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A NOVEL METHOD TO RE-DESIGN METALLIC COMPONENTS, UTILIZING METAL 3D PRINTING ADVANTAGES, BY FUNCTIONALITY AND EFFICIENCY EVALUATION OF THE COMPONENTS USING SIMULATION AND LAB ANALYSIS

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ABSTRACT

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A Novel Method to Re-Design Metallic Components, Utilizing Metal 3D Printing Advantages, By Functionality and Efficiency Evaluation of The Components Using Simulation and Lab Analysis

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Keywords: additive manufacturing, design for additive manufacturing, powder bed fusion, 3D printing, pressing air nozzle.

Flow efficiency and weight are important parts of hydraulic and pneumatic system's industry. As manufacturers keep pushing the limits of flow efficiency every year, applications of 3D printing models for hydraulic and pneumatic parts can play an expanding role.

This master thesis describes the redesign of pressing air nozzle with implementation of metal additive manufacturing featured into the new designs. Better Airflow and weight saving were achieved.

A 3D model for the original pressing air nozzle was developed to obtain the flow characteristic data using Ansys software. The pressing air nozzle was modified in CAD system Solidworks. Better air flow was achieved by Optimization the Internal Channel of the pressing Air nozzle. The implication of the new designs also provided weight saving by 70%.

two different designs were suggested. The flow characteristics were obtained for the new designs using Ansys Fluent software. CFD modeling results for the original and two new suggested design were obtained and compared and the enhancing of the flow was calculated. This modification Improved the flow by 50%.

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Ahmed Abdelsalam
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Finland
May 20th, 2019

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LIST OF SYMBOLS AND ABBREVIATIONS

$\dot{m}$	Mass flow[kg/sec]
ρ	Density [kg/m^3]
Q	Flow [m^3/min]
AM	Additive Manufacturing
ASTM	American Society for Testing and Materials
CAD	Computer Assisted Design
CFD	Computational Fluid Dynamics
CNC	Computer Numerical Control
DFAM	Design for Additive Manufacturing
DMLS	Direct Metal Laser Sintering
EBM	Electron Beam Melting
PBF	Powder Bed Fusion
PF	Pressure Filters
SLM	Selective Laser Melting
SLS	Selective Laser Sintering
STL	Stereo Lithography

1 INTRODUCTION

Additive manufacturing (AM) refers to technologies that can build 3D solid objects from Computer Assisted Design (CAD) models using material accumulation layer by layer (SME, 2018). The technology works by taking a CAD file of a product converts into thin layers (slices) each layer contains information's this information is to be printed. The model is then built one layer in the top of the other until the model is completed (Wong and Hernandez, 2012; Diegel et al., 2010 p. 1). The process can be seen in Figure 1.

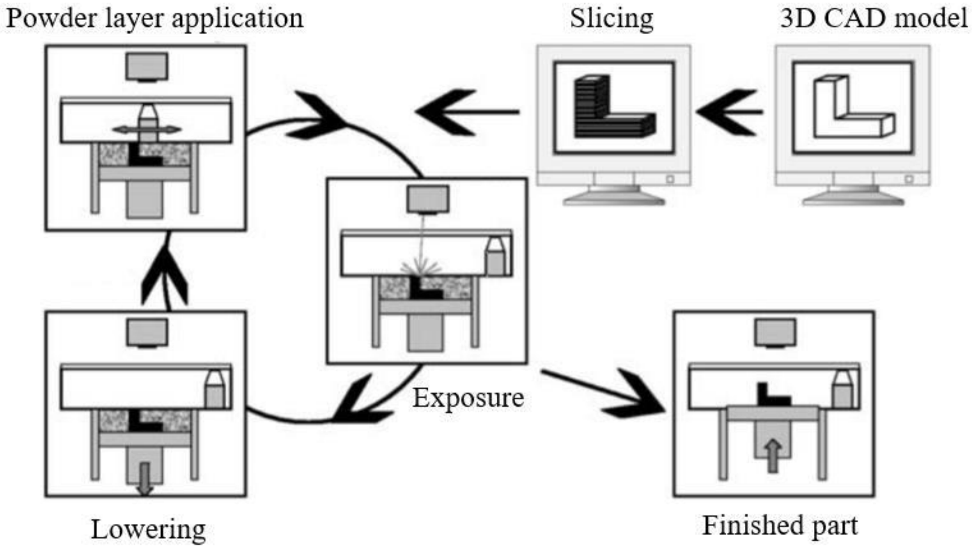

Figure 1. Additive manufacturing process passed on powder (Poprawe, 2005).

Complex shapes can be manufactured using additive manufacturing that's one reason why the technology has emerged as an essential part of modern manufacturing. Using this technology Separately manufactured parts can be now manufactured as one part. (Rosen, 2014; Salonitis, 2016 p. 1–2; p. 990.). The uniqueness of additive manufacturing and its high capabilities has been utilized in many industries such as aerospace, automotive, healthcare, and architecture. (Wong and Hernandez, 2012 p. 2).

With the offered Capabilities by AM, methodologies and practical design frameworks are essential so engineers and designers can generate effective designs for AM. (Diegel et al., 2010 p. 69). For this purpose, the term Design for additive manufacturing (DfAM) has risen so that guidelines, rules, and tools are provided a consideration that facilitates designing for AM. (Diegel et al., 2010; Laverne et al., 2014).

AM for metal parts was extensively investigated through the last ten years. To utilize the benefits of AM it is compulsory to define manufacturing constraints and manufacturing capabilities of additive manufacturing. The development of additive manufacturing functional principle has made it possible to change the way we think about design, in a way that would be impossible in traditional manufacturing. DfAM is providing guidelines, sets, and tools to the constraint and the abilities of AM. By Utilizing the rules of DfAM designers can lighting the weight and improve the efficiency of their designs. (Klocke et al. 2014.).

The connection between nature and the effectiveness of designs has been noticed. AM give the ability to mimic nature in a way that was not possible before. (Emmelmann et al., 2011A.) Now a day’s interest is increasing to implement AM technologies to pneumatic and hydraulic systems. Wight reduction and higher performances have been achieved by applying DfAM techniques to hydraulic manifold designs (Saunders 2015).

Often studies related to DfAM is done inside companies that’s why it’s not easy to collect information’s related to the approach. The aim of this thesis to give information about DfMA by utilizing the advantages of AM to redesign a pressing air nozzle.

2 AIM AND PURPOSE OF LITERATURE REVIEW

The literature review aim is to gather information related to the AM process so the reader can understand the case study. The information collected will explain the different AM technologies, powder bed fusion process, limitation and consideration regarding design for additive manufacturing processes.

3 ADDITIVE MANUFACTURING

3D-printing is a term widely used to describe AM. However, additive manufacturing is more accurate and often used in Academic and professional content. AM is a complex Term. Therefore, in order to understand the technology, this chapter will explain the AM processes.

Additive manufacturing is the process of manufacturing compensates by adding material in layer-by-layer material depositing technic Instead of material removal techniques used in traditional manufacturing. (ASTM F2792-12a). Additive manufacturing or 3D-printing has been invented in the 1980s but not until 2010 the printers became commercially available. The first ever 3D printer was manufactured in 1984 by chuck hull. In recent years sales of 3D-printing machines has increased rapidly and the prices of the machines dropped extraordinarily. (Gibson et al., 2010, p. 69.)

Wohler associated, a famous consulting company that has been in the market for 30 years, they publish an annual report that illustrates the state of the industry of additive manufacturing. In their 2018s report, they showed that the AM market grew by 21% in 2017 and now it´s a $10 billion dollars industry. They have estimated industry growth in 2018 to reach $11.5 billion. The report expected that by 2021 the market will grow to reach $26 billion. (Wohlers Associates, 2019.).

The report also shows that metal printers sales have increased rapidly in the last few years showing a growth of 80% in 2017 over 2016 to reach 1,768 metal machines sales worldwide Figures 2 shows the growth in metal machines sales in the years between 2000 and 2017.(Wohlers, 2019).

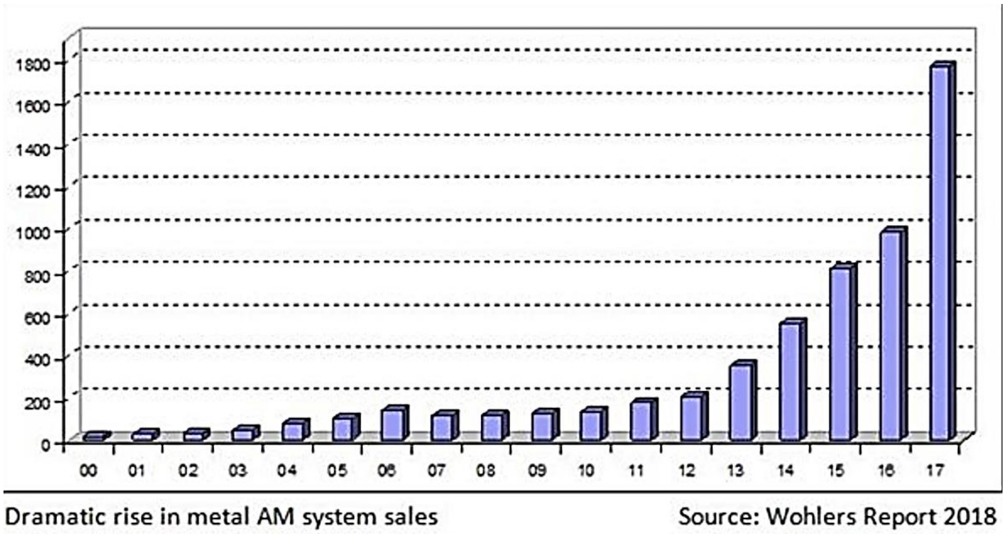

Figure 2. Sales of metal AM systems (Wohlers, 2019)

Metal AM build up objects layer-by-layer using a powder form material. A wide range of different material can be used such as metal, plastic and composite materials. Additive manufacturing can make 3D solid object from almost any shape designed by CAD software. (Gibson, Rosen & Stucker, 2010, p. 1–8.)

AM of Metal has been widely used as a prototyping tool over the last 10 years. Unfortunately, the quality and repeatability of objects manufacturing by the technology are restraining it from being widespread. Therefore, many equipment and tools had been developed and being developed for additive manufacturing. AM is a cost and time effective way to develop products with complex geometry and high material properties. (Gibson, Rosen & Stucker, 2010, p. 1–8.)

Researches and industrial community seem to agree that metallic AM has great potentials and capabilities that conventual manufacturing technologies can’t compete with. But In order to utilize the benefits of AM, it is compulsory to define manufacturing constraints and manufacturing capabilities of additive manufacturing. (Gibson, Rosen & Stucker, 2010, p. 1–8.)

4 STEPS IN ADDITIVE MANUFACTURE

AM has a certain set of operation that needs to be executed step by step in a systematic way. This is a simple model of the process chain, although in some cases differences operations need to be executed this depends on the process and the machine used (Gibson et al., 2010, p. 43.). The purpose of this chapter is explaining the steps used in AM. Usually, there are 8 steps needed in additive manufacturing

1. The design in CAD.
2. STL convert.
3. Transfer file to the machine.
4. Machine setup.
5. Build.
6. Remove.
7. Post-process.
8. Application.

4.1 The Design in CAD

Designing in AM begins with an idea for a product's function. Then a concept is visualized on a paper sketch. The next sequence is to transfer the sketch into a 3D model using a CAD software The model created in 3D must be gapless because the present of gapes in the model leads to low-end product quality or interruptions through the process of building the product. (Gibson et al., 2010, p. 43–45.)

4.2 STL convert

AM machines Usually need STL format to be able to read the file, so the 3D-model must be transferred to STL format. STL files use triangle facets to simulate the original model. The product surface quality is defined by the size and number of the triangles. The resolution of the machine has to be taking into consideration when defining the parameters for the STL File. Triangles on the surface of the product can be seen if the parameters were set incorrectly.

Usually, STL converting process contains flaws. That's why software is being developed in order to reach flawless STL files. (Gibson et al., 2010, p. 45–46.)

4.3 Transfer files to the machine

Several steps usually made after the STL files are transferred to the 3D-printing machine in order to manufacture the part. The part can be adjusted, scaled and modified. Copies of the same part can be printed at the same time. Different part also can be printed on the same platform. STL format software's can manipulate the parts, even split them into several parts in case the part need to be printed in several pieces. (Gibson et al., 2010, p. 47.)

4.4 Machine set-up

Setting-up the AM machine means to set-up the parameters of the product and make some physical preparations (such as filling the powder chambers and level the plate). Parameters set-ups not always necessary, it's possible to print parts without setting-up the machine but often, it results in poor quality products. Usually, the amount of set-up allowed depend on the complicity of the machine, machines that can use different materials and multiple layer thickness requires more set-up than machines using one material and one-layer thickness. (Gibson et al., 2010, p. 47–48.)

4.5 Build

AM first phase process needs to be monitored or controlled manually even though AM is an Automated process. After the first phase, the automated process takes control and a layer by layer manufacturing process takes place. The layer-based process keeps repeating until the part is completed. (Gibson et al., 2010, p. 48.)

4.6 Remove

Sometimes Removing the part from the platform is a challenging process also time consuming, it's also necessary to clean up after every AM process. The absence of support makes it easier to clean up. Some support materials are harder than others to be remove and require manual labor. Metal supports requires the most amount of work and labor to be removed. First, the part must be removed from the platform then the support needs to be removed without damaging the part itself. This is a challenging process that requires a highly skilled operator. (Gibson et al., 2010, p. 48–49.)

4.7 Post-process

Nearly all parts manufactured with AM require some post-processing. Mechanical or visual properties of parts are always not sufficient for the application. Post-processing usually is done manually, and several types of finishing can be used like squeezing, laser sintering, milling or coating. The surface finish required for the product will define the amount of post-processing needed, better surface finishing means a larger amount of post-processing stages. Some AM process produces fragile parts which require heat treatment or coating to strengthen the part. (Gibson et al., 2010, p. 49.)

4.8 Application

The last step is the use of the part. AM manufactured parts might have flaws cues of bonding insufficient, which might weaken the part ability to withstand mechanical stress. Anisotropic properties of the part often caused by AM-processes. It’s not necessary that the features of AM manufactured parts are always good. Depending on the application of the part it can consider to be good or bad to use AM. A crucial part of the designer work is to take these features into consideration while designing the product. (Gibson et al., 2010, p. 49.)

5 ADDITIVE MANUFACTURING TECHNOLOGIES

There a lot of technologies that go under the term additive manufacturing. newcomers to the field can be overwhelmed by the number of possibilities offered by different technologies of additive manufacturing. In addition to that, companies and other institutions developing new processes have created unique names for them to distinguish themselves from the competitors which led to a lot of confusion. (Wohlers, Industry Briefing, 2013.)

In 2012 a list of terms and category-defining AM manufacturing processes have been voted on by the American Society for Testing and Materials (ASTM). (Wohlers, Industry Briefing, 2013). The list approved is listed below (ASTM F2732, 2013).

1. Binder Jetting.
2. Directed Energy Deposition.
3. Material Extrusion.
4. Material Jetting.
5. Powder Bed Fusion.
6. Sheet Lamination.
7. Vat Photo Polymerization.

This thesis will not study all the categorized technologies listed above. Among the listed technologies powder bed fusion (PBF) considered the most suitable manufacturing process for metallic products production and prototyping. Therefore, in this thesis, the focus will be laid on this technology. A description of PBF flowed by A description of Selective Laser Sintering (SLS), Direct Metal Laser Sintering (DMLS) and Selective Laser Melting (SLM) can be found below.

6 POWDER BED FUSION

One of the most popular and among the first commercially used AM processes. It can be defined as one of the AM technologies which use thermal energy to melt the material powder together. (ASTM F2792-12a).

In the PBF process category, a cross-section is created by thermal energy heating the powder. Either an electron beam or laser is utilized to generate the thermal energy.

A typical process is;

- A powder is being distributed in the build surface.
- Material starts to consolidate by milting after the laser or electron beam hit the part's area of cross section.
- Then the next layer is built by lowering the build area.
- The process repeats itself until the build is finished.

Figure 3 shows a typical PBF system.

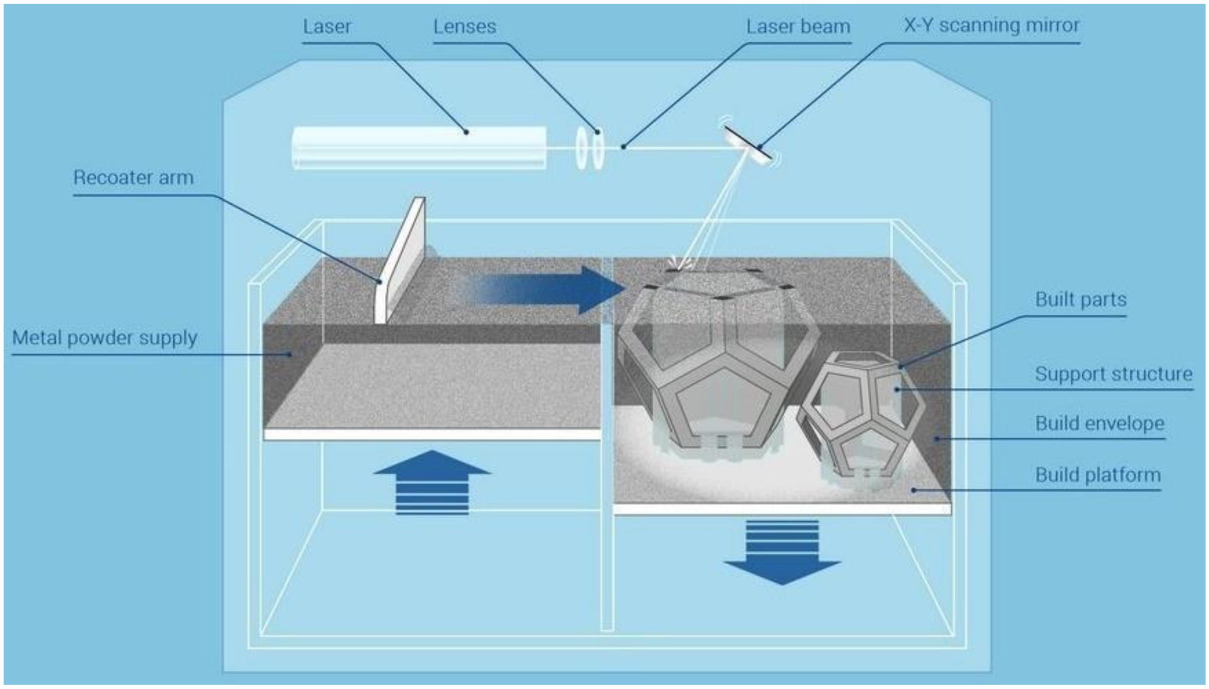

Figure 3. Typical PBF set-up system (Dacide, 2014).

A lot of different material variants are available when it comes to PBF processes such as metals, polymers, ceramics, and other composite materials. In theory, PBF processes can use any material that has the ability to be milted then re-solidified again. However, Metals used in welding considers as best candidates for PBF process. (Gibson, Rosen, & Stucker, 2015.).

As more materials are developed There is a growing number of materials commercially available that can be used for PBF process. Available material in the metallic form is tool steels, titanium, stainless steel, nickel-based alloys, aluminum, cobalt even gold and silver. (Gibson, Rosen, & Stucker, 2015.).

6.1 Benefits and drawbacks with PPF

PBF consider being the most suitable technology for any complex geometry of low and medium-size parts. Nowadays PBF technology is often used for aerospace and biomedical applications due to the complex geometry and weight reduction needed in these industries. The amount of research and development related to decreasing the cost and time of PBF process will likely make it even more competitive. That also indicates that powder bed fusion technology will continue to be one of the most common technologies used in additive manufacturing in the future. One of the main advantages of PBF technology is the wide variety of material. During the building process in PBF, the powder losses can act as support structures which give the chance of complex designs to be built (Gibson, Rosen, & Stucker, 2015.).

A lot of designs guidelines that can be considered when building for PBF technologies and we will go over them in another part of this thesis. But one of the main considerations is overhanging structures, designers and engineers should take in mind that overhang structures over 35°-degree angle (in relative to the building platform) can’t be built without the use of supports. See Figure 4.

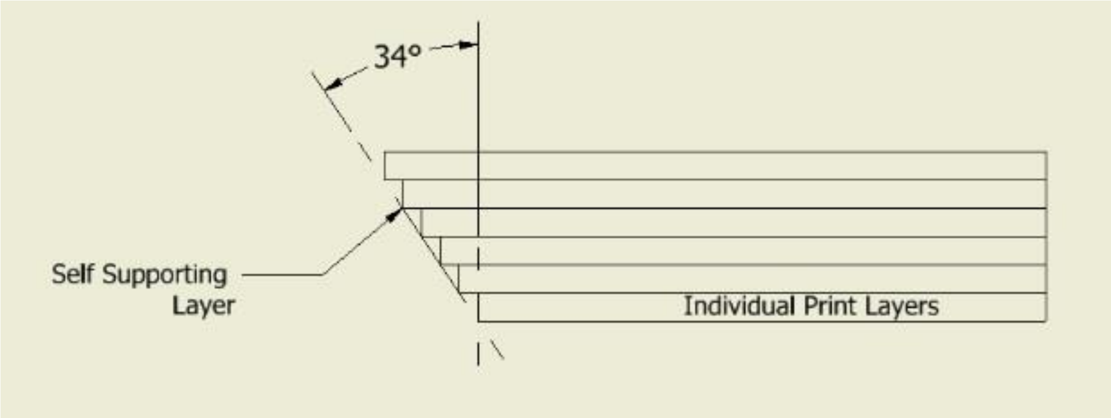

Figure 4. The maximum angle for overhanging structure with no supports needed (Gibson, Rosen, & Stucker, 2015).

If the angle seen in Figure 4. can't be achieved and support structure is needed. The easy access to the support has to be considered or they can't be removed. Also, any unnecessary volume should be avoided in order to decreases the time and cost of the building process. (Stratasys, 2017.).

Disadvantages can also be seen in PBF, for example, excessive warping can occur due to metal fusion and in order to prevent that support structures are needed. Post processing can be time-consuming, expensive and unavoidable in some cases. The Orientation beside the build direction and the location of the supports are key factors for the building process. Poor surface finish and accuracy compared to other AM powder based metallic processes. Powder particle size affect the surface finish so in order to accomplish better surface finish and accuracy a powder with a finer particle can be used, but finer particle powder is harder to spread. Through using Low thermal conductivity materials, better accuracy can be obtained. (Gibson, Rosen, & Stucker, 2015.)

6.2 PBF Processes

The same as most of AM processes, there are several technologies based on PBF. Based on the type of the thermal source technology uses and the powder fusing mechanism a classification has been made. There are four main building mechanisms that are used to bound powder particles together which are (Gibson, Rosen, & Stucker, 2015):

- Solid state sintering.
- Liquid phase sintering (partial melting).
- Full melting.

Laser sintering (LS) is a PBF process in which laser beam paltrily melt the powder bed. In the other hand laser melting (LM) process include full melting of the powder bed (Gibson, Rosen, & Stucker, 2015.).

Additionally, over the years manufactures of additive manufacturing technologies have created several names for PBF technologies however most of the technologies have the same working concept. The most common ones are:

- Selective Laser Sintering (SLS).
- Direct Metal Laser Sintering (DMLS).
- Selective Laser Melting (SLM).

In the other hand, it’s not difficult to distinguish Electron beam melting (EBM) for other BPF technologies since the technology utilizes an electron beam as a thermal source. (Gibson, Rosen, & Stucker, 2015.) in Figure 5 PBF different processes can be seen.

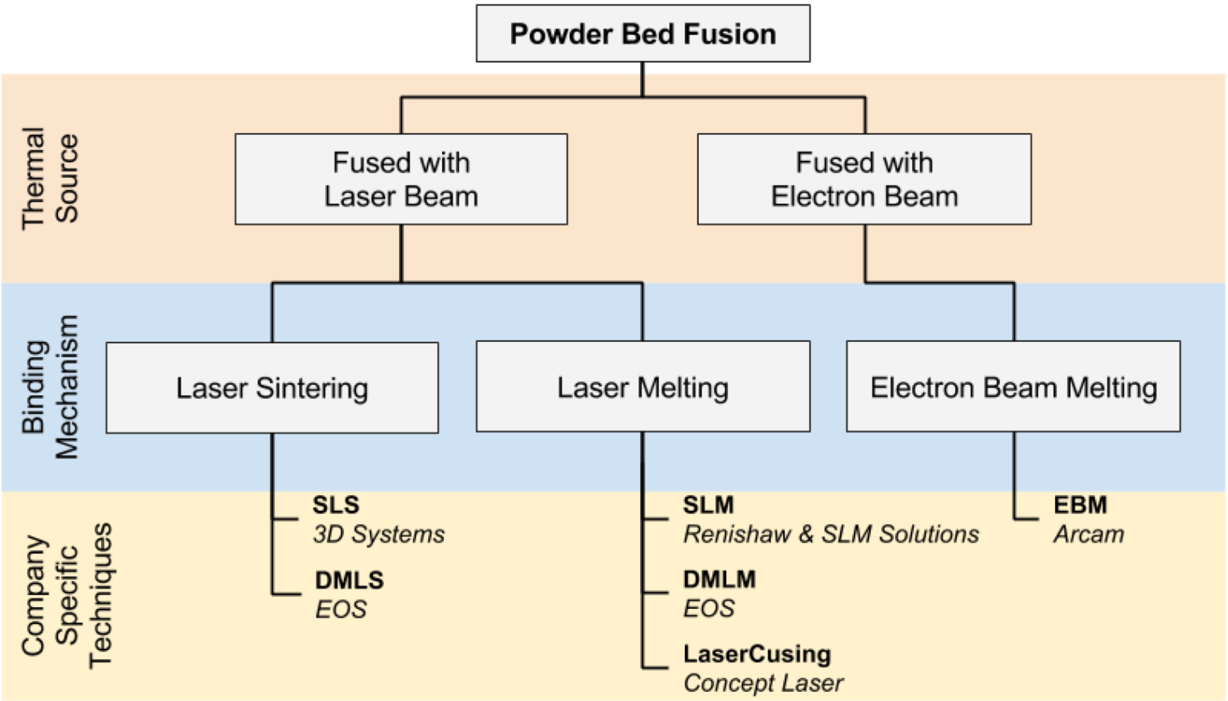

Figure 5. Shows PBF technologies.

In this thesis, only the most common PBF processes will be discussed.

6.2.1 Laser Sintering (LS)

This technology was used for sintering polymer materials. the term SLS is typically used when referring to polymer PBF processes. In the past, the technology used a liquid based sintering technique which involves partial melt of the bed powder. (Dongdong, 2015.). Since sintering typically requires more build time and post-processing if compared to fusion by melting, a small number of additive manufacturing technologies use sintering as the principal of their fusion mechanism today (Gibson, Rosen, & Stucker, 2015).

Selective Laser Sintering (SLS) is the oldest method developed for PBF processes by DTM Corporation in 1992. Laser beam is utilized in this process to partially melt the powder bed in a closed chamber. (Valmik, Prakash, & Shreyans, 2014.) Figure 6 shows SLS machine.

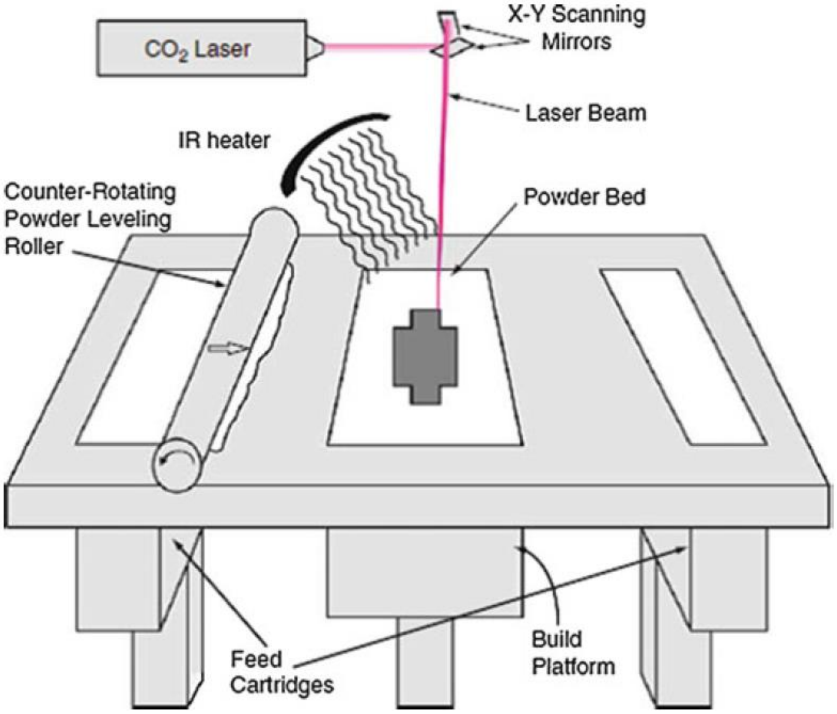

Figure 6. SLS machine layout (Gibson, Rosen, & Stucker, 2015 p.108).

EOS company In Germany introduced the first commercial SLS metallic system in 1995. To differentiate this process, form the old one they created a new unique term called Direct Metal Laser Sintering (DMLS). Even though the term DMLS is used by the company EOS today, the process induces full laser melting. Therefore, the word “sintering” is a historical term and a misnomer. (Valmik, Prakash, & Shreyans, 2014.).

6.2.2 Selective laser melting

Selective laser melting Is considered as an advance SLS process in which one laser or more are used to fully melt the powder bed. This lasers beams fuse each layer of the powder bed into a complete part in an enclosed chamber. The end product is a fully dense component without the need for infiltration. Though as the temperature of the part increases during the build, the resulting material characteristics are very different from cast materials (CES EduPack, 2015.). This is shown in Figure 7.

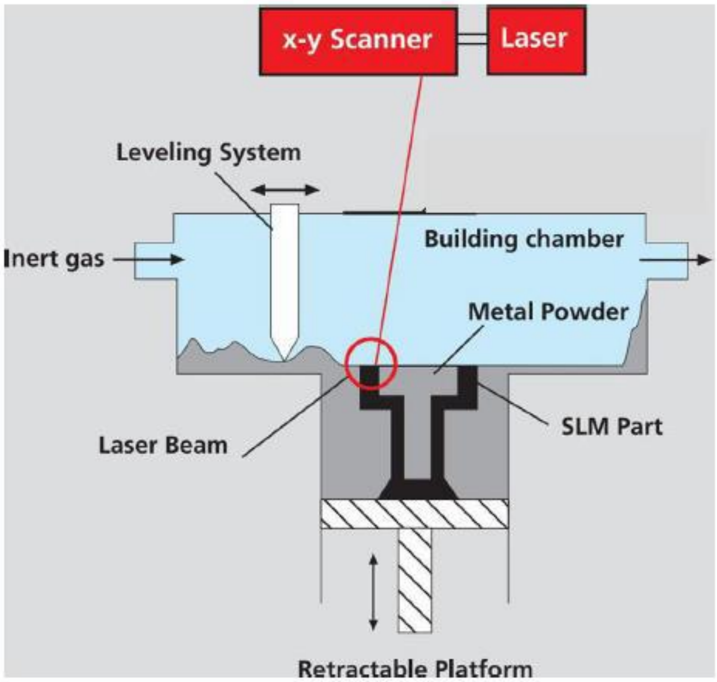

Figure 7. Machine system for SLM (Zhang, Dembinski & Coddet, 2013, p. 22).

SLM Machine system is presented in Figure 4. the temperature of the powder spreaded over the platform is kept close to the melting temperature of the metallic powder. Preheating of the powder by heating the building platform is done, that minimizes the energy needed to reach the fusion point and also prevent warping of the part being built from occurring. Figure 8 to shows the layout of an SLM machine. powder spreaded over the building platform is preserved close to the melting point of metallic powder material. (Gibson et al., 2010, p. 107–109).

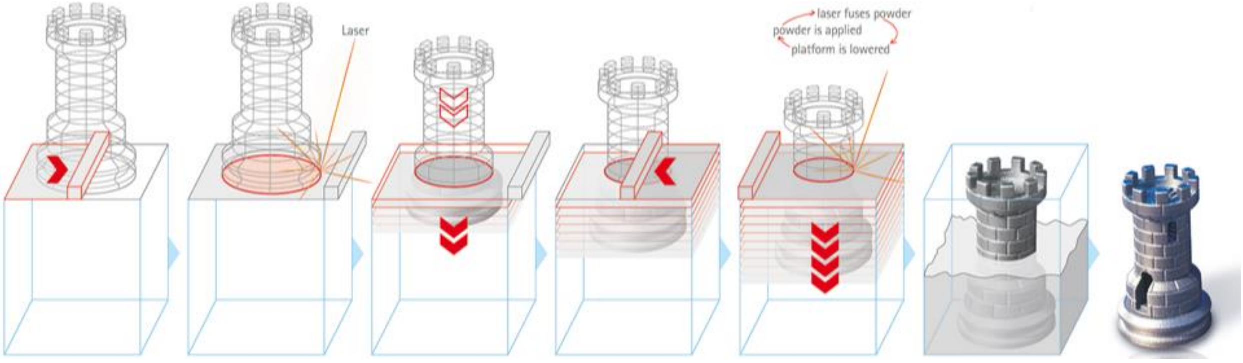

Figure 8. Principle of SLM process (EOS 2019).

As Figure 8 shows, how the part is being built layer by layer by lowering the building platform one-layer thickness at a time and a new layer of powder is being spreader by the recoater then fused by the laser beam. the process is repeated until the build is finished. After that, the part is left to cool down so It can be handled safely. Warping can occur if the heated part was exposed to the atmospheric temperature Before cooling down because of unelevated heat distribution. The final step is removing the surplus powder and the part support structure. (Gibson et al., 2010, p. 107–109.). The process of building parts using SLM is complicated and has a lot of different physical phenomena. (Bauereiβ, Scharowsky & Körner, 2014, p. 2523).

7 DESIGN FOR ADDITIVE MANUFACTURING

This chapter of the thesis explains the limitation, constraints, and rules that should be considered while designing for additive manufacturing using powder bed fusion process. Defects such as breakage and distortion can often be avoided by considering while designing the quality of the surface and ease of the support's removal. After reading this chapter the reader should understand the basics of DfAM.

7.1 Support structures

The support structure is one of the biggest disadvantages of AM. All metallic printed parts require supports to attach the part to the platform (building plate) and to dissipate the heat. Supports are also necessary to avoid deformation of Overhang structures. The overhang structure can be seen in Figure 9 (Wang et al. 2013, p. 1740.).

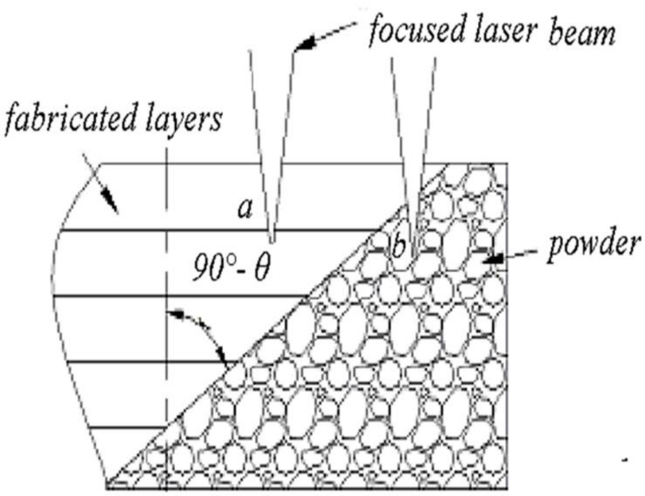

Figure 9. Overhang structure (Wang et al. 2013, p. 1740).

Deformation and defects can occur in overhang structure due to gravity and insufficient ability to dissipate heat as the only thing supporting these structures is the powder laying under it. Metallic components manufactured by PBF require firm solid layers so the layers can be formed above each others without any defects or deformation. Structure supports are essential to produce high build quality components in PBF. (Järvinen et al., 2014, p. 73.)

Self-supporting geometry can be usually designed to decrees the number of supports in the printed parts (Thomas, 2009, p. 159). Usually, the use of supports can't be avoided, and that lead to complication in the post-processing stage, cost (due to the energy consumed to build these supports and man labor needed to remove the support structures) and increases the building time. (Calignano, 2014, p. 203.). Various types of support structures are used depending on the material and the technique the designer attend to use to build the part. (Thomas 2009, p. 178–181). Figure 10 shows the commonly used structures.

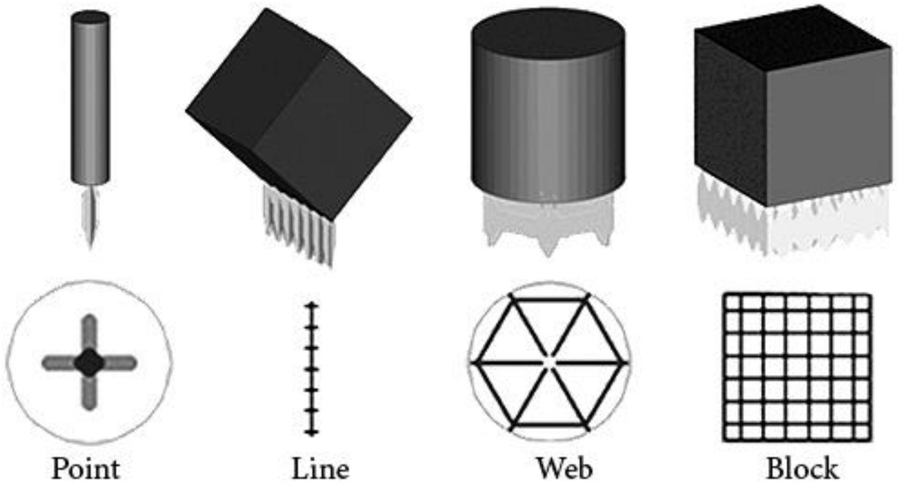

Figure 10. Commonly used supports structures (Thomas 2009, p. 178–181).

The design of the support structure will reflect on the quality of the surface greatly, so it's highly recommended to pay attention to the good design of the support structures. Insufficient connections between the printed part and the support structure can lead to poor surface quality. Pointed tip support (teeth) can be used to ease the removing of the supports from the part. In many cases tools are used to remove the supports (such as saws) and this can cause damage to the printed part. (Calignano, 2014, p. 203.)

7.2 Sharp edges

Building sharp edges accurately is impossible in PBF, and curves can occur and will have shapes that depend on the diameter of the laser beam. (Adam & Zimmer 2014, p. 26; Kruth et al. 2007, p. 03.) This can be seen in Figure 11.

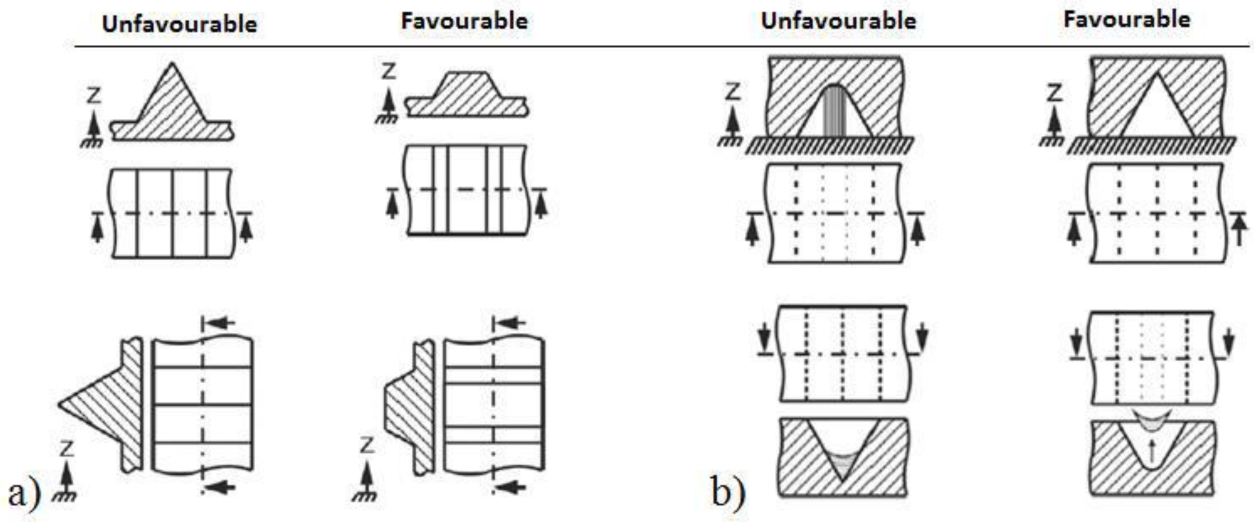

Figure 11. Shape of sharp edges curves (Adam & Zimmer 2014, p. 26).

Sharp edges are shown in Figure 11 are recommended to be avoided in the design stage. using chamfers can solve the problem of defections caused by sharp edges. (Thomas 2009, p. 95.)

7.3 Minimum wall thickness

The wall thickness depends on the capabilities of the AM machines, 0,4 mm is the minimum wall thickness possible as shown in Figure 12 (Thomas 2009, p. 165).

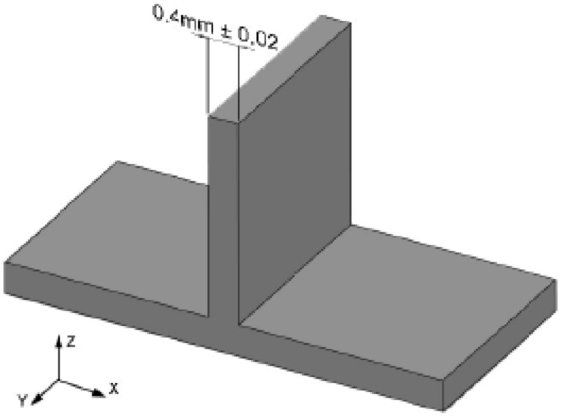

Figure 12. Minimum wall thickness allowed in SLM (Thomas 2009, p. 165).

As shown in Figure 12 the smallest wall will have 0.4 mm thickness with ±0.02 tolerance, walls with thickness less than 0.4mm will be absent in the final printed part. (Thomas 2009, p. 165)

7.4 Gaps between surfaces

The designer must pay attention to the gap size between walls, channels, and pipes in order to avoid surface interaction or merging walls together (Thomas 2009, p. 164). Figure 13 shows the minimum gap allowed between two surfaces.

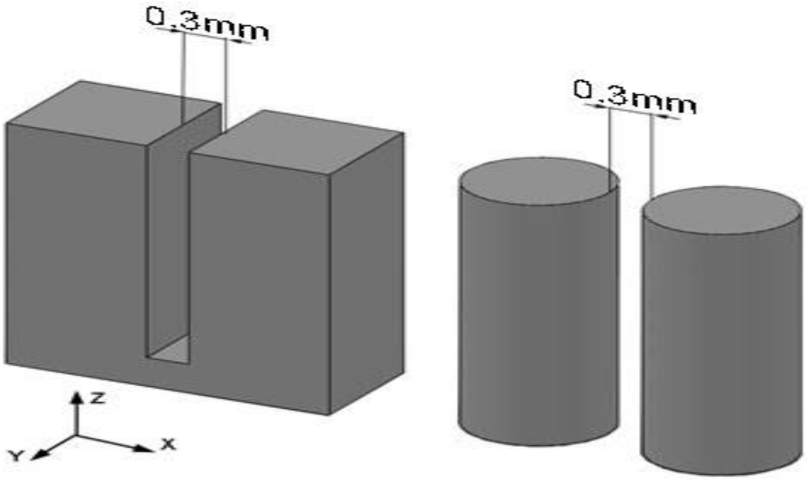

Figure 13. Shows the minimum gap possible between surfaces (Thomas 2009, p. 165).

Figure 13 shows that 0.3 mm is the minimum gap allowed between surfaces. It's recommended to design gaps bigger than 0.3 mm because different orientations require different gaps sizes. The present of supports in the gap area will also affect the minimum size possible for gaps. (Thomas 2009, p. 165.)

7.5 Orientation and surface roughness

Part orientation and the roughness of the surface are connected to each other. By locating the right orientation and the right angle for support structure a better surface quality can be obtained (Thomas 2009, p. 135.) Figure 14 shows the linkage between orientation and surface roughness.

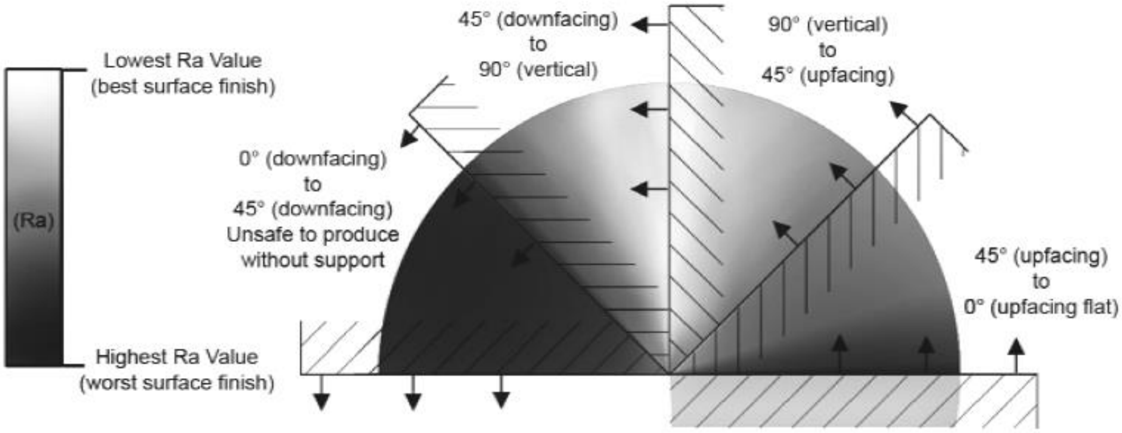

Figure 14. The relation between orientation and surface roughness (Thomas 2009, p. 158).

Part orientation can change the shape and the number of supports dramatically so it has to be wisely considered during designing parts for AM. (Thomas 2009, p. 158) Figure 15 shows three different orientation for the same part and how it affects the number of support structures.

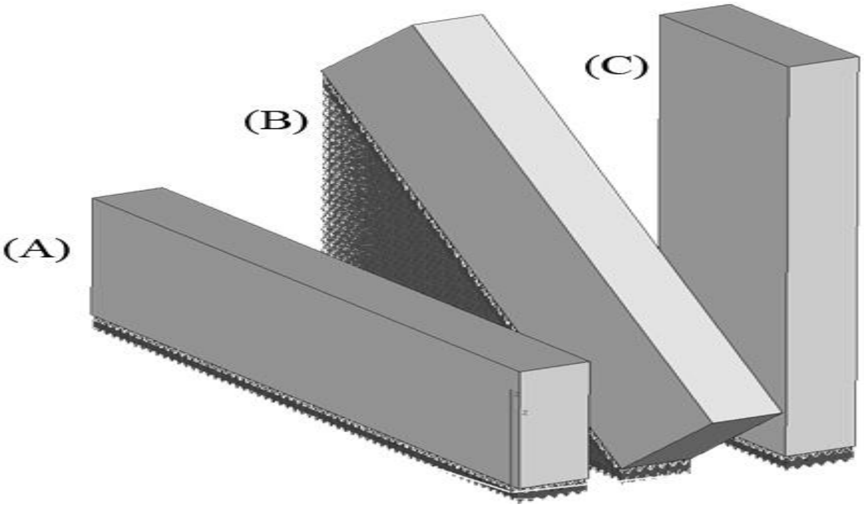

Figure 15. Three different orientations (Thomas 2009, p. 159).

7.6 Chamfers

Chamfers are a curved geometry that can be 3D-printed without the use of supports. (Thomas 2009, p. 167) Figure 16 shows the different designs of chamfers.

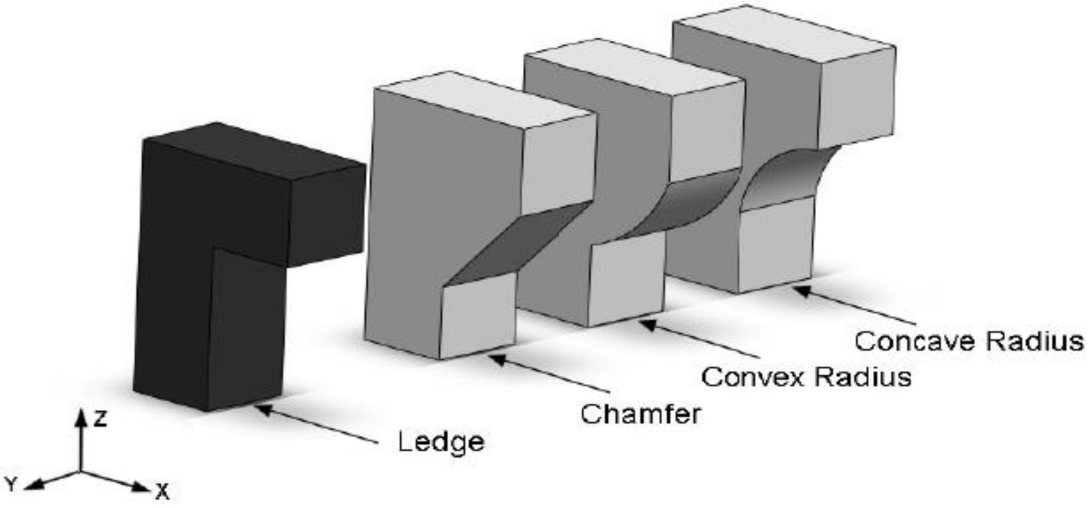

Figure 16. Leg design alternative in SLM (Thomas 2009, p. 167).

Champers is implemented to the design to decrease the amount of support structure and to enhance the surface quality. 45° degree is the ideal angle for champers if used no complications will occur during the building process (Thomas 2009, p. 167). The angle is measured in relative to the building plate as shown in Figure 17.

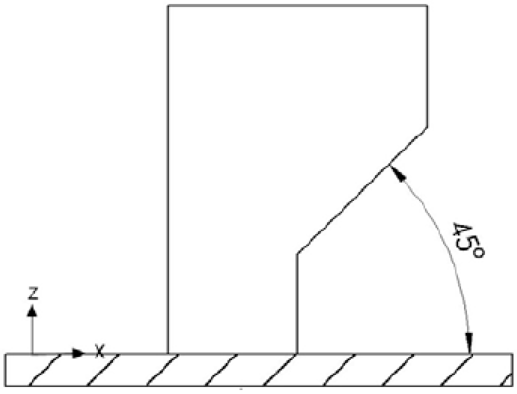

Figure 17. Chamfer angel measuring (Thomas 2009, p. 167).

Holes

Smallest holes that can be built in parallel to the building direction using SLM technology has 0.7 mm in diameter. (Thomas 2009, p. 174). As shown in Figure 18.

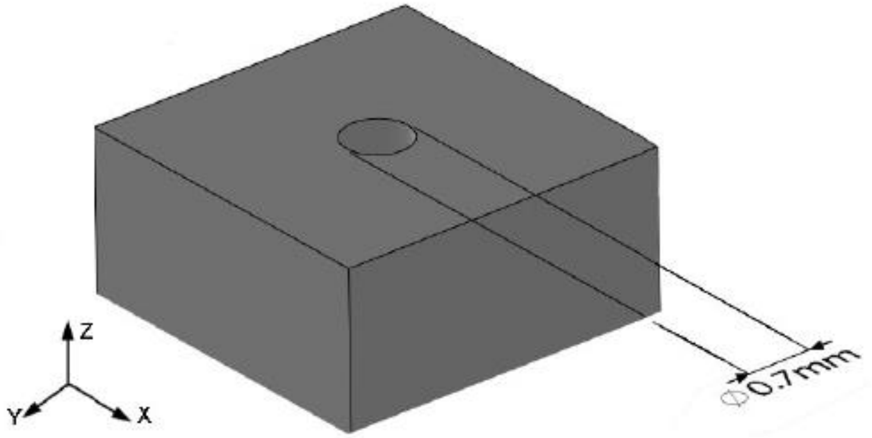

Figure 18. Minimum hole diameter parallel to building direction. (Thomas 2009, p. 175).

Building round shape holes perpendicular to the building direction require supports. Holes that can be built with no support structure has a maximum diameter of 7 mm. (Thomas 2009, p. 175.). Figure 19 shows the minimum and the maximum diameter for holes perpendicular r to the building direction.

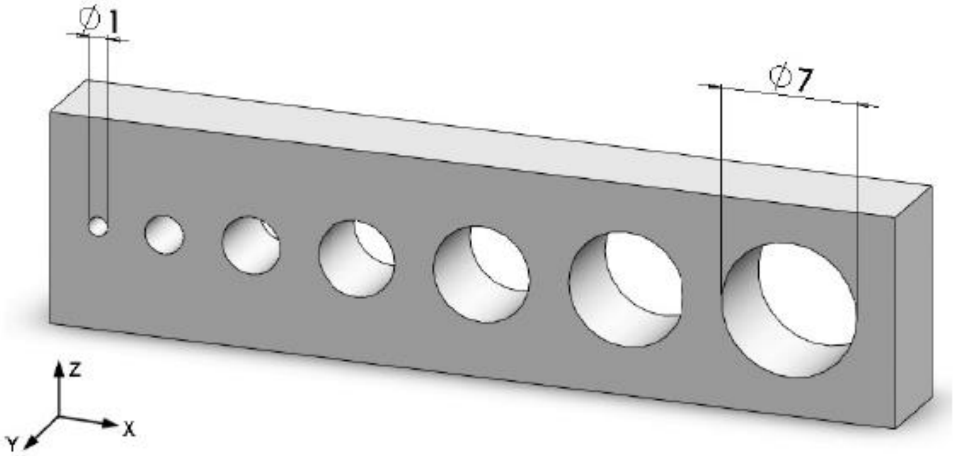

Figure 19. Diameter restrictions for perpendicular holes (Thomas 2009, p. 176).

Holes bigger than 7 mm will have deformations if built with no support structures. (Thomas 2009, p. 177). Figure 20 shows deformation that can occur for holes bigger than 7 mm with no support structure.

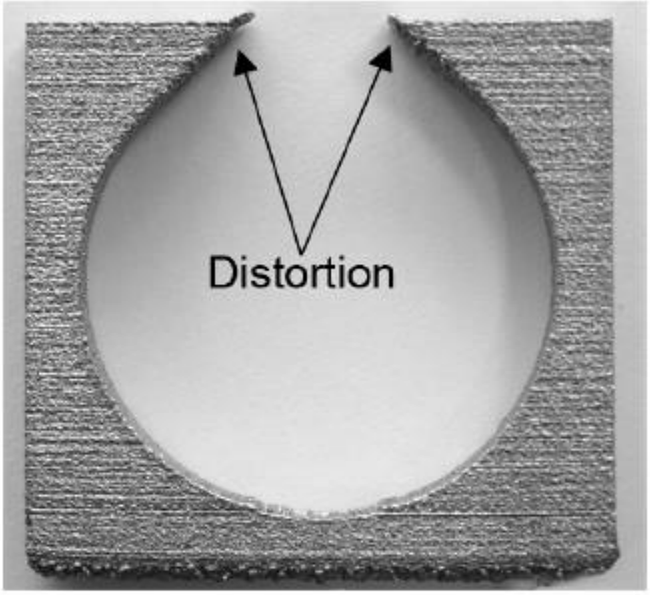

Figure 20. Distortion in PBF build (Thomas 2009, p. 177).

Any hole diameter can be built in SLM technology using supports. Often the holes will have poor accuracy. A sag of 0.5 mm will occur in most holes built with SLM technology with or without support structures (Thomas 2009, p. 178). Figure 21 shows holes accuracy in SLM technology.

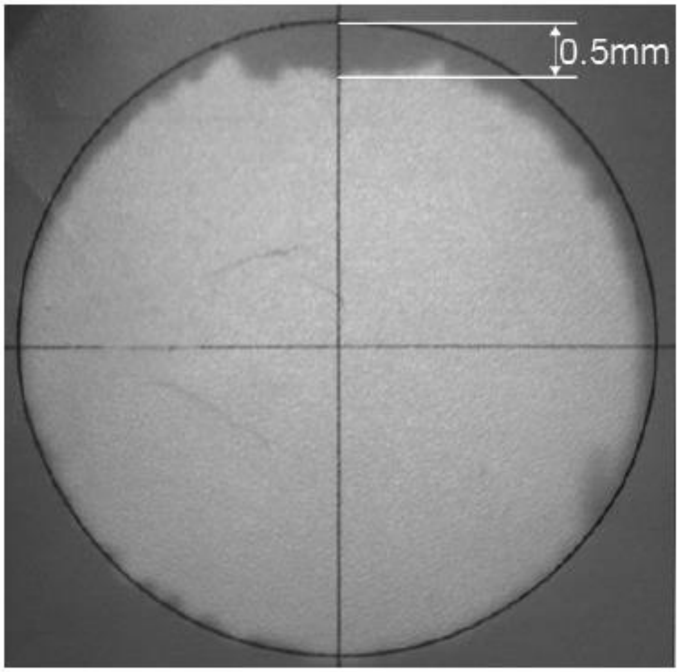

Figure 21. Distortion in SLM (Thomas 2009, p. 178).

Figure 21 illustrates the general tolerance of holes sag built with SLM technology with ±0.5mm, various tolerance can be seen through the surface of the hole. (Thomas 2009, p. 178)

7.7 Self-supporting holes

Building round shape holes perpendicular to the building direction with no support structure is very difficult. Even in some cases, support structures are not possible to be removed due to unreachable positions. Self-supporting holes designs can be used to obtain high-quality holes and to avoid distortion through the surface of the hole. (Thomas 2009, p. 179) Figure 22 Shows a self-supporting hole geometry.

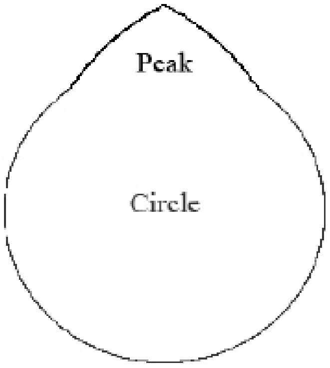

Figure 22. Self-supporting hole geometry (Thomas 2009, p. 179).

As illustrated in Figure 22 the self-supporting hole design has two parts the circle and the peak. Peaks can be designed either in carve shape or 45°straight lines. Curves are mostly used to give holes more circler shape. (Thomas 2009, p. 179). Figure 23 shows printed self-supporting holes.

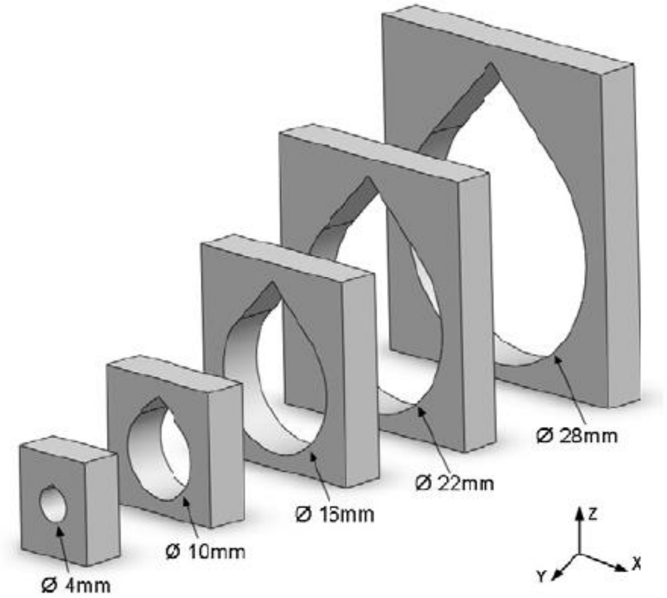

Figure 23. Self-supporting holes printed by SLM technology (Thomas 2009, p. 179).

As shown in Figure 23, using self-supporting geometry results in high accuracy holes with no distortion.

8 AIM AND PURPOSE OF CASE STUDY

The case study chapter aims to redesign a pressing air nozzle used in pressure filters manufactured by Outotec company utilizing PBF technology. The goal of this study is to develop the original part by reaching Higher functionality, lighter weight, and less pressure losses. CAD designs will be developed for all original and suggested designs. The air flow will be analyzed using competitional fluid dynamics (CFD) modeling to calculate the air velocity and the pressure losses inside the air nozzle channels. The air channels geometry will be optimized. The design of the pressing air nozzle will be developed utilizing advantages which only Present in Additive manufacturing.

9 PRESSURE FILTERS

PF (Pressure filters) Has almost the same working concept as rapid filters. The Major differences are that a pressure vessel is used to contain the media and it has a pressure-based operating system. In a pressure-based operating system, a high-pressure source is used on the influent side rather than gravity. (EPA, 2019.)

To rise for the challenge Outotec manufacture a wide variant of dewatering resolution such as tailings, comprising-filtration, and thickening. Pressure filters, Outotec manufacture either vertical presses filters or tower pressure filter (Outotec, 2019.). Figure 24 shows the different types of filters Outotec manufacture.

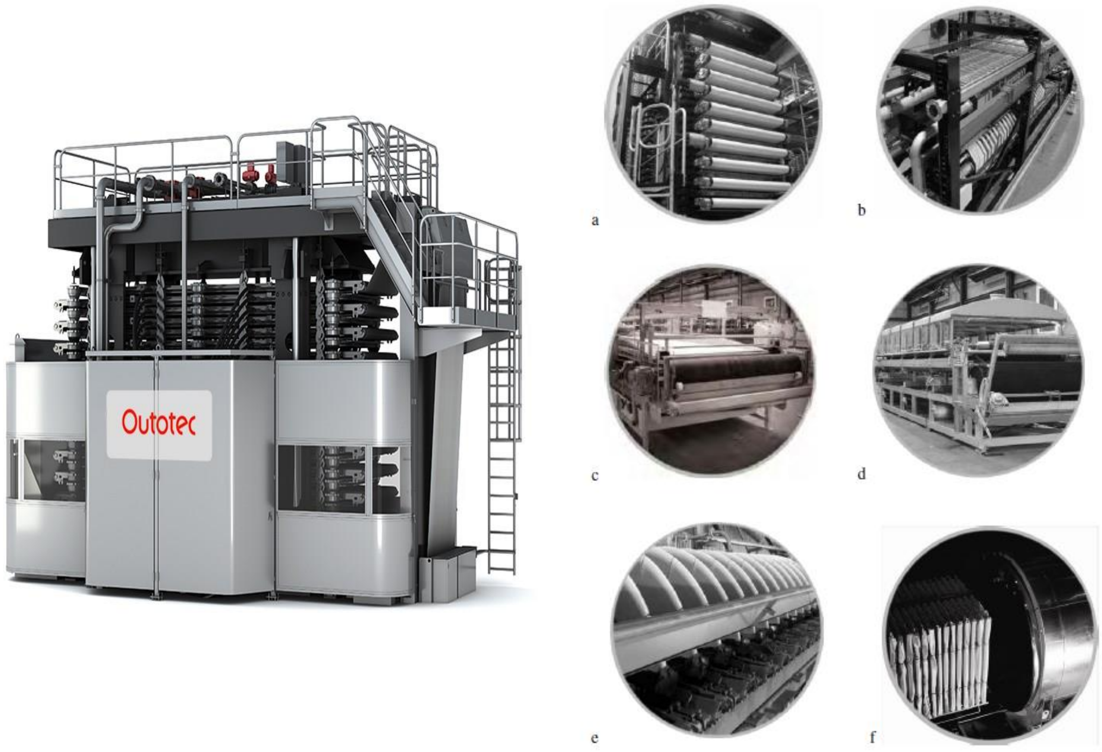

Figure 24. Outotec filters type (Outotec, 2019).

currently, the largest pressure filters in the market are provided by Outotec, these filters can provide filtration area up to 252m^2. Pressure filter are outmetaled machines that are safe to operate (Outotec, 2019.). When vacuum filtration is ineffective pressure filters are used to water solid or fine fractions (Wakeman &Tarleton, 2005). Outotec pressure filters can reach high filtration rate with a capacity of 300t/h. PF are essential for different industries one example is Miming industry, they often use pressure filters due to the difficult dewatering process. In general pressure filters designed by Outotec have a lot of advantages such as adaptability to unsteady process, they have low energy consumption, they are easy to be installed, operate and maintained. (Outotec, 2019.)

10 PRESSING AIR NOZZLE

Pressing air nozzle is an air nozzle used in pressure filters. it’s located in the filter plate. The inlet of the pressing air nozzle is connected to a hose which feeds the part with 16 bars compressed air. Pressing air nozzle can be seen in Figure 25.

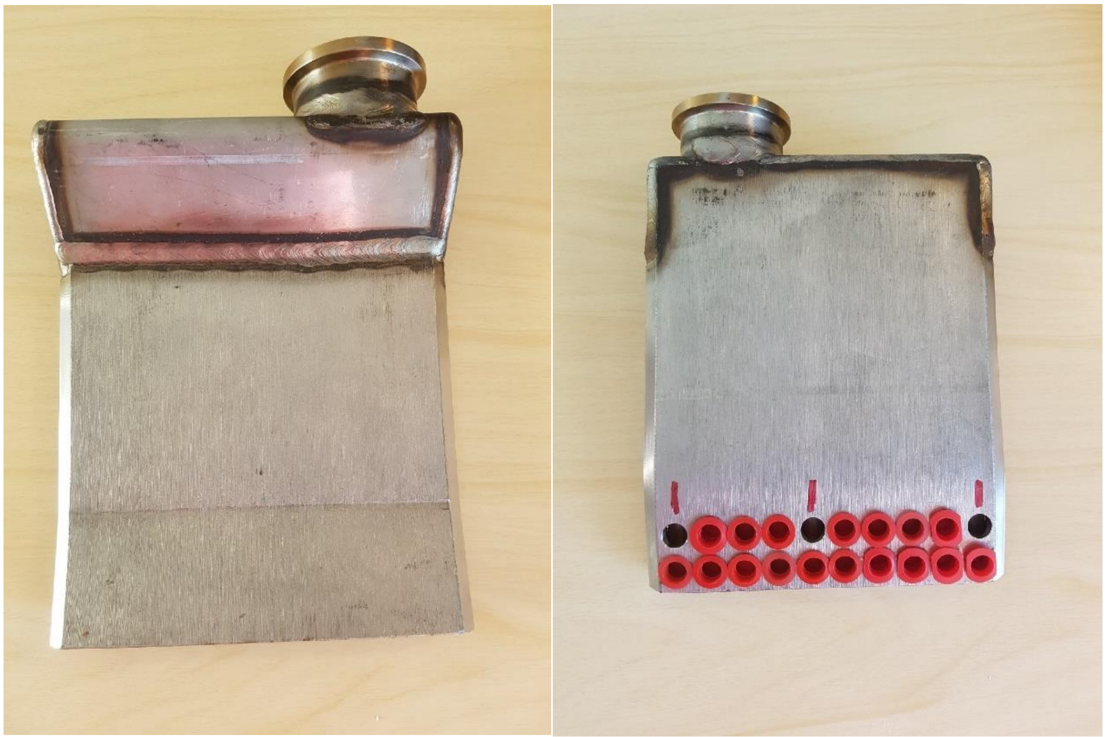

Figure 25. Pressing Air nozzle.

As seen in Figure 25 there are 20 holes in the back of the part act as the outlet. Rubber diaphragms are fixed on the outlet to maintain pressure inside the part. Air is fed to the inlet 4 to 8 times per hour, every air feed continues for 1 to 1.5 minutes. In the beginning, air flows freely inside the plats inflating the diaphragms to compress filtered solid in filter plate chambers as diaphragm pressurized air flow is minimized theoretically to zero just maintaining the pressure inside.

11 CREATION OF CAD-MODEL FOR THE ORIGINAL DESIGN

CAD-models for the original pressing air nozzle design was created based on the geometric information delivered by Outotec company. Figure 26 shows the geometric information's for the inlet of the Air nozzle.

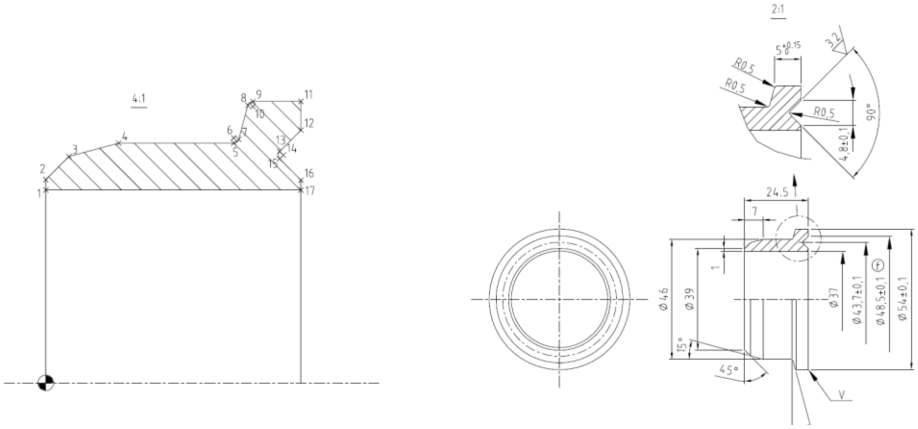

Figure 26. Inlet geometry of the air nozzle.

Figure 27 shows the geometry of the vessel connecting the inlet with the nozzle air channels.

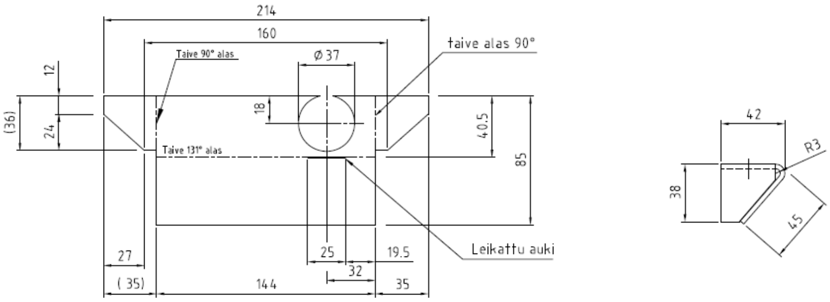

Figure 27. Vessel geometry for the air nozzle.

Figure 28. Shows the geometry of the pressing air nozzle body, where ten air channels are drilled to carry the pressurized air to the outlet.

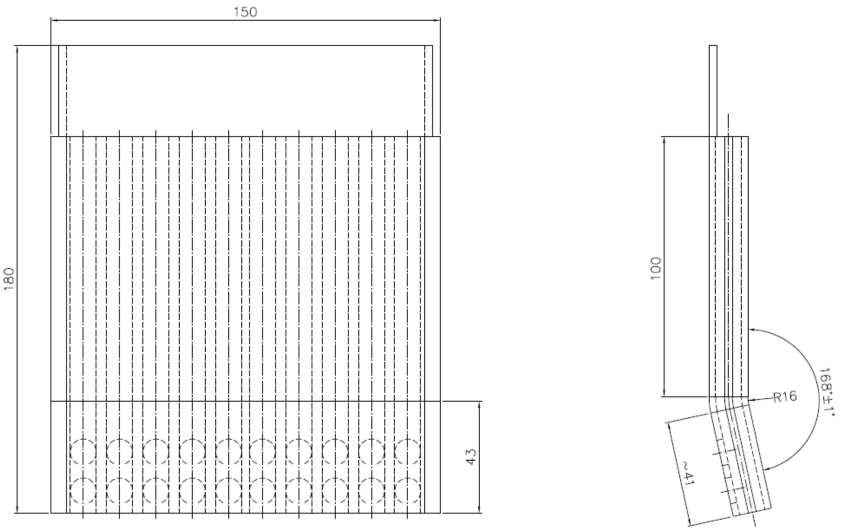

Figure 28. Body of the air nozzle.

Figure 29 shows a 2D assembly of the pressing air nozzle. In the Figure part number 1 illustrates the body of the nozzle, number 2 is the vessel and number 3 illustrate the inlet.

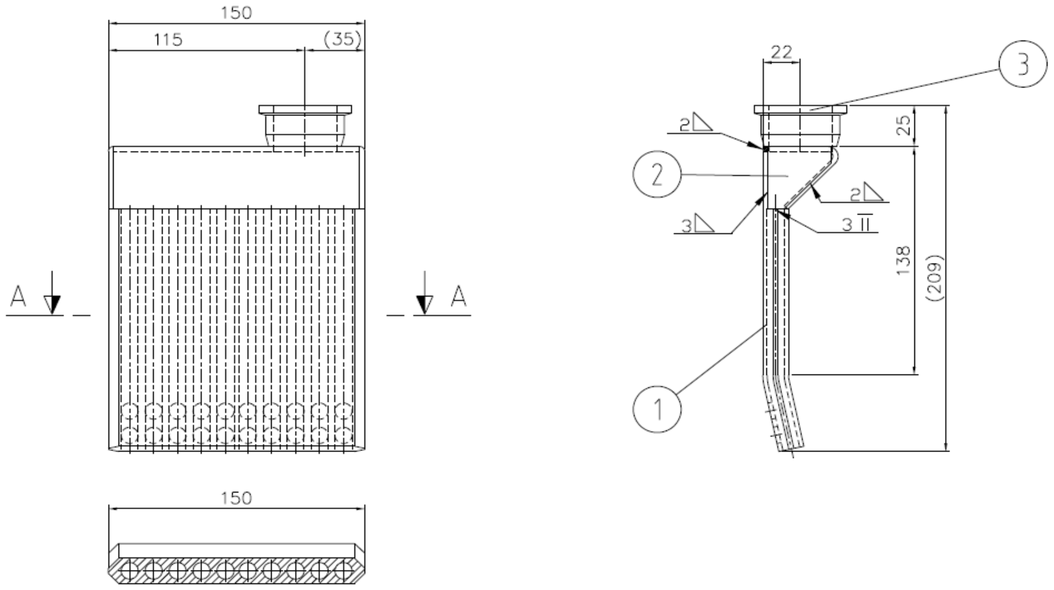

Figure 29. 2D assembly drawing of the pressing air nozzle.

A 3D CAD assembly view of the original design is seen in Figure 30.

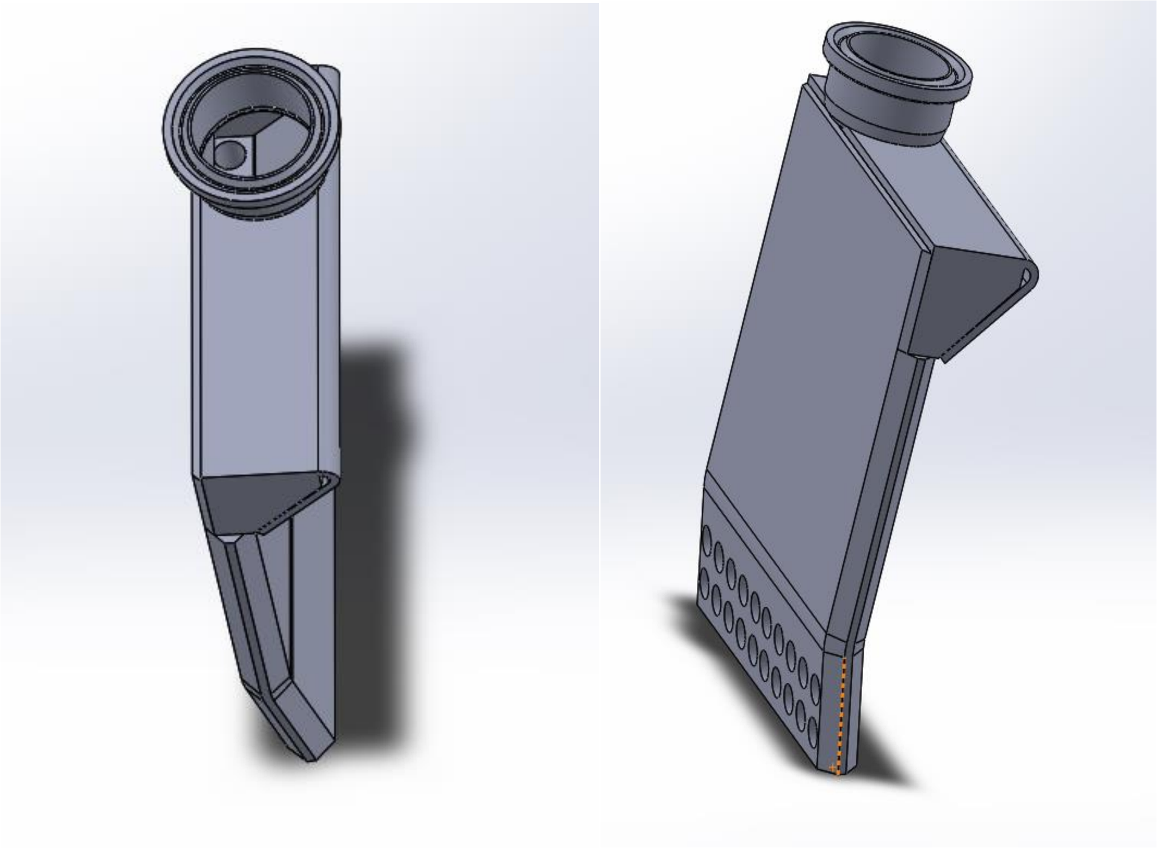

Figure 30. CAD model of the original pressing air nozzle.

As seen, the part consists of inlet, a vessel connecting the inlet and the air channels, ten air channels and twenty holes acting as the outlet of the body. In Figure 31 a side cross-section shows the channels inside of the air nozzle body.

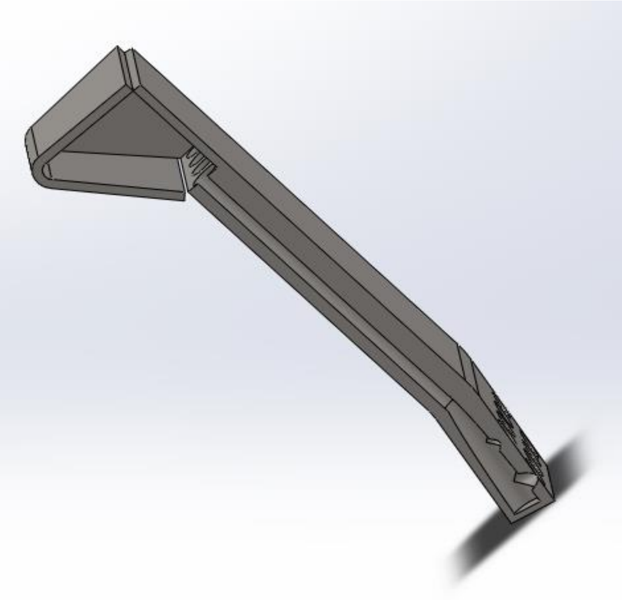

Figure 31. Side Crouse section of the air nozzle original design.

It can be seen from Figure 31 a channel drilled through the body of the air nozzle with 168°-degree angle bent before the outlet.

In Figure 32 a top cross-section view shows the connecting area between the inlet and the air channels.

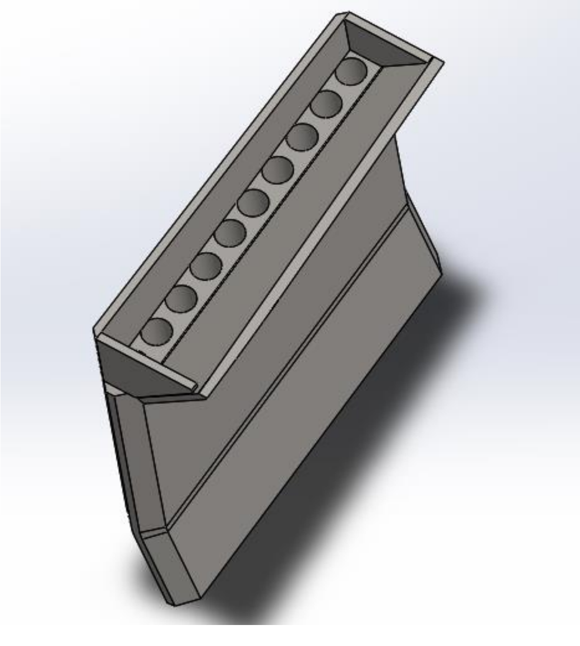

Figure 32. Top Crouse section of the air nozzle original design.

11.1 Original Design Material

The material of the component has been defined by the manufacturer to be AISI 316 Stainless steel. For comparison purposes and weight determination, AISI 316 Stainless steel with a density of 7.8 g/cm3 have been assigned to the CAD-model.

11.2 Original Design Manufacturing Method

The pressing air nozzle is manufactured using conventional computer numerical controlled (CNC) machines. Three different parts are manufactured separately then joint together by welding to form the final product. Figure 31 shows the three different parts before joining.

Figure 33. The three components of the pressing air nozzle

As seen in Figure 33 The pressing air nozzle has straight channels that are bent before the air outlet that was built with a sharp bent angle due to restrictions in the traditional manufacturing processes.

Also, the original model has open spaces between its components that must be welded to maintain the air pressure inside of the air channels. Figure 34 shows the final product after joining by welding.

Figure 34. Welding sections in the pressing air nozzle.

Material losses also must be considered. Due to drilling and cutting in traditional manufacturing processes material losses is expected. By estimating the material volume of the original work peace (raw material) and the material volume used in the finished part the total volume of material losses can be calculated.

12 SELECTION OF AM TECHNIQUE

All of metal AM techniques have been considered and PBF has been selected as the building technique due to its suitability for the investigated application. The reasons other techniques were not chosen for this application are:

- Freedom of design is higher in PBF.
- Final machining is not required to reach the tolerance needed.

12.1 Selection of powder bed fusion Process

As mentioned in the theory section, PBF systems use either a laser beam (LM) or an electron beam (EBM) to melt regions of a powder bed. LM systems outperform EBM in three ways that make LM considered as more suitable at the present time for this application, these are:

- There are more materials available for SLM.
- Better surface quality can be obtained using SLM technology.
- Build size is larger in SLM technology.

12.2 Material Selection

As mentioned before the original part is manufactured in steel AISI 316 Stainless steel. Stainless steel (316L) material was chosen for both suggested design due to its similarity to the original part material so no compromise is made regarding the part material.

12.3 Development of a Concept

Two new suggested design (design concept A and design concept B) for the pressing air nozzle have been developed in a way that suites AM technology. The advantages of AM have been used in both designs to modify the internal air channels and to lighten the weight of the part.

12.4 Constraints and Design Method

Before redesigning some constraints where set, so that minimum changes will be applied to the original system environment. The following limitations for the new designs were set:

- Dimensions and Positions for the air outlet is not changeable.
- The wide and length of the air nozzle is not changeable.
- 2 cm is the maximum allowable change in the inlet position and dimension.
- 1 mm minimum wall thickness, to bear the 16-bar pressure.

While designing the pressing air nozzle, design for additive manufacture approach has been used, the following considerations have been taking into account during the designing process:

- Avoid adding material where it’s not needed. Enough material is added to withstand load applied to the part.
- Building direction decision.
- Avoid overhanging as much as possible.
- Minimize the amount of support structure as much as possible.
- Utilize the advantage of design freedom offered by AM, to modify the internal channels and give them smother radiuses.

This approach has been considered in designing concept A and concept B. Both suggested designs were given smother radiuses and the amount of material used has been significantly decreased.

13 DESIGN CONCEPT A

Design concept A is the first designed suggested as an alternative design for the pressing air nozzle. Based on the limitations mentioned and the DfAM approach, A CAD model has been created. Figure 35 shows the assembled model

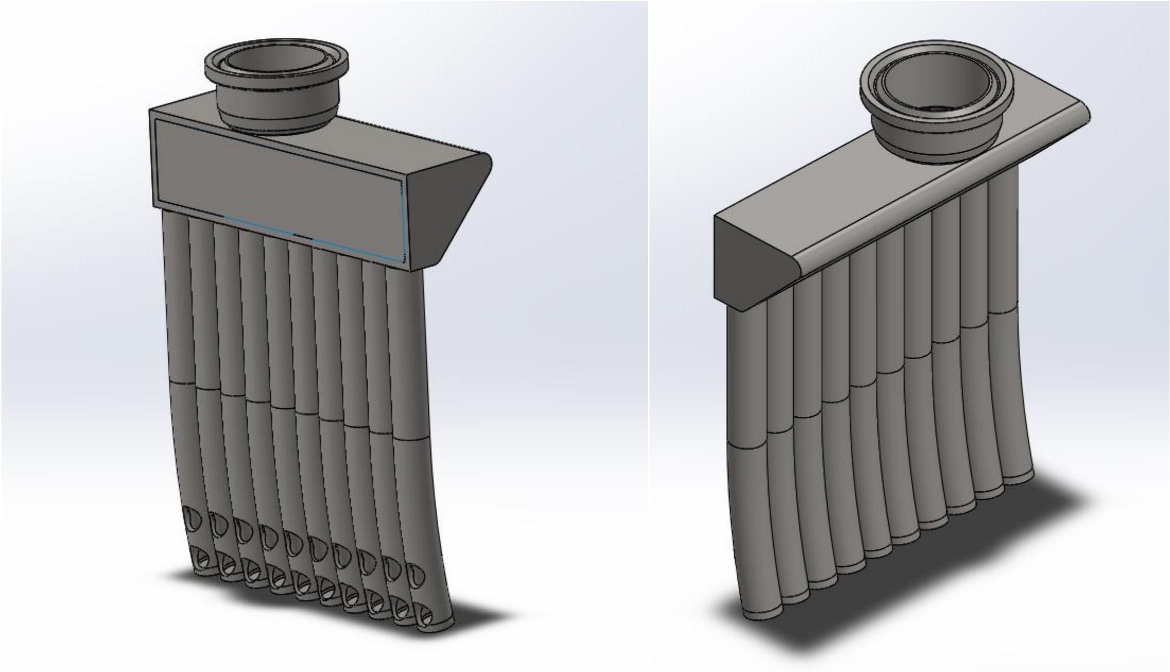

Figure 35. Assembled view of Design concept A.

See Figure 36 for a side cross section showing the enhanced air channels the new design A has. Air channels with smother reduce transition and less material has been obtained.

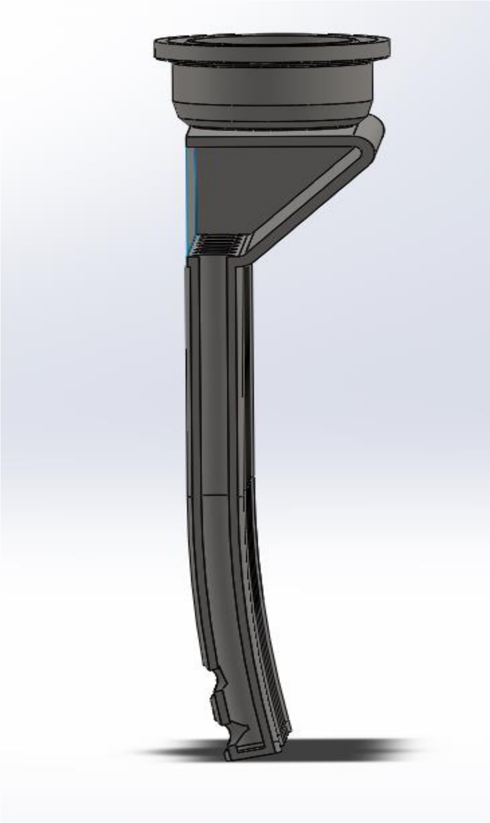

Figure 36. Side view of design concept A.

13.1 Building direction

It's important to consider the building direction while designing for AM. Powder bed fusion technology bed powder is acting as a support structure to some extent if overhanging structures are existing. In order to minimize the number of support structures, overhanging below 35°-degree angle are recommended. Figure 37 shows the intended building direction of the air nozzle (design A).

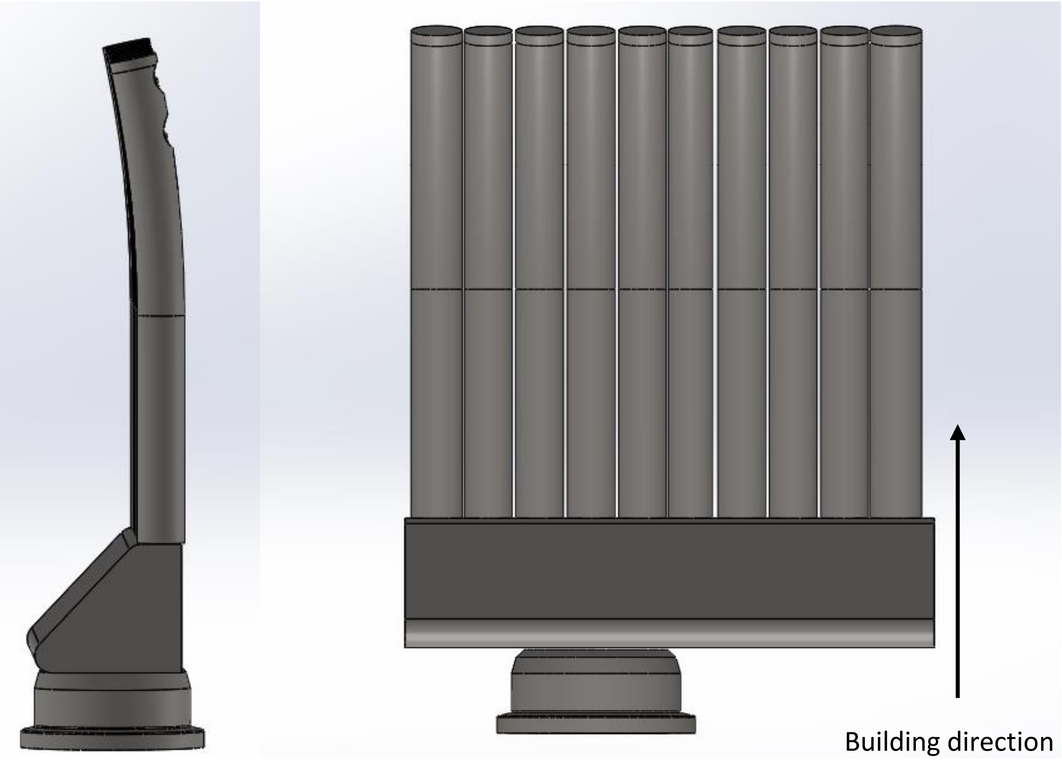

Figure 37. Building direction for design concept A.

As shown in Figure 37 Smother radial transition have been applied to air channels in order to add material outward.

13.2 Weight Reduction

Regarding saving material, a significant reduction in the consumption of material has been accomplished and logically that lead to significate weight reduction. Presented in Figure 38 a comparison between the original design and design concept A. The intention of the Figure is to show the material cut down in the new design A.

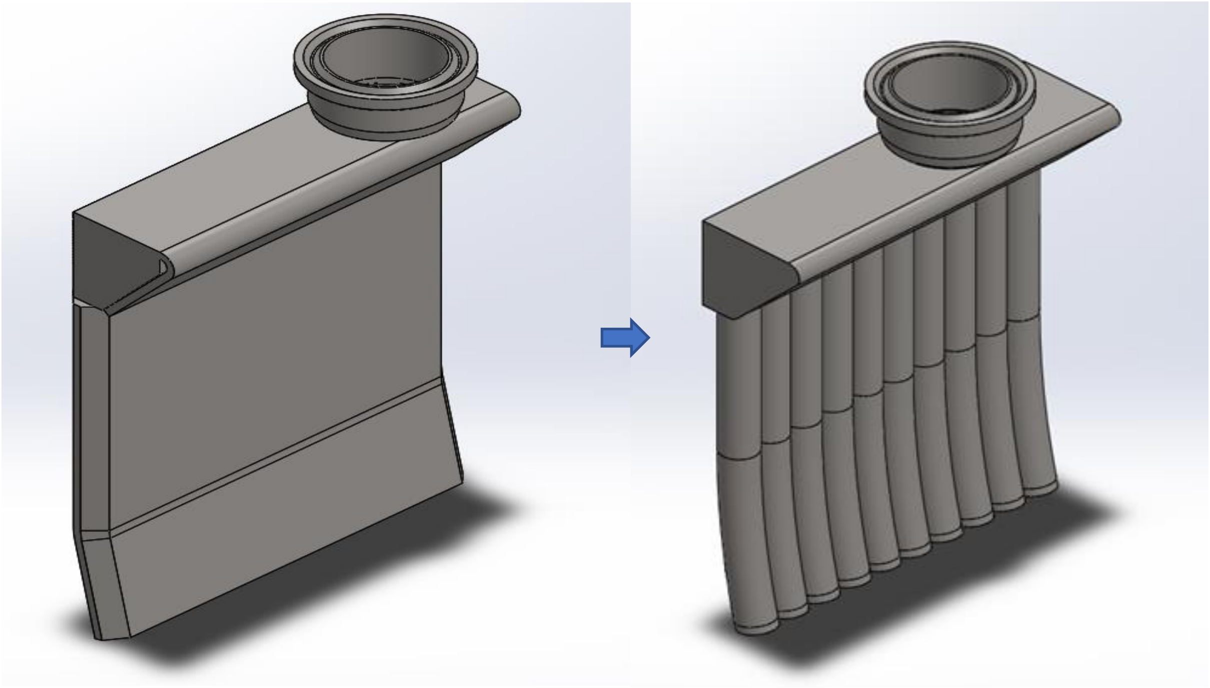

Figure 38. Original design vs. new design concept A.

The weight difference between the two designs can be seen in Table 1. 316L stainless steel assigned as material to the new Design A. The weight data have been extracted from the CAD-model.

Table 1. Weight comparison for design A.

Design	Total weight[gram]
Original design	2144.19
New design A	1109.36

As seen in Table 1 a weight reduction by 48.3 % has been accomplished. Which make the new design A almost 1 kg lighter than the original one.

14 DESIGN CONCEPT B

As same as concept A, concept B was designed based on the limitations mentioned and the DfAM approach. A CAD model has been created using Solidworks. Figure 39 shows the assembled model.

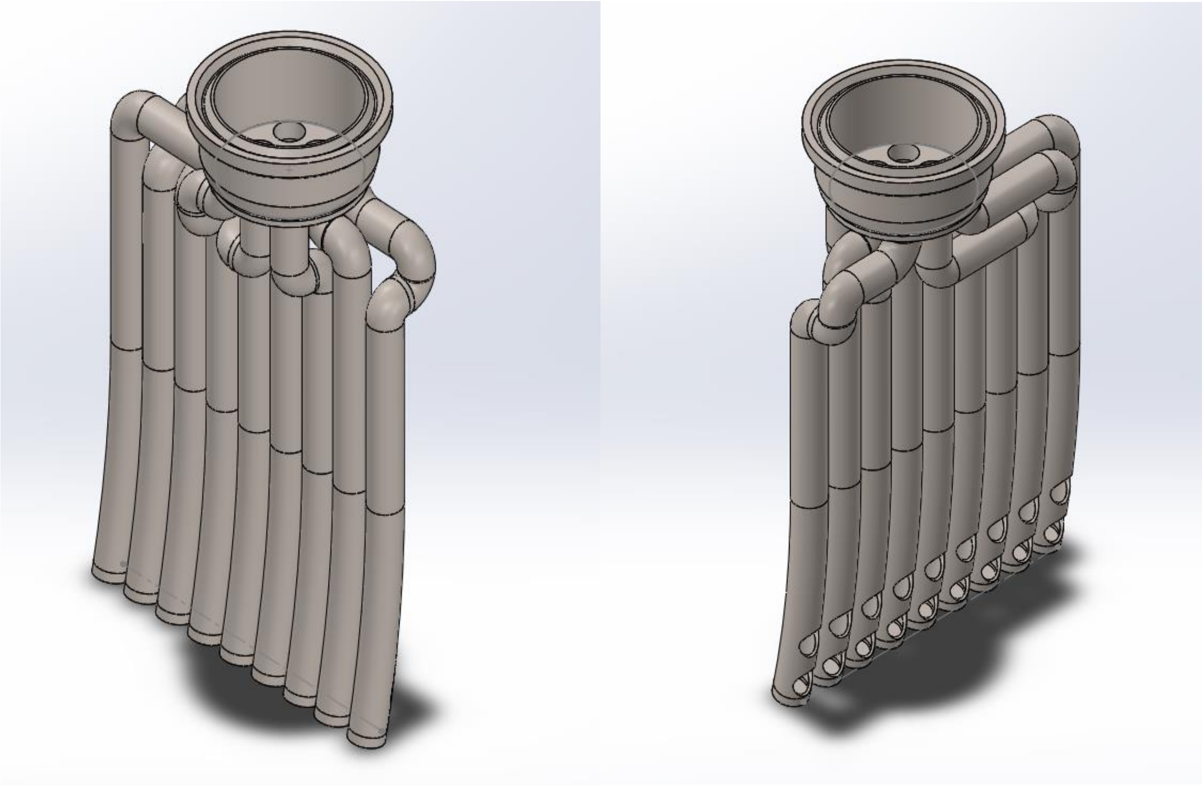

Figure 39. Assembled view of Design B.

As seen from Figure 39 in design concept B the vessel part connecting between the inlet and the air channels has been removed, and air channels start directly from the air inlet.
See Figure 40 for a side cross section showing the enhanced air channels the new design B has.

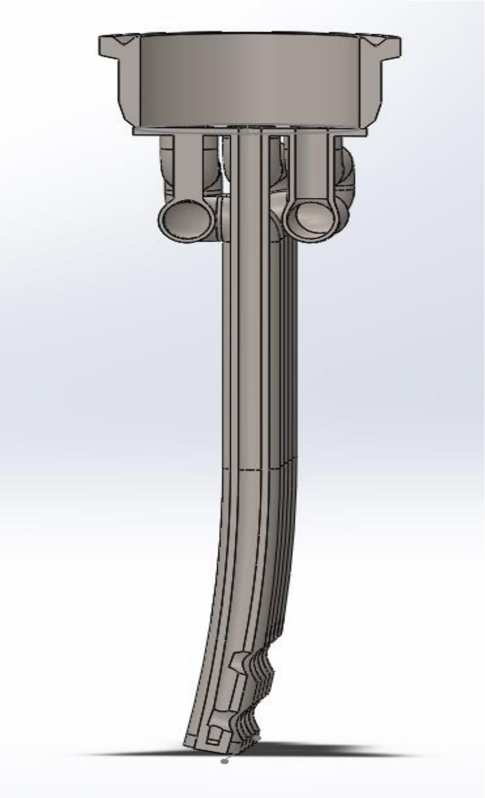

Figure 40. A cross-sectional view of design concept B.

As seen from the Figure air channels with smother reduces transition and less material has been obtained.

14.1 Building direction

The same consideration mentioned before have been made while deciding the building direction for design concept B. Figure 41 shows the intended building direction of the pressing air nozzle (concept B).

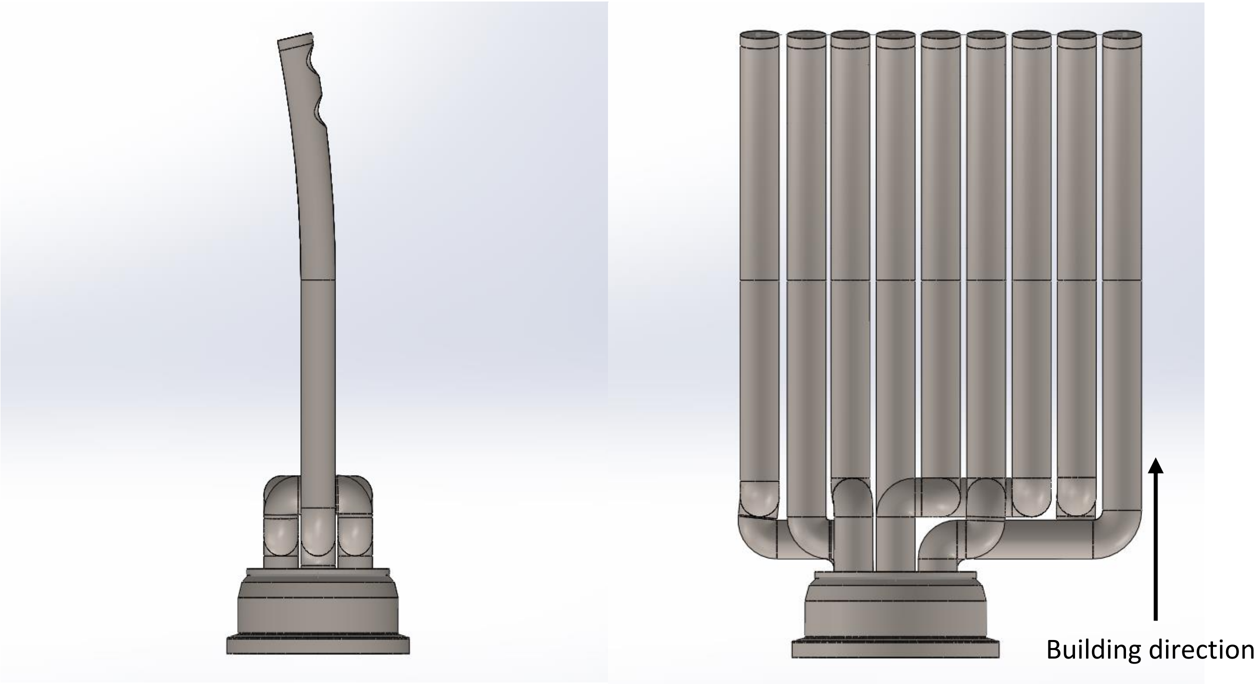

Figure 41. Building direction for design B.

14.2 Weight Reduction

Regarding saving material, a significant reduction in the consumption of material has been accomplished and logically that lead to significate weight reduction. Presented in Figure 42 a comparison between the original design and design B. The intuition of the Figure is to show the material cut down in the new design B.

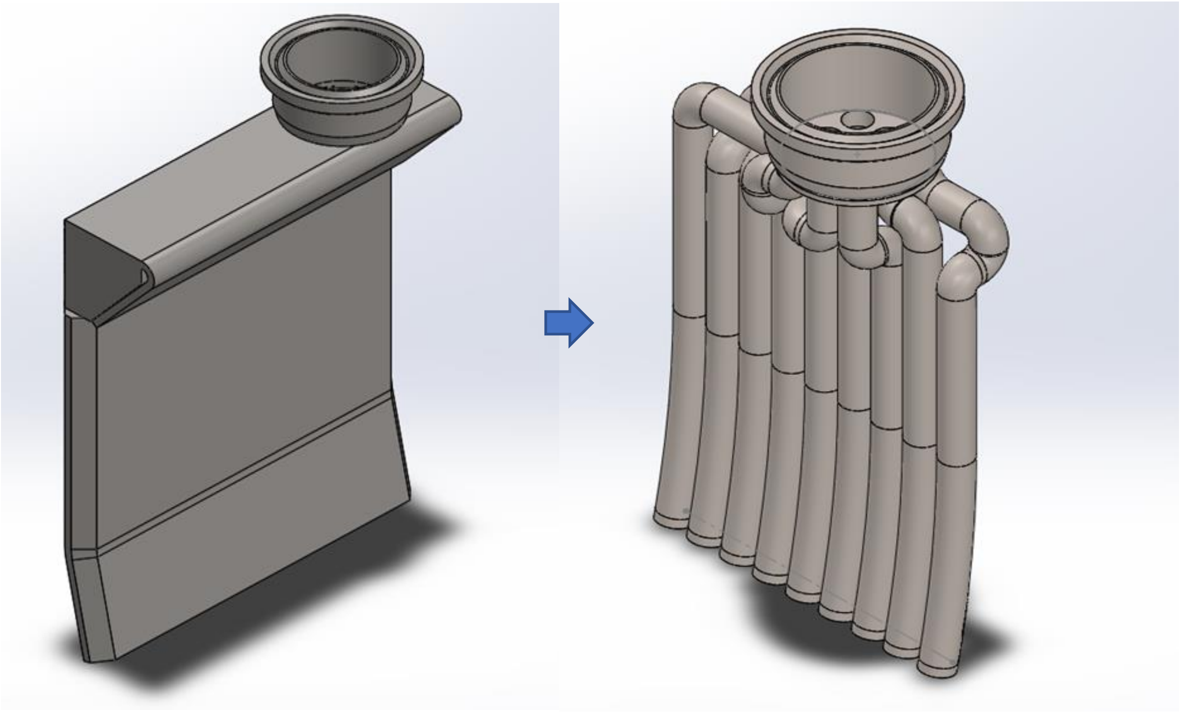

Figure 42. Original design vs. new design B.

The weight difference between the two designs can be seen in Table 2 316L stainless steel assigned as material to the new Design A. The weight data have been extracted from the CAD-model.

Table 2. Weight comparison between the original design and design concept B.

Design	Total weigh[gram]
Original design	2144.19
New design A	652.08

As seen in Table 2 a weight reduction by 70.3 % has been accomplished. Which make the new design A almost 1493 gram lighter than the original one.

15 CFD ANALYSIS

Pressure losses and velocity drop are calculated numerically in Ansys Fluent. In this chapter, the pressure losses and velocity will be calculated for all the designs the original one, concept A and concept B. The CAD models designed for every concept (in SolidWorks) will be exported to ANSYS Fluent to obtain the CFD analysis results.

15.1 CFD Simulation of The Original Design

The mesh is defined with fine global sizing with a maximum element face size of 1 mm complemented with all flow channel walls as a boundary. The inflation mesh consists of 0.5 layers and a growth rate of 1.2. The final complete mesh of the original flow channel consists of 1553813 elements and 275134 nodes with tetrahedrons fine mesh. For the mesh quality, we obtained average element quality 0.85529, orthogonal quality 0.79523 and aspect ratio 1.8451. Figure 43 shows the mesh for the original design.

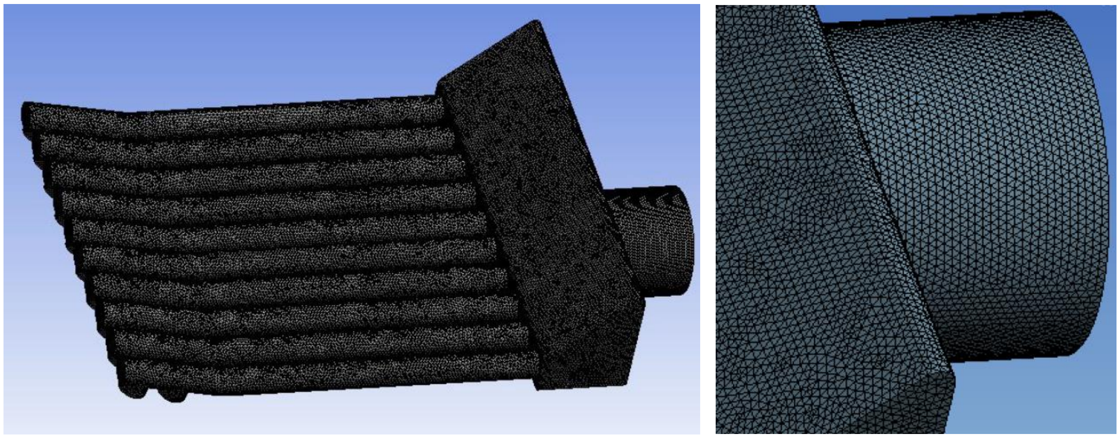

Figure 43. Original design mesh

In ANSYS Fluent, the CFD simulation is set up as a Turbulent modal with K-Epsilon flow. The fluid parameters used in this simulation can be seen in Table 3.

Table 3. Fluid parameters.

Material Properties	Air
Density	1.225 kg/m3
Specific Heat	1006.43 J/kg-k
Thermal Conductivity	0.0242 w/m-k
Viscosity	1.7894e-05 kg/m-s

As boundary conditions, the inlet is defined as a constant mass flow inlet Q 3.06 m^3/min with a gauge pressure of 0 Bar. The maximum flow is 3.06 m^3/min and the fluid density ρ 1.225 kg/m^3 is known, the mass flow $\dot{m}$ can be calculated to:

$$\dot{m} = Q\rho = (3.06/60) * 1.225 = 0.0624 \text{ kg/sec} \qquad (1)$$

The outlet is defined as a pressure outlet with a constant gauge pressure of 16 Bar. The pressure velocity coupling in solution method is defined as "simple" and with settings as presented in below Table 4.

Table 4. Spatial discretization settings in solution methods.

Gradient	Least Square Cell Based
Pressure	Second Order
Momentum	Second Order Upwind

The pressure loss is equal to the inlet pressure subtracted with the outlet pressure. The total pressure loss on the original design flow channel is shown in Table 5.

Table 5. Pressure loss on the original design.

Inlet pressure [Pa]	1.628e+06
Outlet pressure [Pa]	1.6e+06
Pressure loss [Pa]	28000

Pressure volume rendering and Pressure streamline trajectory along the cross-section of the flow channel is shown in Figure 44 and 45.

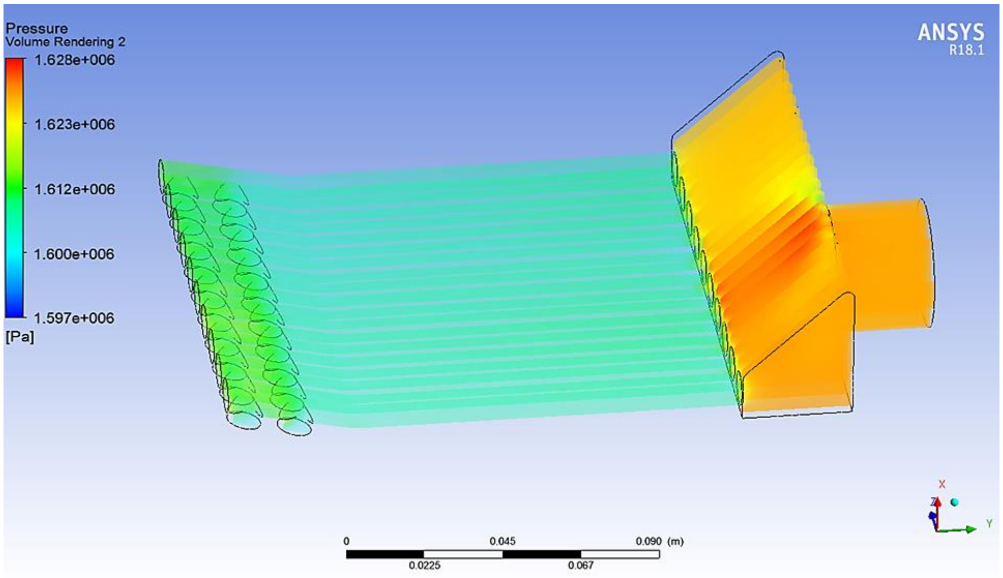

Figure 44. Pressure-volume rendering for the original design.

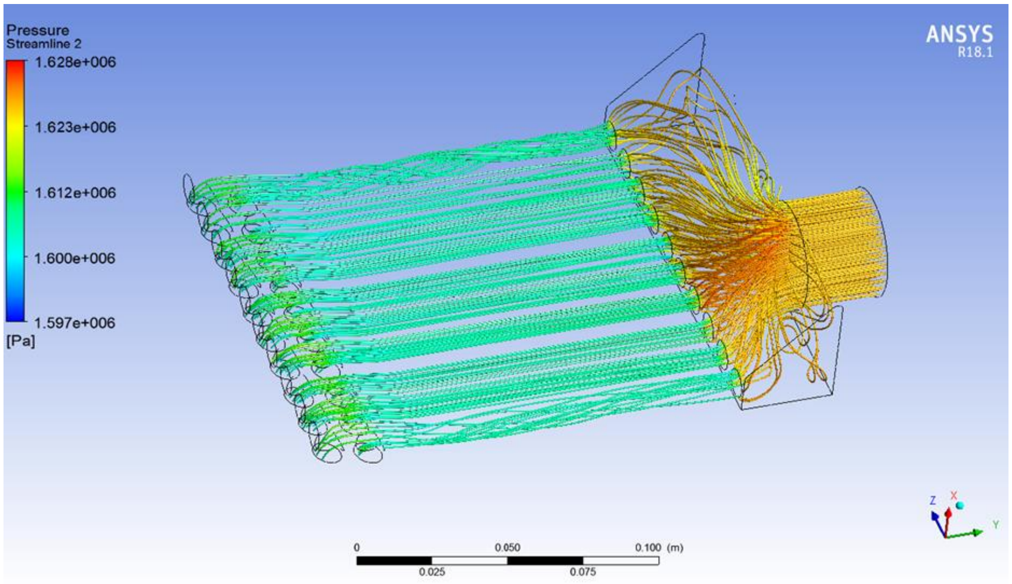

Figure 45. Pressure streamline trajectory for the original design.

Velocity volume rendering and Velocity streamlines trajectory along the cross-section of the flow channel is shown in Figure 46 and 47.

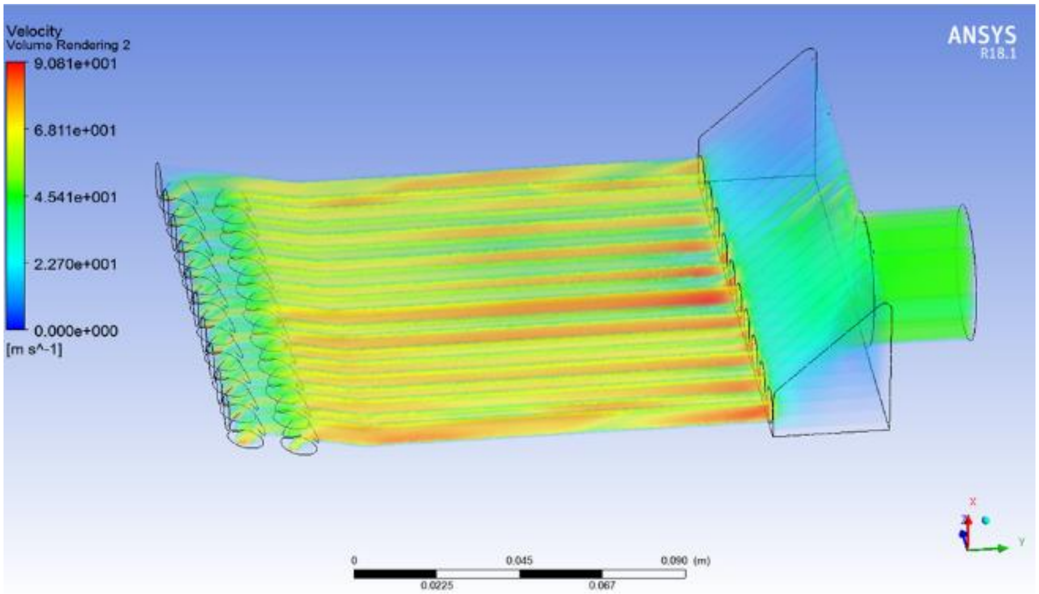

Figure 46. Velocity volume rendering plot for the original design.

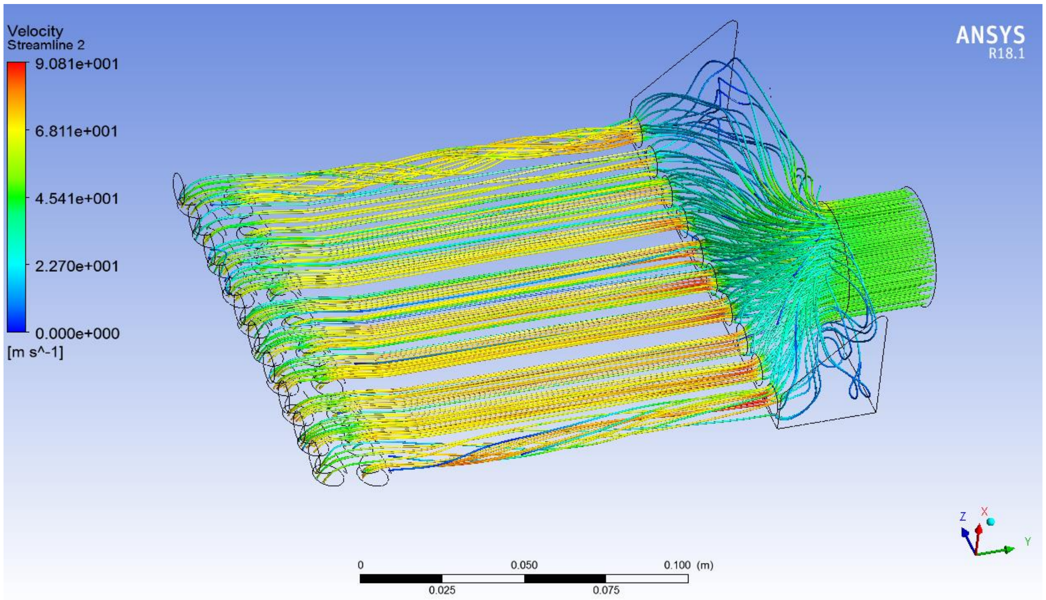

Figure 47. Velocity streamlines trajectory plot for the original design.

The velocity loss is equal to the inlet velocity subtracted with the outlet velocity. The total velocity loss on the original flow channel is shown in Table 6.

Table 6. Velocity loss on the original design.

Inlet Velocity [m/sec]	47.3988
Outlet Velocity [m/sec]	74.7786
Velocity drop	27.079

15.2 CFD Simulation of Design Concept A

The mesh is done using a similar setting and method as the previous one. Figure 48. Represent the final mesh.

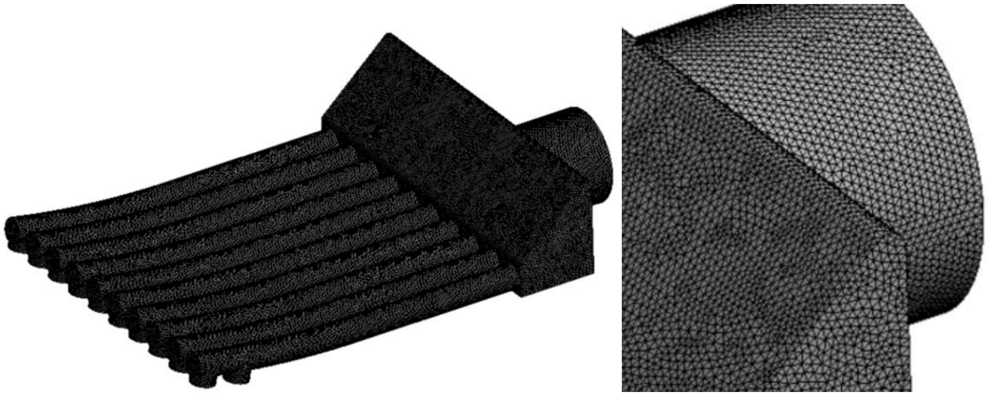

Figure 48. Design concept A mesh.

To ensure residual convergence the velocity residuals convergence criterion is set to 0.0001 and the continuity residual convergence criterion is set to 0.00001. The obtained residual levels indicate that the numerical solution is well converged. To ensure convergence the inlet pressure was monitored for every fifth iteration.

The pressure loss is equal to the inlet pressure subtracted with the outlet pressure. The total pressure loss on the original flow channel is shown in Table 7.

Table 7. Pressure loss on the design concept A.

Inlet pressure [Pa]	1.61958e+06
Outlet pressure [Pa]	1.6e+06
Pressure loss [Pa]	19580

Pressure volume rendering and Pressure streamline trajectory along the cross-section of the flow channel is shown in Figure 49 and 50.

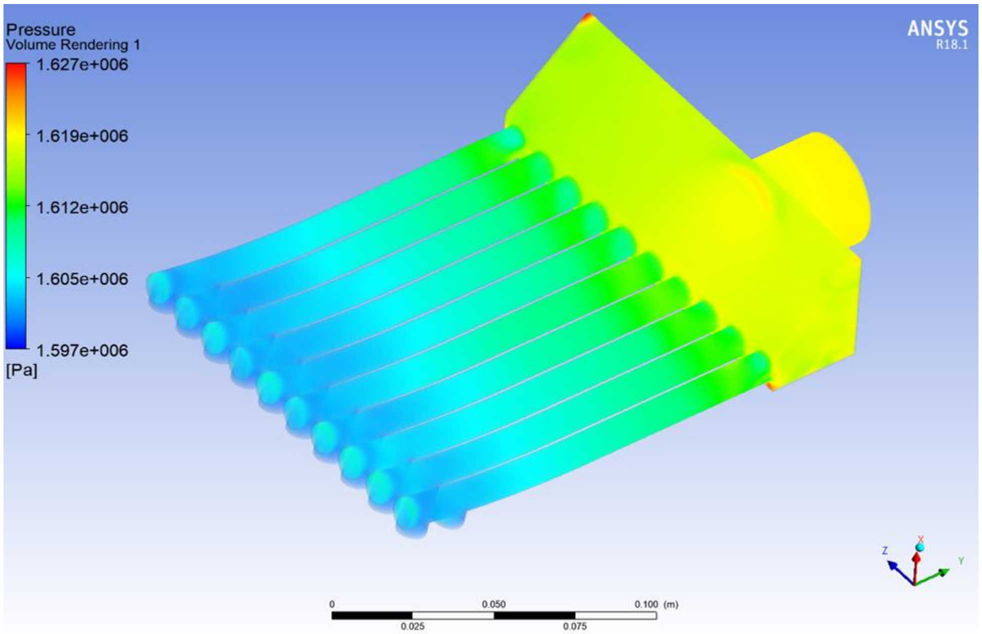

Figure 49. Pressure volume rendering plot for design concept A.

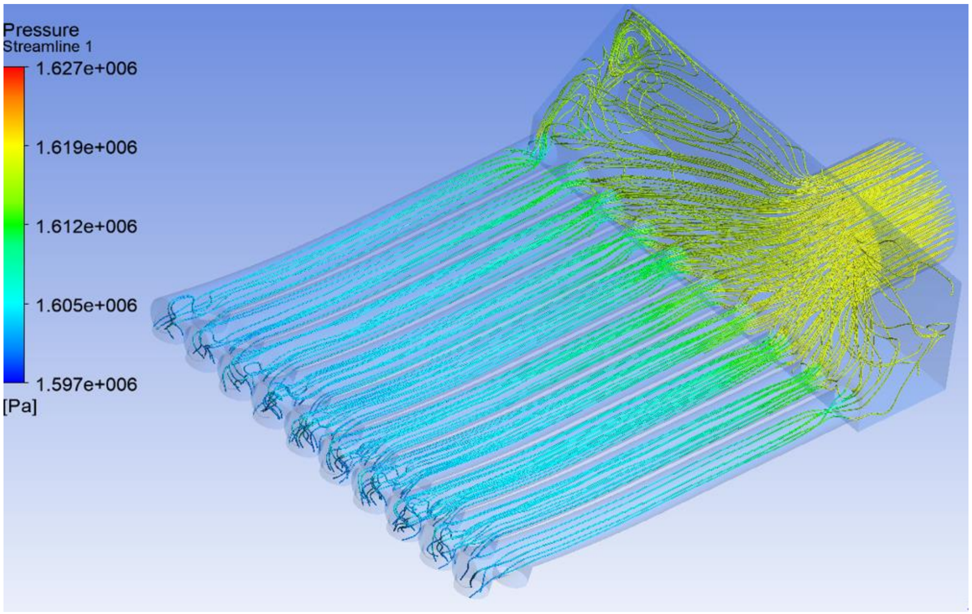

Figure 50. Pressure streamline trajectory plot for design concept A.

A velocity volume rendering and Velocity streamline trajectory plot along the fluid section of the flow channel has been obtained. This can be seen in Figure 51 and 52.

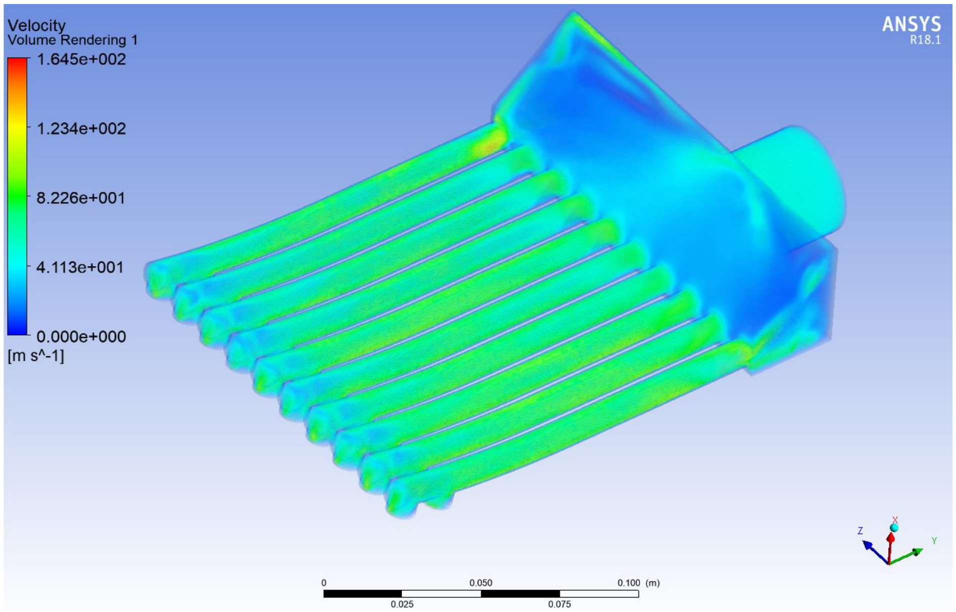

Figure 51. Velocity volume rendering plot for design concept A.

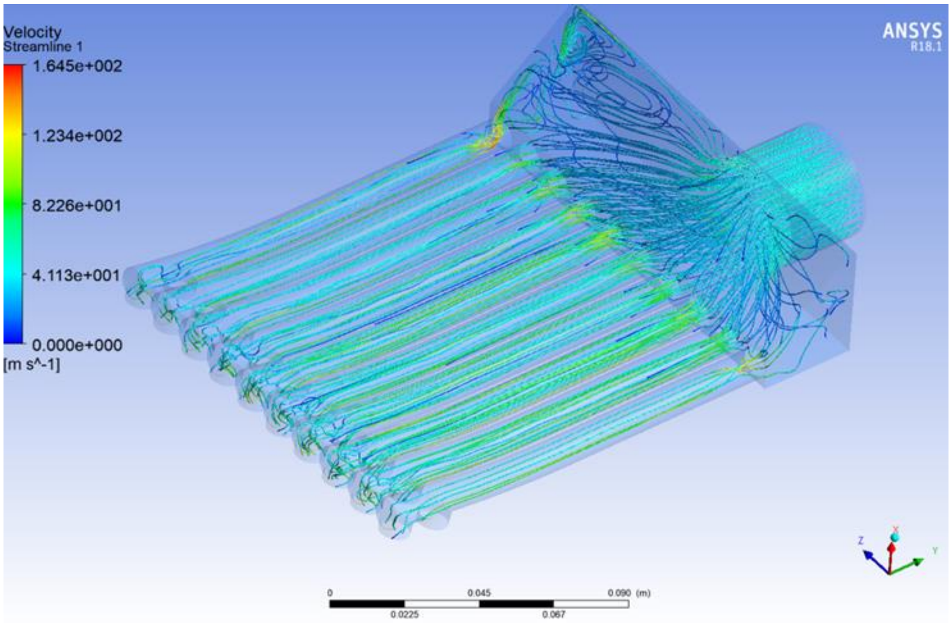

Figure 52. Velocity streamline trajectory plot for design concept A.

The velocity loss is equal to the inlet velocity subtracted with the outlet velocity. The total velocity loss on the original flow channel is shown in Table 8.

Table 8. Velocity loss in design concept A.

Inlet Velocity [m/sec]	47.3988
Outlet Velocity [m/sec]	79.6748
Velocity drop[m/sec]	32.276

15.3 CFD Simulation for Design concept B

The mesh is done using a similar setting and method as the previous one. Figure 53. Represent the final mesh of design concept B.

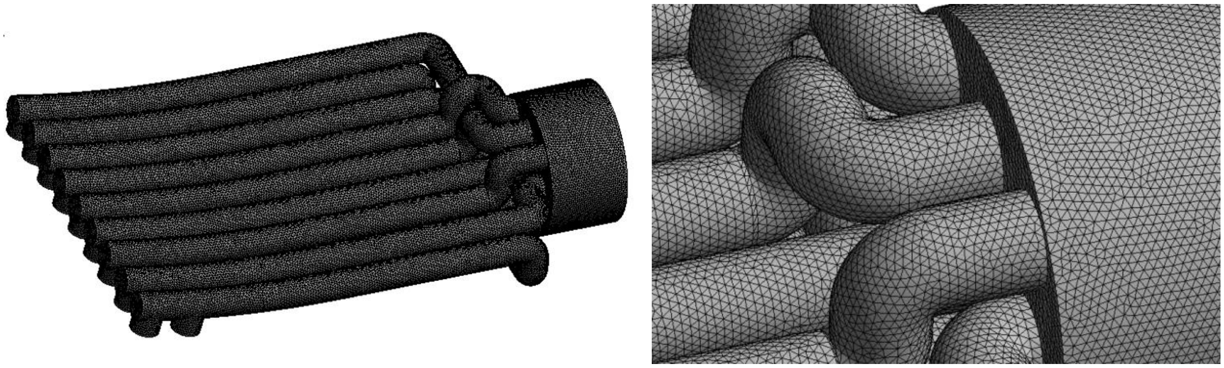

Figure 53. Design concept B mesh.

The CFD modeling has been set up with similar parameters and conditions as preciouses' simulations and pressure losses have been obtained. The total pressure loss on the original flow channel is shown in Table 9.

Table 9. Pressure loss in design concept B.

Inlet pressure [Pa]	1.61389e+06
Outlet pressure [Pa]	1.6e+06
Pressure loss [Pa]	13830

A pressure volume rendering and streamline trajectory plot for design concept B is shown in Figure 54 and Figure 55.

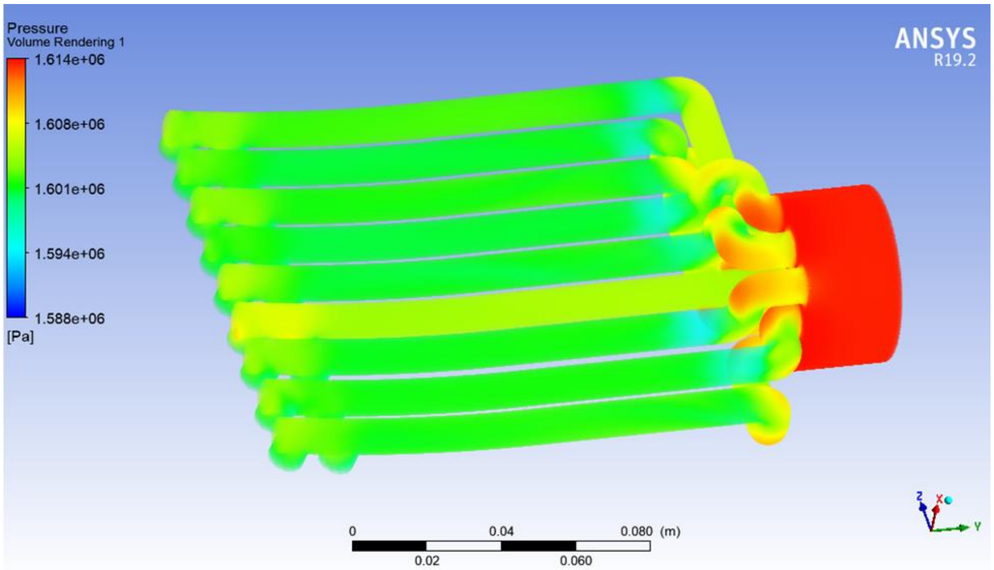

Figure 54. Pressure volume rendering plot for design concept A.

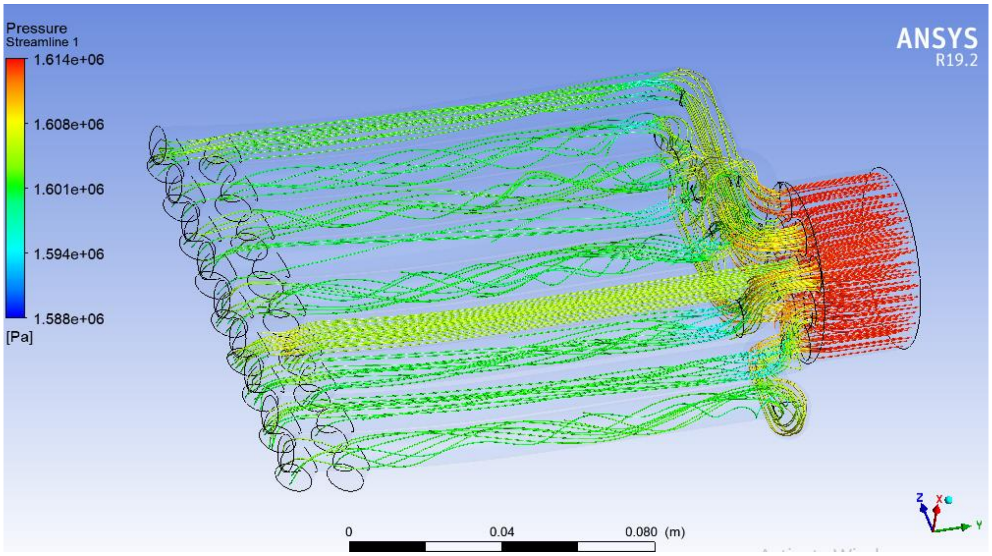

Figure 55. Pressure streamline trajectory plot for design concept B.

A velocity volume rendering and Velocity streamline trajectory plot along the fluid section of the flow channel has been obtained. This can be seen in Figure 56 and 57.

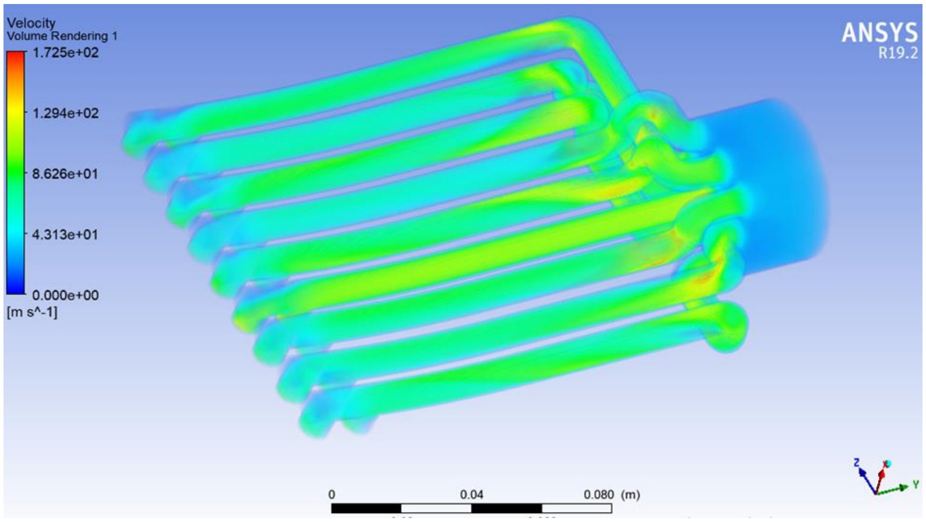

Figure 56. Velocity volume rendering plot for design concept B.

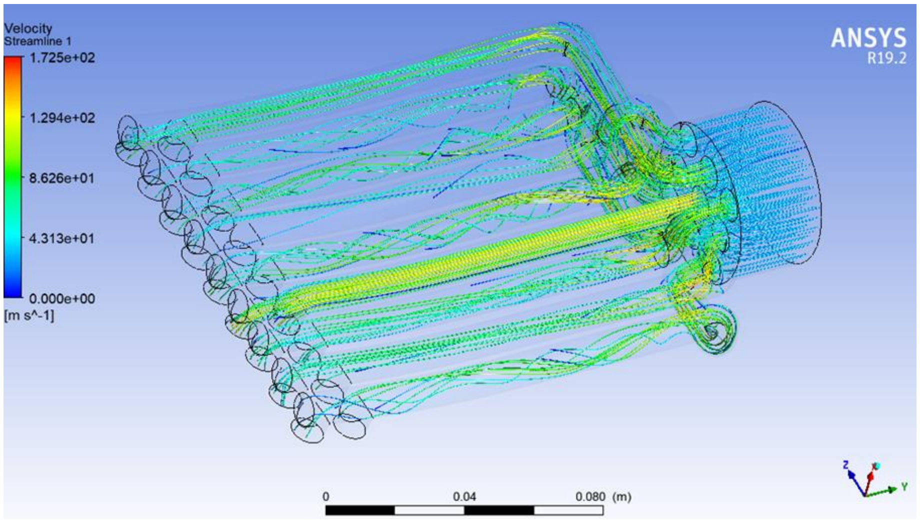

Figure 57. Velocity streamline trajectory plot for design concept B.

The velocity loss is equal to the inlet velocity subtracted with the outlet velocity. The total velocity loss on the original flow channel is shown in Table 10.

Table 10. Velocity loss of design concept B.

Inlet Velocity [m/sec]	28.1582
Outlet Velocity [m/sec]	82.1384
Velocity drop [m/sec]	53.9802

16 RESULTS AND DISCUSSION

This chapter summaries and discuss the design improvements made regarding airflow efficiency, material, assembly, and weight reduction.

A tremendous weight reduction has been accomplished by fixing the part geometry and remove all unnecessary material. Two Higley efficient designs concept were created which lightened the weight of the part scientifically without jeopardizing the strength of the part. Table 11 shows the weight reduction accomplished using DfAM approaches for concept A.

Table 11. Weight reduction for concept A.

Name	Weight [grams]
Original design	2144.19
Design concept A	1109.36
Weight Reduction [%]	48.3

Design concept A developed for AM is 1109 gram which makes it 48.3% lighter. But is the other hand parts manufacturing by AM have less surface quality compared to the traditional manufacturing processes. Therefore, often AM manufacturing parts need post processing and surface treatment and, in some cases, it can be costly and time-consuming. Table 12 shows weight reduction accomplished in design Concept B.

Table 12. Weight reduction for concept B.

Name	Weight [grams]
Original design	2144.19
Design concept A	652.08
Weight Reduction [%]	70.3

Design concept B developed for AM is 652 gram which makes it 70.3% lighter than the original design. Design B has the lightest weight because of the material reduction made by removing the vessel connecting between the inlet and the air channels, but still that resulted in high bent angels and different air channels geometry that led to poor air disruption. Changes to the inlet dimension also had to be made to fit all the channels in the inlet area which will lead to changing in the part working environment.

Regarding Air flow efficiency in the pressing air nozzle. Airflow channels in the original pressing air nozzle tend to suddenly meet at an angle that affects flow efficiency. The pressing air nozzle has a sudden 168° bent before the outlet due to the restrictions of the drilling process in traditional manufacturing. These types of issues have been investigated and by using AM it was possible to ease this bent angle in all channels in design concept A and B. in order to analyses the modification made to the air channels a CFD simulation was conducted. And the results can be seen in Table 13.

Table 13. Results of CFD simulation for all designs.

Design	Inlet pressure (Pa*10^{6})	Outlet pressure (Pa$*$ 10^{6})	Pressure drop (Pa)	Inlet velocity (m/sec)	Outlet velocity (m/sec)	Velocity drop
Original design	1.6280	1.6000	28000	47.3988	74.3988	27.079
Design concept A	1.6195	1.6000	19580	47.3988	79.6748	32.276
Design concept B	1.6138	1.6000	13830	28.1582	82.1384	53.9802

Table 13 clearly shows that regarding the pressure losses design concept B is the most efficient design with 50.6% less pressure losses. Also, design concept A has 30 % less pressure losses. The simulations results can be used as guidance for choosing the most efficient design, but the result doesn't indicate the actual pressure loses for the whole system because pressure losses due to surface roughness have not been included in the simulation.

In the other hand manufacturing using metallic AM is more expensive than manufacturing parts using traditional manufacturing methods so it´s important to estimate whether manufacturing certain components using AM will repay the investment and deliver cost-saving over traditional manufacturing.

Stainless steel 316L has been chosen as the material for AM design concept A, and B due to similarities with the original part material. However, investigating the material may lead to a better material option that has a faster building rate and better properties for both design concepts.

Regarding the Assembly process, the original design is manufactured in 3 different parts and then all these parts have to be assembled together by welding. Concept Design A and B can be manufactured in one take without the need for any assembly process. In the other hand, the surface finish of the 3D-printed parts will need post processing to reach the required surface quality.

When comparing between design concept A, and design concept B we can notice that design concept B has 29% less pressure losses and 40% lighter weight than design A. But in same time design concept A has better air distribution and less velocity drop due to less carves in the design geometry. Structural bends at the inlet of design B causes more turbulent flow and higher velocity drop.

17 CONCLUSIONS

The goal and purpose of this study case were to redesign a pressing air nozzle to achieve weight reduction, better efficiency, and functionality. The designs developed during the study was designed using Solidworks 2018 CAD software. The CFD modeling of All three designs was obtained using Ansys Fluent software. it can be concluded that design Concept B has a significate weight reduction of 70% which make it almost 1.5 kg lighter than the original design. Also, a significant enhance made in the efficiency of the air flow inside of the air channels by 50% less pressure loses. While design concept A has 48% weight reduction which makes it almost 1kg lighter than the original design beside 30% less pressure losses than the original design. Reduction of weight made in both designs can lead to easier handling, installing and reduce the energy while transportation besides the raw material saving will decreases the material waste which has a good environmental impact. Pressure losses made in both designs will lead to less energy losses during power generation.

AM leads to less assembly time due to its capability of reducing the number of the components. In the original pressing air nozzle design consists of three different components while both new designs can be manufactured in one take as one part with no assembly needed.

It also can be concluded that certain steps constraints and rules should be taken into consideration when designing for additive manufacturing and that, not all component are fit to be designed using AM technologies. AM technologies such as PBF is suitable to manufacture complex metallic parts increasing their functionality and reducing their weight.

18 FURTHER WORK

The models can continue to develop in several ways. Topology optimization ca be used to reach even more weight reduction this will lead to lowering the coast and decrease the building time. If it’s possible lattice structure can be also used to reach less time and cost. Evolution of surface roughness impact on the flow can be carried out.

CFD modeling results can be used to reach more enhanced flow channels. Manufacturing of the designs and lab testing are recommended to validate the manufacturability and the functionality of the designs.

Support structures can be modeled manually or by means of software’s available for this purpose (such as DeskArtes 3Data Expert), minimizing the support structures can lead to better build and surface quality.

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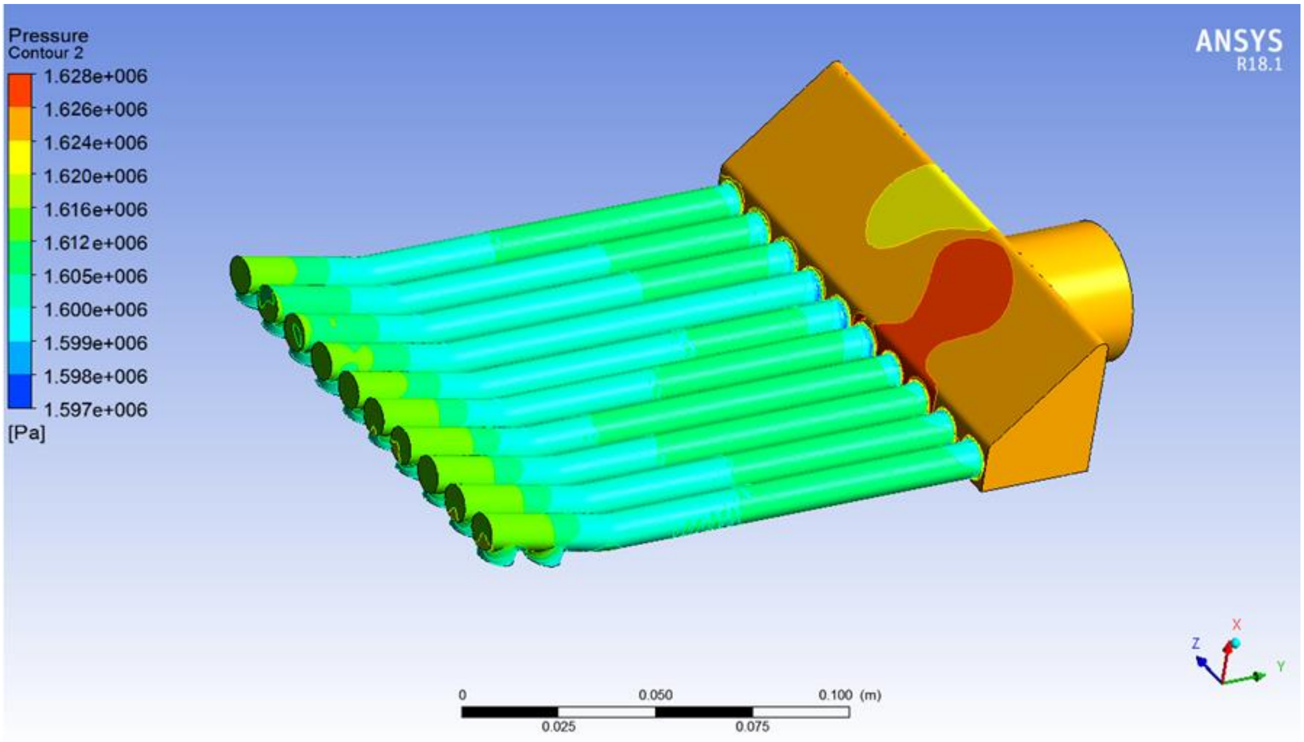
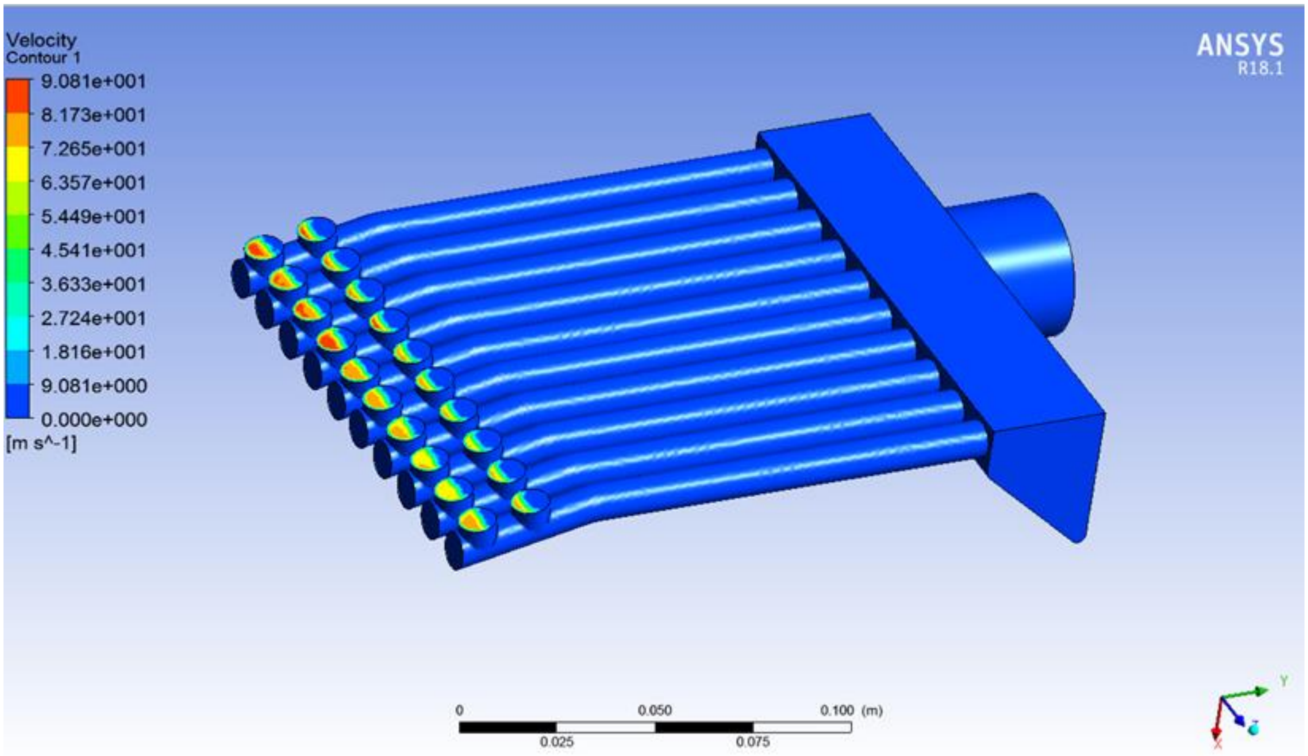
CFD Simulation results



APPENDIX I, 2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6.357e+001
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4.541e+001
3.633e+001
2.724e+001
1.816e+001
9.081e+000
0.000e+000
[m s^-1]
ANSYS
R18.1
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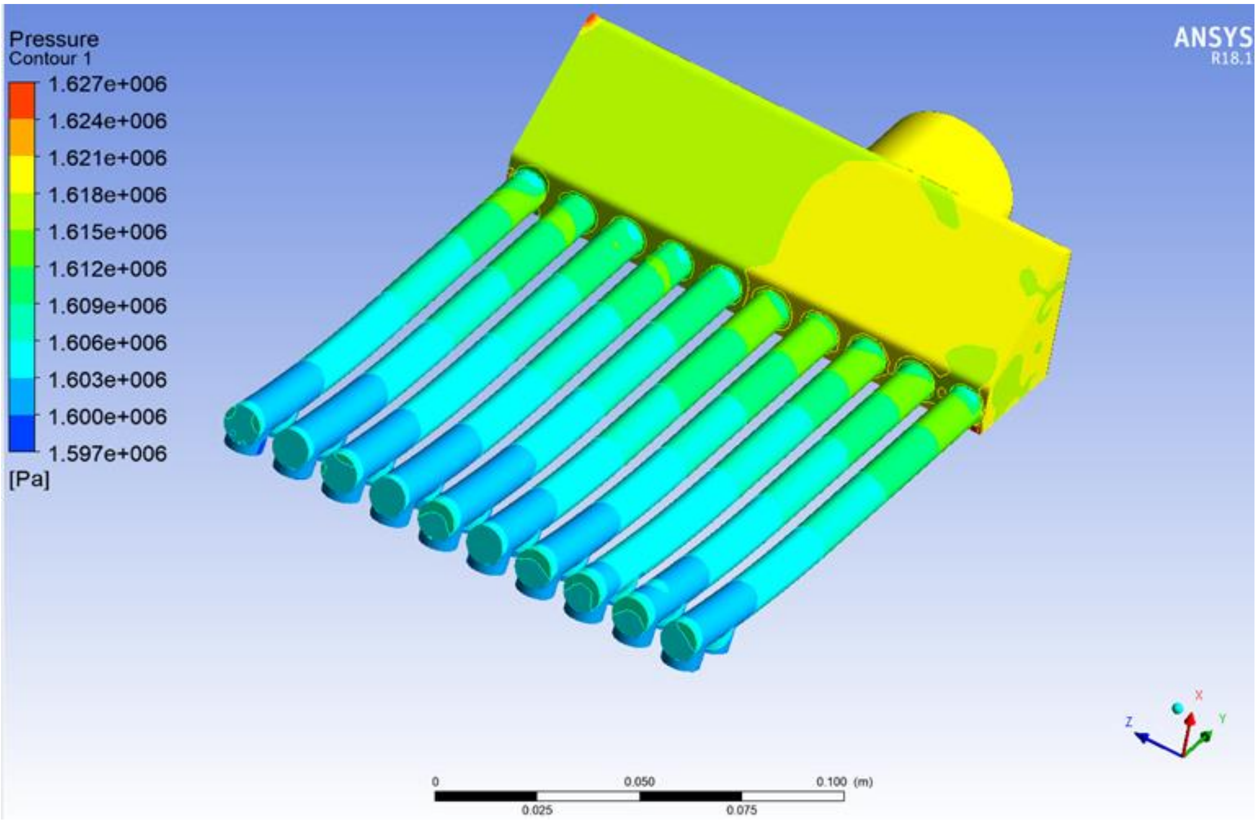
0.100 (m)
0.025
0.075
Y
X

APPENDIX I,3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1.603e+006
1.600e+006
1.597e+006
[Pa]
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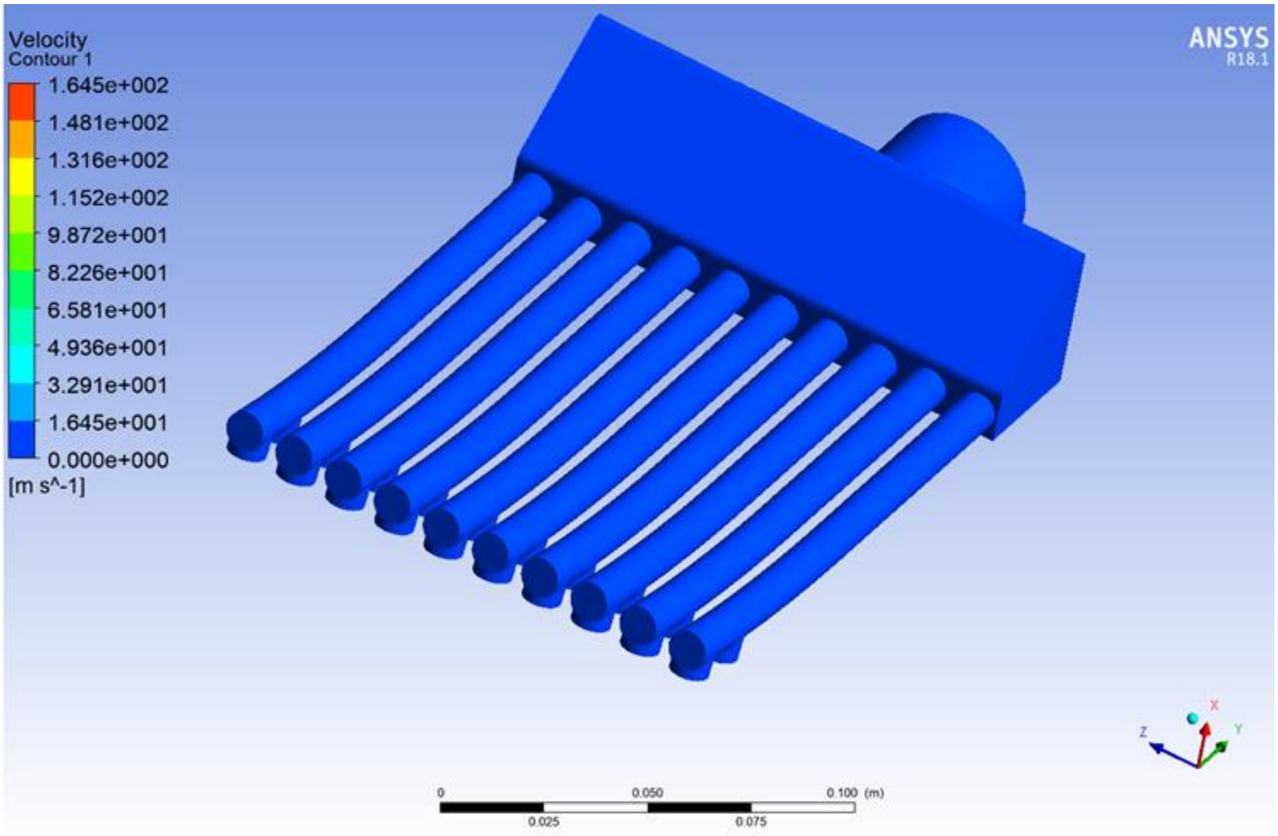
0.100 (m)
0.025
0.075
X
Y
Z

APPENDIX I, 4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4.936e+001
3.291e+001
1.645e+001
0.000e+000
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ANSYS
R18.1
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Y
Z
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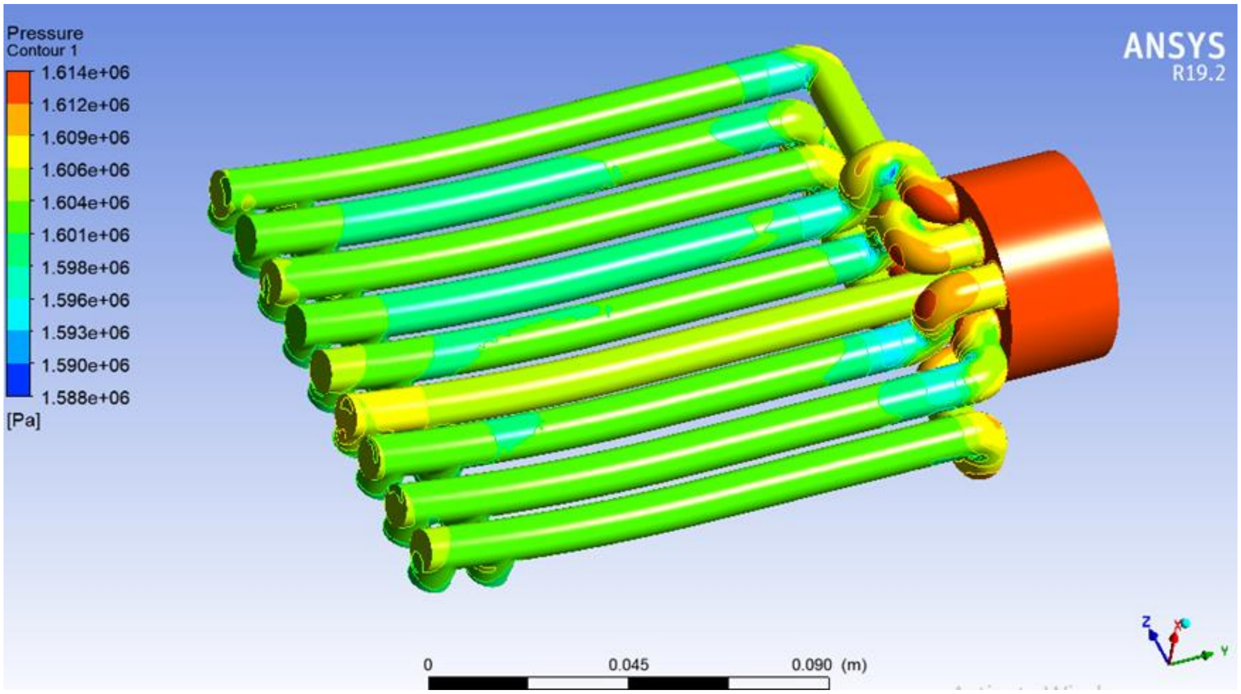
0.100 (m)
0.025
0.075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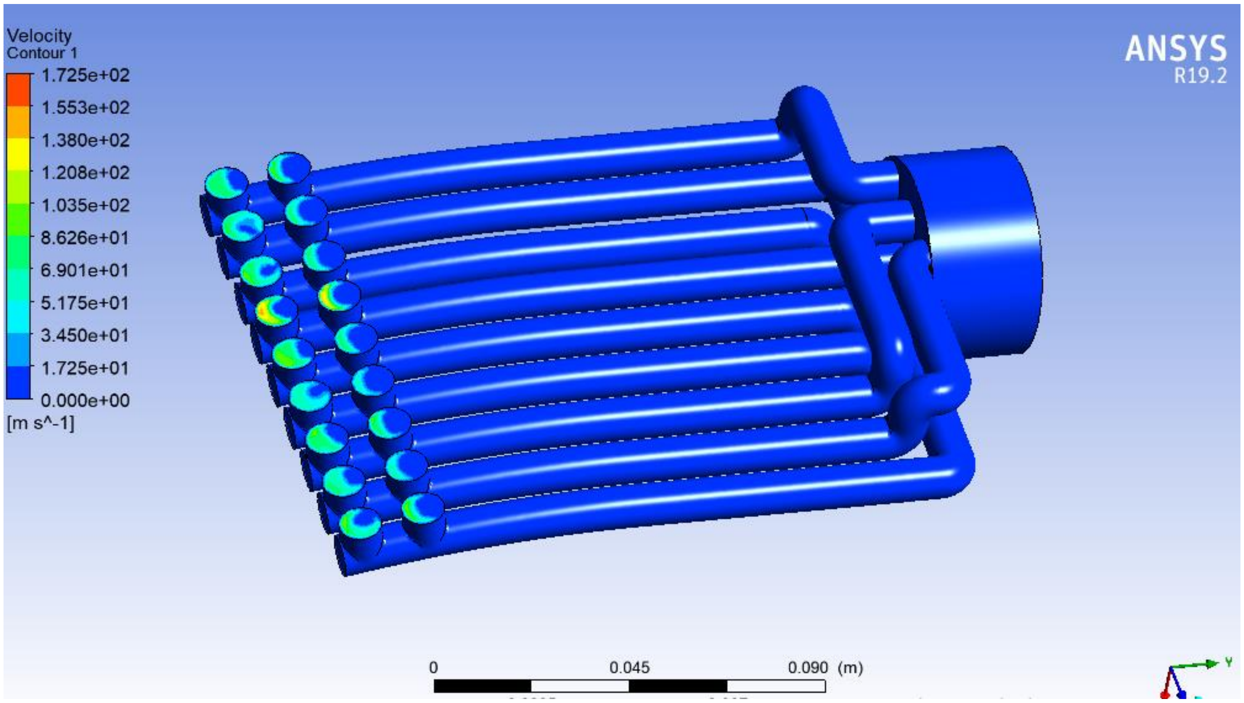
APPENDIX I, 6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5.175e+01
3.450e+01
1.725e+01
0.000e+00
[m s^-1]
ANSYS
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0.090 (m)
Y