Chekurov, Sergei; Kajaste, Jyrki; Saari, Kari; Kauranne, Heikki; Pietola, Matti; Partanen, Jouni

Additively manufactured high-performance counterflow heat exchanger

Published in:
Progress in Additive Manufacturing

DOI:
10.1007/s40964-018-0059-x

Published: 01/03/2019

Document Version
Peer reviewed version

Please cite the original version:
Chekurov, S., Kajaste, J., Saari, K., Kauranne, H., Pietola, M., & Partanen, J. (2019). Additively manufactured high-performance counterflow heat exchanger. *Progress in Additive Manufacturing*, *4*(1), 55-61. https://doi.org/10.1007/s40964-018-0059-x

Title: Additively Manufactured High-Performance Counterflow Heat Exchanger

Abstract:

The purpose of this article is to demonstrate that additive manufacturing is a viable method for producing counterflow heat exchangers that have a very high power to volume ratio. For this study, a heat exchanger with 144 flow channels in a checkerboard pattern was designed and additively manufactured from AlSi10Mg. The heat exchanger was tested by measuring the heat transfer between two liquids in a counterflow set-up, where it reached exceptionally high performance when considering its volume and weight. The heat transfer properties of the heat exchanger were verified analytically through calculations, which identified that the high surface roughness of the channels provides a significant improvement in heat transfer properties. The heat transfer capabilities were measured on two separate occasions to investigate the possible change of properties of additively manufactured heat exchangers over time when used with tap water. A moderate decrease in heat flow and increase in pressure drop were noted between the measurements. The deterioration of heat transfer capabilities could present a significant challenge for additively manufactured heat transfer applications and will be closer examined in future research.

Keywords: Digital Manufacturing, Additive Manufacturing, DfAM, heat transfer, heat exchanger, counterflow

Article Classification: Research Paper

1. Introduction

The goal of this study is to demonstrate that additive manufacturing (AM) enables the production of compact and efficient counterflow heat exchangers. The main functional advantage of AM regarding heat exchangers relates to the possibility to design and dimension the shape of the exchanger and its internal flow channels more freely than in subtractive manufacturing. Additionally, AM allows for miniaturization of heat transfer elements to provide higher performance. From the manufacturing point of view, AM offers a significant reduction of the number of parts, which minimizes the need for assembly [1]. High surface roughness, which is typically considered a challenge in additively manufactured parts, can be a beneficial property in heat exchangers with small hydraulic cross-sectional flow areas and relatively short channels. This is due to the fact that the ratio of surface roughness to the diameter of the flow channels becomes very high, which enhances the turbulence of the flow and ensures the start of the turbulent flow conditions from the very beginning of the flow channel. The heat transfer coefficient for turbulent flow is much higher than for laminar flow both in thermally developing flow conditions and in fully developed flow conditions [2]. In addition, the high surface roughness of AM components increases the heat transfer surface of the flow channel and thus increases the heat transfer between the flowing fluid and the walls, resulting in a high heat transfer coefficient [3]. On the other hand, the rough surface and the smaller diameter of channels also result in somewhat higher pressure losses [4].

AM heat exchangers can be designed purely from the point of view of optimal geometry and can include elements such as very small and intricate channels that would not be possible to manufacture with traditional methods. The possibility to shape freely the internal flow channels offers an improved possibility to influence the properties of flow. This can be done, for example, by creating some discontinuity in the channels and/or by using other methods that either partly prevent the formation of a laminar boundary layer on the flow channel walls or break the already formed boundary layer and help to keep the flow turbulent, which enhances the overall heat transfer coefficient of the exchanger.

Therefore, AM enables manufacturing of miniaturized counterflow heat exchangers whose heat transfer rates per volume or weight are far better than those of conventional tube or plate heat exchangers. The compact structure results in remarkably smaller heat exchangers, which are needed, for example, in environmental control, avionics and engine oil cooling systems in aerospace, and in waste heat recovery and exhaust recirculation systems in the automotive industry [5]. A further asset of AM is that it also enables individualizing the exchanger volume and shape according to the requirements of the application in question.

From the manufacturing perspective, AM enables significant reduction of heat exchanger parts and consequently enables avoiding the laborious assembly methods that are typically needed in heat exchanger manufacturing. For example, in plate or tube type heat exchangers the parts that make the flow channels are typically joined together by pressing, soldering or welding. In this type of joining, the sealing between parts needs to be secured to avoid both internal leakage (leakage between the heat transferring flow channels) and external leakage (leakage to the outside of the structure) of the exchanger. The more channels a heat exchanger has, the more sealing points and possibilities of leakage are present. Since AM enables manufacturing the exchanger in one piece, no separate seals between flow channels are needed, and the only sealing points in the structure are at the flow channel inlets and outlets of the exchanger that exist in all types of exchangers. In addition to these advantages, the heat expansion problems that exist in pressed, soldered and welded heat exchangers, are avoided in AM components [6].

Several high profile projects related to additively manufactured heat exchangers have been conducted in recent years funded by Boeing and the United States Department of Defense [7–9]. These projects focused on the reduction of weight and thickness of heat exchangers and on the reliability of the AM process to manufacture parts without defects. In relevant peer reviewed research, Wong et al. presented an additively manufactured heat sink from aluminium 6061 in 2005. Wong et al. noted that the potential for creative new designs and applications was clear but that laser melting parameters needed to be developed in order to produce high performance heat exchangers [10]. Ventola et al. created another additively manufactured heat sink from aluminium alloy and observed a 50% increase in thermal properties when compared to the traditionally manufactured copper heat sink [11]. Thompson et al.'s additively manufactured flat-plate oscillating heat pipe performed 400–500% better than its counterpart that was traditionally manufactured from solid TI-6Al-4V [12]. Neugebauer et al. presented an AM air-to-water heat exchanger and a counterflow liquid-to-liquid heat exchanger, but presented no performance figures [1]. Several other studies have been published on AM gas-to-liquid heat exchangers but, so far, very little information on AM liquid-to-liquid heat exchangers has been presented.

For this study, a counterflow liquid-to-liquid heat exchanger was designed. The design incorporated dividing the flows from the two large inlet channels into 144 very narrow heat-transferring channels that were again redirected into two outlet channels at the other end of the exchanger. The design was manufactured with AM because the flow redirection done at each end requires a level of complexity that is not viable to achieve with traditional manufacturing technologies.

The design research questions that apply in this case are whether it is possible to manufacture hundreds of small flow channels next to one another in a way that not a single wall between the channels breaks, and if a redirection system can be designed to reliably redirect flow from one large channel into numerous small ones and back again. The characteristic heat transfer research questions regarding this study are whether the traditional equations for heat transfer efficiency and pressure loss are applicable to this kind of additively manufactured narrow channel heat exchanger structures where some assumptions must be made related to the exact geometry, hydraulic diameter, and surface roughness of the channels. Furthermore, if the traditional equations are not applicable, there is a need to investigate which phenomena should be taken into account to provide reliable calculation results.

2. Methods

The main element of the heat exchanger was designed to be a 12-by-12 checkerboard matrix of square tubes with the channels containing hot and cold liquids. This way every channel is surrounded on all four sides by a liquid of opposite temperature. The principle is demonstrated in Figure 1 as a 6-by-6 matrix. Placing the channels tightly close to each other offers significant benefits regarding component volume, heat transfer capability and pressure resistance.

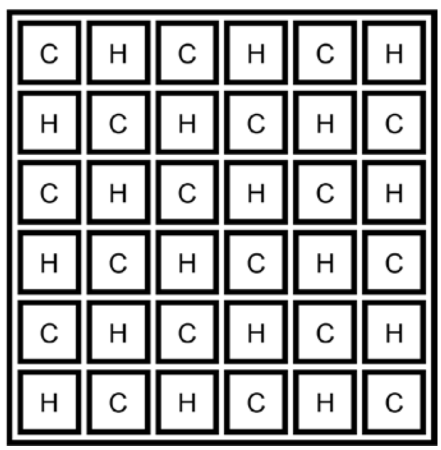

Figure 1. Counterflow heat exchanger matrix used in the developed heat exchanger

A novel redirection system was required to connect the two sets of 72 miniature channels together at the ends of the heat exchanger to form the two inlets and two outlets of the exchanger. To achieve this, the 72 hot and 72 cold adjacent channels were spread out to 3 mm from each other. The cold channels were directed into a lattice, which connected the channels together and led to a flow port placed on the side of the heat exchanger. This redirection was done at both ends of the exchanger. The hot channels were in turn directed through the openings of the lattice into a funnel type chamber, which connected the channels together and led to a flow port placed at the end of the heat exchanger. Like with the cold channels, this redirection was done at both ends of the exchanger. The redirection principle used in the heat exchanger is demonstrated in Figure 2 along with a side view of the flow channels.

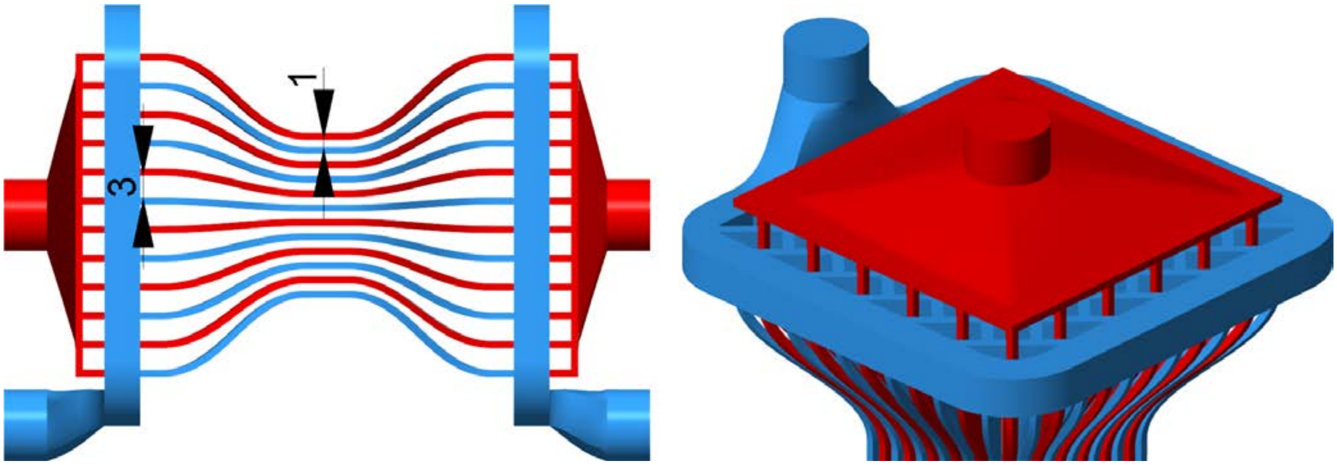

Figure 2. A side view of the flow channels and the lattice-and-chamber redirection method

Because the heat exchanger was produced by AM, the flow channels could be designed to be as small as 1 mm * 1 mm. The small diameter and large number of channels increases the area of heat exchange and makes the flow distribution even because the pressure loss in the channels is greater than in the chambers and lattices.

The heat exchanger was designed to be manufactured with selective laser melting (SLM) using AlSi10Mg as the material and therefore the design guidelines provided by the manufacturer had to be considered. The walls separating the flow channels were to be as thin as possible for good heat transfer properties, while simultaneously being thick enough to be successfully produced and to withstand the pressure difference between channels. The thinnest walls that are guaranteed to be manufactured successfully according to the material manufacturer are 0.3–0.4 mm [13]. However, the rupture of a single wall in the heat exchanger would mean that the flows (either liquids or gases) could leak into one another and become mixed. To minimize this risk, a wall thickness of 1 mm was used. Because the material used for the heat exchanger was an aluminum alloy, the wall thickness did not form a significant bottleneck in reaching a high heat transfer coefficient because, in this case, the restricting heat transfer interface was between the fluid and the structure. If the exchanger were to be manufactured from steel or other materials with lower thermal conductivity, the impact of wall thickness would be more significant. The pressure resistance of the heat exchanger is excellent because the walls of the channels are comparatively thick when considering the miniature flow area of the channels, which is only 1 mm^2. The most vulnerable parts of the object are the outer walls of the lattice and funnel chambers, which are only 0.5 mm thick. However, even at this thickness the heat exchanger has shown no signs of failure.

The heat exchanger was manufactured from AlSi10Mg with an EOS M400 machine using the layer thickness of 60 μm. The connecting ports of the component were then threaded manually to fit the hydraulic measurement components. The heat exchanger was tested by feeding two fluids of different temperatures (approximately 56 °C and 6 °C) at varying flow rates in a counterflow set-up. The temperatures and pressures were recorded at each inlet and outlet. The measurement system of the experiment is shown in Figure 3. The measurements were conducted first immediately after manufacturing the part and then after two months to investigate if there was any difference in performance after a prolonged period. The heat exchanger was kept connected to the testing set-up for the entire period of inactivity, which means it was entirely filled with water for the duration.

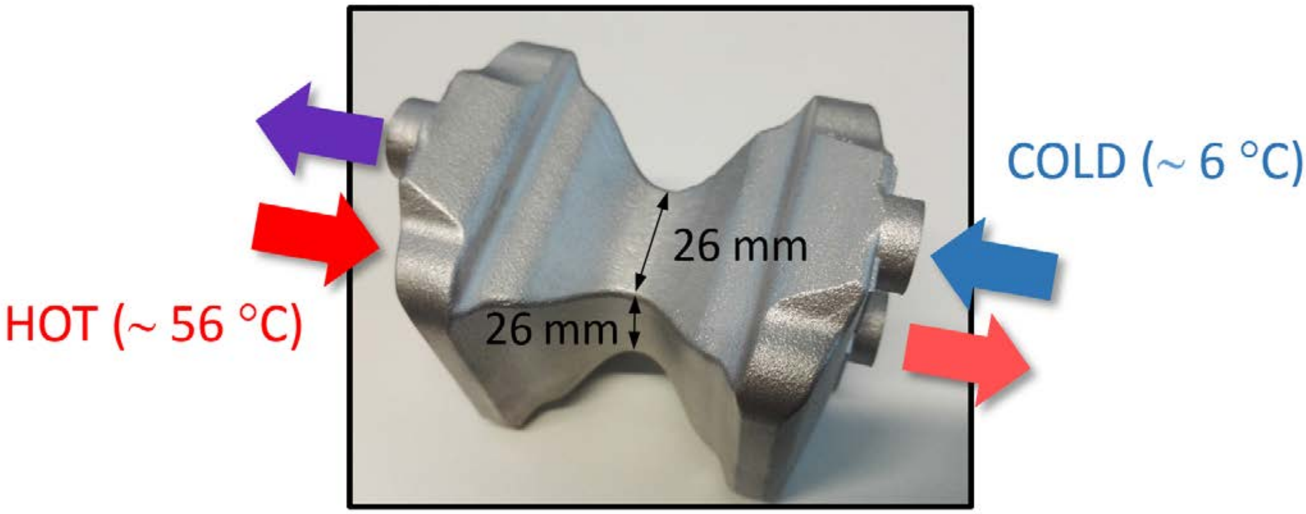

Figure 3. Measurement set-up of the heat transfer experiment

The heat transfer coefficient of channel flows is calculated using dimensionless correlations, where the Nusselt number is a function of Reynolds number, Prandtl number and the friction coefficient. The Nusselt number of the fluid flow is defined as

$$Nu = \frac{\alpha d_h}{\lambda} \tag{1}$$

where α is the heat transfer coefficient of the fluid flow, $d_h$is the hydraulic diameter of the flow channel and λ is the heat conductivity of the fluid. The dimensionless heat transfer coefficient inside channels with rough surfaces can be presented as

$$Nu = \frac{f}{8} Re_D Pr^{1/3} \qquad \text{Colburn analogy} \tag{2}$$

or

$$Nu = \frac{f}{8} Re_D \frac{Pr}{1+5\sqrt{\frac{f}{8}}(Pr-1)} \qquad \text{Prandtl analogy} \tag{3}$$

where *f* is the friction coefficient of the fluid flow, *Re* is the Reynolds number of the flow and *Pr* is the Prandtl number of the fluid [14]. The laminar heat transfer is calculated using the equation

$$Nu = 4{,}36 + \frac{0{,}1/X}{1+0{,}1/X^{0,8}} \tag{4}$$

Here $X = \frac{L}{D_h Re Pr}$, where L is the length of the channel and D_h is the hydraulic diameter.

The overall heat flow and pressure drop calculations include also the ends of the heat exchanger.

3. Results

Figure 4 presents the calculated theoretical heat flow values of the clean heat exchanger using the transition Reynolds numbers as a parameter. If the local Reynolds number of the flow is larger than the transition Reynolds number (*Re* = 500, 1000 or 1500), the flow is assumed to be turbulent, and if it is lower, the flow is assumed to be laminar. The calculated values correspond best to the measurements when the transition Reynolds number is 500, which indicates that the flows within the heat exchanger turn from laminar to turbulent at much lower velocities than in normal smooth tubes. In calculations, the transition to turbulent flow in the rough flow channel is therefore assumed to happen when the local Reynolds number is 500.

The results of the heat flow and pressure drop measurements as well as the calculated theoretical values at varying flow conditions are presented in Figures 5 and 6. The results are given for both the cold and the hot side of the heat exchanger.

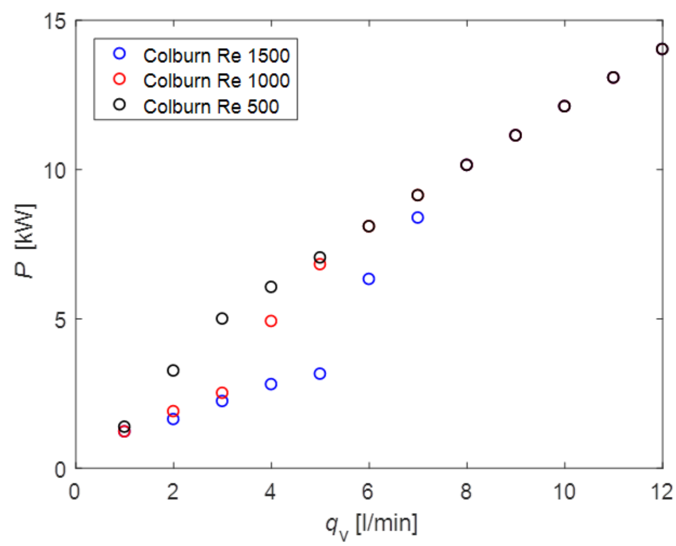

Figure 4. The calculated heat flow of the clean heat exchanger with three different limiting transition Reynolds numbers. The transition from laminar to turbulent flow conditions is assumed to occur when the local Reynolds number is *Re* = 500, 1000 or 1500.

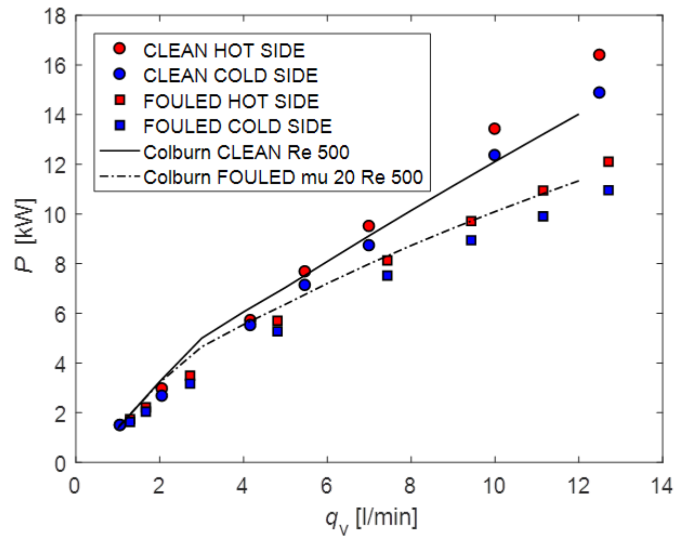

Figure 5. Measured and calculated heat flow values for hot and cold fluid flows in a clean and fouled heat exchanger. The assumed thickness of the fouling deposit layer is 20 μm with the heat conductivity of 2.2 W/mK.

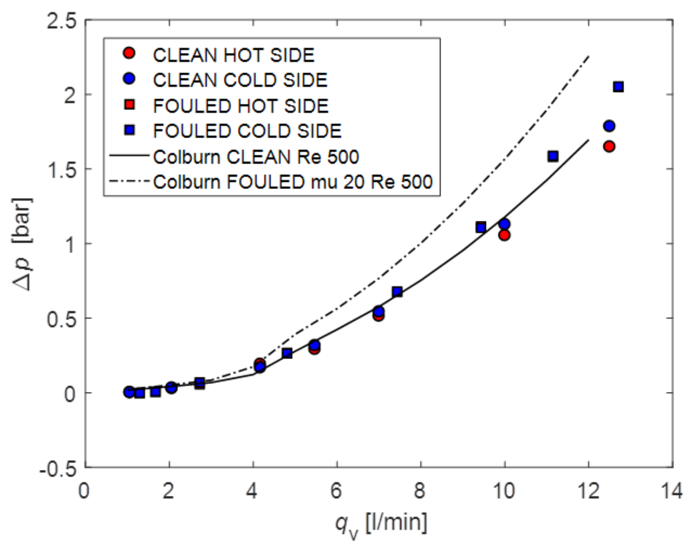

Figure 6. Measured and calculated pressure drop values for hot and cold fluid flows in a clean and fouled heat exchanger. The calculated values correspond to hot flow conditions. The assumed thickness of the fouling deposit layer is 20 μm.

The measurements show a deterioration of the heat transfer properties of the heat exchanger between the first and second set of measurements. The measured increase of the pressure drop between the measurements indicates that the channels have become contracted. A likely explanation for this phenomenon is that the channels were coated in a layer of a fouling deposit during the period of inactivity. The most likely source of fouling in this case was calcium carbonate found in the water that filled the heat exchanger during the inactivity period.

The legend reflects the condition of the heat exchanger during the measurements as it was clean during the first measurement and fouled during the second measurement. The presented theoretical values of the clean heat exchanger are based on the Colburn analogy and calculated with an assumed average surface roughness of 80 μm Ra. The layer of the fouling deposit was assumed to be calcium carbonate ($CaCO_3$), the conductivity of which is 2.2 W/mK. The thickness of the fouling deposit layer was set to 20 μm in the calculations because then both the heat flow and the pressure drop match well with all the measured results performed after the period of inactivity of the heat exchanger.

The heat flow measurements correspond well to the calculated values of both sets of measurements. The pressure drop measurements of the clean heat exchanger also correspond well to the theoretical values, but the measured pressure drop of the fouled heat exchanger is slightly lower than calculated. While there was a small difference in pressure drop between the hot and cold sides in the clean heat exchanger, they became equal when measured in the fouled condition. In general, the measured difference in heat flow between the clean and the fouled heat exchanger was approximately 25% and the increase in pressure drop was similarly approximately 25%.

4. Discussion

Manufacturing of the narrow channels of the heat exchanger was successful and no leakage between the two sets of 72 opposing flow channels was detected. However, it is not certain how close to 1 mm * 1 mm the profiles of the channels really are. It is equally uncertain whether the hydraulic diameter of the channels stays constant throughout the length of the curving channels, and whether the surface roughness of the channels is at the assumed level. The surface roughness of the flow channels was set to 80 μm Ra in the calculations because it matches the results across all measurements. The assumed surface roughness is high for the SLM process that was used to produce the heat exchanger. However, the exceptionally high value can be explained by the square geometry of the flow channels. Because internal supports are not allowed in the production of this geometry, one of the walls of the channels must be built as an overhang, resulting in a higher surface roughness than that of supported features. Surface roughness values of this magnitude for overhanging structures have been previously reported [15]. It would be of interest to see how the heat exchanger would perform if it were manufactured using Electron Beam Melting (EBM), as the surface roughness of EBM is typically higher than that of SLM. However, EBM is also less accurate than SLM, which could lead to problems with the geometrical stability of the flow channels [16].

The material used for the heat exchanger was AlSi10Mg, which is a suitable material for this kind of applications especially due to its corrosion resistance [17]. Nevertheless, the properties of heat transfer elements would benefit from AM materials specifically developed for these purposes.

The flow conditions in the heat exchanger were affected by the large relative surface roughness, small hydraulic diameter, and flow velocity. The turbulent flow in the tested heat exchanger seems to begin at much lower limiting Reynolds number than in normal heat exchangers with a larger hydraulic diameter and smaller relative roughness. The experiments show an almost linear correlation between heat flow and liquid volume flow rate. When the limiting Reynolds number is approximately Re = 500, the calculated values in Figure 6 correspond to measured values. With larger limiting Reynolds number values, the measurements and calculated values do not match.

The designed counterflow heat exchanger performed efficiently when taking its volume and length into account. In the performed tests, the exchanger achieved heat transfer efficiency of 16 kW with the input flow temperatures and the highest flow rate measured. However, this is not a limit for the heat exchanger since both the temperature differences and flow rates of the counter flowing fluids can be larger. The tested exchanger can transfer much higher thermal powers and, due to its construction, is able to withstand the hydraulic pressures (i.e. pressure drop) that are generated at high flow rates through the exchanger. Additionally, the hydraulic power losses that originate from these pressure losses are minimal compared with the transferred thermal power when operating at the measured flow rates. Although the achieved heat transfer rate of the tested exchanger in relation to its volume and mass is already excellent, further research needs to be conducted in this area, especially in optimizing the current design of lattices and chambers and implementing longer narrow flow channels.

The moderate deterioration of the heat transfer properties observed in the second measurement cannot be attributed solely to the decreased water temperature difference, as it remained roughly constant between the two measurements. The temperature differences of the water were on average 50.4°C for the first reported measurement and 48.3°C for the second reported measurement.

The increased pressure drop may indicate a partial blockage of the channels, which could be caused by calcium carbonate deposits from the tap water, corrosion of the aluminium alloy, or residue from the measuring instruments. The first two causes could potentially pose a significant challenge for additively manufactured heat exchangers. Therefore, further research needs to be conducted to find out the exact cause of the degradation and possible solutions to solve the issue.

In AM heat exchangers with small hydraulic diameters in flow channels, the relative pipe roughness of the flow channels is unusually high. In the case of the heat exchanger developed in this study, the relative pipe roughness is so high that it cannot be found in the standard Moody diagram. This means that the heat flow and pressure drop are higher than in normal sized smooth channels, which is a favourable property in short heat exchangers that are designed to be powerful relative to their size. The flow channels of the tested prototype were quite short ($L / D = 60$) so the velocity and temperature profiles were fully developed only at the end of the channels, which means that the average heat transfer is higher than in long channels. If the transition from laminar to turbulent flow conditions in the tested heat exchanger is assumed to happen with much smaller Reynolds numbers than in normal heat exchangers, the Colburn heat transfer correlation for rough channels corresponds well to the test results. The heat transfer and laminar to turbulent transition in small AM heat exchangers with a high relative pipe roughness should however be studied further to verify the operation and capabilities of this kind of small AM heat exchangers.

The developed heat exchanger design can be used also when manufacturing plastic heat exchangers for applications where at least one of the flow agents is a gas. The heat transfer between gas and construction is typically weaker than that between liquid and construction, so the heat transfer of gases should not be bottlenecked if the material used is switched from metal to plastic. This applies especially when the heat exchanger is made from plastic that has decent thermal conductivity.

AM technologies are improving at a fast pace. Therefore, it will be possible to create larger heat exchangers in the future with longer and more intricate flow channels. When build chambers of AM machinery increase in size, it will be possible to put more channels side by side and increase the size of the matrix significantly. Additionally, producing heat exchangers by AM means that they can be tested more often in the design stage and can be subjected to new production paradigms, such as distributed manufacturing. AM of heat exchangers omits several production steps, such as welding and assembly, and can therefore reduce manufacturing costs of these components in the future.

While this heat exchanger is a good example of a component that benefits greatly from AM, it is also potentially suitable for hybrid manufacturing. The counterflow matrix can potentially be lengthened with an array of 1 mm * 1 mm square pipes that are fitted and brazed together. The lattice and chamber ends of the component would then be the only part produced by AM, which would mean that similar heat exchangers could be manufactured at a reduced cost. However, this method would negate the benefit of AM in which the component is produced as one part without the need for sealing. One way to retain this benefit while still using hybrid manufacturing is to embed the pipe matrix in a powder bed machine, level the top layer with the top layer of the matrix, and produce the lattice and chamber ends directly on top of the pipes. This kind of technology is currently being researched but is not yet commercially available.

5. Conclusion

An aluminium alloy heat exchanger with a lattice-and-chamber flow redirection system was designed, manufactured, and tested in this study. The heat exchanger performed extremely well because it was designed for AM in such a way that defies the traditional design principles of subtractive manufacturing. The 144 small channels of the counterflow matrix were manufactured with no signs of leakage. Through analytical heat transfer calculations, it was verified that the inherent surface roughness of AM in the internal channels contributes a great deal to improving the heat flow properties of the heat exchanger.

A moderate diminishment of the heat transfer properties of the heat exchanger was observed when conducting measurements two months after the initial experiments. While this issue is potentially limiting for additively manufactured heat exchangers and should be the focus of future research, the heat exchanger developed in this study still performed extremely well compared to conventionally manufactured counterflow heat exchangers even when accounting for the deterioration. Because the results of the study are so promising, we encourage fellow researchers to conduct further studies on counterflow AM heat exchangers. Further research is also possible in the plastic AM heat exchanger field.

Acknowledgements

This research was conducted as a part of the Superefficient 3D Heat Exchangers project and funded by the Tekes Challenge framework.

Conflict of interest statement

On behalf of all authors, the corresponding author states that there is no conflict of interest.

References

1. Neugebauer R, Müller B, Gebauer M, Töppel T (2011) Additive manufacturing boosts efficiency of heat transfer

components. Assem Autom 31:344–347

2. Achenbach E (1977) The effect of surface roughness on the heat transfer from a circular cylinder to the cross flow of air. Int J Heat Mass Transf 20:359–369

3. Sam Huang H, Varshney V, Wohlwend JL, Roy AK (2013) Heat Transfer at Aluminum–Water Interfaces: Effect of Surface Roughness. J Nanotechnol Eng Med 3:6

4. Tsopanos S, Sutcliffe CJ, Owen I (2005) The Manufacture of Micro Cross-Flow Heat Exchangers by Selective Laser Melting. In: Proc. of the 5th Int. Conference on Enhanced, Compact and Ultra-Compact Heat Exchangers: Science, Engineering and Technology. pp 410–417

5. Muley A (2014) Advanced Heat Exchangers for Enhanced Air-Side Performance: A Design and Manufacturing Perspective. 14

6. Olakanmi EO (2013) Selective laser sintering/melting (SLS/SLM) of pure Al, Al-Mg, and Al-Si powders: Effect of processing conditions and powder properties. J Mater Process Technol 213:1387–1405

7. ARPA-E (2015) A Case Study on the Impact of Additive Manufacturing for Heat/Mass Transfer Equipment used for Power Production. https://arpa-e.energy.gov/?q=slick-sheet-project/next-generation-air-cooled-heat-exchangers. Accessed 21 Feb 2017

8. ARPA-E (2015) Novel Polymer Composite Heat Exchanger for Dry Cooling of Power Plants. https://arpa-e.energy.gov/?q=slick-sheet-project/advanced-heat-exchangers. Accessed 21 Feb 2017

9. SBIR (2016) Additive Manufacturing Development of Naval Platform Heat Exchangers. https://www.sbir.gov/sbirsearch/detail/871215. Accessed 21 Feb 2017

10. Wong M, Tsopanos S, Sutcliffe CJ, et al (2007) Selective laser melting of heat transfer devices. Rapid Prototyp J 13:291–297

11. Ventola L, Chiavazzo E, Calignano F, et al (2014) Heat Transfer Enhancement by Finned Heat Sinks with Micro-structured Roughness. J Phys Conf Ser 494:9

12. Thompson SM, Aspin ZS, Shamsaei N, et al (2015) Additive manufacturing of heat exchangers: A case study on a multi-layered Ti-6Al-4V oscillating heat pipe. Addit Manuf 8:163–174

13. EOS GmbH – Electro Optical Systems (2014) Material data sheet: EOS Aluminium AlSi10Mg.

14. Hoffmann KA, Chiang ST, Siddiqui S, Papadakis M (1996) Fundamental Equations of Fluid Mechanics. Engineering Education System, Wichita, KS

15. Wang D, Mai S, Xiao D, Yang Y (2016) Surface quality of the curved overhanging structure manufactured from 316-L stainless steel by SLM. Int J Adv Manuf Technol 86:781–792 . doi: 10.1007/s00170-015-8216-6

16. Chastand V, Quaegebeur P, Maia W, Charkaluk E (2018) Comparative study of fatigue properties of Ti-6Al-4V specimens built by electron beam melting (EBM) and selective laser melting (SLM). Mater Charact. doi:

10.1016/j.matchar.2018.03.028

17. Cabrini M, Lorenzi S, Pastore T, et al (2016) Corrosion resistance of direct metal laser sintering AlSiMg alloy. Surf Interface Anal 48:818–826