EXPLORING A NEW ENERGY-EFFICIENT WAY TO HEAT WATER

Design of a Heat Exchanger for laundry machine applications produced using Additive Manufacturing

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1. Additive Manufacturing of Heat Exchangers in metal

This section contains a background of AM of heat exchangers followed by research questions and delimitations.

1.1 Introduction

With the unique benefits of Additive Manufacturing (AM) with metals through technologies like *Electron Beam Melting* (EBM) and *Laser Powder Bed Fusion* (LPBF), comes new ways of creating products that can increase performance while also reducing development time and material waste. The most unique feature of AM is the possibility to create very advanced geometries like complex lattice structures without much effort when compared to traditional manufacturing where it could be impossible or extremely costly. Designers can use these complex geometries to create products that have higher surface area to volume ratio with the help of *triply periodic minimal surface* (TPMS). In addition, the geometry of such structures like the gyroid lattices helps to increase the surface area without decreasing the hydrodynamic flow too much. These characteristics make the AM technology highly suitable for heat exchangers (HX) as they require high surface area with minimized pressure drop to create efficient transfer of heat between matter (Peng et al., 2019).

A market research on the use of AM for HX quickly showed that this is an upcoming field with a lot of potential as some companies like *Conflux* and *re-generate* specialize solely on using AM to produce products for heat transfer (figure 1).

Figure 1. Heat exchangers for Additive Manufacturing designed by Conflux (left) and re-generate (right).

To help in producing such parts the company nTopology provides a modern CAD modeling software specialized to handle complex geometries (VELO3D, 2020). In one of their webinars with VELO3D they present a redesign of a traditional HX that reduces pressure drop by more than 6 times while having 60% more surface area and thus also being much more efficient (figure 2). Similarly, the simulations of a study by Peng et al. (2019) on a HX done with AM showed that heat transfer were more than 7 times better than a traditional plate heat exchanger.

Figure 2. Comparison of traditional heat exchanger and heat exchanger with triply periodic minimal surfaces.

Note: From the webinar *VELOVirtual: Next Generation Heat Exchangers* by VELO3D and nTopology (2020).

One other aspect of AM is the high freedom of design and decreased development time as no tooling is needed when parts are built layer by layer. nTopology compared traditional HXs with HXs created with AM and found these benefits: (1) reduced number of parts and thus lower assembly cost, (2) weeks instead of months per design iteration, (3) shorter lead time per part led to the possibility to make more design iterations (VELO3D, 2020).

Heat exchangers, or more generally, components that transfer heat are used in many different types of products for cooling in refrigerators or cars and for heating buildings and water. Laundry machines are one such product and the heated water that is required is by far the most energy consuming of all energy needs during a laundry cycle. Numbers naturally vary but a regular wash usually requires around 1 kWh to heat the water for one laundry cycle (Golden et al., 2010). Similar to a water kettle, laundry machines use simple heating rods to heat the water while the water is resting in a basin. While it is true that laundry machines have become more energy efficient over the years by for example reducing the amount of water used, there seems to be a lack of development when it comes to finding new, more efficient ways of heating the water.

1.2 Aim of the exploratory research project

With the increasing popularity of AM with metals, the technology finds more and more applications and heating laundry water could be one. To further explore how AM can be used to transfer heat to water more efficiently, a concept will be created to harness the power of AM to produce a HX for laundry machines. The aim is to develop an AM-specific design as a prototype that can be used as a proof of concept to help future development of a modern and energy efficient way to heat water for laundry or similar. More specifically, can a HX with complex lattice structures be created with AM to heat water for a laundry machine and can it have the potential to be more efficient than traditional heating methods?

1.3 Delimitations

As the project is part of a school course at Chalmers University of Technology some delimitations apply. The concept will be designed to fit the size and material regulations of the LPBF-printer EOS M290 provided by Chalmers and adhere to other general limitations of LPBF printing. Moreover, since the designed component is only a prototype, some elements (e.g. insulation layer, heat source and post-processing of the component) will not be included in the delivered product, even though they were taken into consideration during the design.

2. Theory on Heat Transfer

An important part of the pre-study is studying the physics behind the concepts that are considered. This part the findings regarding the heat source and heat exchangers are presented.

2.1 Conduction vs. induction

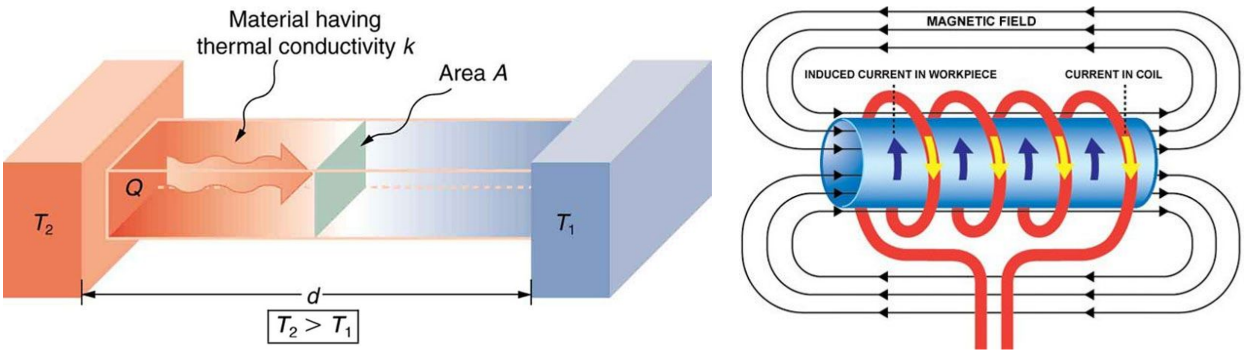
Two methods of heat transfer were considered - conduction and induction heating. The two of them are very different and are operating based on different physics phenomena.

Conduction heating occurs when the moving molecules of the bodies collide transferring kinetic energy. Conduction is therefore possible only when the bodies that exchange the energy are in direct contact (figure 3). The rate of the heat transfer depends on the temperature difference between the bodies as well as thermal properties of the bodies' materials (von Böckh & Wetzel, 2012). Overally, the conduction heating is pretty straight forward, therefore it would be easy for us to implement it in our HX, providing an external heat source is incorporated in the design.

The principles of the induction heating, on the other hand, is not as intuitive. Induction heating is based on direct resistance heating, where the increase of temperature is caused by electric current flowing through the body heated (Lupi et al., 2015). In the induction heater, the heated object (made from ferrous metal) is placed inside the coil connected to AC current generator. This induces a rapidly changing magnetic field, that in turn is a cause of so called eddy currents (figure 3.). As opposed to the conduction heating, induction heating does not require any external heat sources, as the heat is generated directly inside the body, which leads to much quicker temperature rise.

As none of the people for the group working on this project had much understanding of this method and did not have any previous experience, it was decided that induction heating involves too many unknowns and uncertainties for us and it would be better to proceed with the former method of heat transfer. Moreover, since the metal in the induction heating case must be ferrous, the choice of material for the heat exchanger would decrease significantly, as neither aluminium nor copper fulfill this requirement. Additional argument for the conduction heating was the possibility to set up the experiments to calculate real efficiency of the component, providing it could be printed early enough.

Figure 3. Schematics of two methods of heating: conduction (left) and induction (right)



Sources: Openstax College Physics (left), Chengdu Duolin Electric Co., Ltd., https://www.duolin.com/induction_heating/ (right)

2.2 Other considerations

While designing a heat exchanger, there are several aspects that need to be evaluated. Peng et. al (2019) listed four factors that are important to consider.

- *Operating pressure and temperature.* These parameters have a strong influence on the choice of the material. They can also impact the final decision of the designer regarding the type of the heat exchanger.

- *Pressure drop.* To force the passage of fluid from one place to another with higher potential, the fluid must be under enough pressure. In fluid mechanics, energy losses are reflected in pressure losses. In this case maintaining a high fluid velocity of pressure after the heat exchanger is not crucial, since the water flows into the laundry machine directly from HX, nevertheless, too high pressure losses can put the flow to the halt.
- *Thermal effectiveness.* Two components are responsible for a good thermal effectiveness - large heat transfer surface area and large heat transfer coefficients of the materials. High surface area can be obtained with the help of AM.
- *Fouling.* Excessive accumulation of dirt/particles should be avoided, so the design of the heat exchanger needs to account for that.

3. Development of the concept

Figure 4 illustrates and summarizes the process of developing a part created for AM where the main focus area for this project has been to conceptualise and design a product that is well suited for such a manufacturing method. Hence, this section describes the background of the concept, its three design iterations, and the final concept. Details regarding material choice, lattice structures and AM-specific design features will follow after.

Figure 4. A development process for LP-PBF starting with concept & design. Image of all iterations below.

Concept & design → AM-specific design in Fusion 360 & nTopology

Build preparation → Part prepared in Materialise Magics

Printing → Part printed on an EOS M290 at Chalmers

Unpacking → Unpacking made by staff at Chalmers

Thermal treatment → Stress relieving

Build plate removal → Removal made by staff at Chalmers

Support removal → Not needed as no supports are printed

Post processing → Hot Isostatic Pressing (HIP) treatment

Finished part → Assembly with heating cartridge & cabling

3.1 Collaboration with Mimbly and Podab

The market research showed that use of Additive Manufacturing (AM) for transferring heat in an efficient way is still in its infancy which led the group to contact multiple companies within relevant fields to see if they had some product or development project that could benefit from a HX created by AM. The startup Mimbly is developing the product Mimbox that reuses and filters laundry water and was in need of a way to heat the water that was going to re-enter the laundry machines after being filtered. As the company stems from Chalmers Ventures and one of the group members had been in contact with their Chief Design Officer Emil Vestman before, it was a natural fit to explore how metal AM could benefit their product development.

At the initial exploratory meeting Vestman presented the Mimbox and spoke of how the product might need to re-heat the water that would go back to the laundry machine after passing through its cleaning system. Possible ways for heating with traditional heat exchangers were discussed and also on possible placement for such a product within the Mimbox which did not have a lot of spare space left. As AM-HXs are more space efficient it could be the way to go. The group also discussed if the AM-HX should be placed by the laundry machine instead to reduce heating loss during the meter-long tubing from the Mimbox to the laundry machine. All agreed that adding an AM-HX by the laundry machine was the best option and Vestman thus introduced the group to Jimmy Nilsson, the CEO of Podab that collaborates with Mimbly by providing professional laundry machines like the Podab HX 65 for testing with the Mimbox (figure 5).

The group then contacted Nilsson to further discuss how their laundry machines use heating rods to heat the water to the required levels for each wash and if an AM-HX could be more efficient and thus better for the environment. Nilsson quickly became intrigued by the idea and provided some energy data on their laundry machine Podab HX 65 so that the group could start working on a proof of concept for more energy efficient heating of laundry water.

Figure 5. Representation of how Mimbox could be used with a Podab laundry machine.

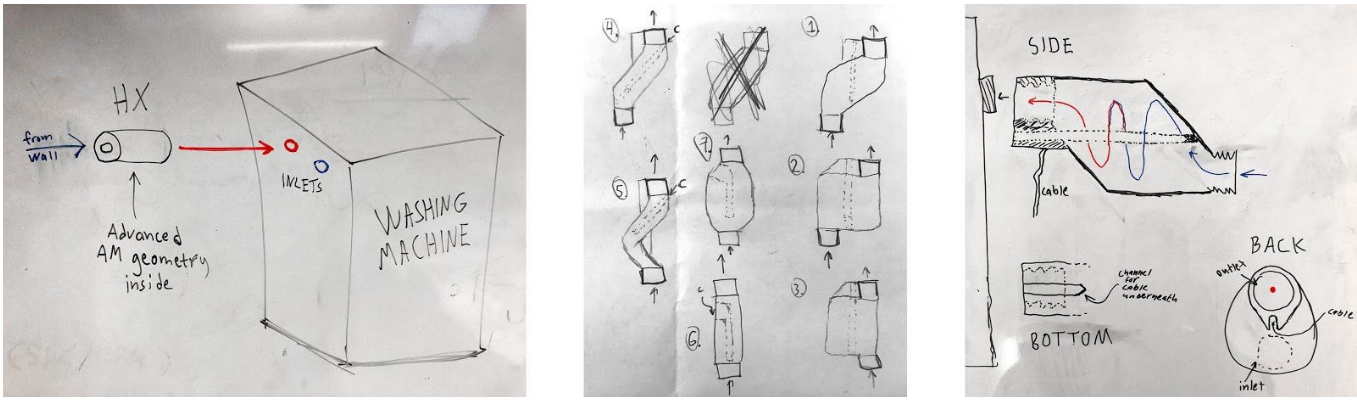
3.2 Concept ideation

The discussions with Vestman and Nilsson gave the group a starting point for brainstorming on how water could be heated efficiently with the delimitations of the project in mind. For faster iteration and testing of prototypes the group decided to create a heat exchanger that attaches to the outside of the laundry machine rather than on the inside. To be as energy efficient as possible, the first concept was aimed at creating a single phase heat exchanger(hot liquid heats a cold liquid or vice versa) but as the flow of hot and cold water was not constant, the group decided to explore other methods like conduction and induction. Induction was beneficial as it could heat the liquid without touching the metal casing or water but this would also require a bigger effort on isolating the product as it would be out in the open which could harm users.

3.2.1 Exploring conduction concepts

To take full advantage of AM technology the group aimed to create a product that would need little to no post-processing like support, removal, drilling or surface finishing. Early sketches explored how a product could be shaped so that an inlet and outlet for water could be printed so that it could attach directly in between a laundry machine and the normal cold water inlet. The sketches also explored various shapes to give space for inserting an electrified heating cartridge and also allowing lattice structures to circle around that axis. Inspiration was taken from 3D printers that use such a heating cartridge to heat the surrounding metal and thus also heating the plastic filament passing through the metal channel (figure 6).

Figure 6. Concept idea (left), shape variations (middle), iteration 1 (right).



3.2.2 Vertical cartridge insertion (Iteration 1)

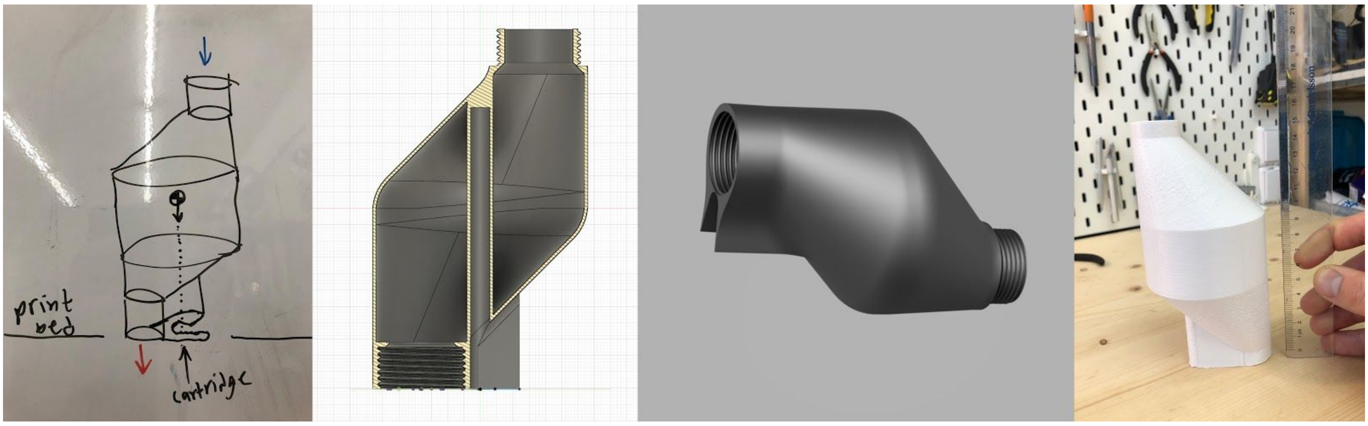
After exploring various shapes the group found that a vertical alignment of inlet, outlet and cartridge channel would be a good design for printing with AM. Using the sketch and size limitations of the project, a first CAD model was created in Fusion 360 and printed as a prototype with one of the group members' FFF printer.

Figure 7. Test prints to find the right scaling of threads for good fit.

In this stage, simple tests were also made with various scaling of thread models that were printed to test how well they would fit with real water couplings used with laundry machines. Tests with FFF and SLA printing showed that a scaling of 4 percentage points was sufficient to fit well (figure 7).

A vertical alignment worked well for AM printing but the group found that creating lattice structures around the cartridge channel was not really efficient as some water would drift too far from the heating source (see the right image of figure 8 for a sketch of the water flow).

Figure 8. Concept sketch (left), section analysis (middle left), render (middle right), FFF print (right).

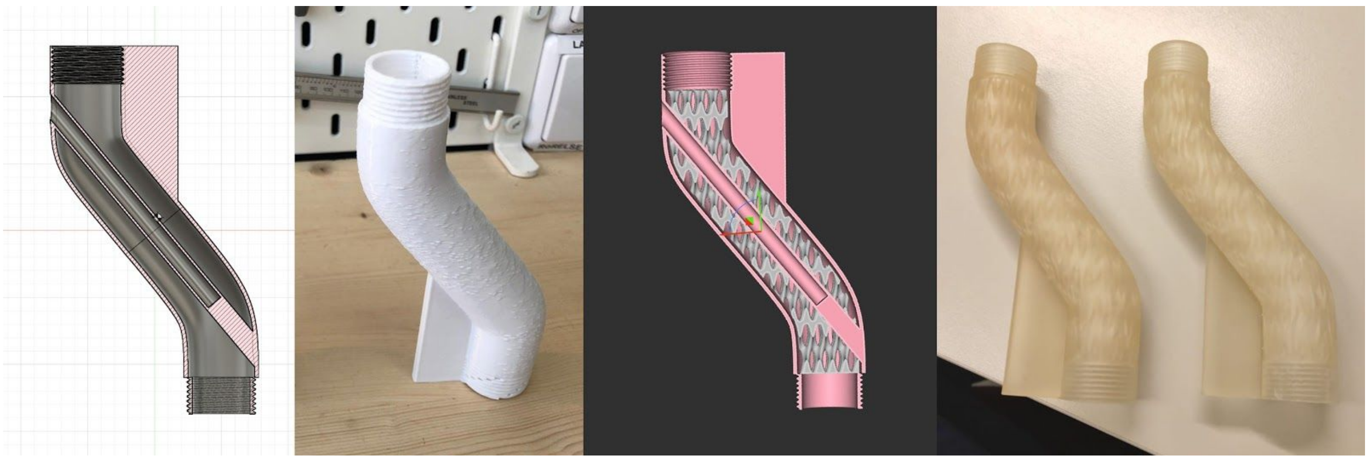


3.2.3 Thin diagonal cartridge insertion (Iteration 2)

Learning from the first iteration, the group decided to create a diagonal design with a longer and smaller tube shape where the cartridge would be inserted diagonally (figure 9). Still keeping in mind LPBF printing limitations, a 45° angle was deemed printable without support.

After the basic shape was modelled a test print was conducted to verify coupling fitting and printability with an FFF printer. When printed successfully the model was sent to nTopology which was used to create a gyroid lattice structure. The outer shell from Fusion 360 was merged with the lattice structure from nTopology and sent as an STL mesh to Chalmers for printing in their resin printer Zortrax Inkspire.

Figure 9. Steps of the second iteration process.

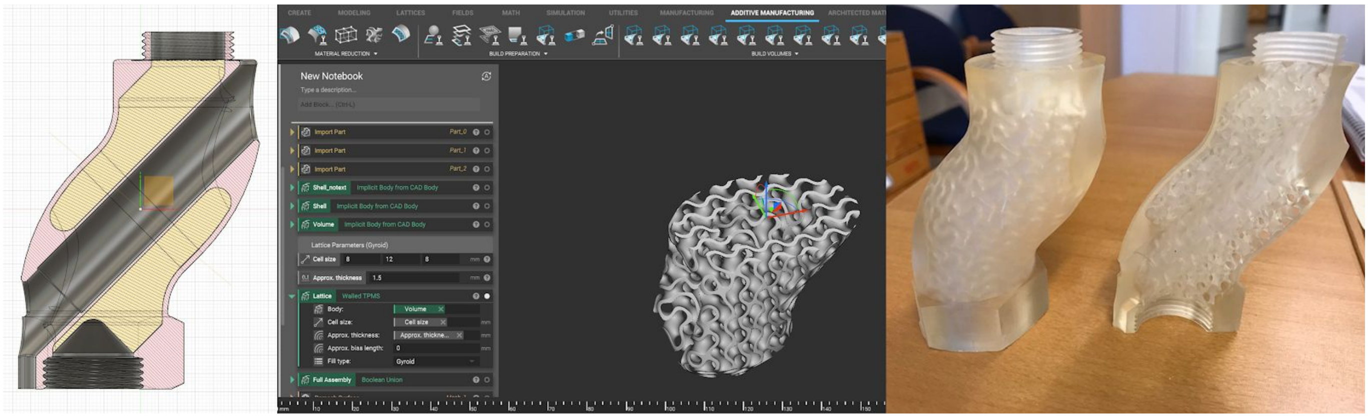


The high resolution resin prints were great to evaluate the design of iteration 2 and also test the fitting of these threads to Podabs laundry machine. At this stage the group evaluated the possible efficiency when using heating cartridges with a 6 mm diameter and found that more power is needed which can be achieved through either thicker or longer cartridges.

3.2.4 Thick diagonal cartridge insertion (Iteration 3)

By altering the design to give space for a heating cartridge of 16 mm diameter with the length of 60 mm, the group could attain 630W of heating power. This increased width of the cartridge channel made the whole shape wider which made it look and feel more sturdy. For ease of installation a nut shape was added to the base of the design. To be able to print without supports, the yellow lattice volume begins with a cone shape in the bottom of the model (figure 10).

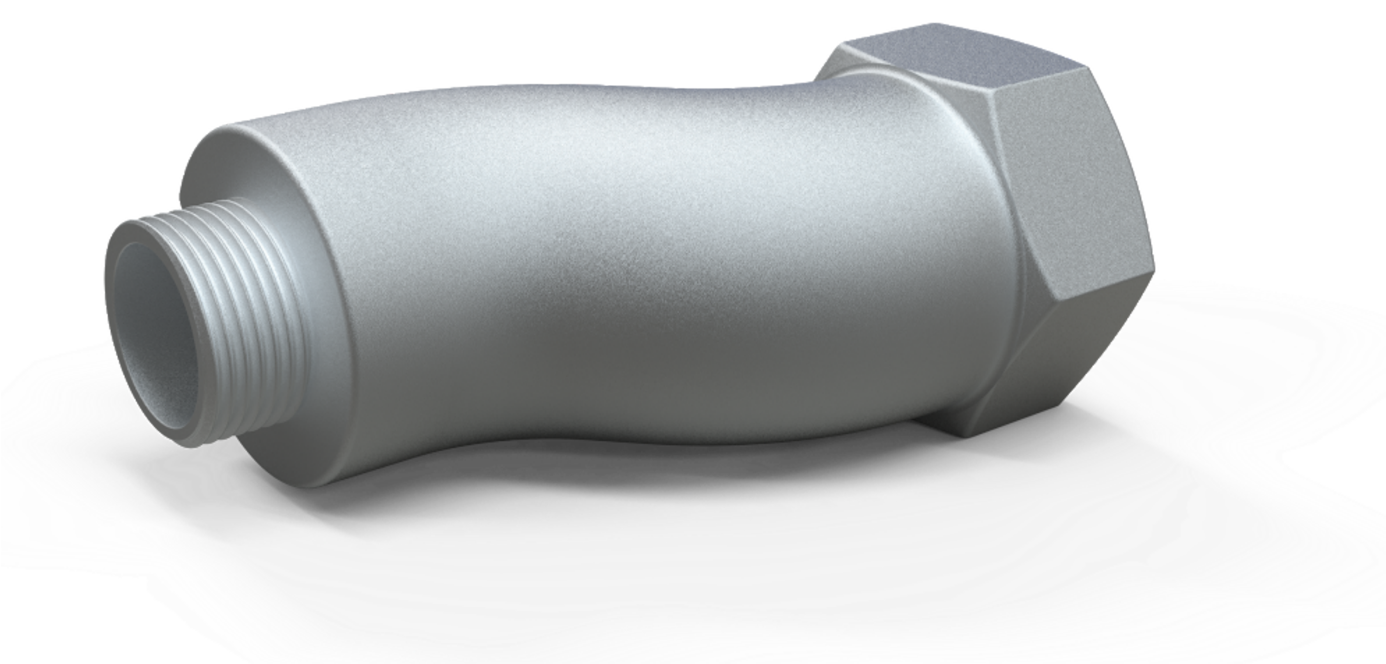
Figure 10. Steps of the third iteration process.



3.3 The final concept: The HeatAdd

With its wider body and ease of installation, iteration three was chosen as the main concept to print in metal. Its design makes it ready to be tested without the need to machine threads or drill holes after printing. By adding a heating cartridge the product can be tested with standard tubings and laundry machines. This makes the metal prototype ready to be used for evaluation of its real world efficiency for heating water.

Figure 11. Rendering of the AddHeat.



For future alterations it is very easy to adjust the size to handle various heating needs as there are many manufacturers of heating cartridges, and most of them do custom sizes and wattage which would make the concept easily scalable for various needs. Furthermore, the lattice structure within this modular shape can easily be changed for various water pressure and flow needs. The CAD model that was made in Fusion 360 is parametric and thus easily adjusted so that a volume for the lattice structure can be exported to nTopology for further work and meshing into a final, 3D-printable part.

Table 1. Specifications of the product visible

Size	103 (H) x 43 (W) x 70 (D) mm
Weight	185 gram
Connection	Standard ¾ inch
Material	AlSi10Mg
Power	630 W, 230 V

Figure 12. Close-up of threading and nut with inside cone

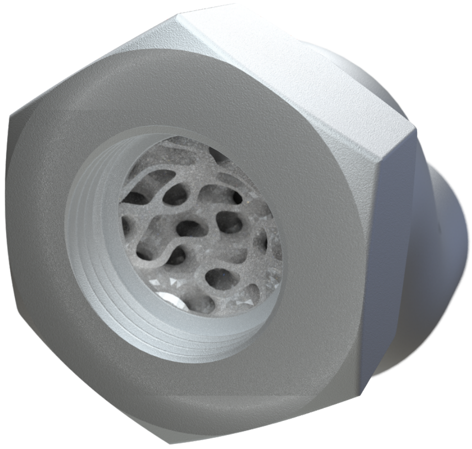
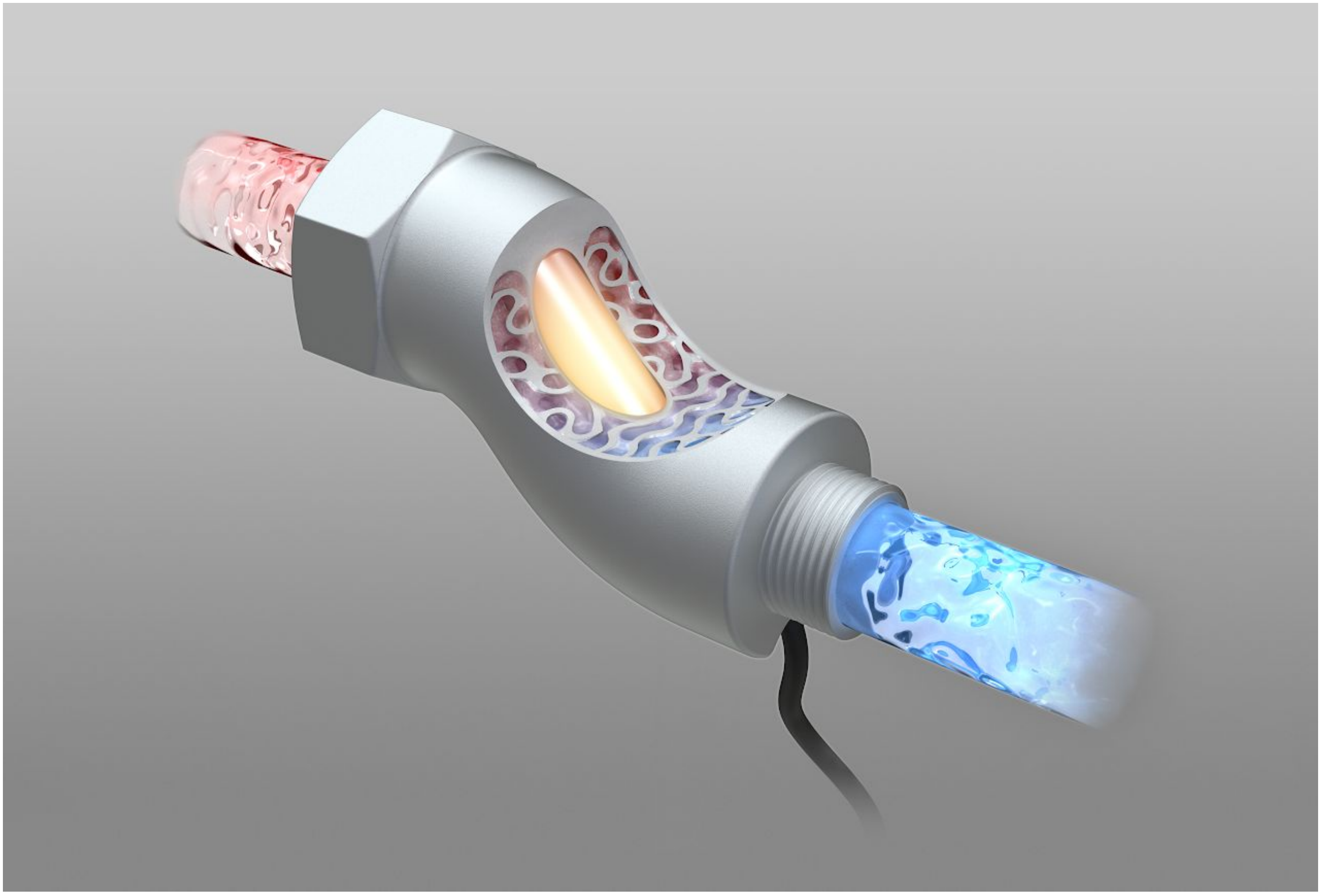


Figure 13. Rendering of the HeatAdd concept to show its functionality.



4. Development for Additive Manufacturing of the concept

This section covers the manufacturing concept of HeatAdd. This gives detailed steps and ideas involved in the selection of AM process, the material used, CAD modelling and simulation. It summarizes how the design for additive manufacturing methodology is used to develop HeatAdd with respect to AM process and material selected.

4.1 Selection of Additive Manufacturing method

Heat Exchangers are an important part of industrial equipment. They are complex and time consuming to manufacture by traditional techniques. Moreover, the market is demanding for more efficient heat exchangers which cannot be manufactured by conventional methods that lead to the use of AM technologies (Application Spotlight, 2019). In order to fully utilise the benefits of AM, the process selection plays a significant role, especially when it comes to metal AM. Since the prototype, which is introduced in this report, has complex geometries with thin walled TPMS structure, Laser based powder bed fusion (LB-PBF) would be an apt process. The laser melting process has already shown promising outcomes in various application fields including heat exchanger areas (Expert Interview, 2019). In addition to that, LB-PBF has a benefit of removing unused powder easily and can be reused. Apart from this, the availability of the machine is also an important criterion to reduce the cost and the lead time for prototyping. Hence, considering all the aforementioned factors, EOS M290 which is a Laser based technology that is available at the Chalmers University of Technology is used for printing.

4.2 Material selection

A wide variety of materials are qualified for additive manufacturing, especially for heat exchangers. The main material properties that are to be considered are thermal conductivity and corrosion resistance. Appropriate materials are listed for the aforementioned properties in the table below.

Table 2. Materials for HeatAdd (EOS Aluminium AlSi10Mg, n.d) (EOS Stainless 316L, n.d) (EOS Copper Cu, n.d) (Uddeholm, AMcorrax, n.d)

Material	Thermal Conductivity @ 20°C (W/mK)	Density (g/cm^3)
316L (EOS)	43	>7.97
AM Corrax (Uddeholm)	-	>7.7
AlSi10Mg (EOS)	103 ∓5	>2.97
High Purity Copper (EOS)	~394	-

From the table and considering the concept, application area and feasibility of this particular product, AlSi10Mg material is chosen. AlSi10Mg has good thermal conductivity and a passive layer of aluminium oxide formed on the surface protects the product from corrosion This material has already been used in the development of heat transfer devices. For example, the Conflux heat exchanger concept has proved to have better heat transfer with mass reduction (Expert Interview, 2019). EOS has qualified this material and concluded appropriate parameters for their machines. The properties may vary depending on the quality of the metal powders. But still, properties are significant for the HeatAdd. According to the EOS material data sheet (EOS Aluminium AlSi10Mg. n.d), the Aluminum alloy composition and their physical properties are shown below.

Figure 14. Chemical composition and physical properties of AlSi10Mg (EOS Aluminium AlSi10Mg, n.d).

Element	Min	Max
Al	Balance	
Si	9.0	11.0
Fe	---	0.55
Cu	---	0.05
Mn	---	0.45
Mg	0.25	0.45
Ni	---	0.05
Zn	---	0.10
Pb	---	0.05
Sn	---	0.05
Ti	---	0.15

Physical properties of parts

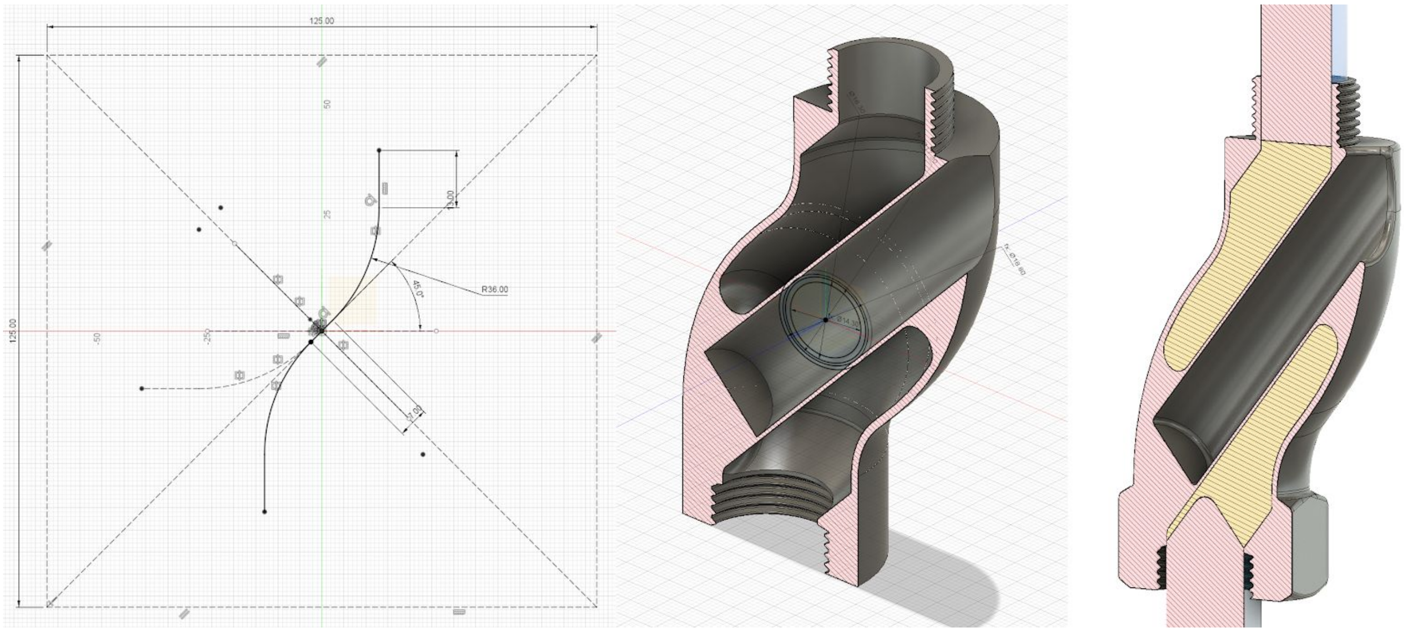
Part density, typical [2]		2.67 g/cm^3
Surface roughness, typical [3]	as manufactured	R_a 9 - 20 µm; R_z 70 - 120 µm R_a 0.4– 0.8 x 10^{-3} in R_z 2.7 – 4.7 x 10^{-3} in
	after microblasting	R_a 6 - 15 µm; R_z 50 - 100 µm R_a 0.2 – 0.6 x 10^{-3} in R_z 2.0 – 3.9 x 10^{-3} in
Volume rate [4]		5.1 mm³/s (18.36 cm³/h) 1.1 in³/h

4.3 Additive Manufacturing-specific part design in Fusion 360

To have a part that is easily modified, the group built the part with a parametric framework in Fusion 360. To begin with, a spline with a diagonal line set at an AM safe angle of 45° so that a general pipe shape could be created as a shell from this. Print size limitations were also added in this sketch for reference. A pipe was created and its endpoints altered so that standard ¾ inch male and female connections were added and scaled up and down (4 percentage points) to allow fit after print.

Perpendicular to the first line at 45°, a sketch was created to extrude the internal channel for the heating cartridge. The ¾ connections and main body were connected with various fillets to allow for a better water flow and printability. For ease of installation, a nut with the same dimensions as the pipe was attached to the bottom. Lastly, the original pipe volume was used to intersect with the shell so that a body could be sent to nTopology for making the internal lattice structure (figure 15 in yellow). A third body was also made so that water flow could be simulated through other software as well.

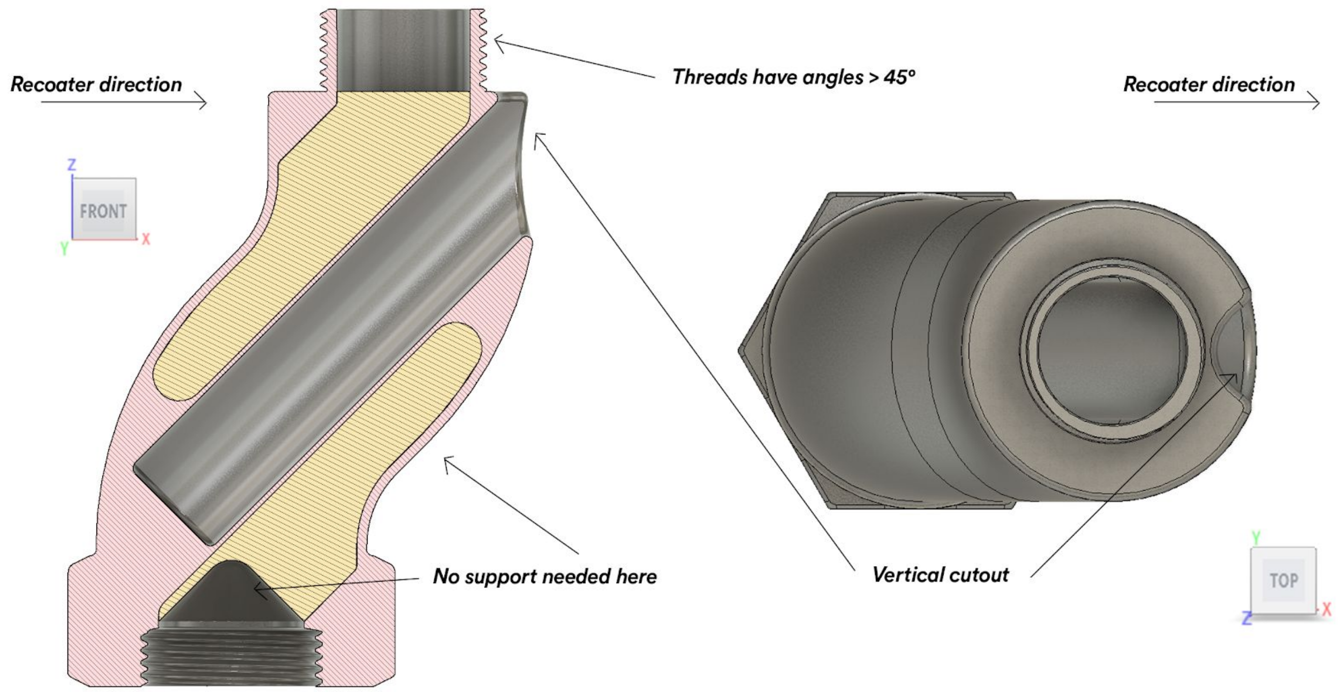
Figure 15. Some steps of the design process in Fusion 360.



The goal was to make an AM-specific design and thus many features of the part are directly adapted for that. The pipe shape starts and ends vertically with a diagonal middle section. This way the recoater will not have to meet any large or overhanging surfaces for each printing layer (figure 16, left). As the part is cylindrical, the recoater should not have any problems in regards to the xy-plane if the part is properly aligned for printing so that the recoater does not have to face one of the flat surfaces on the bottom nut (figure 16, right).

Furthermore, as the diagonal middle part is not too long, no outside support is needed. The cone shape on the bottom starting point of the yellow lattice volume makes the need for support in this place abundant (figure 16, left). Although the AddHeat has details around the top and bottom threads that have angles above 45°, they are small and should be printable. The group decided that a ready made part is better than one that needs to have threadings machined afterwards - especially when the part does not require extreme tolerances when being fitted to various connections in plastic materials (if needed, post processing of threads could be done to increase accuracy).

Figure 16. AM-specific design in front view (left) and top view (right). Part with yellow is the lattice volume.



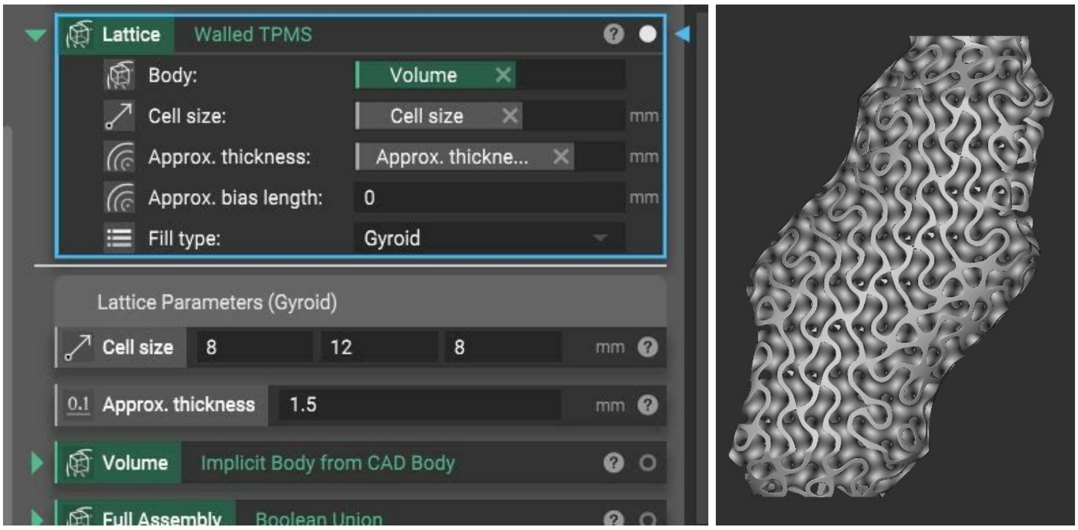
No thin slots exist in the shell design but the combination of the shell and generated lattice could create some small thin details that could have trouble printing properly. This should still let the part be printed properly and if there are damages to the lattice structure the water will still pass fine. If the lattice structure would be made to separate two liquids, more caution would have been needed. Regarding wall thickness the group decided that 1,5 mm would be suitable for a first proof of concept prototype although lesser thickness could have been used for the shell or the lattice structure.

The channel for the heating cartridge is quite wide with a diameter of 17.3 mm but as it is angled at 45° and ends with a vertical cutout it should print fine as there are no large upper circular features that could print poorly (figure 16, right). The added nut makes the bottom area relatively large so that the part adheres strongly to the build plate. This is good for stability during the print but the rather large mass could create some residual stresses. Luckily, the void from the female connection in the bottom will help to relieve these stresses so there should not be any risks for breaking while printing.

4.4 Lattice design in nTopology

In order to have optimal heat transfer by an improved surface interface between the liquid and the metal, gyroid surfaces are introduced which act as fins to improve the heat transfer capacity. Gyroid surfaces are triply periodic minimal surfaces (TPMS). TPMS are innovative models to produce porous structures. Creating TPMS using normal CAD modelling software like CATIA can be time exhausting and inefficient. Hence, nTopology platform which has inbuilt capability to create these complex surfaces for additive manufacturing is used. The parameters that can be controlled while creating these surfaces are wall thickness and cell size (figure 17). Wall thickness is a crucial parameter. A very thick wall can reduce the heat transfer rate while a very thin wall <1mm becomes vulnerable to print. Hence, wall thickness of 1.5mm is chosen to secure proper build with AM as well as to have good heat transfer. The other important lattice parameter is the cell size which can be used to control the flow rate/pressure drop. The Lattice cell of 8x12x8 mm is chosen to attain the desired flow rate. This slight elongation in "y" direction in cell size is to reduce the flow and to make sure the HeatAdd has enough time to raise the temperature of the water to the intended level.

Figure 17. Lattice cell size and structure of HeatAdd.



4.5 Simulations of optimal design for Additive Manufacturing

Usually, before releasing or even producing a prototype of any product, numerical simulations are performed using e.g. finite element method (FEM). The reason for that is to evaluate the performance of the product without the need to produce expensive prototypes and conducting time-consuming tests. This would be especially helpful in our case, since the complex geometry of HeatAdd it is impossible to assess the efficiency of the component with only "engineering intuition", especially when the previous experience in heat exchangers was very limited in the group.

4.5.1 Computational fluid dynamics

In the case of HeatAdd, it was planned to do such simulations with commercial computational fluid dynamics (CFD) software Fluent. The goal was to calculate the water temperature change between the inlet and the outlet of the heat exchanger, pressure loss and the flow path of the water (to ensure there are no places where dirt from the water can accumulate). These solutions would be extremely helpful to assess whether or not our product is physically feasible to use in real-life.

There were several difficulties that were expected to appear: achieving a good quality of mesh, license problems due to too high number of mesh cells and very long computation time (CFD simulations can be up to several days long). The biggest issue that the group encountered was connected to the mesh creation and prevented us from performing even one CFD simulation.

Fluent requires as one of the inputs so-called "Named selections", so the group of nodes of finite elements that respective boundary conditions are applied to. The lattice structure was created in nTopology and it was only possible to export it as a stl file or a mesh. The stl file was hard to work with as both creating Named selections and a mesh was required (both were attempted and neither was possible for the group to achieve). More promising seemed to be creating CFD mesh in nTopology and exporting it directly with the selections assigned to respective surfaces. Unfortunately, for unknown reasons the named selections were not apparent after importing the mesh to Fluent. The cause of it could be that nTopology is relatively new software and issues like this would be fixed in later releases.

4.5.2 Other calculations

Instead of CFD, a very simple hand and FEM calculations were performed. First one was regarding how much energy is required for water to increase its temperature from 15°C to 40°C. The formula for the the amount of thermal energy needed to produce a certain temperature change is as follows:

$$q = cm\Delta T \tag{1}$$

Where:

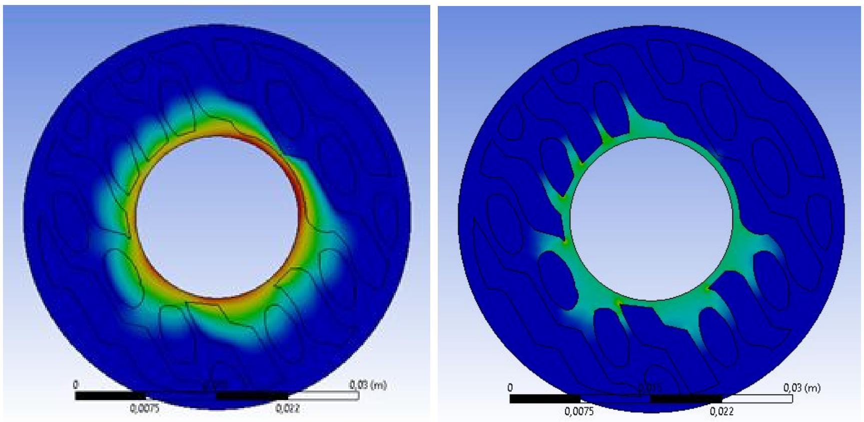
c is thermal capacity of water = 4184 J/(kg*°C),
m is the mass of the water = 7l/min = 0.12 kg/s,
ΔT is required change in temperature = 25°C.

From equation (1) it can be calculated, that the water would need 12,2kW to heat up 0.12 kg of water every second up from 15°C to 40°C. It is way more than any currently existing heat cartridge with reasonable size can provide.

The simplified FEM simulation was done as a 2D steady-state thermal simulation using a cross-section of the HeatAdd. Convection film coefficient of water was applied to the boundaries between metal (here aluminium alloy) and water, heat flux was applied to the inner edge as a heating cartridge and insulation was applied to the outer surface. The values of the convection coefficient and heat flux were estimated, as the simplified nature of the simulation allowed only to observe the temperature and heat flux distribution, but not the precise values these would have.

Figure 18 left presents the temperature distribution in the cross section. It can be observed that in places where the bodies of water were relatively small and did not obstruct the path of the heat flux (figure 18, right), the temperature distribution was much more even and the temperature change was reaching further from the centre of the heat exchanger. On the right side of the cross-section there is a long passage of water that obstructs the way of the heat distribution and an aluminium part between the heating cartridge and water reaches much higher temperatures than in the rest of the cross-section. This may be an argument why the HX with a lattice structure works better than the classic one - heat convection between two faces (aluminium and water) is limited, therefore larger area of heat transfer helps in distributing the energy from one material to another, instead of just increasing the temperature of one material.

Figure 18. Temperature distribution (left) and heat flux (right) in the cross-section of HX.

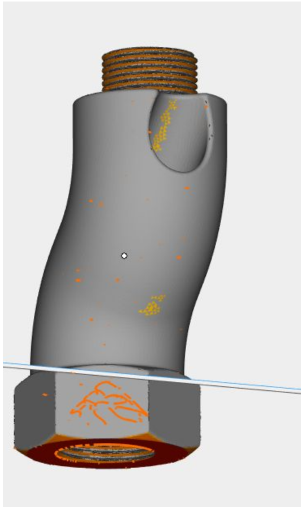


5. Additive Manufacturing of concept

5.1 Build preparation and printing

When producing parts using additive manufacturing, proper support structures design and component orientation on a build plate is nearly as important for successful manufacturing, as the geometry of the part itself. The build preparation is a crucial step in AM - it is when the stl part is positioned in the machine, the supports are generated and the printing batch is transformed into a format of understandable by the machine slices. Build preparation was done in the commercial software Materialise Magics.

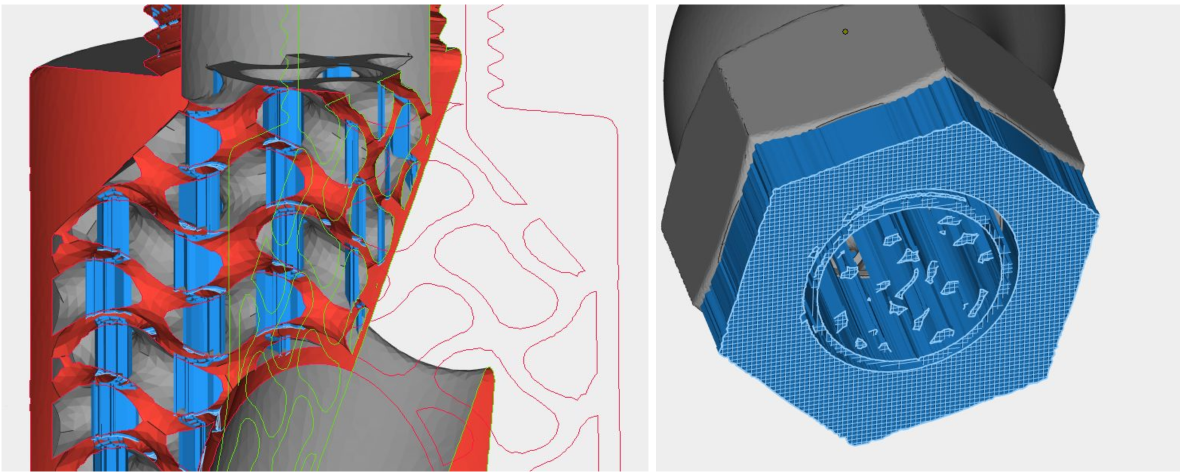
Figure 19. Overhangs



As HeatAdd was optimized towards printing limitations, there is no need for excessive support generation. The areas highlighted on figure 19. have the surface angle equal or greater than 45deg, where only the ones marked with red are significantly more horizontal than the chosen angle. Therefore, only the bottom surface of the part will require supports, which is precisely what was aimed for.

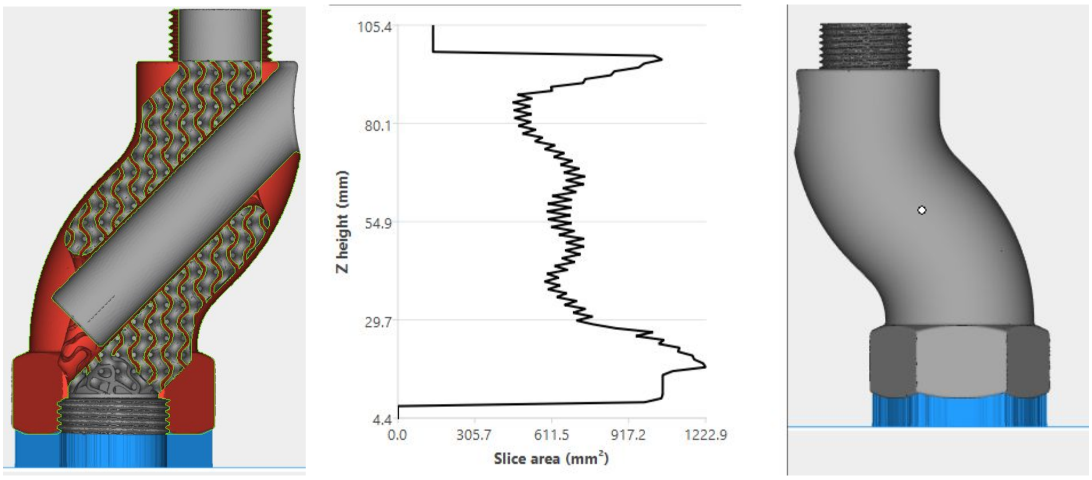
Automatic support generation, however, showed that there are more areas that may require support. It seemed that the lattice structure should be supported as well. While the bottom supports (figure 20, right) would be relatively easy to remove, the same cannot be said about the support structure inside of the heat exchanger. However, because of the geometry type, the lack of supports in these places is unlikely to pose a risk to the printing process, but rather just a poorer surface quality, which is not regarded as a problem in this case. Therefore it was decided not to include them in the printing set-up.

Figure 20. Preview of automatically created supports.



After all additional supports were discarded, the final support structure was attached only to the very bottom of the component (figure 21, left). That reduces the amount of support removal to the minimum. The right picture on figure 21 shows how the cross-section in the z-direction area (excluding supports) changes in the component. It can be observed that there are no big, rapid changes that could create a risk for the printing process.

Figure 21 Final form of the support structure (left) and the cross-section area in xy direction (right)



5.2 Post-processing

Most of the additive manufactured components have to undergo post processing in order to improve the mechanical performance and its look. The type of post processing depends on product type and application. For HeatAdd, stress relieving and hot isostatic pressing are important post AM processing. Before removing the support structures and base plate, the product needs to undergo stress relieving at 270°C for 90 min as per EOS material datasheet. It is done to remove residual stresses that were built due to the high temperature gradient during printing. In order to attain the properties mentioned in the datasheet, the material has to be inserted into a preheated oven and need to ensure that overheating is less than 5°C (EOS Material datasheet flexline, n.d). Then Hot Isostatic Pressing (HIP) is done. Before the HIP process, support structures and base plate are removed using a handsaw. The use of the HIP process is to remove porosities and surface defects. The HIP process cannot provide excellent surface finish but the process reduces the surface roughness comparatively. Hence it is advantageous to apply paint or insulation coating on the outside surface of the HeatAdd and moreover, the rough surface of the lattice which acts as fins intends to increase the heat transfer which is the primary job of the product.

In addition to that, the overhangs on the threads might need a re-thread to ensure the proper mating between the threads during the fixing of the HeatAdd. As the surface finish from AM is not perfect, the internal channel for the heating cartridge would probably benefit from being drilled as a perfect fit for the heating cartridge will increase the heat transfer from the cartridge to the AM part (thermal paste should also be used to create a perfect contact when assembling the parts).

5.3 Quality control and non destructive testing

Ensuring the quality of the 3D printed component is a tricky subject - though the methods designed especially for AM exist and are used in practice, they are still under development. For powder bed fusion printing one of the most promising quality control methods is using thermal sensors to measure the temperature of the powder layers. Kim et al. (2018) cites several research studies where the distribution of the temperature is used as an input for a quality assurance, which indicates a high interest in further development of this technique.

Since the printed component can distort its shape because of the residual stresses, dimensional validation is frequently implemented for AM. The components manufactured using AM have more often than not complex shapes, so Coordinate Measuring Machines may not be the best fit for dimensional validation here. Therefore 3D scanning is more often used, where the point cloud from the scanning is compared to the CAD model (Cotteleer et al., 2018).

When it comes to non destructive testing (NDT), there are a number of methods taken from conventional manufacturing, but more are still under development, such as using ultrasonic imagining (Prevorovsky et al. 2017) or eddy currents (Du et al., 2018) to detect flaws in manufactured components. However, it must be noted that no ISO standard for NDT for AM exists as of now (ISO/ASTM DTR 52905). With little to no established techniques for testing the quality of printed components, it is impossible to decide which method would be the most suitable in the HeatAdd case.

5.4 Cost evaluation for printing one part

A cost evaluation for producing a part can vary greatly depending on which work is included in the calculation. The most tangible cost for producing parts is the cost for the required material which is based on the weight and material of the part.

One method for calculating other related costs of producing parts is the *self cost calculation* method that takes salaries, tools, shipping, marketing, patents and more into account. In such calculations the cost for research and development is seldom included as that process is before any tangible or profitable products exist. In the case of HeatAdd, the costs for material, printing and relevant parts as the heating cartridge are taken into account. As the concept is meant to be customized for various heating and flow needs the work to modify the CAD model and post-print work like post processing and assembly is also included.

The time for doing a proper modification of the part for a new use requires adjustments of the general shape in Fusion 360 but also of the lattice structure in nTopology. Each of these tasks are estimated to require one working day of eight hours and at a consulting cost of 100 € excluding tax per hour. Given that the metal printing has been tested and perfected before, the work to print a plastics prototype is not deemed necessary. Although AM suffers from failed prints from time to time, this calculation regards the first try as a success especially when the part has been designed according to AM specific constraints.

Today, there are modern online services that provide 3D printing with various technologies and materials without the need for tedious emails, calls or visits to these companies. Two popular options are *Craftcloud3d.com* and *3dhubs.com*. Through their online tools, the customer can easily upload their model and view it in 3D space where the service assesses its printability and provides a cost calculation for the chosen material and printing technology. Usually these prices include build preparation, material, printing and build plate removal. Also, many services provide various post processing options but for this project such processes are deemed unnecessary as the prototype is a proof of concept and not meant to be touched much or visible to users. Shipping costs are not included in the following calculation but needs to be considered for actual part orders.

Table 3. Cost estimates for powder material for AM.

Powder provider	Product	Cost	Comment
Höganäs	316L	30 - 35 €/kg	They do not have Copper powder
Sandvik	316L	72 €/kg	
Sandvik	HCCU	100 €/kg	Copper alloy

Note: The cost per kilo was provided by Höganäs and Sandvik.

For the sake of clarity, material costs have been investigated to illustrate how much of the costs from using online services actually are related to the material cost (table 3). Any large volume discounts these services might have are not taken into account. There are multiple world-renowned steel manufacturers in Sweden which provide metal powders for AM that the group contacted so that a somewhat equal comparison could be made of 316L (although other western or asian manufacturers could have been chosen, the average cost would probably vary deeply and be harder to interpret). The group could not find any specific costs for the chosen aluminum powder but the calculations in the online services (table 4) indicate that the price is similar to stainless steel 316L. For reference the cost of copper was added to table 3 as well.

Table 4. Cost estimates for Additive Manufacturing of the HeatAdd.

Service provider	Printing cost per part (1 ordered)	Printing cost per part (25 ordered)	Comment
Craftcloud	355 €	320 €	Online quote service, aluminum (China)
3D Hubs	1 387 €	297 €	Online quote service, DMLS aluminum
3D Hubs	1 494 €	307 €	Online quote service, DMLS stainless steel
AMPOWER Report	310 - 428 €	60 - 83 €	Online calculator, LBPF aluminum
AMPOWER Report	372 - 455 €	134 - 164 €	Online calculator, LBPF steel

Table 4 shows that an average cost for getting an AddHeat printed in aluminum costs around 300 - 400 € while steel is a little bit more expensive. *3D Hubs* takes a premium price for single parts while *Craftcloud* has a low starting price with a marginal rebate on volume orders. The more general calculation tool found on *AMPOWER Report* did not assess an uploaded part and thus is less accurate as it only regarded size and weight of the part. Even so, the single part price is similar to the one of *Craftcloud* so an average price for ordering a single part could be rounded up to 400 €. As the material cost for a part of 185 grams stainless steel 316L only is around 7 - 14 € (table 3), one can see that the printing process is the largest cost by far when manufacturing AM parts.

Table 5. Total cost estimates for providing one finished prototype.

Cost type	Supplier/Staff	Printing cost per part	Comment
Model adaptation in Fusion 360 & nTopology	CAD designer	16(h) x 100 = 1 600 € excluding tax	Also includes preparation of model in Magics
Main part of 185 grams	Craftcloud or similar	400 €	
Heat treatment/HIP	-	-	Not available
Cartridge heater 630 W	https://www.cartridge-heater.com	10 €	16 mm diameter, 60 mm length, 220 V
Wiring	Random supplies company	5 €	Wires, power socket and rubber
Assembly and testing	Engineer	2 (h) x 100 = 200 € excluding tax	Test leakage and fit
Total		**2 215 €**	

With the ease of online services like *3D Hubs* one can attain professional 3D printed parts in metal without having to own highly expensive machines. Heat treatment did not seem to be done by these online services, which is why it is not taken into account for this cost estimation. Taking a couple of hours for assembly and testing into account, the total price for the part is estimated at around 2 200 € (table 5). Without design alterations the printing cost is estimated to 400 € with an added cost for additional parts, assembly and testing of 215 €.

6. Discussion

Additive manufacturing is an emerging technology with many uncertainties regarding the design and production process. However, the benefits and possibilities it brings, attracts the researchers from various fields to continue working on it. With that much research effort put into it, the AM technology becomes more mature every year.

Not only AM is changing - the world does as well. In March 2021 the energy efficiency labels for the washing machines will be rescaled, so that the A+++ to D scale will be replaced by A to G scale (European Commission, 2020). Interesting aspect here is that none of the existing products will get the A class - it will be reserved for the future products whose energy efficiency exceeds the existing limits. Energy efficiency and ecodesign is a big topic and AM heat exchangers may be the answer to reaching the new A class.

For heat exchangers, AM allows for increasing efficiency due to more freedom in geometry design and decreasing the cost compared to traditionally manufactured products with similar level of geometry complexity. HeatAdd was designed to minimize the amount of post processing, it requires only easily removable supports on the bottom surface that attach it to the build plate and it doesn't carry any excessive risks for failures during the printing process. The cost of a singular part is still quite high, mostly due to the cost of machine operation, so as the AM technology will become more mature, the price will decrease.

The development process of HeatAdd could be described as agile, with three sprints that each was concluded with producing a prototype and discussions about results. The first one had a focus on the general shape of the HeatAdd, the second one on the lattice structure and the third one included final adjustments in dimensions and lattice. Doing a few short agile sprints instead of one big design-build-test cycle of waterfall methodology, allowed for finding the errors earlier and avoiding big last-moment changes. Implementing agile in the group's work was possible only thanks to plastic AM, that made producing prototypes quick, easy and inexpensive.

From the group's analysis and understanding of heat exchangers, using AM to produce them allows for increasing the area of heat transfer and increasing turbulence that increase the heat transfer rate. However, since no detailed simulations were managed to be performed the hypothesis is yet to be proved. How HeatAdd performs against fouling is also not determined yet - the rough surface of LB-PBF and the shape of lattice structure may cause dirt and particles to accumulate. Therefore as a future work it is recommended to give the simulations another try and try to achieve meaningful results that could help to assess the performance of the HeatAdd.

Another aspect that would be interesting to work with further is the lattice structure. nTopology offers several different types of lattice structures to create options to alter their size, orientations, and other parameters defining it. Unfortunately, due to the time constraints and resources, exploring all the possibilities that the software gives to create the most optimized lattice structure was not possible. Nevertheless, nTopology seems to be a good tool to aid design for additive manufacturing, though perhaps requiring a little bit more development.

Finally, in section 4.5 it was mentioned that the water needs almost 20 times more power than the heating cartridge can provide. However, the final conditions that the HeatAdd will work in can be different from the ones that were assumed. An experiment done at Mimbly showed that it takes one minute to fill the laundry machine with water and five minutes to heat the water to the desired temperature. This means that the flow of the water through HeatAdd could be much slower while the product would be more time-efficient than traditional heating. Moreover, the heating cartridge that was used is not the most powerful that is available on the market, however, with the higher power comes the increase in the size. It is then possible to incorporate more powerful cartridges in the product, but the part dimensions would increase. The first metal prototype is designed for a smaller, weaker heat source to lower the costs of the production, with the note that it may change in the future.

HeatAdd was initially designed for a laundry machine, however, it does not mean that it cannot be used for other applications. By scaling it or changing some dimensions, HeatAdd can be used in other household appliances, such as taps or dishwashers. Potentially it can be connected in series or designed to be longer and bigger to create a more powerful heat exchanger. The flexibility of HeatAdd allows it to be adapted to different markets without much changes in the design.

7. Conclusion

The best method to produce a heat exchanger in this manufacturing era is by using additive manufacturing. The benefits of 3D printing creates new specs which are much needed for today's fast changing world. The HeatAdd is one of its kind as this product is created using exceptional design using additive manufacturing. Keeping in mind, the product is produced for increasing the energy efficiency of washing machines, the flexible design with minimal size and optimal heat transfer with lattice structure would be its advantage. Hence, the prototyping of HeatAdd proves that a product for heat transfer applications can be easily developed with lattice structures using additive manufacturing with the help of today's technology. By using a metal print of the designed model, further research and testing can be done regarding the efficiency of water heating.

In addition to testing, its potential of being efficient could also be evaluated by doing more intensive simulations. Accordingly, it is a good starting point for further research. This simulation may also lead to new lattice design. The heat source is another area which can be improved. Having heating cartridges readily available in the market is advantageous for HeatAdd as they also can be ordered with the specs needed for a certain task. High density heating cartridges could be a sufficient heating source to use with the HeatAdd but should be further investigated. Although this project shows that heating water more efficiently could be possible with AM-HX, heat exchangers produced by additive manufacturing are expensive compared to traditional methods. Hence, current printing methods need to be developed in order to reduce the cost of heat exchangers and moreover, substantial studies need to be conducted on the printed material to make sure the process is reliable.

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