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LPMat2 - Energy Efficient Crossflow Heat-Exchanger
Organisation
Kungliga Tekniska Högskolan

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Nyckelord
Elektronikkylning, Gyroid-kylfläns, Icke-uniform värmetillförsel, Värmeöverföringssimulering med CFD, Additiv Tillverkning

Förord

The project has been financed by Swedish Energy Agency through the LPMat2 project, under the Termo Program.

Innehållsförteckning

Sammanfattning

LPMat2 utvecklade direkta och indirekta precisionskyllösningar för icke-uniforma värmekällor, vilket representerar realistiska termiska förhållanden inom kraftelektronik. Detta är särskilt relevant för att förbättra värmehanteringen och möjliggöra återvinning av spillvärme vid låg temperatur från kraftelektroniska system. Denna rapport sammanfattar två viktiga metoder: indirekt kylning med hjälp av Triply Periodic Minimal Surface (TPMS)-strukturer och direkt kylning via flera stötande strålar. En ny gyroidbaserad kylfläns med ett enda inlopp designades för elektronisk kylning och återvinning av spillvärme vid låg temperatur.

Jämfört med konventionella pin-fin-kylflänsar uppvisade den gyroidbaserade designen betydande förbättringar i termisk prestanda, inklusive minskad maximal temperaturökning, lägre värmemotstånd och förbättrad temperaturuniformitet under både enhetliga och icke-enhetliga värmeflödesförhållanden, över varierande flödeshastigheter och porositeter. Byggande på detta utvecklades och utvärderades en innovativ gyroidbaserad kylfläns med två inlopp och med samma arbetsflöde, vilket uppnådde upp till 40 gånger högre värmeavledning än designer utan TPMS och effektivt mildrade icke-enhetliga värmekällor (hotspots) genom att kontrollera topptemperaturer och leverera en mer enhetlig temperaturprofil vid utloppet.

Rapporten dokumenterar också additiva tillverkningen av den tvåinloppsbaserade gyroidkylflänsen med hjälp av Fused Deposition Modeling (FDM) för PLA-polymerprototyper och Laser Powder Bed Fusion (PBF-LB) för metallkomponenter med en Ni-baserad legering. En detaljerad litteraturgenomgång genomfördes för att stödja designprocessen, med fokus på avstånd mellan strålar och ytor, munstyckskonfigurationer, impingementvinklar, flödesbegränsning, arraylayout och strategier för att justera strålar med icke-enhetliga värmefördelningar. Designarbetet pågår. Slutligen diskuterar rapporten den industriella relevansen av de utvecklade lösningarna.

Summary

LPMat2 developed direct and indirect precision cooling solutions for non-uniform heat sources, representing realistic thermal conditions in power electronics. This is particularly relevant for enhancing thermal management and enabling low-temperature waste heat recovery from power electronic systems. This report summarizes two key approaches: indirect cooling using Triply Periodic Minimal Surface (TPMS) structures, and direct cooling via multiple impinging jets. A novel gyroid-based heat sink with a single inlet was designed for electronic cooling and low-temperature waste heat recovery. Compared to conventional pin-fin heat sinks, the gyroid-based design demonstrated significant improvements in thermal performance, including reduced maximum temperature rise, lower thermal resistance, and improved temperature uniformity under both uniform and non-uniform heat flux conditions, across varying flow rates and porosities. Building on this, an innovative two-inlet gyroid-based heat sink was developed and evaluated using the same workflow, achieving up to 40 times higher heat dissipation than non-TPMS designsand effectively mitigated non-uniform heat sources (hot spots) by controlling peak temperatures and delivering a more uniform temperature profile at the outlet.

The report also documents the additive manufacturing of the two-inlet gyroid heat sink using Fused Deposition Modelling (FDM) for PLA polymer prototypes and Laser Powder Bed Fusion (PBF-LB) for metal components with a Ni-based alloy. A detailed literature review was conducted to support the design process, addressing jet-to-surface spacing, nozzle configurations, impingement angles, flow confinement, array layout, and strategies for aligning jets with non-uniform heat distributions. The design work is ongoing. Finally, the report discusses the industrial relevance of the developed solutions.

Inledning/bakgrund

Electrification of society and industry will require a massive electricity transport infrastructure (including converter transformers). The residual heat from the transformers will be up to 5-10 TWh of heat per year for Sweden alone and is a valuable source for use in our district heating networks. As of today, the cooling water from converter transformers is too cold for direct use and this project is a first step to removing that limitation. HEATWISE gathers an equipment manufacturer, innovative researchers, and stakeholders from district heating. It aims to use precision cooling to enable novel transformer's cooling design that increase the cooling circuit exit temperature while securing long lifetime of the equipment. The works will investigate innovative cooling solutions (direct and indirect) and tailor them to the challenge at play. We will use advanced numerical simulations to explore rapidly option and prove the concept with physical experiments. Precision cooling consists of targeting high heat-fluxes in critical regions like hot spots [3]. Doing so, the cooling can be performed with less fluid and/or at higher temperature. It opens for a more uniform temperature and a higher coolant exit temperature. The former secures a longer lifetime of the component while the second offer possibilities for recovery the heat at higher temperature. Focusing on converter transformers for an electrified society, we consider power electronic cooling classified into direct and indirect cooling techniques [3]. Also, we consider non-uniform heat sources with hot spots mirroring the structure and placement of the chip [4-5]. Direct cooling consists of air cooling, spray [6] and jet impingement [1] cooling, immersion cooling, and droplet electrowetting [3]. It consists in increasing locally the heat-transfer coefficient using flow features. It is a dynamic solution that easily adapts to the sources. Indirect cooling includes microchannel, heat pipe, thermoelectric, and Phase Changed Material. It consists in increasing the heat-sink locally and smoothing the hot spots in larger volumes using thermal conduction. Porous interface are popular solutions [2, 3, 7, 8] corresponding to heat-exchangers with porosity. Recent years, some studies [7-13] have been conducted with the aim of investigating heat transfer in porous media with complex structure – in other words improve heat transfer using material porosity. For example, work at DTU [10] has shown interesting properties of a modified "shell-and-tube" heat exchanger with porous filling. Work at NTNU has shown improvements in heat transfer into a heat pipe by using metal foam [11]. These studies reported interesting improvements, but the detailed improvement mechanisms are still not fully understood. Reasons include the randomness of the geometry (predictability issues), the lack (until recently) of the proper simulation tools (conjugate heat-transfer in complex geometries) and the difficulty to manufacture such units before the rise of additive manufacturing. When dealing with transient and non-uniform heat sources, both direct and indirect precision cooling options are viable, and event combinations are of interest. While these solutions are not yet available, the tools for understanding the heat-transfer and empowering the engineers are available. For example, the computing capacity and modelling processes are available to perform such simulations and makes it possible to carry out accurate flow and heat simulations including optimization [1, 2, 14, 15].

Our group is leading in that activity, and we have started working on this new generation of material for heat ink in 2018 and selected the Triple Periodic Minimum Surface geometry – TPMS. This activity was supported by Swedish Energy Agency within the projects LPMat1 and LPMat2. Although LPMat2 is not fully finished, it was distinguished and selected by the Swedish Engineering Academy IVA for its potential to develop into innovations, business development or other forms of benefit [16]. LPMat 1 and 2 have demonstrated a unique ability to harvest heat and the success of the concept. However, LPMat 1 and 2 have not dealt with non-uniform heat sources and have limited to steady-state operation.

HEATWISE builds upon the successes of LPMat 1 and 2 and leverages the exceptional properties of the material for indirect heat-harvesting and will combine with direct cooling capabilities to ensure a smooth heat-transfer. It is a step between the more fundamental studies of heat-transfer intensification and use for heat-harvesting. As of today, there is no published study using TPMS heat-intensification for non-uniform and transient heat-sources. Preliminary work conducted by our group has demonstrated the potential of TPMS structures for effectively managing hotspots under steady-state flow conditions [2]. It is a promising step forward but still not enough for real applications that experience rapid changes of cooling demand. HEATWISE will answer this need and create the knowledge for combining direct and indirect methods while understanding the heat-transfer details.

This project is a clear collaboration, between academia and industry and answers the call purpose to develop knowledge and competences for addressing energy efficiency challenges, creating a novel (and overlooked) for recovery of residual heat and production of heat for district.

Genomförande

This project will enable novel heat-recovery from transformers for societal benefit. It leverages recent progresses for creating new models for designing and simulating complex shaped heat-exchangers. It will also educate experts who can take the new tools into engineering practices. This project is a collaboration between KTH and two industrial actors Swegon and Hitachi Energy. The project also leverages the knowledge, methods and facilities at KTH, the TPMS simulations methods/software/knowhow and the Supercomputing facilities at PDC.

The technical goals of the project have been reached and are to:

- design using Computational Fluid Dynamics (CFD) new heat-exchange units and to evaluate both direct and indirect precision cooling techniques. This includes the use of various families of

Triply Periodic Minimal Surface (TPMS) structures and multiple jet impingement configurations.

- The developed designs are validated through 3D additive manufacturing, establishing a novel and integrated workflow for the design.
- The methods will make it possible to create novel precision cooling solutions evaluate the performance together with industry.
- These results will serve as proof-of-concept and pave the way for future product design and energy and resource efficient production of these new solutions.
- The goals are to produce new knowledge and methods that will be reported in scientific journals and presented at scientific conferences.

Arbetspaket (AP)

To achieve the stated objectives, a novel TPMS-based single-inlet heat sink was designed and analysed its thermal performance [17]. Key parameters—including mean temperature deviation, thermal resistance, maximum temperature rise, and required pumping power—were evaluated across a range of flow rates and porosities. The results were compared with the conventional pin-fin heat sink design. Gyroid structures were chosen for their smooth internal surfaces, high surface area, and well-balanced thermal-hydraulic characteristics. The analysis was conducted under both uniform and non-uniform heating conditions, reflecting heat flux distributions typical of power electronic modules. The simulation framework is built in ANSYS Workbench, where conjugate heat transfer (CHT) simulations are carried out to analyse heat dissipation through both solid and fluid domains. The flow through the gyroid structure is assumed laminar and incompressible, governed by the Navier–Stokes and energy equations.

Building on the success of the single-inlet gyroid design, a novel two-inlet TPMS based heat sink (Figure.1) [18] was proposed and developed to address limitations related to non-uniform temperature distribution and elevated outlet temperatures. In the single-inlet configuration, the cold fluid stream is gradually heated as it flows through the heat sink, leading to reduced heat dissipation from hotspots near the outlet and consequently compromising the overall cooling efficiency. By introducing a second inlet or the cross flow, the internal flow distribution within the TPMS structure becomes more balanced, effectively reducing localized thermal gradients and enhancing temperature uniformity both throughout the heat sink and at the outlet. Figure 1 presents the two-inlet heat sink, which incorporates a Gyroid-TPMS structure along with both solid and fluid domains. The flow domain is composed of two separate, fully connected flow regions, divided by a smooth wall shaped according to the TPMS geometry. These regions represent two independent flow channels, where the fluids remain non-interacting, however the heat is transferred between them through the TPMS walls. A non-uniform heat flux boundary condition with multiple localized peaks is applied to the bottom plate of the heat sink to replicate realistic non-uniform heating scenarios (Figure 3 in [18]).

3D printing by using the additive manufacturing techniques

Design for additive manufacturing

When designing components for AM (additive manufacturing), it is essential to apply Design for Additive Manufacturing (DfAM) principles. Part geometry should be tailored specifically for AM rather than adapted from conventional manufacturing, allowing for optimized structures such as lattices, internal channels, and topology-optimized forms. For many AM techniques, for metal AM processes, support structures are also often required to stabilize overhangs and dissipate heat during the build. Support structures introduce additional steps in both design and post-processing and the need for supports should therefore be reduced through geometry design and selection of print orientation. Furthermore, the part orientation affects surface quality, print time, and residual stresses.

LPMat2 part geometry

The part geometry developed for the tests in the LPMat2 project is shown in Figure 1. It is a fluid heat sink exchanger with manifolds and is based on a TPMS structure of gyroid type. The TPMS unit was defined with a cell size of 10 mm, a wall thickness of 2 mm and a porosity of 0.8 indicating that 80% of the volume is void space available for fluid flow.

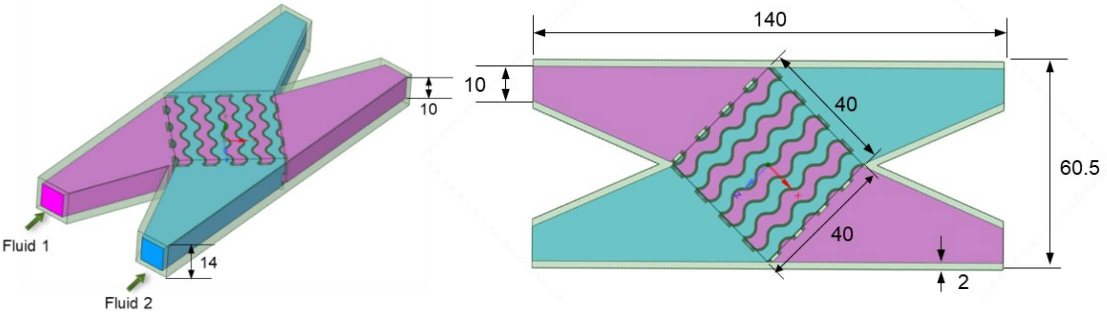

Figure 1. Selected geometry with dimensions in mm.

The part developed for the LPMat2 project align well with several DfAM principles for metal printing using PBF-LB. The TPMS structure is particular well-suited for PBF-LB as it provides self-supporting features in multiples orientations and a high strength-to-weight ratio. The porosity of 0.8 ensures that a significant portion of the internal volume is open which should allow for effective powder removal pathways possible, which reduce the risk of trapped powder after printing.

The wall thickness falls also within the printable range for most common AM alloys currently printable with PBF-LB. In addition, the consistent wall thickness is also beneficial for thermal stability during the build and minimizes the risk for stress concentrations.

Nevertheless, despite being generally compatible with PBF-LB, several issues challenger must be considered. For example, local overhangs within the TPMS structure may fall below critical angles (<35-40°) which may cause poor surface quality or incomplete fusion in these areas. Part orientation is also an aspect, and the part should not be printed flat as this may introduce large unsupported surfaces.

Material

Based on applications such as low-temperature waste heat recovery, low-pressure-drop and low-fouling environments, passive cooling in HVDC stations, and ventilation heat recovery in buildings, the material for the TPMS-based heat exchanger should be carefully selected based on the balance of thermal performance, corrosion resistance, manufacturability via AM, and mechanical properties. For the applications within the LPMat2 project, the material of interest is an Al alloy, e.g., AlSi10Mg or similar. One of the primary reason for this is Al alloys' high thermal conductivity. In addition, their low weight and corrosion resistance make them suitable for use in building ventilation system, where both structural weight and exposure to humid air are important to consider. From a manufacturing point of view, these Al alloys are highly compatible with PBF-LB as they offer excellent processability and good dimensional accuracy allowing for fabrication of thin-walls, lattice structures and TPMS geometries. Furthermore, Al is non-magnetic and electrically conductive which is good when electromagnetic interference should be avoided in, e.g., HDVS converter stations. However, the metal prototype manufactured in this task is made of a Ni based superalloy, specifically Inconel 939. This choice was solely due powder availability and practical considerations related to processing. For the LPMat2 tests, this material difference was not expected to have any significant impact.

Application to industry and return of experience

During the LPMat2 project Swegon have learned about TPMS heat exchanger designs and their potential advantages in HVAC application. Several different applications with in the present Swegon portfolio have been identified.

- Air to air heat recovery heat exchangers with low pressure drop that are less prone to freeze leading to both improved SFP values of our air handling units and reduce the number of defrosting cycles.
- Smaller air to water heat exchangers that reduces the embedded CO_2 footprint of our active chilled beams and fan-coil units.
- Heat exchangers with high efficiency can improve the efficiency of thermoelectric chillers/heat-pumps. This would enable the use of refrigerant and compressor free heating/cooling solutions with acceptable efficiencies.

- The use of heat exchangers is expected to increase in thermal energy storage solutions integrated in HVAC systems. Thermal energy storage enables increased use of renewable energy and help to peak shave heating/cooling production allowing for smaller systems to be installed.

The main challenge identified is the use of additive manufacturing in high volume production. Swegon are using 3D printing for prototype production of smaller plastic parts during early-stage prototype development. To learn more about the potential for additive manufacturing in other material than plastic and for production purposes rather than for prototyping Swegon have been in contact with Uddeholm who are experts in additive manufacturing in metallic materials. A TPMS heat exchanger design was shared by KTH. The CAD model was used to perform CFD simulations of flow distribution and pressure drops. Furthermore, a heat exchanger was printed in polyamid PA66 which was the material available at Swegon R&D. Polyamid is not an ideal material for heat exchangers from heat transfer perspective, but it proved that the TPMS geometries are possible to produce using additive manufacturing. The printed heat exchanger was tested in the lab and pressure drop and heat exchange efficiency was evaluated.

Literature Review and designing

A detailed literature review is being conducted to support the development of a direct precision cooling solution using multiple impinging jets. The review focuses on determining the optimal jet-to-surface spacing and nozzle configurations, evaluating the effects of jet impingement angle, confinement, and array layout, and exploring strategies for aligning jet positions with non-uniform heat source distributions. The insights gained from this review will guide the design of a custom perforated nozzle plate that positions the impinging jets over high-heat-flux regions, specifically those found in Hitachi Energy's device models.

Resultat/ Diskussion

The TPMS based single inlet heat sink exhibits a unique 3D helical flow structure, formed by eight key planes per unit cell that rotate 45° successively, creating four intertwined helical streams with enhanced convective mixing. This geometry enables a central high-velocity core within each stream, improving heat transfer and flow uniformity. Compared to the pin fin heat sink (PHS), the gyroid heat sink (GHS) consistently shows lower thermal resistance and temperature non-uniformity across all porosities and flow rates, though at the cost of higher pumping power. Reducing porosity and increasing flow rate further enhance thermal performance by increasing surface contact and fluid velocity. Under non-uniform heating, the GHS maintains up to 30% lower temperature rise at hotspots and achieves significantly more uniform temperature distribution, outperforming the PHS by 14–17% in hotspot temperature variation across different heating scenarios. The modelling and simulation efforts led to the publication of a peer-reviewed article in Energy Conversion and Management, titled “A gyroid TPMS heat sink for electronic cooling” [17].

The two-inlet TPMS heat sink (TIHS) effectively manages non-uniform hotspots applied at the bottom heated plate by spreading them across the domain, thereby significantly reducing hotspot intensity. A major advantage of this design is its use of two independent flow streams, which regulate local temperatures in critical regions—whether excessively hot or overcooled (dead zones)—through thermal conduction across the TPMS walls. When a hotspot or cold spot cannot be sufficiently addressed by one channel alone, the adjacent flow stream aids in balancing the local temperature via inter-channel heat transfer. This mechanism leads to a more uniform temperature distribution throughout the heat sink and at the outlet. Comparative analysis shows that the two-inlet gyroid based heat sink can dissipate nearly 40 times more heat from hotspots than a non-TPMS design, while maintaining the same peak surface temperature, highlighting its superior thermal management performance. The outcomes of this research have been published in the peer-reviewed journal Energy Conversion and Management: X, under the title "A Novel Gyroid-Based Two-Inlet Heat Sink for Enhancing Heat Dissipation and Mitigating Hot Spots in Power Electronics Cooling" [18].

3D printing by using additive manufacturing techniques

Design for additive manufacturing

The printed components are shown in Figures 2 and 3. Figure 2 shows the PLA prototype, manufactured with the dimensions specified in Figure 1. Figure 3 displays the metal parts, which were printed using the EOS M290 system. Two versions were printed in each material: one representing the complete geometry intended for testing, and one halved version designed to visualize the internal TPMS structure. Printing parameters for printing Inconel 939 had been optimized in a previous project and the same were applied for the LPMat2 part. The part was oriented with the long side parallel to build direction during the build.

Figure 2 Printed polymer prototypes. Printed with MakerBot Replicator Z18 using PLA filament.

During the metal printing, some issues were encountered. Initial attempts failed due to poor hatching results, which were traced back to issues with the STL file where the mesh used contained a high number of broken or non-manifold triangles. The slicing software could not repair these and instead a more sliceable STL file was created with a reduced mesh size. It should also be mentioned that the gyroid contouring was not applied due to warnings of over melting. This might have affected the surface and increased its roughness. In addition, the print was paused two time to allow for powder refill resulting in layer lines on the wall. However, it was not expected to affect the LPMat2 test results.

(a) (b) (c)

Figure 3 Printed metal prototypes. (a) and (b): the final version to be used for the tests and (c): the cross-section showing the internal TPMS structure.

Test in industry

Figure 4 present the heat-exchanger (HTX) tested at Swegon's facilities. The printing process was not entirely straight forward. Several attempts were made before a sample that did not leak between the warm and cold side could be produced. This resulted in slightly thicker wall of the inner structure than what would be ideal for heat exchanger performance.

This HTX was tested in the experimental set-up sketched in Figure 5. Air to air heat exchange was tested at Swegon Arvika test centre. Room air around 20°C was used as cold air stream. To generate a temperature difference a warm air stream was "created" using a duct heater. The size to the prototype was limited by the 3D printer available at that moment. It resulted to be difficult to control and measure the low air flows going through the heat exchanger, hence operating with significantly higher air flows than anticipated. Figures 6 and 7 present the results. Defining HTX efficiency as the temperature increase of the cold air stream as part of the totally available temperature raise i.e. the difference between cold air going in and warm air going in. The noise in the data is partly explained by the low resolution of temperature readings. The HTX efficiency here is relatively stable. The general feeling however was that the efficiency was relatively low but that was also expected considering the size of the unit (compared to the present airflow) and the material used (plastic). Two limitations arose, (i) the wall of the inner structure was thicker than hoped (limitations of the 3D printer to ensure no leakage) and (ii) the plastic use in the test showed a very low conductivity. Both limitations can be overcome with more modern 3D printers and choice of a high conductivity plastic.

The 3D printed heat exchanger worked and the performance could be easily increased using better material and designing with thinner walls. Furthermore the experimental set-up was not flexible enough for testing a heat exchanger of this size. The air flows used were small (in order to get any measurable temperature difference) which made it difficult to measure with any accuracy. Despite the experimental challenges the tests confirmed that it was possible to 3D print the TPMS structure and to get a heat exchanger that did not leak and can operate in a ventilation setting.

Consequently, the TPMS design is interesting for HVAC applications especially if it can help to reduce risk for freezing of the cold corner of a cross flow plate heat exchanger. This was not possible to verify with the prototype printed.

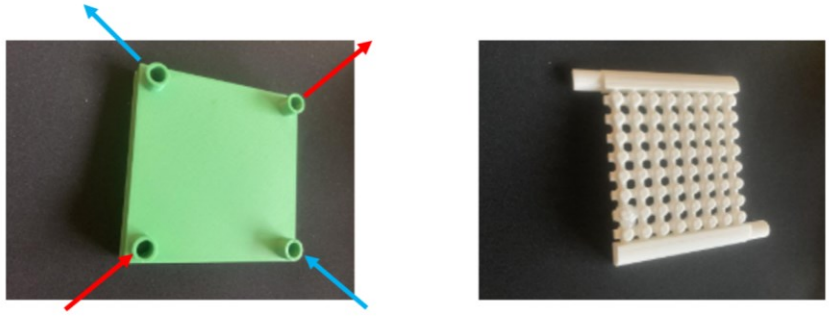

Figure 4: Plastic heat exchanger in 3D to the left. The inner “channel” (of of the fluids) printed to show the geometry in the picture to the right

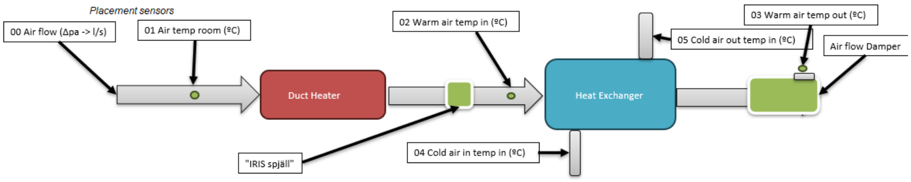

Figure 5: Experimental set-up. Air to air heat exchange was tested in a relatively simple set-up at Swegon Arvika test centre. Room air around 20°C was used as cold air stream.

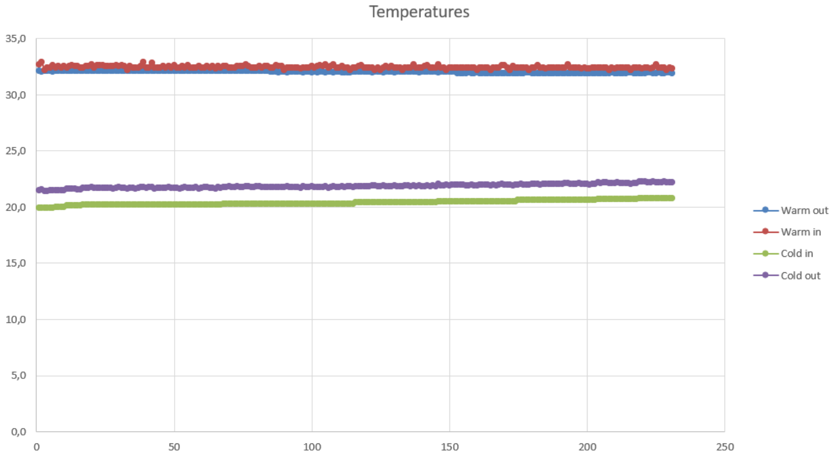

Figure 6: Experimental results for the HTX operation with a cold and hot stream. Temperature in C are plotted vs time in h.

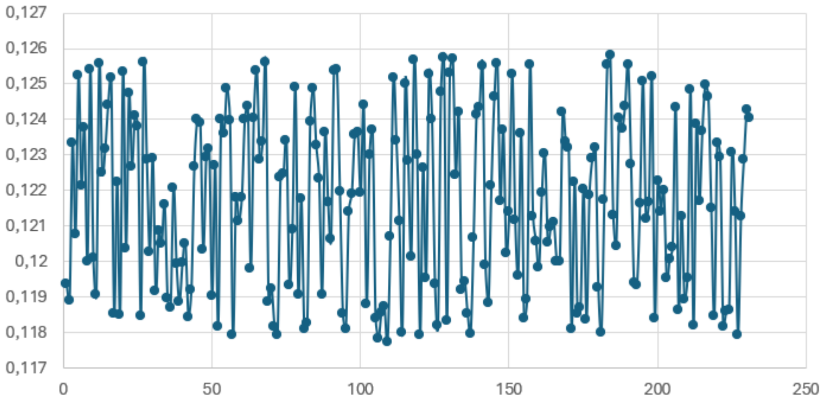

Figure 7: Heat-Exchanger Efficiency plotted versus time (h).

Application to industry and return of experience

Knowledge of TPMS heat exchangers and their advantages have been shared within the Swegon organization. Several applications for TPMS heat exchangers have been identified, with main benefits being improved energy efficiency and material efficiency both leading to reduced CO_2 emissions from a HVAC system over its lifetime. A physical TPMS heat exchanger

was printed in house. This confirmed the possibility to produce the complex 3D geometry using additive manufacturing. To produce a more efficient heat exchangers other materials should be used.
Meetings have been held with experts in additive manufacturing to evaluate the feasibility to produce heat exchangers in metal. More work is needed to understand what applications to start with and what materials to use. In parallel Swegon need to learn more about additive manufacturing for high volume production. The present estimated time to produce a heat exchanger in combination with investment cost for an industrial 3D printer will make it difficult to compete with the present heat exchanger designs used. However, additive manufacturing is quickly becoming commodified and the value of reducing CO_2 footprint of products are increasing so at some point in time it might be economically feasible to used TPMS heat exchangers in HVAC applications.

The conclusion of the project is that TPMS heat exchanger designs are interesting and provide some clear advantage over existing heat exchanger solutions used in the HVAC business. Before a next step is taken it would be good to understand the TRL of 3D printing for production purposes and the cost structure related to that type of production. Next experimental testing should be done with prototypes made of materials with better heat transfer characteristics and using a set-up with better accuracy and resolution for flow and temperature measurements at this range of air flow and temperature differences.

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[Klicka och skriv]