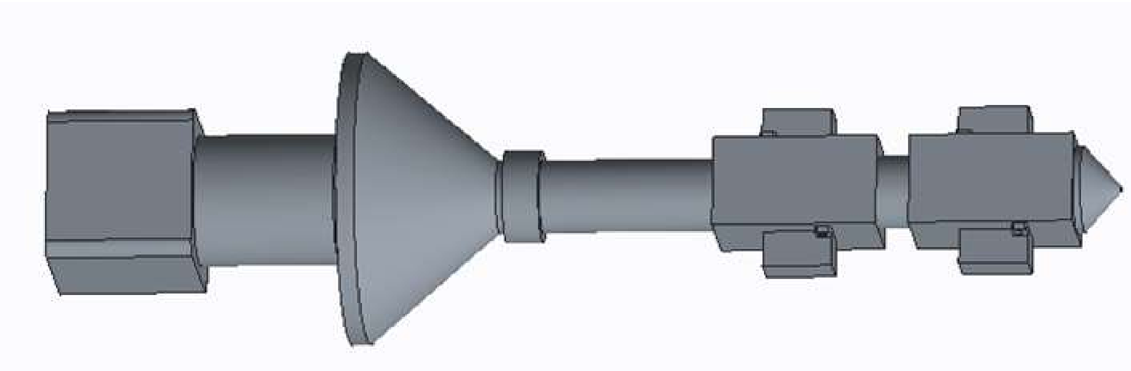


Figure 42. 3D model with the two heaters assembled to the cylinder.

On the other side of the heater, which was left empty, the fan that makes temperature regulation will be located. Obviously this fan will not be placed on the heater surface as it would heat up a lot and would not perform its function well. Following the example of existing extruders, the airflow is separated a few centimeters from the heater. In this way it helps the action of air, so it cools more uniformly on all sides of the extruder, ensuring better temperature control. The fans chosen are: MULTICOMP MC36257. It is an axial fan, which works with 12 VDC, providing up to 0.226 m^3/min. The main problem with the fans is that we can't determinate before starting the machine how much air flow we are going to need. For this reason, we have chosen a fan that can be easily changed for another one more powerful with the same dimensions. In addition, the way the fans are attached to the system, makes it very easy to change them by any other fan. More information can be found on the data sheet of this family of fans on the annex 10.3 below.

The positioning of these fans will be explained below, since they are screwed to the fixing system of the extruder. In addition, further information about the heaters design and dimensions can be found on the annex 10.4.

6.7.1 MELTING POWER NEEDED

We are going to calculate the energy that is necessary to provide to the plastic to melt it. We have already chosen our resistances, ensuring that allow us to obtain the required temperature of 200ºC, as they can reach 250ºC. However, we think is also good to have an approximation of the power that they will need.

The power needed can be calculated with the next equation:

$$W = \rho * V * C * \Delta T$$

Where:

Power per second needed: W.

Plastic density: $\rho = 1.3 * 10^{-6} \frac{kg}{mm^3}$.

Volume: V.

Heat capacity of the material: C= 1386 J/Kg*K.

Temperature increase: $\Delta T = 200 - 20 = 180ºC$.

To calculate the volume enclosed inside the extruder we depreciate the volume occupied by the screw helix. In this way, the volume of plastic will be the difference between the volume of the chamber inside the cylinder and the volume occupied by the screw.

The volume of the hole of the cylinder is:

$$V = l * \pi * r^2$$

Where:

Length: l=150mm.

Radio: D= 15.06mm.

So:

$$V = 150 * \pi * 7.53^2 = 26507.19\, mm^3$$

The volume of the screw will be divided in three different zones as it is in:

Feeding zone length: $L_1 = 33mm$ and $r = 4.5mm$.

Compression zone length: $L_2 = 52mm \;\; r = 4.5mm \;\; R = 6.5mm$.

Metering zone length: $L_3 = 65mm$ and $R = 6.5mm$.

For the feeding zone the volume is the volume of a cylinder so:

$$v_1 = l_1 * \pi * r^2 = 33 * \pi * 4.5^2 = 2099.37\, mm^3$$

For the compression zone the volume is the volume of a trunk cone so:

$$v_2 = \frac{l_2 * \pi}{3} * (r^2 + R^2 + r * R) = \frac{52 * \pi}{3} * (4.5^2 + 6.5^2 + 4.5 * 6.5) = 4996.18\, mm^3$$

For the metering zone the volume is the volume of a cylinder so:

$$v_3 = l_3 * \pi * R^2 = 65 * \pi * 6.5^2 = 8627.6\, mm^3$$

Therefore, the volume of plastic that must be melted:

$$V_t = V - v_1 - v_2 - v_3 = 10784.04\, mm^3$$

So if we go back to the equation of the power:

$$W = \rho * V * C * \Delta T = 1.3 * 10^{-6} * 10784.04 * 1386 * 180 = 3497.52\, J$$

This value represents the heat to be provided by resistance, when all the material needs to be melted inside the extruder.

As we can see on the data sheet of the resistance, which can be found on the annex 10.3, the resistances provide 12.5 watts. We have 4 resistances so we can give to the extruder 50 joules every second. So the time we have to wait until all the plastic is melted is:

$$t = \frac{Requiered\ power}{Resistance\ power} = \frac{3497.52}{50} = 70\ s$$

This will be the time that the printer needs to be ready to print every time we turn it on.

6.8 FIXING SYSTEM

What we have called fixing system, it is nothing but the pieces we have designed to set our extruder on the head of the machine. This fixation system is responsible for holding the extruder and the rest of the pieces, so they move with the machine, creating this way the 3d printer head. In addition, as we said before, the fixing system will hold the fans that cool the cylinder down to control the temperature inside it. Moreover, it also has to hold the layer fans support, which we will explain later. Therefore, the pieces we have to design should perform simultaneously three different functions.

To start designing the pieces we look at the machine in which we are going to assemble the extruder, which we have described above. This machine has a metal plate with holes prepared to screw the extruder at different heights. This allows to adjust the extruder to the height we want. In addition, the heater system is designed in a way so that the fixing system has to be allocated between both of the heater pieces.

So we thought of a piece C-shaped, with holes for the screws on one side. On the other side 4 holes for the bolts of the layer fans support and a hole to pass the cylinder and the heating system. The last side we will use it to assemble the fans for the cooling system.

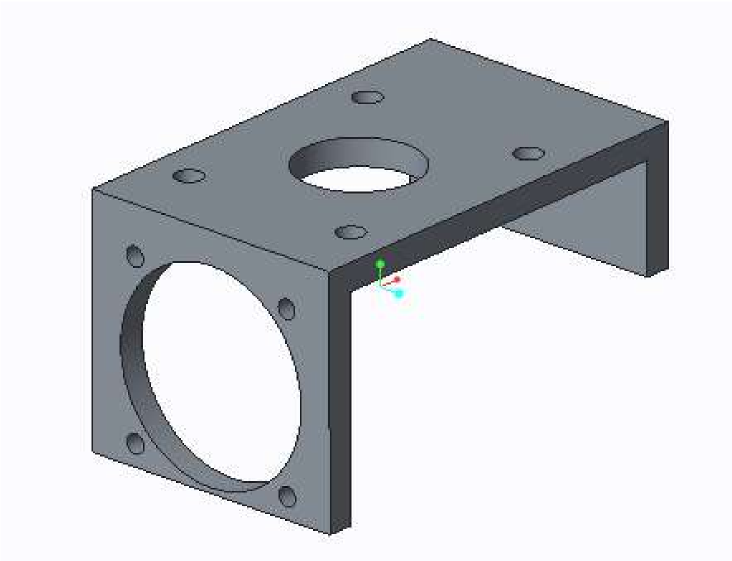


Figure 43. 3D model of the fixing piece with the holes for the fan and the bolts.

The piece is made in aluminium of 5 mm of thickness because it is a cheap and easy folding and drilling material but enough resistant. It is also resistant to high temperatures. This piece would be sandwiched between the 2 pieces of the heater system. Since these two pieces are threaded on the cylinder they can be tightened to ensure that the fixing piece will not move. Then, the piece is screwed to the plate of the machine being fixed and integral with the movement of the extruder machine. The fans will be simply bolted to the plate. The dimensions are detailed on the annex 10.4 below.

Because we have to put two fans, one for each zone of the heating system, we will have two similar pieces. Thus, the fixing of the extruder to the machines head will be double. This ensures a solid fixation and help to keep the extruder straight during the printer movement.

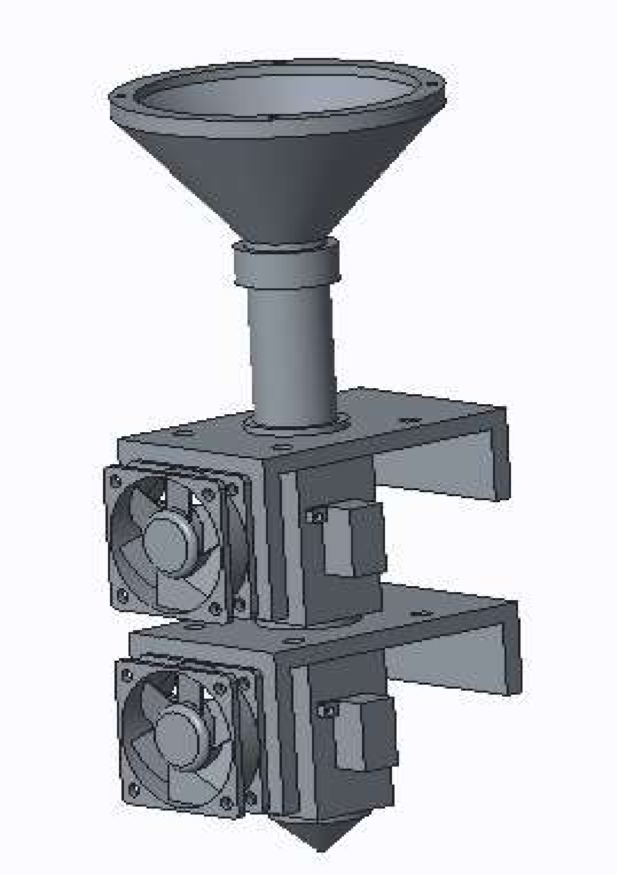


Figure 44. 3D model with the fixing system assembled. It is also visible the way the fans, from the cooling system, are attached.

We have also added a final piece to our fixing system. As we already mentioned the support part will be sandwiched between the two parts of the heater. This means that the heat of these parts is transmitted to the holder piece. However, on one part of the support will be placed the fan, which is made of plastic. So if the plate is too warm it could melt the fan. For that it has been included a teflon joint which isolates the fixing piece from the heaters.

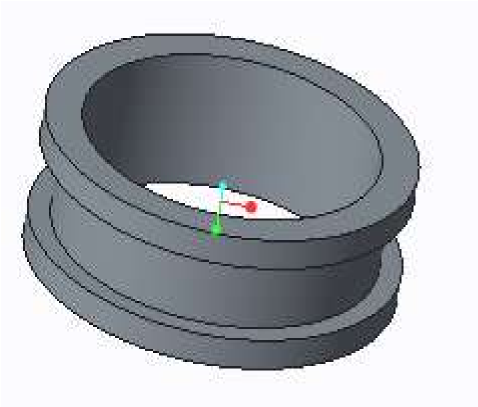


Figure 45. Teflon joint which isolates the extruder support from the heating system pieces.

This joint will be fit in the hole that the plate has to pass the cylinder and the heaters. Due to its shape the heaters will rest on the joint instead of doing it on the plate. Thus the transmission of heat is avoided.

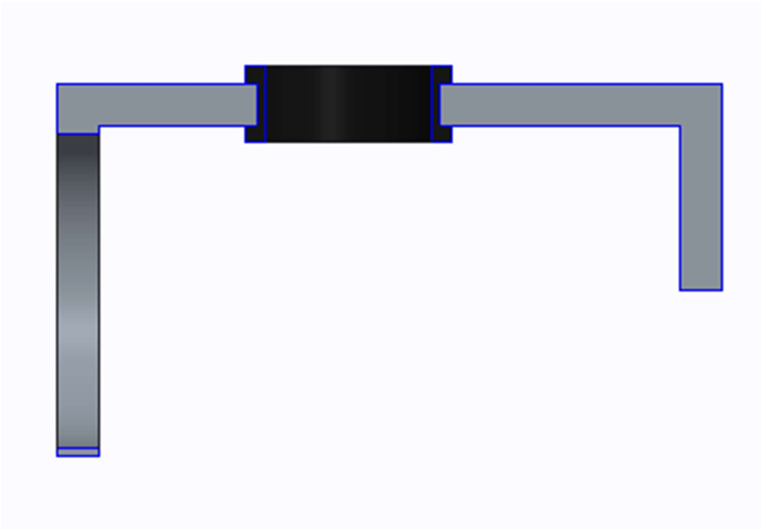


Figure 46. Section with the joint assembled to the plate

The material is the same material used for the other joint. It resists temperatures up to 260 degrees. More information can be found on the drawing in the annex 10.4.

6.9 LAYER FANS SUPPORT DESIGN

When printing PLA is important to add layer fans to the printer that cool down the plastic deposited on the base. Just as the Delta rocket, we have decided to add 2 fans to perform this function. Therefore, it was necessary to design a completely new support that fits in our printer head.

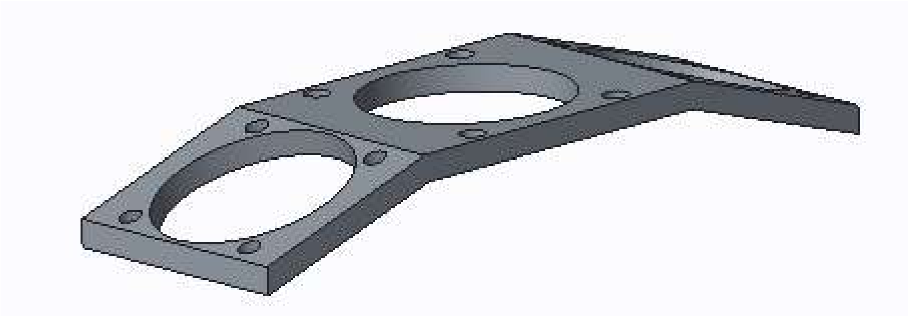


Figure 47. 3D model of the fans layer support.

The design shown in the figure is inspired by the existing one on the delta rocket. It will be printed in PLA or ABS plastic, which makes it a very cheap piece. The piece has a hole in the middle so the nozzle fits in and two more in each side to allows the fans blow air on the printed plastic. The fans are fixed to the support by 4 screws each. The entire structure will be suspended in the air, held by four bolts on the plate that holds the extruder head to the three axis machine. This plate is the same where the cooler fans from the heater system are placed.

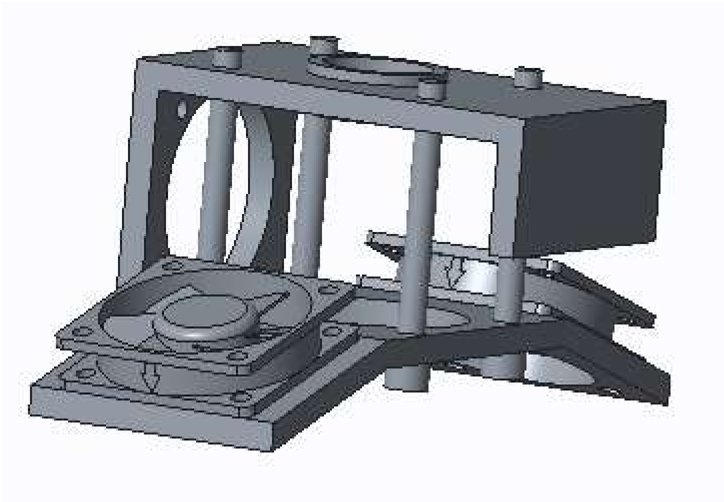


Figure 48. Image with the assembly of the layer fans support with the four bolts and the extruder support.

The details of the design can be found on the annex 10.4 below.

The fans chosen are the same that in the delta rocket: MULTICOMP MC36257. It is an axial fan, which works with 12 VDC, providing a flow up to 0.226 m^3/min. The technical data sheet for the fans can be found on the annex 10.3 below. The reason for choosing these fans and not others, is to try to change as less as possible the parameters with respect to the Delta rocket. Since the flow which we are working with is the same as in the Delta rocket, the fans should work under similar conditions as they do in the existing printer.

7. ASSEMBLY

At this point we will explain how all the pieces presented in the previous section will be assembled. Similarly, we will explain how the printer will be set to the head of the existing machine.

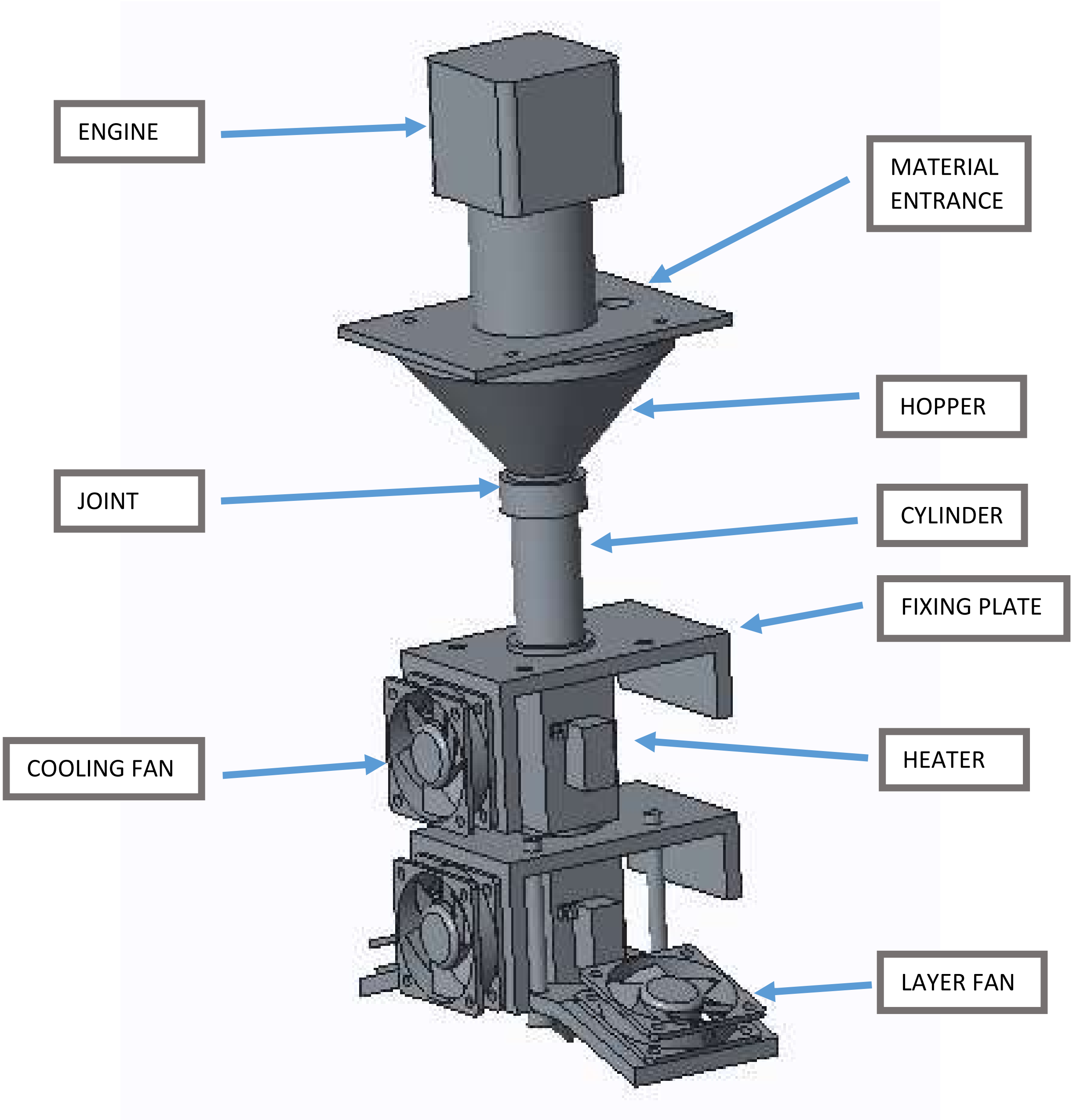


Figure 49. 3d Model of the final assembly with all the parts of the printer's head.

This is the general view of the assembly of the design of the printer's head. We have indicated all important elements and only the connections between them, such as screws or threaded studs, are missing for simplicity of the figures. As we had been saying throughout the memory the main points for this design are making the head as small as possible and design an extruder for been able to print starting from granulate plastic. In addition, it is also able to control the temperatures along the whole process in order not to have problems of stagnation. In the previous point we had already explained how we have designed all the elements, in order to achieve these main points. In this section we will focus in the head as an assembly. Explaining how all parts are assembled together and how the final assembly is joined with the existing machine.

7.1.1 ASSEMBLY PROCESS

First of all, we are going to explain how all the elements are mounted one to each other. We will proceed with the explanation ordering the assembly steps. For the process of mounting the printer head, we have to divide the assembly into two parts.

In one side we have three elements: the engine, the plate where the material entrance hole is located and the screw. The first step is to attach the engine to the plate by the four screws that the engine has in the speeder part. We can see the holes made for this purpose in the following figure. In addition, the screw will be attached to the engine by pressing fit. As we created a whole in the screw with the dimensions of the engine, it will be easy to carry it out successfully. It is shown below how the three elements look like after attaching them:

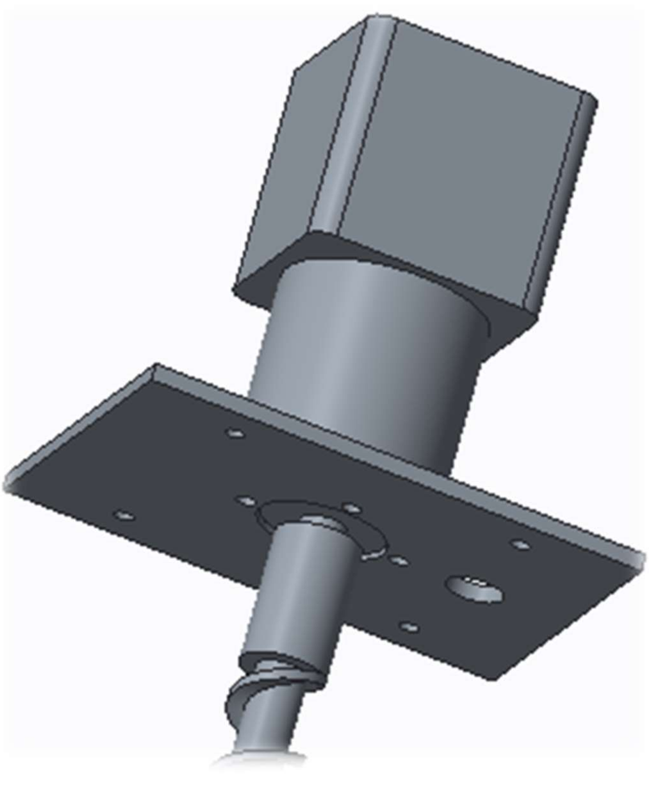


Figure 50. First assembly with the engine, the hopper plate and the screw.

In the other side, we have the rest of the elements of the head. This part is more complex to be assembled, as there are many elements and most of them have to be attached in a specific order. The first step is to screw all the fans and all the resistors in order not to have to do it later, when the spacing of manoeuvrability will be much smaller. The fans, both the layer ones and the ones to control the temperature of the material inside the cylinder, have four screws to be attached to the plates where they have to be placed. In the same way, the resistors need two screws to be joined to the heater pieces. In addition, the teflon joint, which isolates the plate from the heaters as it has been explained before, will be mounted in this step to the fixing plate.

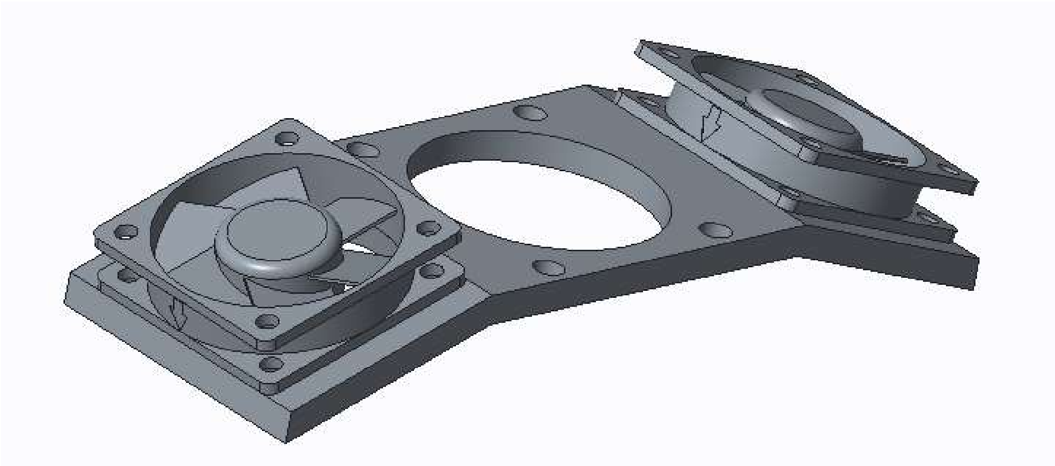


Figure 51. Layers fan assembly.

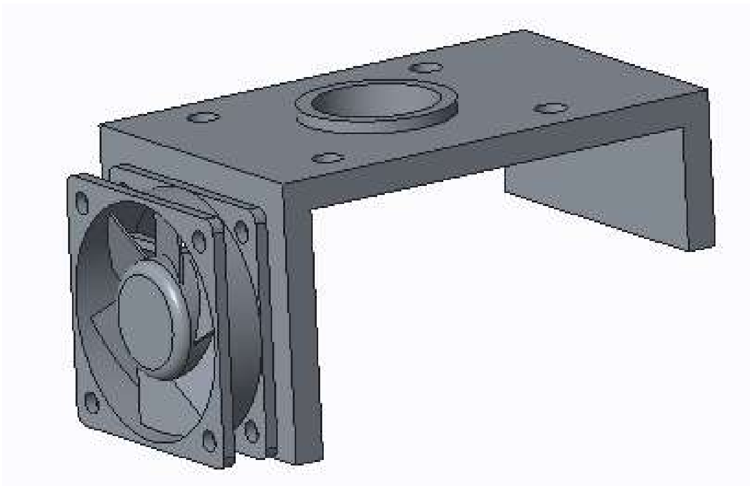


Figure 52. Fan and joint assembly to the fixing plate.

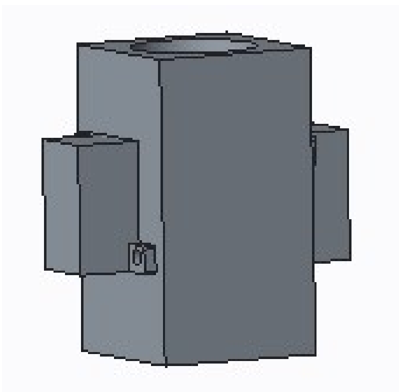


Figure 53. Resistance assembly to the heater piece.

In the figures 51, 52 and 53 you can see how the assemblies will look like after the assembly of the fans, the joints and the resistances.

Once you have this prepared, you have to assemble everything into the cylinder. We will begin threading the lower heater piece to the cylinder and the nozzle. So then we have the three elements assembled to each other.

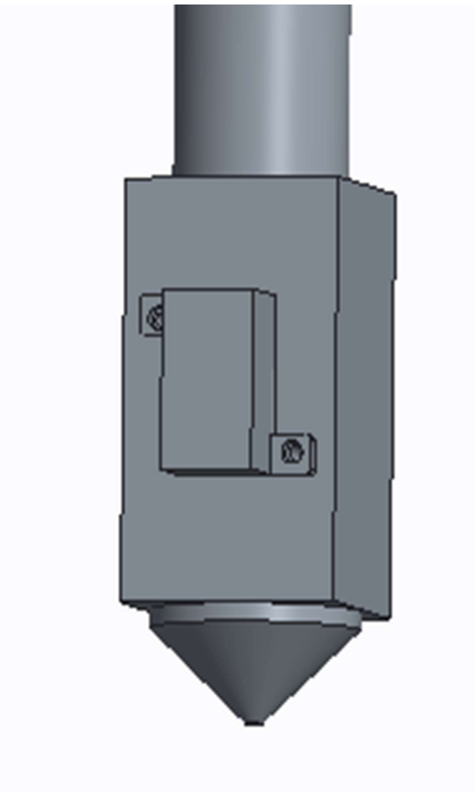


Figure 54. Assembly of the cylinder, nozzle and the heater piece.

After that, we will start introducing the elements in order throughout the cylinder from its upper part. The parts have to be assembled in the following order:

1. The first fixing plate.
2. The upper heater piece.
3. The temperature sensors.
4. The layer fans support.
5. The second fixing plate.

While mounting the parts we have to be sure that all the elements have the pretended orientation. In the following figure can be seen how the parts should be after assembly. The orientation of the parts is important because after, the whole assembly must be fixed to the mobile head machine. Therefore, the position of the fixing plates determines the position of the fans, heaters and the layer fans support.

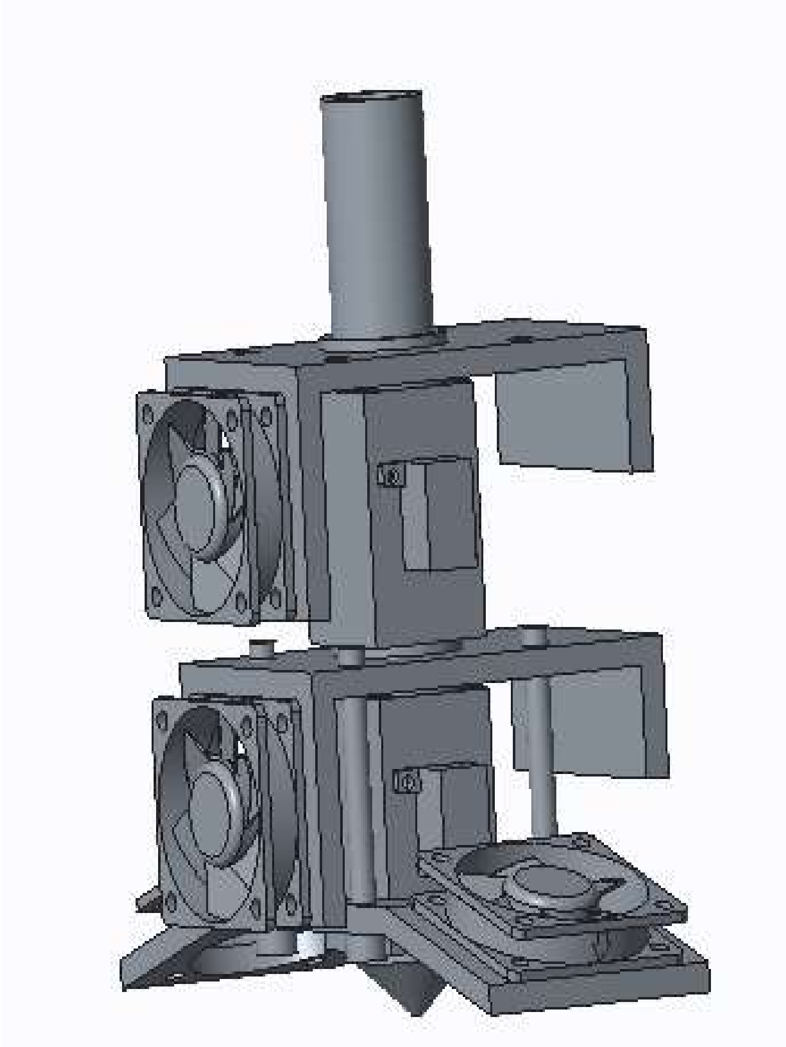


Figure 55. Model with the heaters, the fixing plates and the layer fans support assembled to the cylinder.

As you can see in the figure 55 we will use four threaded studs to fix the plate for the layer fans to the first fixing plate. Notice that the layer fans support is rotated 90 degrees with respect to the position of the fixing plate.

Finally, we have to assemble the last elements:

6. The Teflon joint.
7. The hopper.

These parts will be just threaded in this order at the highest part of the cylinder. In the next figure it is possible to see how the last pieces will be after they have been assembled.

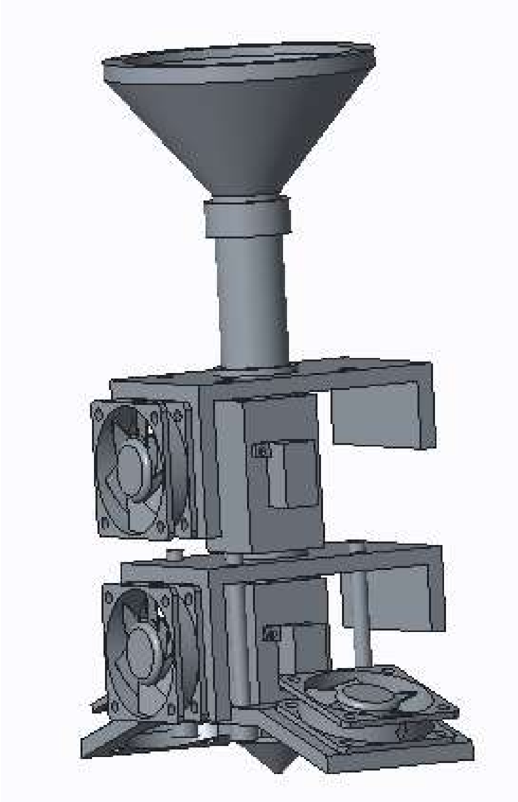


Figure 56. Model of the second assembly after all the pieces have been assembled.

Once we have the two sides assembled the only step missing is to fix one to the other. We can do this thanks to the four holes that the hopper and the plate where the engine is supported have. Therefore, the final step is to introduce the extruder screw in the cylinder until the plate rests on the hopper. Then, we fix both assemblies with 4 screws. Thus, mounting the printer head would be complete. The final appearance can be seen in figure 56 shown above.

8. CONCLUSIONS

With the information explained above we can say, as a general conclusion, that the realization of a 3D printer that works with plastic granulates instead of the common wire is possible. The calculations made and collected in this study allow us to conclude that it is possible to obtain a piece by 3D printing, using plastic pellets as feed material in an extruder.

However, we can also conclude that it will be necessary to apply to the plastic a series of transformation process before it is ready to extrusion. As we have proposed the use of PLA for the printer, it will be necessary to subject the plastic to a drying process before the extrusion process. In addition, due to the small size of the extruder the pellets must be transformed into powder. The fact of using powder instead of pellets allows us to reduce the size of the extruder greatly, which is a huge advantage.

The calculations presented here are made with the idea of minimizing the size, and therefore the weight, of the extruder. The choice of diameter D =15 mm and the relationship with the length L / D =10 has been made because it was in accordance with the machine in which we were going to mount the printer. Nevertheless, this dimensions are not the only solution. Other configurations are possible and may be valid. For this reason, we have added the calculations for the other configurations in the annex 10.1 below.

In addition, we have tried to maintain the maximum possible DeltaRocket elements, so that elements such as fans can be replaced by other similar. The other elements that do not exist in the market and have been designed by us, have been designed trying to lighten the printer as much as possible while ensuring the proper functioning of it.

Finally, note that this project is nothing but the first step of a larger project. It should be continued with the construction of the elements, mount the printer, make the implementation of the electrics and electronics required and the realization of the program that controls the motors, the temperatures and the speeds. In addition, the printer, once completed, should be tested to determine the correct parameters with which the machine works better as they may differ from those calculated above. For example, the air flow necessary to control the cylinder temperature cannot be calculated until the machine is tested.

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10. ANNEXES

10.1 CALCULATTIONS TABLES

Screw parameters	FINAL									UNITS
L/D	10	20	20	15	15	15	10	10	10	
Diameter (D)	15	15	20	10	15	20	10	20	10	mm
Length (L)	150	300	400	150	225	300	100	200	100	mm
Pitch (t)	15	15	20	10	15	20	10	20	10	mm
Helix angle (φ)	0,30805	0,30805	0,30805	0,30805	0,30805	0,30805	0,30805	0,30805	0,30805	rad
Number of canals (m)	1	1	1	1	1	1	1	1	1	
Ridge width (e)	1,8	1,8	2,4	1,2	1,8	2,4	1,2	2,4	1,2	mm
Initial Clearance (h1)	3	3	4	2	3	4	2	4	2	mm
Filet clearance (δ)	0,03	0,03	0,04	0,02	0,03	0,04	0,02	0,04	0,02	mm
Final clearance (h2)	1	1	1,333333	0,666666	1	1,333333	0,666666	1,333333	0,666666	mm
Compression relation (z)	3	3	3	3	3	3	3	3	3	
Feed zone length (L1)	33	65	87	33	49	65	22	43	22	mm
Compression zone length (L2)	52	104	139	52	78	104	35	70	35	mm
Metering zone length (L3)	65	131	174	65	98	131	44	87	44	mm
initial root radio (r)	4,50	4,50	6,00	3,00	4,50	6,00	3,00	6,00	3,00	mm
end root radio (R)	6,50	6,50	8,67	4,33	6,50	8,67	4,33	8,67	4,33	mm

Dice parameters	FINAL									UNITS
Initial conical zone diameter (d0)	15,06	15,06	20,08	10,04	15,06	20,08	10,04	20,08	10,04	mm
End conical zone diameter (d1)	0,4	0,4	0,4	0,4	0,4	0,4	0,4	0,4	0,4	mm
cylindrical zone diameter (d2)	0,4	0,4	0,4	0,4	0,4	0,4	0,4	0,4	0,4	mm
conical zone length (l1')	8	8	8	8	8	8	8	8	8	mm
cylindrical length (l2')	2	2	2	2	2	2	2	2	2	mm
conical zone constant(k1)	0,008635	0,008635	0,011592	0,005678	0,008635	0,011592	0,005678	0,011592	0,00567878	
cylindrical zone constant (k2)	0,000314	0,000314	0,000314	0,000314	0,000314	0,000314	0,000314	0,000314	0,000314	
geometrical constant (k)	0,0003031	0,0003031	0,0003058	0,0002976	0,0003031	0,0003058	0,0002976	0,0003058	0,0002976	

FLOW RATE	FINAL									UNITS
Flow (Q)	4,67E+00	4,67E+00	4,67E+00	4,67E+00	4,67E+00	4,67E+00	4,67E+00	4,67E+00	4,67E+00	mm^3/s
Drag flow (α)	847,276	847,276	2008,358	251,044	847,276	2008,358	251,044	2008,358	251,044	mm^3
Pressure flow (β)	0,0572079	0,0286039	0,0678019	0,0113003	0,0381386	0,0904026	0,0169504	0,1356039	0,0169504	mm^3
Filtration flow (ϒ)	7,065E-06	3,532E-06	8,374E-06	1,395E-06	4,710E-06	1,116E-05	2,093E-06	1,674E-05	2,093E-06	mm^3
Dice constant (K)	0,0003031	0,0003031	0,0003058	0,0002976	0,0003031	0,0003058	0,0002976	0,0003058	0,0002976	mm^3
output speed (v)	58,3125	58,3125	58,3125	58,3125	58,3125	58,3125	58,3125	58,3125	58,3125	mm/s
Angular velocity (η)	62,683221	31,506787	31,036657	43,443273	41,898931	41,335754	64,607440	61,933947	64,607440	rpm

This tables shows the parameters of our screw, the ones in the yellow boxes, comparing them with other options that we could have chosen for our screw. The other options differ from our screw mainly in the length and the diameter of the screw.

10.2 PARAMETERS SUMMARY

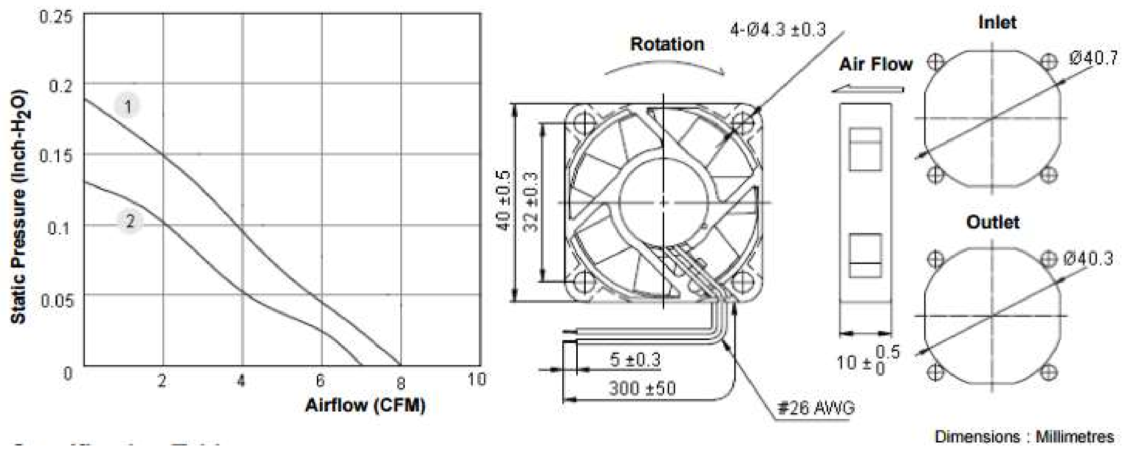
In order to sum up and to clarify the dimensions and parameters of our extruder and printer here we present a table with all the final parameters.

SCREW PARAMETERS	VALUE	UNITS
L/D	10/1	
Diameter (D)	15	mm
Number of canals (m)	1	
Pitch (t)	15	mm
Ridge width (e)	1,8	mm
Helix angle (φ)	17,65	º
feed zone length (L1)	33	mm
compression zone length (L2)	52	mm
metering zone length (L2)	65	mm
Compression relation (z)	3	
Initial Clearance (h1)	3	mm
Final clearance (h2)	1	mm
Filet clearance (δ)	0,03	mm
initial root radio (r)	4,5	mm
end root radio (R)	6,5	mm
EXTRUDER PARAMETERS		
Flow rate (Q)	4,67	mm^3/s
Power needed (N)	1.513	W
Maximum pressure (Pmax)	98,97	bar
PRINTER		
Movement speed	58.375	mm/s

10.3 DATASHEET

10.3.1 FANS

MULTICOMP MC36257 Axial Fan, Brushless Motor, Tubeaxial, Sleeve, 12 VDC, 40 mm, 10 mm, 7 cu.ft/min, 0.226 m³/min



- **Supply Voltage** 12VDC
- **Fan Frame Size** 40mm
- **External Depth** 10mm
- **Flow Rate - Imperial** 7cu.ft/min
- **Flow Rate - Metric** 0.226m³/min
- **Noise Rating** 27dBA
- **Bearing Type** Sleeve
- **Power Connection Type** Wire Leaded
- **Frame Dimensions** 40mm x 40mm x 10mm
- **External Width** 40 mm
- **Current Type** DC
- **Current Rating** 90 mA

10.3.2 ELECTRIC RESISTANCE

Wirewound Resistors, Military, MIL-PRF-18546 Qualified, Type RE, Aluminum Housed, Chassis Mount

FEATURES

- Molded construction for total environmental protection
- Complete welded construction
- Meets applicable requirements of MIL-PRF-18546
- Available in non-inductive styles (type NH) with Aryton-Perry winding for lowest reactive components
- Mounts on chassis to utilize heat-sink effect
- Excellent stability in operation

STANDARD ELECTRICAL SPECIFICATIONS

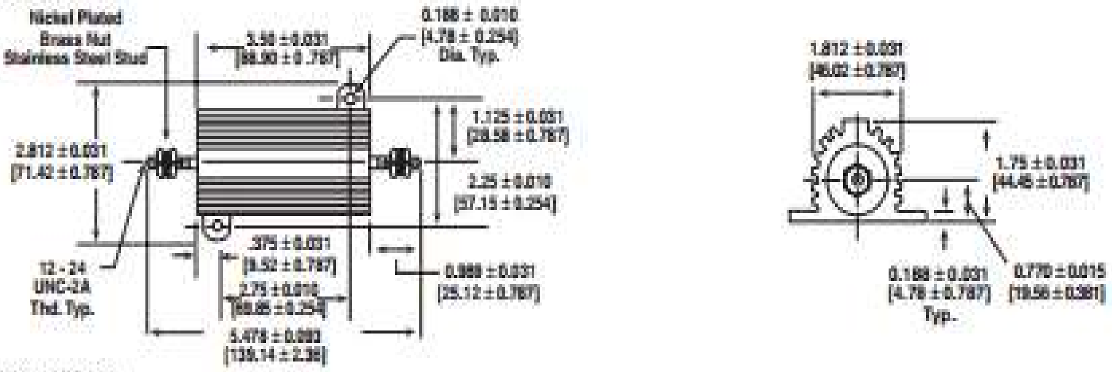
MODEL	MIL-PRF-18546 TYPE	POWER RATING $P_{25°C}$ W		RESISTANCE RANGE MIL. RANGE SHOWN IN BOLD FACE Ω				WEIGHT (Typical)
		DALE	MILITARY	± 0.05%, ± 0.1%	± 0.25%	± 0.5%	± 1%, ± 3%, ± 5%	g
RH-5	— RE60G	7.5 (5)	5	0.5 - 6.75k —	0.1 - 8.6k —	0.05 - 8.6k —	0.02 - 24.5k 0.10 - 3.32k	3
NH-5	— RE60N	7.5 (5)	5	0.5 - 2.32k —	0.1 - 3.27k —	0.05 - 3.27k —	0.05 - 12.75k 1.0 - 1.65k	3.3
RH-10	— RE65G	12.5 (10)	10	0.5 - 12.7k —	0.1 - 16.69k —	0.05 - 16.69k —	0.01 - 47.1k 0.10 - 5.62k	6
NH-10	— RE65N	12.5 (10)	10	0.5 - 4.45k —	0.1 - 5.54k —	0.05 - 5.54k —	0.05 - 23.5k 1.0 - 2.8k	6.8
RH-25	— RE70G	25	20	0.5 - 25.7k —	0.1 - 32.99k —	0.05 - 32.99k —	0.01 - 95.2k 0.10 - 12.1k	13
NH-25	— RE70N	25	20	0.5 - 9.09k —	0.1 - 12.8k —	0.05 - 12.8k —	0.05 - 47.6k 1.0 - 6.04k	16.5
RH-50	— RE75G	50	30	0.5 - 73.4k —	0.1 - 96k —	0.05 - 96k —	0.01 - 273k 0 .10 - 39.2k	28
NH-50	— RE75N	50	30	0.5 - 26k —	0.1 - 36.7k —	0.05 - 36.7k —	0.05 - 136k 1.0 - 19.6k	35
RH-100	— RE77G	100	75	0.5 - 90k —	0.1 - 90k —	0.05 - 90k —	0.05 - 90k 0.05 - 29.4k	350
NH-100	— RE77N	100	75	0.5 - 37.5k —	0.1 - 37.5k —	0.05 - 37.5k —	0.05 - 37.5k 1.0 - 14.7k	385
RH-250	— RE80G	250	120	0.5 - 116k —	0.1 - 116k —	0.05 - 116k —	0.05 - 116k 0.10 - 35.7k	630
NH-250	— RE80N	250	120	0.5 - 48.5k —	0.1 - 48.5k —	0.05 - 48.5k —	0.05 - 48.5k 1.0 - 17.4k	690

DIMENSIONS

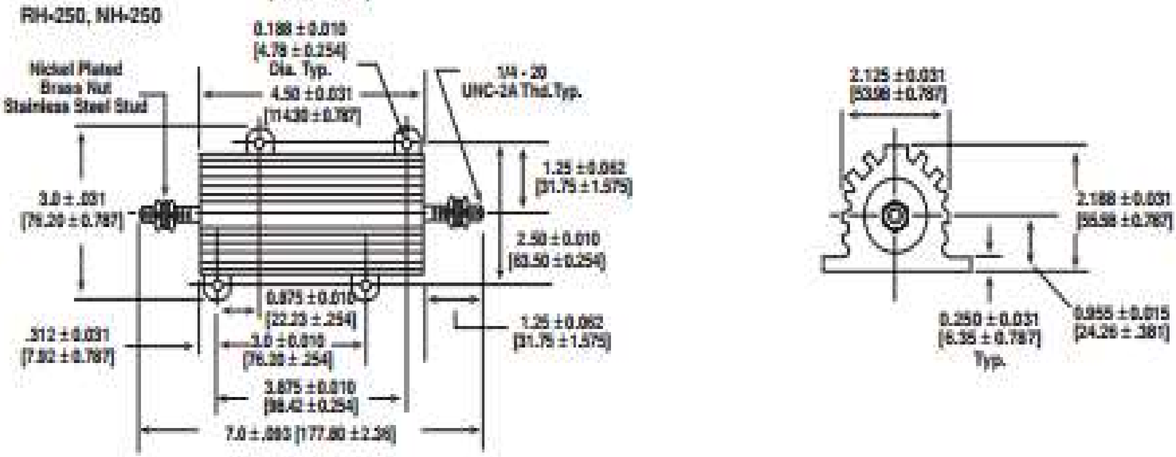
RH-5, -10, -25, -50
NH-5, -10, -25, -50

MODEL	DIMENSIONS in inches [millimeters]													
	A	B	C	D	E	F	G	H	J	K	L	M	N	P
RH-5 NH-5	0.444 ± 0.005 [11.28 ± 0.127]	0.490 ± 0.005 [12.45 ± 0.127]	0.600 ± 0.031 [15.24 ± 0.787]	1.125 ± 0.062 [28.58 ± 1.57]	0.334 ± 0.015 [8.48 ± 0.381]	0.646 ± 0.015 [16.41 ± .381]	0.320 ± 0.015 [8.13 ± 0.381]	0.065 ± 0.010 [1.65 ± 0.254]	0.133 ± 0.010 [3.38 ± 0.254]	0.078 ± 0.010 [1.98 ± 0.254]	0.093 ± 0.005 [2.36 ± 0.127]	0.078 ± 0.015 [1.98 ± .381]	0.050 ± 0.005 [1.27 ± 0.127]	0.266 ± 0.062 [6.76 ± 1.57]
RH-10 NH-10	0.562 ± 0.005 [14.27 ± 0.127]	0.625 ± 0.005 [15.88 ± 0.127]	0.750 ± 0.031 [19.05 ± 0.787]	1.375 ± 0.062 [34.93 ± 1.57]	0.420 ± 0.015 [10.67 ± 0.381]	0.800 ± 0.015 [20.32 ± 0.381]	0.390 ± 0.015 [9.91 ± 0.381]	0.075 ± 0.010 [1.91 ± 0.254]	0.165 ± 0.010 [4.19 ± 0.254]	0.093 ± 0.010 [2.36 ± 0.254]	0.094 ± 0.005 [2.39 ± 0.127]	0.102 ± 0.015 [2.59 ± 0.381]	0.085 ± 0.005 [2.16 ± 0.127]	0.312 ± 0.062 [7.92 ± 1.57]
RH-25 NH-25	0.719 ± 0.005 [18.26 ± 0.127]	0.781 ± 0.005 [19.84 ± 0.127]	1.062 ± 0.031 [26.97 ± 0.787]	1.938 ± 0.062 [49.23 ± 1.57]	0.550 ± 0.015 [13.97 ± .381]	1.080 ± 0.015 [27.43 ± 0.381]	0.546 ± 0.015 [13.87 ± 0.381]	0.075 ± 0.010 [1.91 ± 0.254]	0.231 ± 0.010 [5.87 ± 0.254]	0.172 ± 0.010 [4.37 ± 0.254]	0.125 ± 0.005 [3.18 ± 0.127]	0.115 ± 0.015 [2.92 ± 0.381]	0.085 ± 0.005 [2.16 ± 0.127]	0.438 ± 0.062 [11.13 ± 1.57]
RH-50 NH-50	1.562 ± 0.005 [39.67 ± 0.127]	0.844 ± 0.005 [21.44 ± 0.127]	1.968 ± 0.031 [49.99 ± 0.787]	2.781 ± 0.062 [70.64 ± 1.57]	0.630 ± 0.015 [16.00 ± 0.381]	1.140 ± 0.015 [28.96 ± 0.381]	0.610 ± 0.015 [15.49 ± 0.381]	0.088 ± 0.010 [2.24 ± 0.254]	0.260 ± 0.010 [6.60 ± 0.254]	0.196 ± 0.010 [4.98 ± 0.254]	0.125 ± 0.005 [3.18 ± 0.127]	0.107 ± 0.015 [2.72 ± 0.381]	0.085 ± 0.005 [2.16 ± 0.127]	0.438 ± 0.062 [11.13 ± 1.57]

RH-100, NH-100



RH-250, NH-250



TECHNICAL SPECIFICATIONS

PARAMETER	UNIT	RH RESISTOR CHARACTERISTICS
Temperature Coefficient	ppm/°C	± 100 for 0.1Ω to 0.99Ω, ± 50 for 1Ω to 9.9Ω, ± 20 for 10Ω and above
Dielectric Withstanding Voltage	V_{AC}	1000 for RH-5, RH-10 and RH-25, 2000 for RH-50, 4500 for RH-100 and RH-250
Short Time Overload	-	5 x rated power for 5 seconds
Maximum Working Voltage	V	$(P \times R)^{1/2}$
Insulation Resistance	Ω	10,000 Megohm minimum dry, 1000 Megohm minimum after moisture test
Terminal Strength	lb	5 minimum for RH-5 and RH-10, 10 minimum for all others
Solderability	-	MIL-PRF-18546 Type - Meets requirements of ANSI J-STD-002
Operating Temperature Range	°C	- 55/+ 250

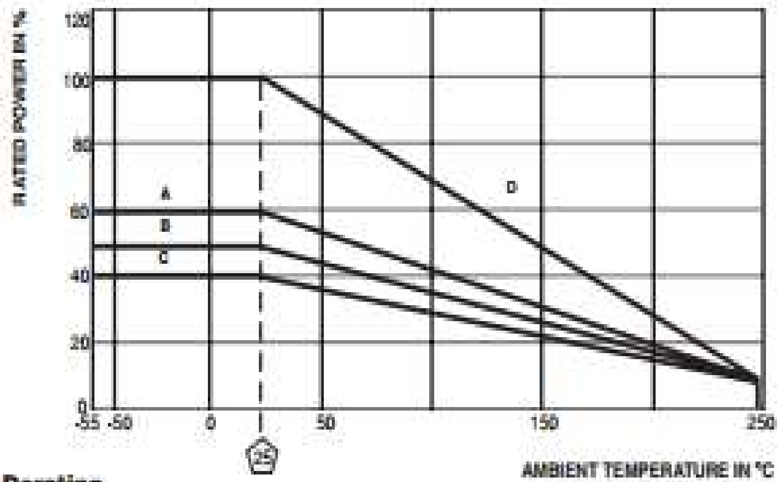
POWER RATING

Vishay RH resistor wattage ratings are based on mounting to the following heat sink:

RH-5 and RH-10:	4" x 6" x 2" x 0.040" thick aluminum chassis (129 sq. in. surface area)
RH-25:	5" x 7" x 2" x 0.040" thick aluminum chassis (187 sq. in. surface area)
RH-50:	12" x 12" x 0.059" thick aluminum panel (291 sq. in. surface area)
RH-100 and RH-250:	12" x 12" x 0.125" thick aluminum panel (294 sq. in. surface area)

AMBIENT TEMPERATURE DERATING

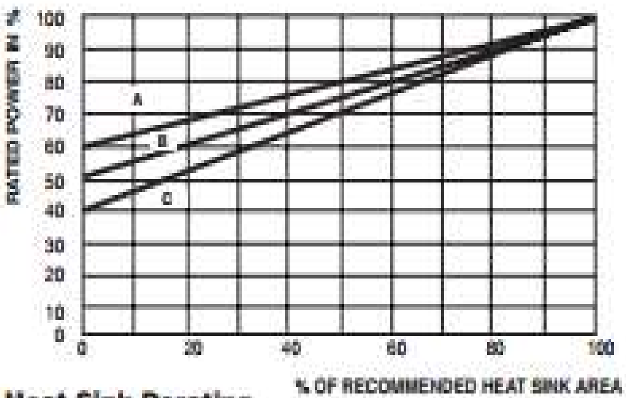
Derating is required for ambient temperatures above 25°C, see the following graph.
Curves A, B, C apply to operation of unmounted resistors. Curve D applies to all types when mounted to specified heat sink.
A = RH-5 and RH-10 size resistor, unmounted
B = RH-25 size resistor, unmounted
C = RH-50, RH-100 and RH-250 size resistor, unmounted
D = All types mounted to recommended aluminum heat sink



Derating

REDUCED HEAT SINK DERATING:

Derating is also required when recommended heat sink area is reduced.
A = RH-5 and RH-10 size resistor
B = RH-25 size resistor
C = RH-50, RH-100 and RH-250 size resistor



Heat Sink Derating

MATERIAL SPECIFICATIONS

Element: Copper-nickel alloy or nickel-chrome alloy, depending on resistance value

Core: Ceramic, steatite or alumina, depending on physical size

Encapsulant: Silicone molded construction

Housing: Aluminum with hard anodic coating

End Caps: Stainless steel

Standard Terminals: Tinned Copperweld® on RH-5 through RH-50 size, threaded stainless steel terminals on RH-100 and RH-250

Part Marking: DALE, Model, Wattage, Value, Tolerance, Date Code

NH NON-INDUCTIVE

Models of equivalent physical and electrical specifications are available with non-inductive (Aryton-Perry) winding. They are identified by substituting the letter N for R in the model number (NH-5, for example).

SPECIAL MODIFICATIONS

A number of special modifications to the aluminum housed resistor style are available upon request. Special modifications include:

- Terminal configurations and materials
- Resistance values and tolerances
- Low resistance temperature coefficient (RTC)
- Housing configuration
- Threaded mounting holes
- Preconditioning and other additional testing

APPLICABLE MIL SPECIFICATIONS

MIL-PRF-18546 is the military specification covering aluminum housed, chassis mount, power resistors. VISHAY RH and NH resistors are listed as qualified on the MIL-PRF-18546 QPL.

PERFORMANCE

TEST	CONDITIONS OF TEST	TEST LIMITS
Thermal Shock	Rated power applied until thermally stable, then a minimum of 15 minutes at - 55°C	± (0.5% + 0.05Ω) ΔR
Short Time Overload	5 x rated power for 5 seconds	± (0.5% + 0.05Ω) ΔR
Dielectric Withstanding Voltage	1000Vrms for RH-5, RH-10 and RH-25; 2000Vrms for RH-50 4500Vrms for RH-100 and RH-250; duration one minute	± (0.2% + 0.05Ω) ΔR
Temperature	250°C for 2 hours	± (0.5% + 0.05Ω) ΔR
Moisture Resistance	MIL-STD-202 Method 106, 7b not applicable	± (1.0% + 0.05Ω) ΔR
Shock, Specified Pulse	MIL-STD-202 Method 213, 100g's for 6 milliseconds, 10 shocks	± (0.2% + 0.05Ω) ΔR
Vibration, High Frequency	Frequency varied 10 to 2000Hz, 20g peak, 2 directions 6 hours each	± (0.2% + 0.05Ω) ΔR
Load Life	1000 hours at rated power, + 25°C, 1.5 hours "ON", 0.5 hours "OFF"	± (1.0% + 0.05Ω) ΔR
Terminal Strength	30 second, 5 pound pull test for RH-5 and RH-10, 10 pound pull test for other sizes, torque test - 24 pound inch for RH-100 and 32 pound inch for RH-250	± (0.2% + 0.05Ω) ΔR

10.3.3 ENGINE

1.8° NEMA 17 GEARED STEPPER MOTOR WITH PLANETARY GEARBOX

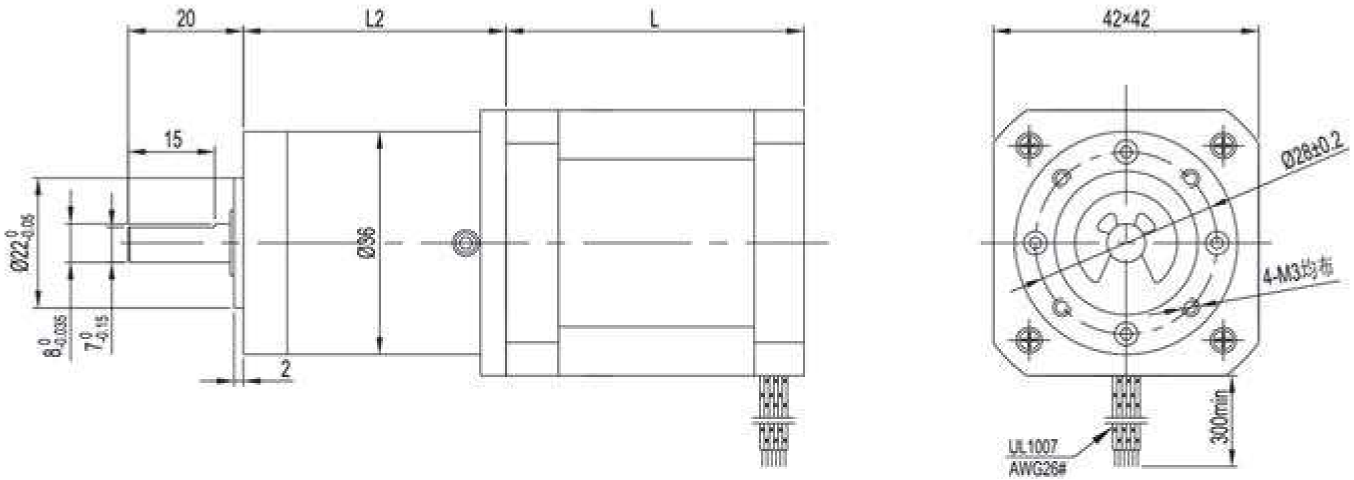
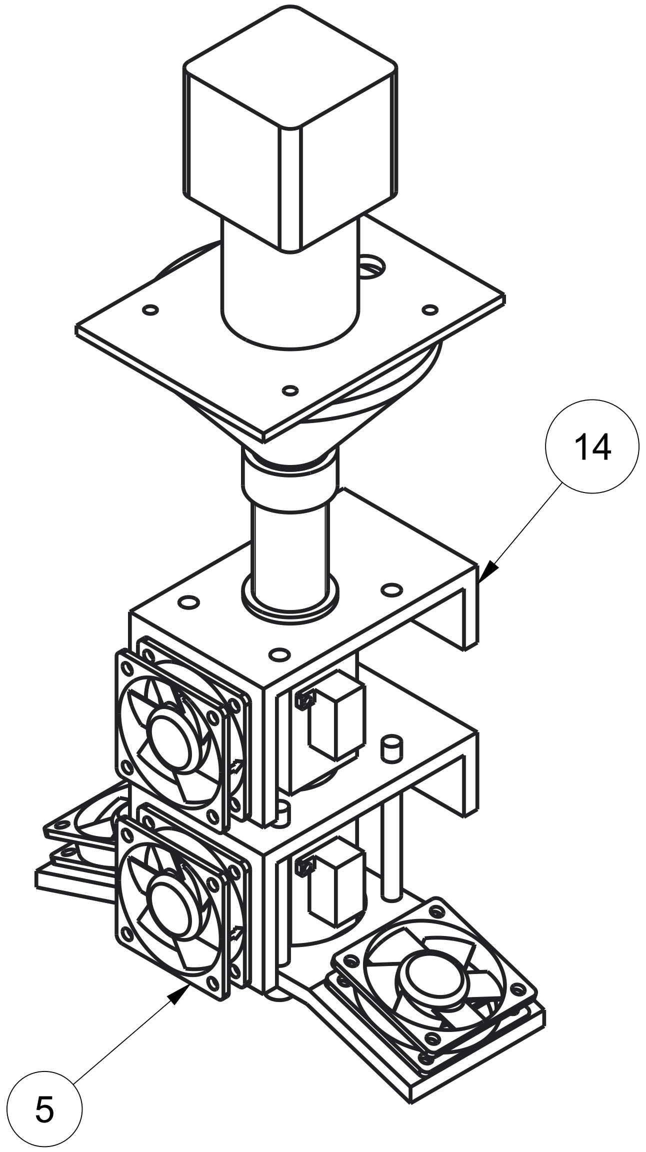


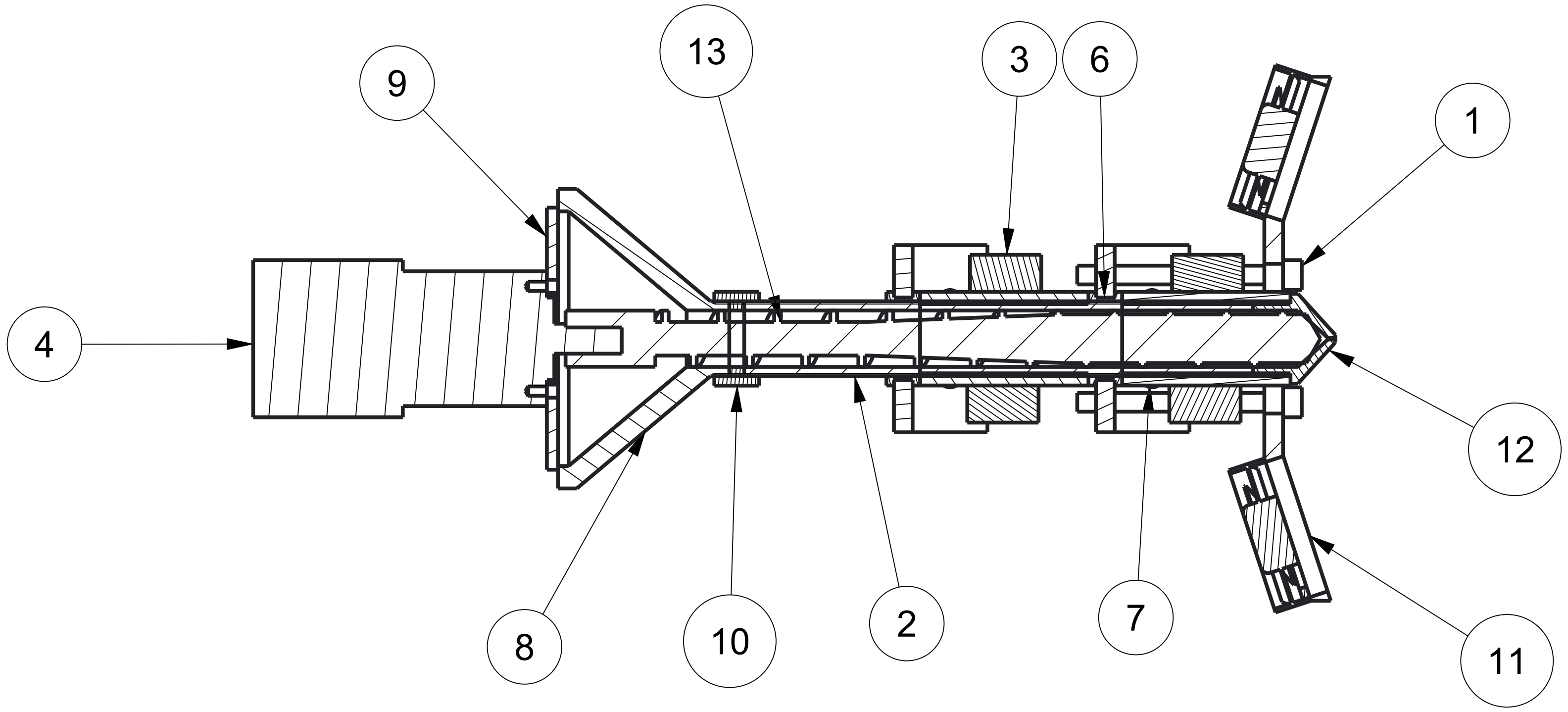
TABLE 1. MOTOR SPECIFICATIONS

Model	Length L	Rated Current	Resistance	Inductance	Holding Torque	Holding Torque	Rotor Interia	Lead wires	Weight
	mm	A	Ω/Phase	mH/Phase	Oz.in	N.m	g.cm2		g
42HS20-0804Z	20	0.8	3.8	4.5	14.2	0.1	24	4	120
42HS28-0604Z	28	0.6	8	10	17	0.12	30	4	150
42HS34-1304Z	34	1.3	2.4	2.8	40	0.28	34	4	220
42HS34-0406Z	34	0.4	30	18	40	0.28	34	6	220
42HS40-1304Z	40	1.3	2.5	5	57	0.4	54	4	280
42HS40-1704Z	40	1.7	1.5	2.8	57	0.4	54	4	280
42HS48-1304Z	48	1.3	3.2	5.5	74	0.52	68	4	350
42HS48-1704Z	48	1.7	1.8	3.2	74	0.52	68	4	350
42HS60-1704Z	60	1.7	2.3	4.6	100	0.7	80	4	480
42HS60-2304Z	60	2.3	1.4	2.5	100	0.7	80	4	480

TABLE 2. GEARBOX SPECIFICATIONS					
Model		36PLGB1-xxZ	36PLGB2-xxZ	36PLGB3-xxZ	36PLGB4-xxZ
Number of gear trains		1	2	3	4
Gear ratio		3.7, 5.2	14, 19, 27	51, 71, 100, 139	189, 264, 369
Length L2	mm	31	38.5	48.4	55.8
Rated output torque	N.m	0.3	1	2	3
Max output torque	N.m	0.9	3	6	9
Efficiency	%	9	81	73	66
Weight	g	191	207	288	312

10.4 DRAWINGS





Nº	PART NAME	NUMBER OF PIECES	DECRIPTION	MATERIAL
14	SUPPORT	2		ALUMINUM
13	SCREW	1		STEEL F-174
12	NOZZLE	1		BRASS
11	LAYER_FAN_SUPPORT	1		PLA
10	JOINT	1		TEFLON
9	HOPPER_PLATE	1		ALUMINUM
8	HOPPER	1		CORZAN
7	HEATER	2		ALUMINUM
6	FIXING_JOINT	2		TEFLON
5	FAN	4	MULTICOMP MC36257	
4	ENGINE	1	NEMA17: 42HS40-1704Z -36PLGB2-xxZ	
3	ELECTRIC_RESISTANCE	4	RH10 RE65G	
2	CYLINDER	1		STEEL F-174
1	BOLT	4	DIN 912 M5 X 55	STEEL

ISO-symbool

katholieke hogeschool vives associatie KU Leuven

Doorniksesteenweg 145
8500 Kortrijk
T +32 (0)56 26 41 20
F +32 (0)56 21 98 67

Model		
Tekening	ASSEMBLY	31/05/2016
Gezien		

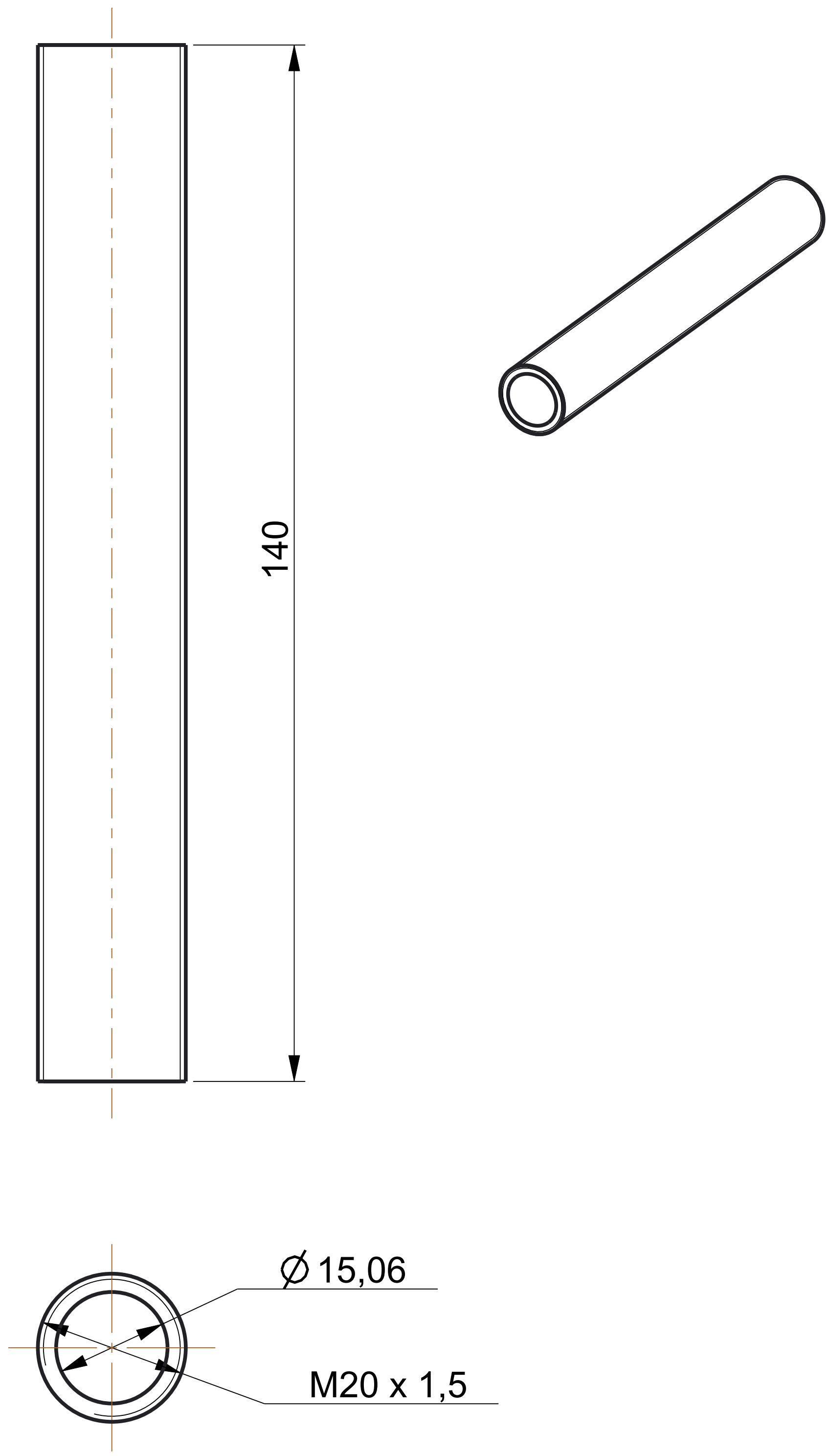
Schaal: 1:2

ARTURO ANDRÉS SACRISTÁN

Blad: 1 12

Model: EXTRUDER_ASSEMBLY DWG: ASSEMBLY

A3

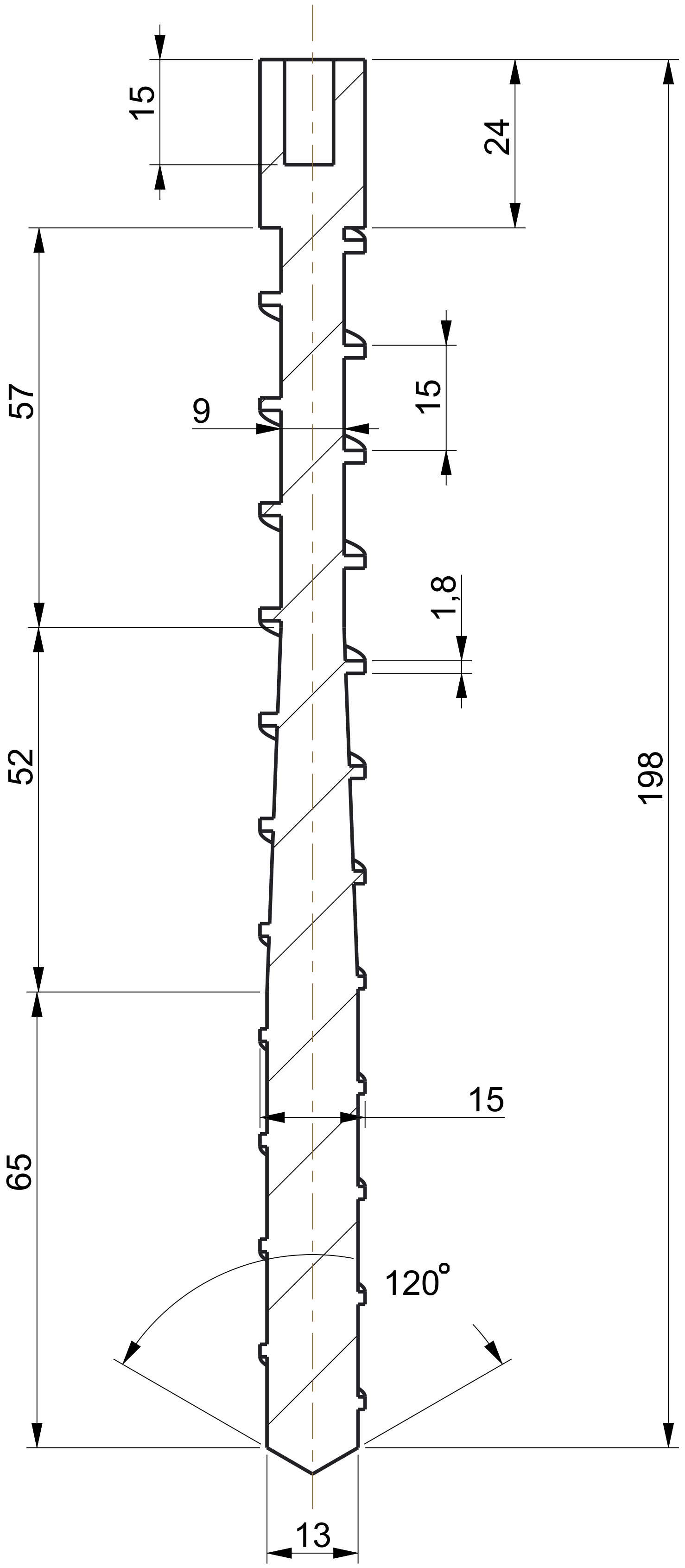


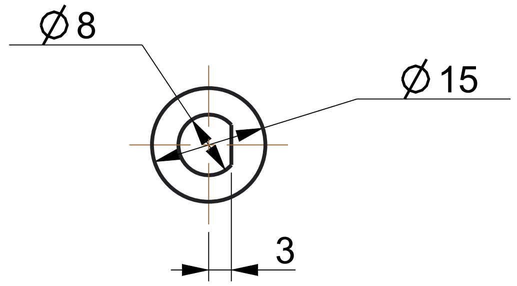
ISO-symbool	katholieke hogeschool associatie KU Leuven vives	Doorniksesteenweg 145 8500 Kortrijk T +32 (0)56 26 41 20 F +32 (0)56 21 98 67	Model		
			Tekening	CYLINDER	31/05/2016
			Gezien		

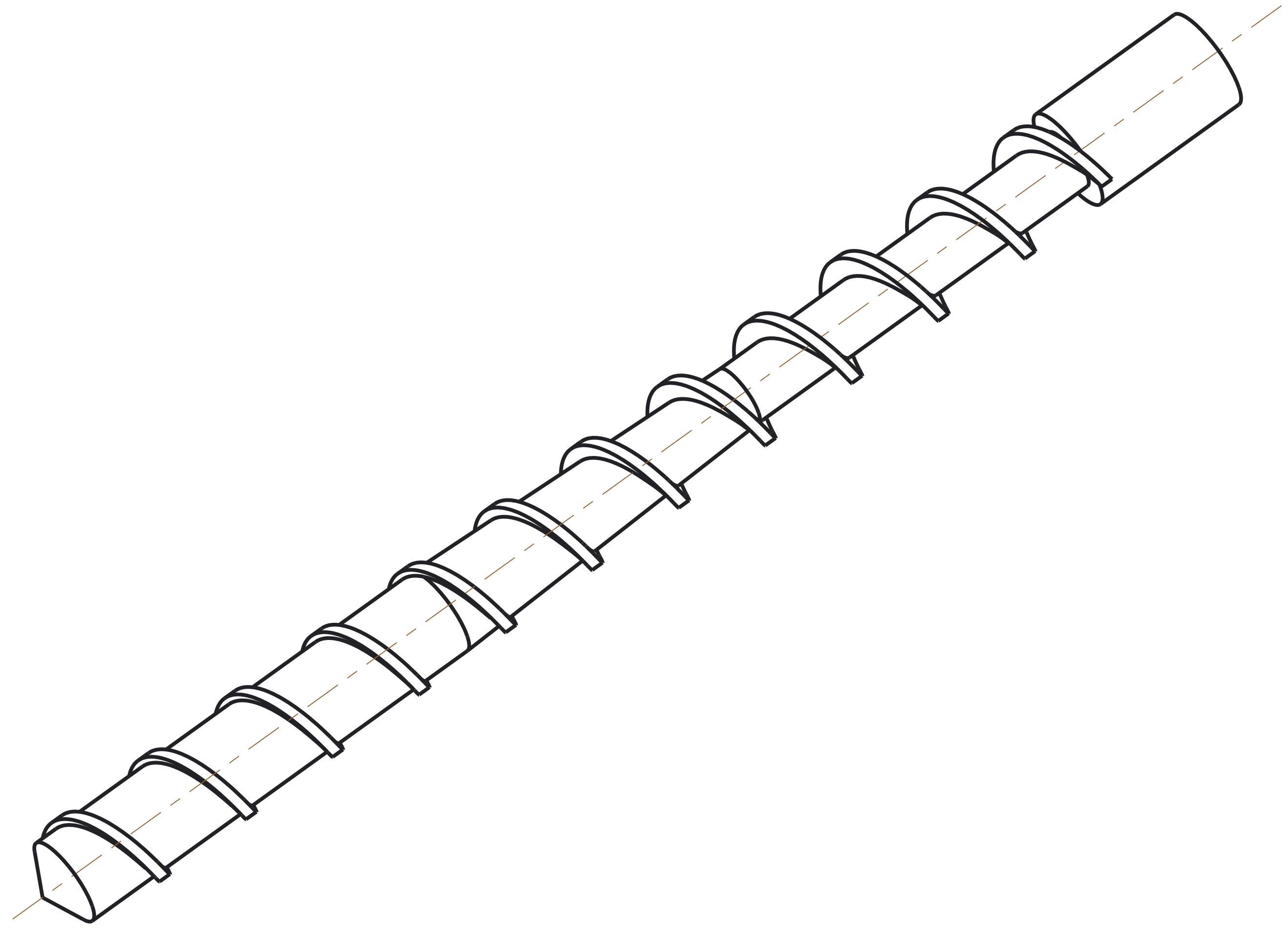
Schaal: 1:1	ARTURO ANDRÉS SACRISTÁN	Model: BARREL	DWG: CYLINDER
Blad: 2	12		

A4

SECTION A-A







ISO-symbool

katholieke hogeschool vives associatie KU Leuven

Doorniksesteenweg 145
8500 Kortrijk
T +32 (0)56 26 41 20
F +32 (0)56 21 98 67

Model		
Tekening	SCREW	30/05/2016
Gezien		

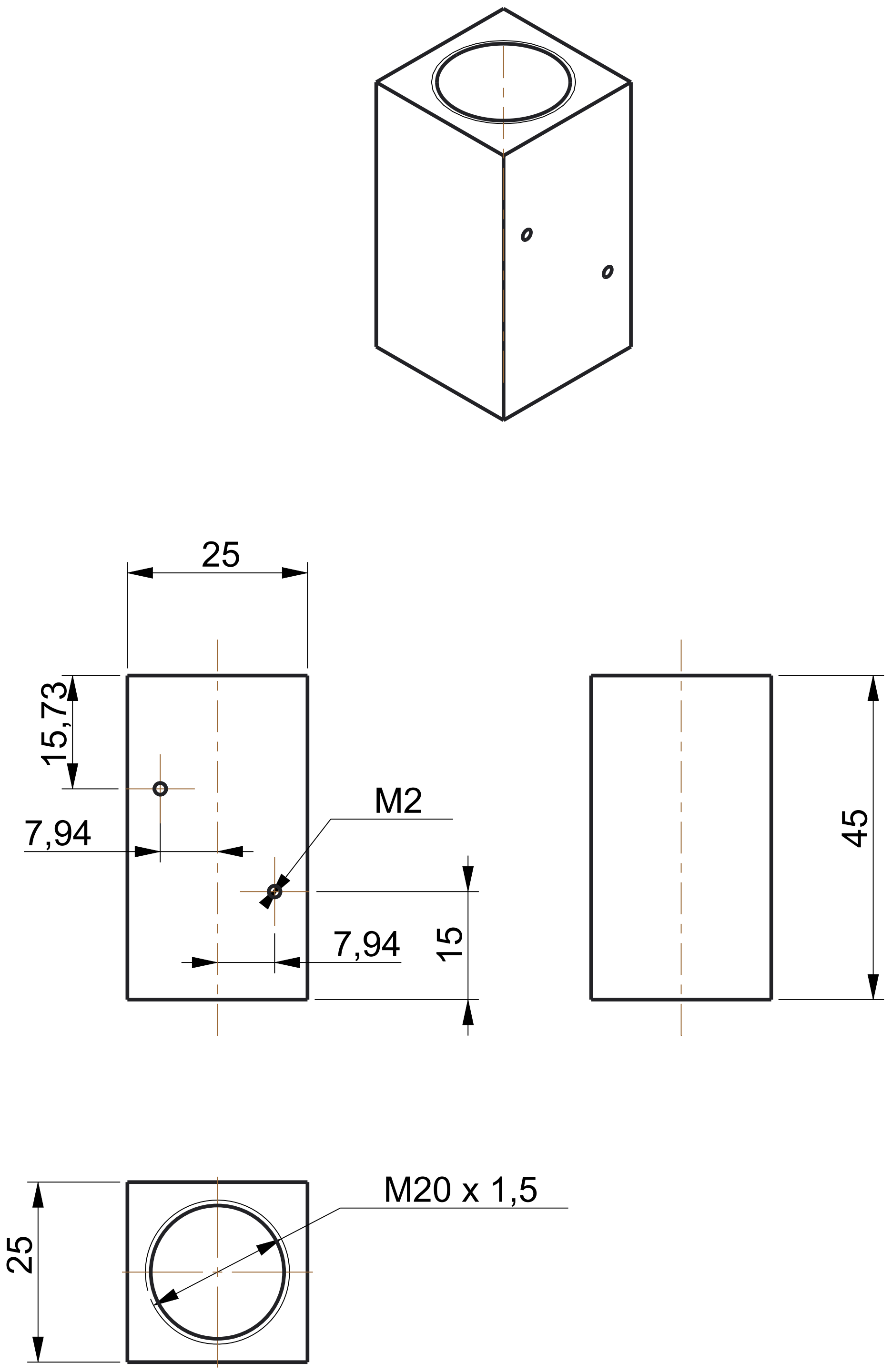
Schaal: 1:1

ARTURO ANDRÉS SACRISTÁN

Blad: 3 12

Model: SCREW DWG: SCREW_

A3



ISO-symbool

katholieke hogeschool vives
associatie KU Leuven
Doorniksesteenweg 145
8500 Kortrijk
T +32 (0)56 26 41 20
F +32 (0)56 21 98 67

Model		
Tekening	HEATER PIECE	31/05/2016
Gezien		

Schaal: 1:1

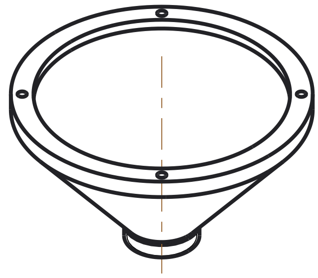
ARTURO ANDRÉS SACRISTÁN

Blad: 4 | 12

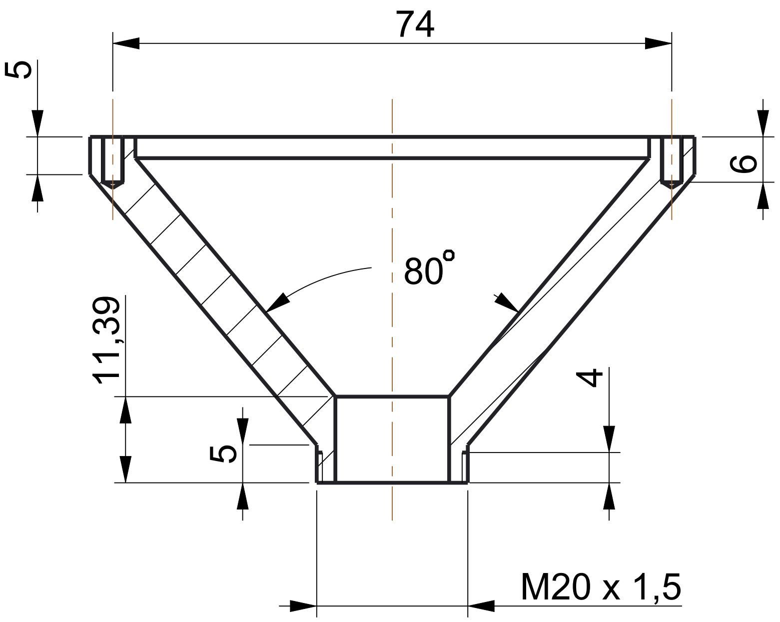
Model: CALENTADOR

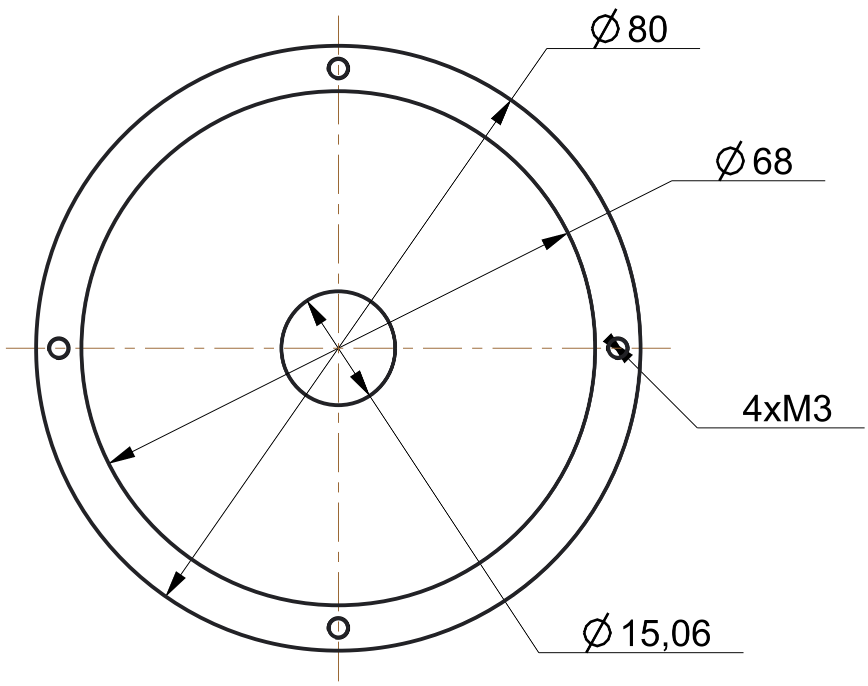
DWG: HEATER_PIECE

A4



SECTION A-A



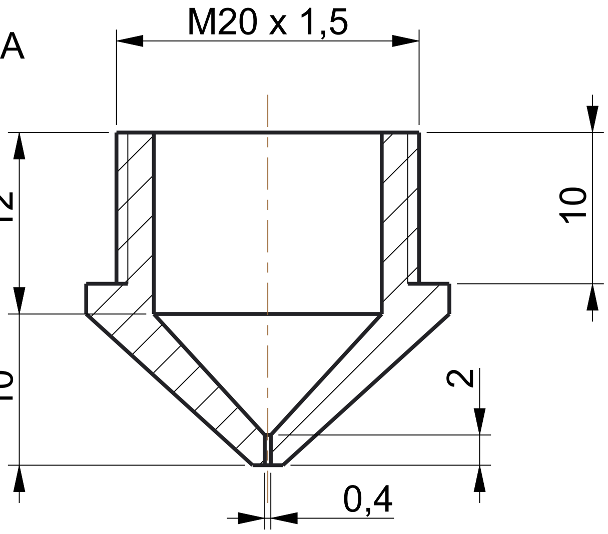


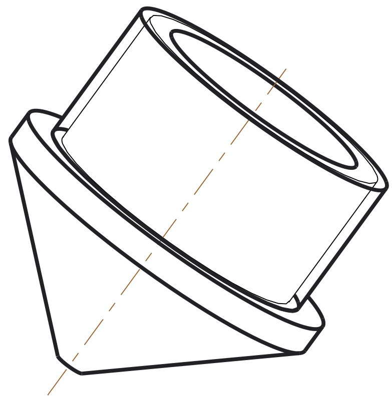
ISO-symbool	katholieke hogeschool vives associatie KU Leuven	Doorniksesteenweg 145 8500 Kortrijk T +32 (0)56 26 41 20 F +32 (0)56 21 98 67	Model		
			Tekening	HOPPER	31/05/2016
			Gezien		

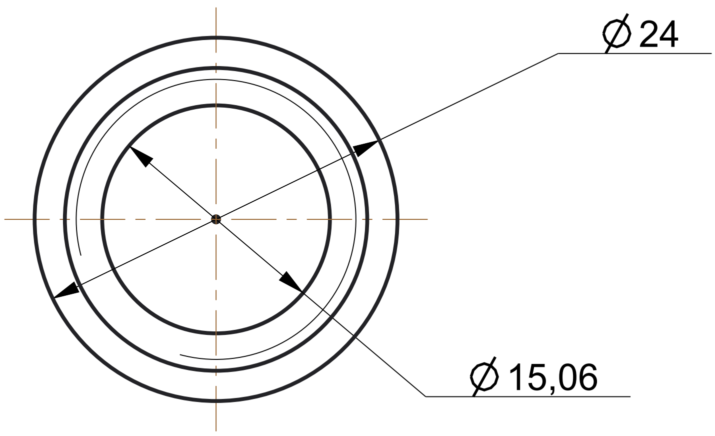
Schaal:			Blad:	
1:1	ARTURO ANDRÉS SACRISTÁN		5	12
		Model: HOPPER	DWG: LOWER_HOPPER	

A4

SECTION A-A

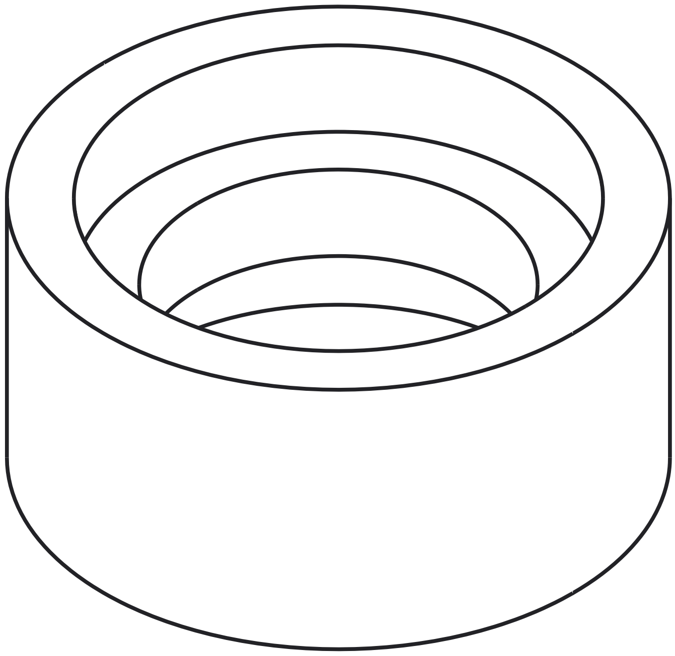


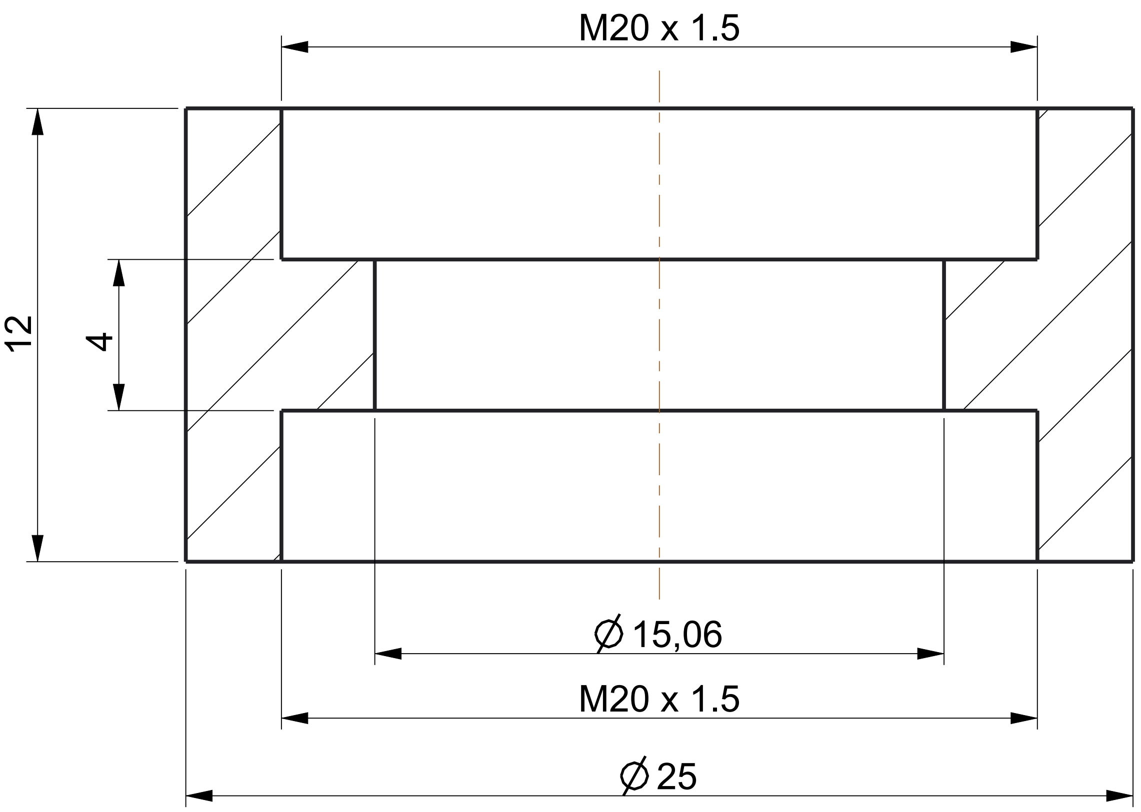




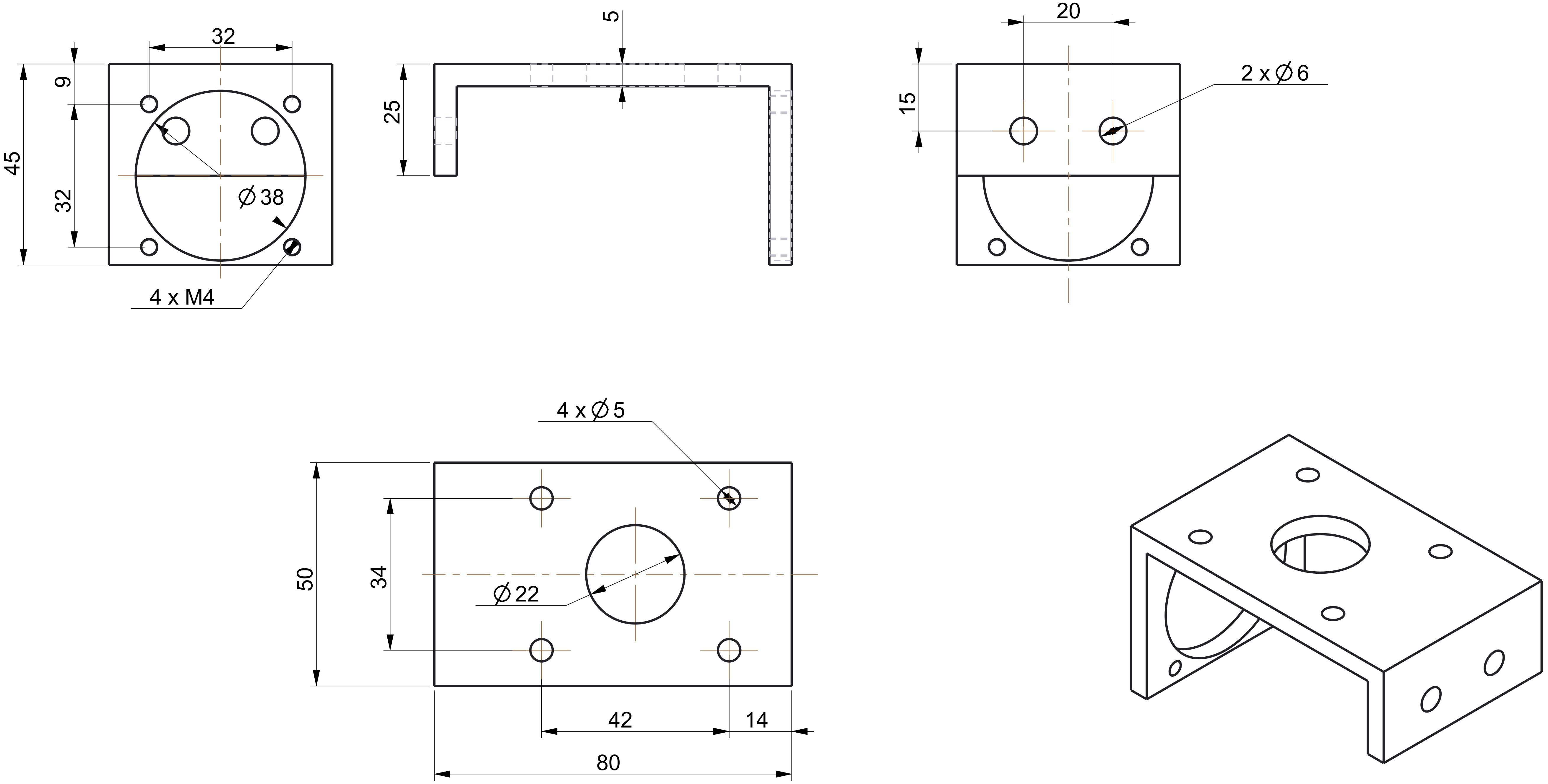
ISO-symbool	katholieke hogeschool associatie KU Leuven vives	Doorniksesteenweg 145 8500 Kortrijk T +32 (0)56 26 41 20 F +32 (0)56 21 98 67	Model		
			Tekening	NOZZLE	31/05/2016
			Gezien		
Schaal: 2:1	ARTURO ANDRÉS SACRISTÁN		Model: DIE	DWG: NOZZLE	Blad: 6 12

A4



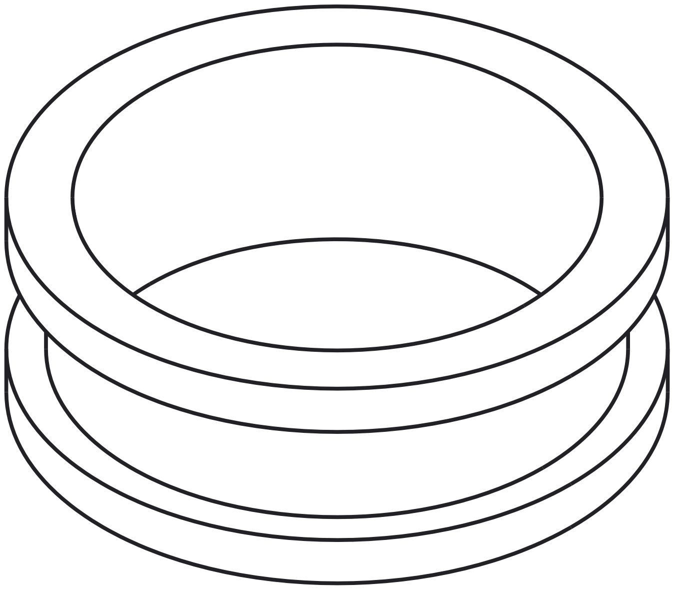


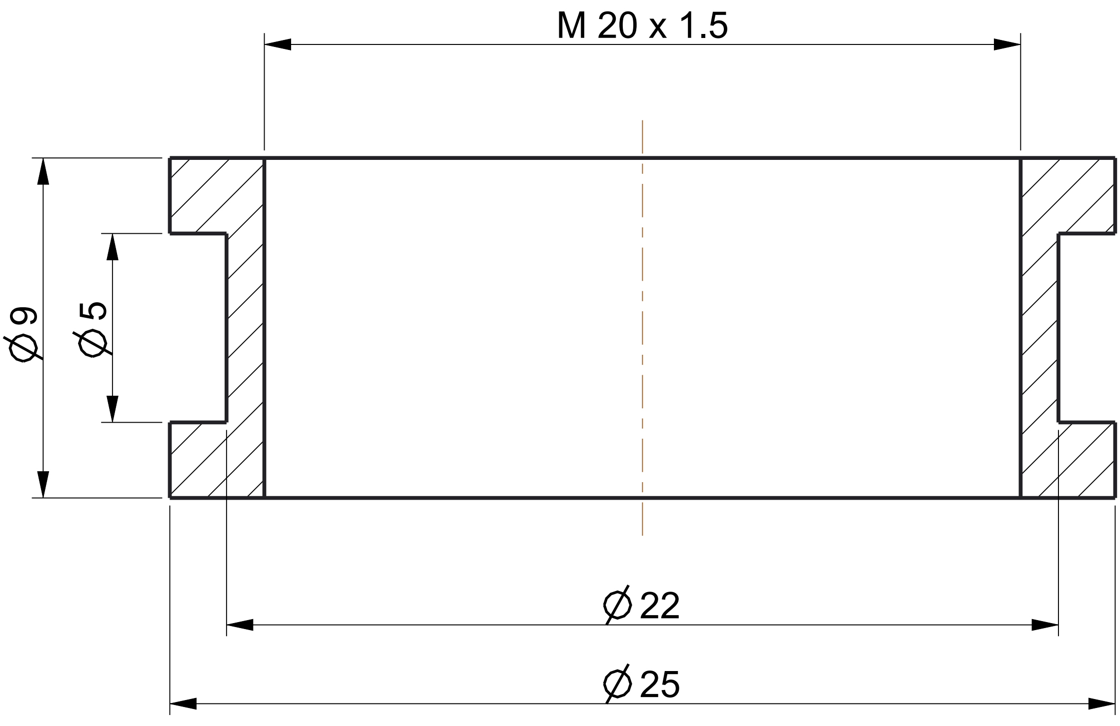
ISO-symbool	katholieke hogeschool vives associatie KU Leuven	Doorniksesteenweg 145 8500 Kortrijk T +32 (0)56 26 41 20 F +32 (0)56 21 98 67	
Model			
Tekening	JOINT	31/05/2016	
Gezien			
Schaal: 5:1	ARTURO ANDRÉS SACRISTÁN	Model: JOINT	DWG: JOINT
Blad:	7	12	A4



ISO-symbool	Doorniksesteenweg 145 8500 Kortrijk T +32 (0)56 26 41 20 F +32 (0)56 21 98 67	Model	
		Tekening	SUPPORT — 01/06/2016
		Gezien	
Schaal: 1:1	ARTURO ANDRÉS SACRISTÁN	Blad: 8 / 12	
		Model: SUPPORT	DWG: SUPPORT

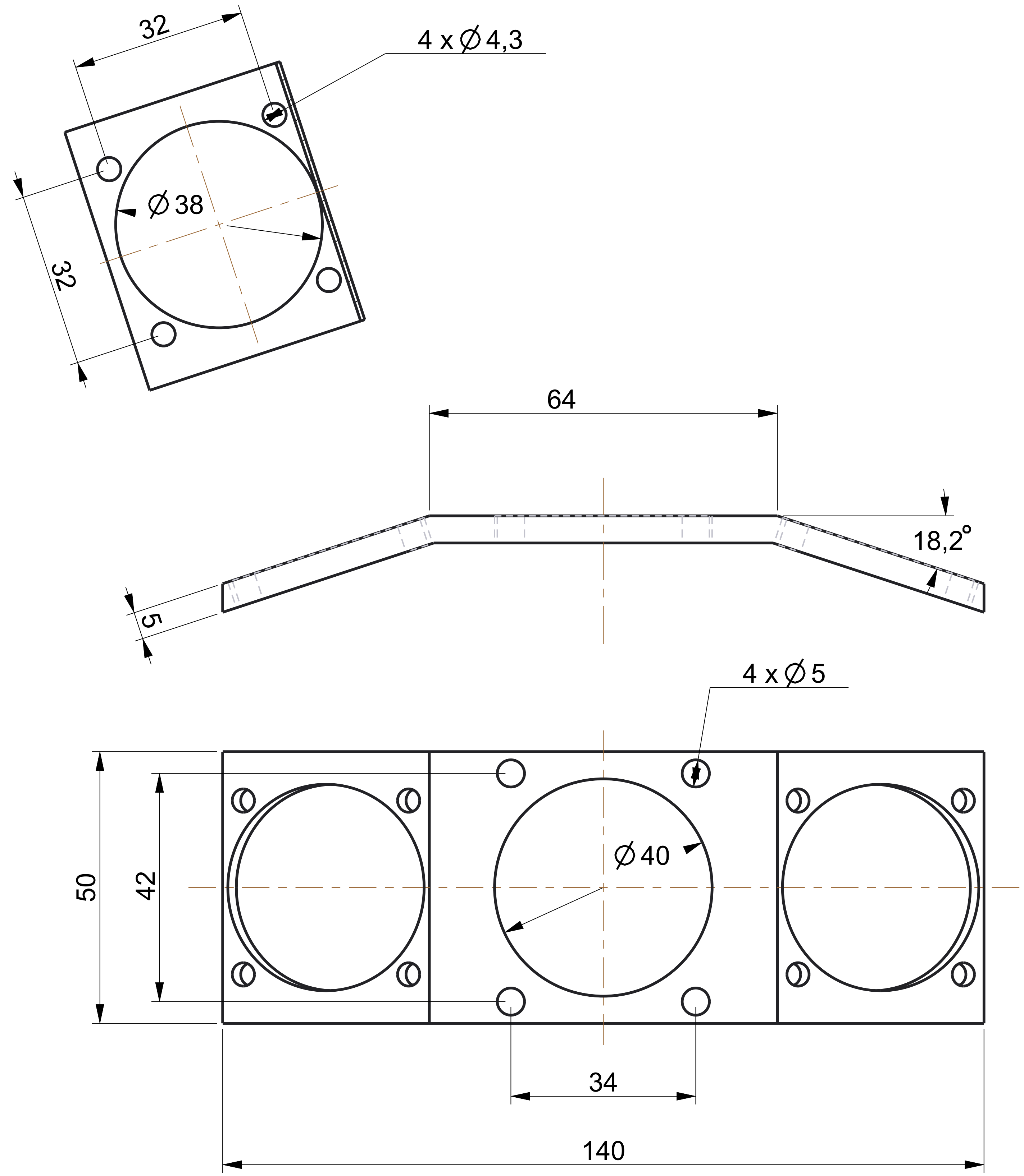
A3

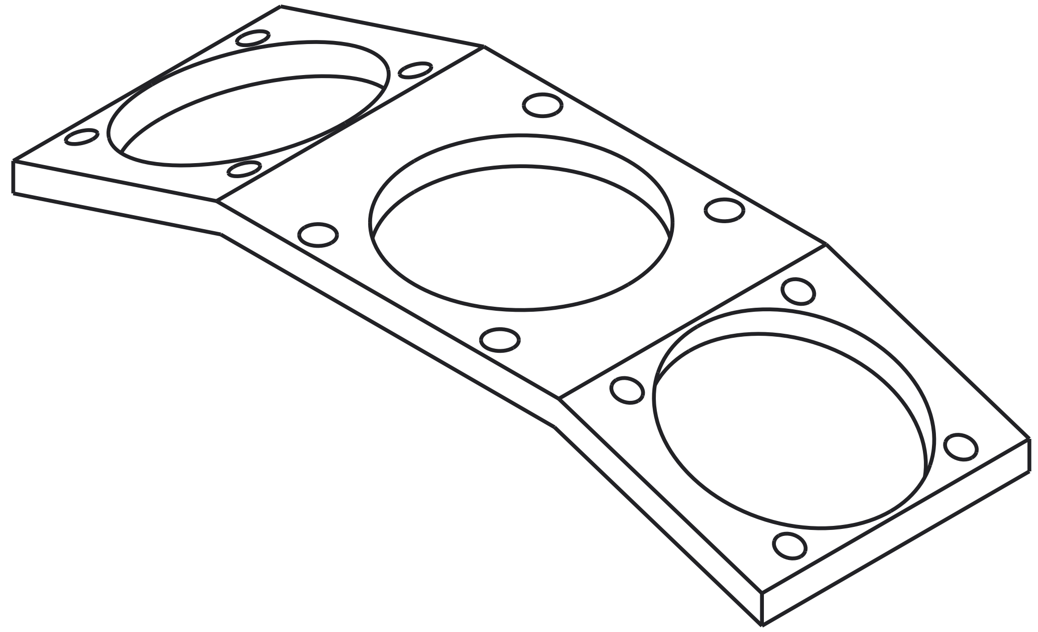




ISO-symbool	katholieke hogeschool vives associatie KU Leuven	Doorniksesteenweg 145 8500 Kortrijk T +32 (0)56 26 41 20 F +32 (0)56 21 98 67	
		Model	
		Tekening	JOINT SUPPORT — 31/05/2016
		Gezien	
Schaal: 5:1	ARTURO ANDRÉS SACRISTÁN	Blad: 9 / 12	
		Model: FIXING_JOINT	DWG: FIXING_JOINT

A4

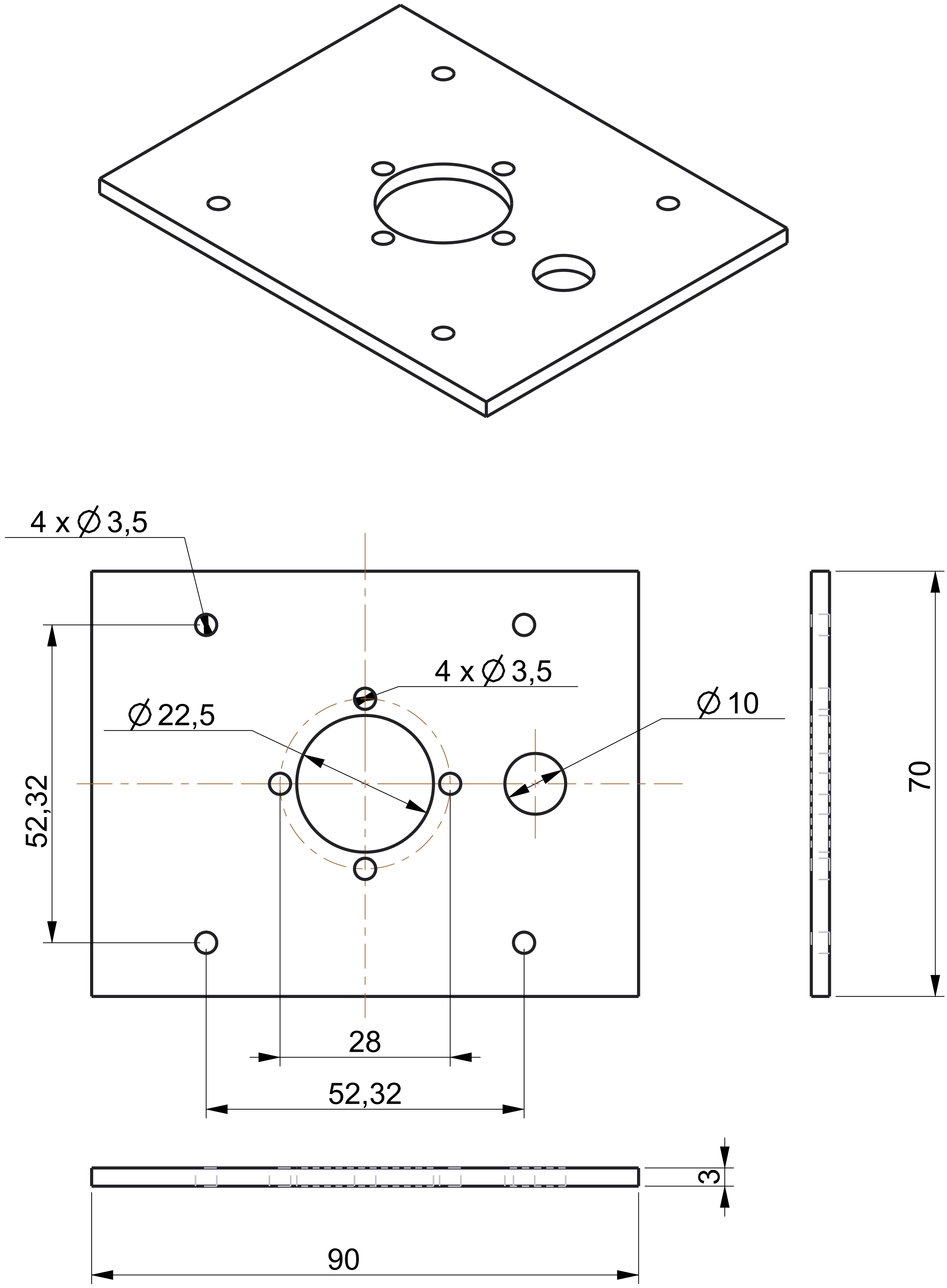




ISO-symbool	katholieke hogeschool vives associatie KU Leuven	Doorniksesteenweg 145 8500 Kortrijk T +32 (0)56 26 41 20 F +32 (0)56 21 98 67	Model	
			Tekening	LAYER FAN SUPPORT 31/05/2016
			Gezien	
Schaal: 1:1	ARTURO ANDRÉS SACRISTÁN			Blad: 10 12

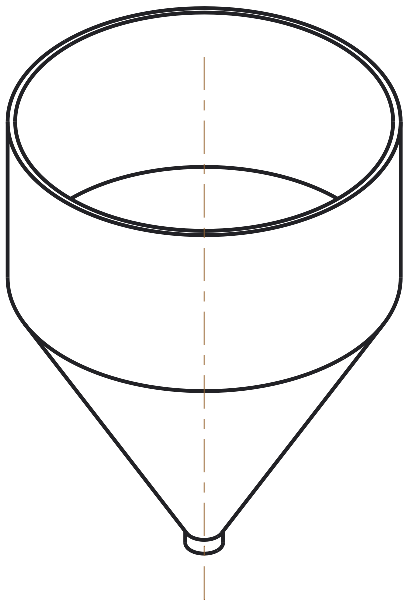
Model: LAYER_FAN_SUPPORT DWG: LAYER_FAN_SUPPORT

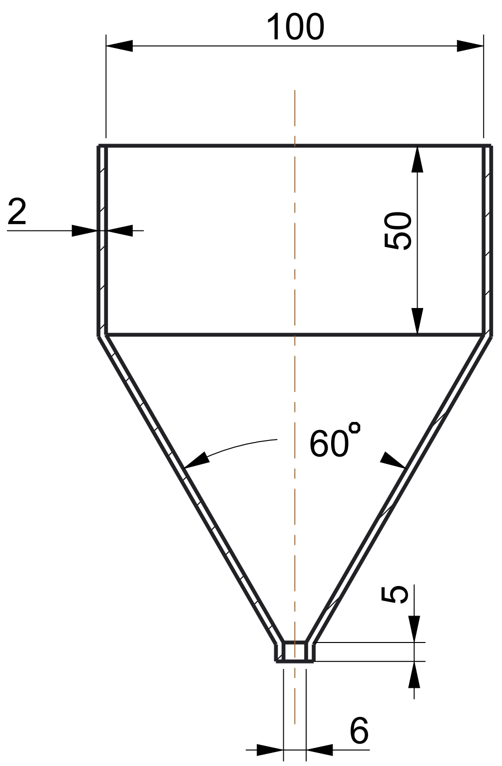
A3



ISO-symbool	katholieke hogeschool associatie KU Leuven vives	Doorniksesteenweg 145 8500 Kortrijk T +32 (0)56 26 41 20 F +32 (0)56 21 98 67	Model		
			Tekening	HOPPER PLATE	31/05/2016
			Gezien		
Schaal: 1:1	ARTURO ANDRÉS SACRISTÁN		Model: HOPPER_PLATE	DWG: HOPPER_PLATE	Blad: 11 12

A4





ISO-symbool	katholieke hogeschool associatie KU Leuven vives	Doorniksesteenweg 145 8500 Kortrijk T +32 (0)56 26 41 20 F +32 (0)56 21 98 67	Model		
			Tekening	UPPER HOPPER	31/05/2016
			Gezien		

Schaal:			Blad:	
1:2	ARTURO ANDRÉS SACRISTÁN		12	12
		Model: UPPER_HOPPER	DWG: UPPER_HOPPER	A4