LATVIAN JOURNAL OF PHYSICS
AND TECHNICAL SCIENCES
2024, N 6

DOI: 10.2478/lpts-2024-0045

AIR FLOW ANALYSIS FOR TRIPLY PERIODIC MINIMAL SURFACE HEAT EXCHANGERS

A. Kancs

WEMPS SIA,
3 Straupes Str., Riga, LV-1073, LATVIA
E-mail: arturs.k@wemps.eu

Due to the increasing popularity of additive manufacturing technologies, more varied and complex shapes of heat exchangers can be produced that can be optimised to be more compact and efficient. In this paper, a triply minimal periodic surface – gyroid structure – is designed to study the applicability of such structures in compact air-to-air heat exchangers used in residential ventilation recuperation systems. Gyroid surface structures could potentially decrease overall heat exchanger size, pressure and increase heat transfer. Several geometry variations with different flow rate values were analysed to compare the efficiency of heat exchanger designs. Additionally, a literature review was conducted to identify more adaptable geometric parameters of the gyroid structure. To calculate the pressure difference, temperature and heat transfer in each variation, SolidWorks Flow Simulation was used. The results showed that by using gyroid structures, heat exchanger energy transfer can be optimised for required back pressure and heat transfer, while reducing the overall dimensions, compared to conventional heat exchangers. By incorporating low cost, printed thermal recuperators, thermal efficiency of residential buildings can be improved. Suitable materials, manufacturing methods and application limitations are discussed.

Keywords: *Additive manufacturing, CFD, gyroid, heat transfer, thermal recuperator.*

1. INTRODUCTION

Household energy efficiency is becoming more and more important, as it is one of the options to improve sustainability. At the same time, 3D printing technologies are becoming more advanced, allowing higher complexity and larger models to be printed, as well as increasing the available material list for this process. This results in almost any geometry being physically producible, such as TPMS (triply periodic minimal surfaces). Surfaces like these are found in nature, and lately have been studied for use in engineering applications, such as heat exchangers for residential heat recovery. By using these novel methods, more compact size devices with lower pressure loss, noise and higher thermal efficiency could be implemented. Nearly limitless possibilities in design using 3D printing methods give way for numerous options for research and development of such structures.

During the analysis of publications, the results of research and experiments of TPMS structure use in heat transfer applications, such as heat exchangers and cooling ribs, were collected and analysed. The most studied and practically used types of these surfaces are Schwarz-diamond and gyroid, and this study will focus mostly on gyroid structure. Below, the equation of the single-cell approximations of gyroid surface by the spatial coordinates of x, y, z is provided [1]:

$$\sin(x)\cos(y) + \sin(y)\cos(z) + \sin(z)\cos(x) = 0. \quad (1)$$

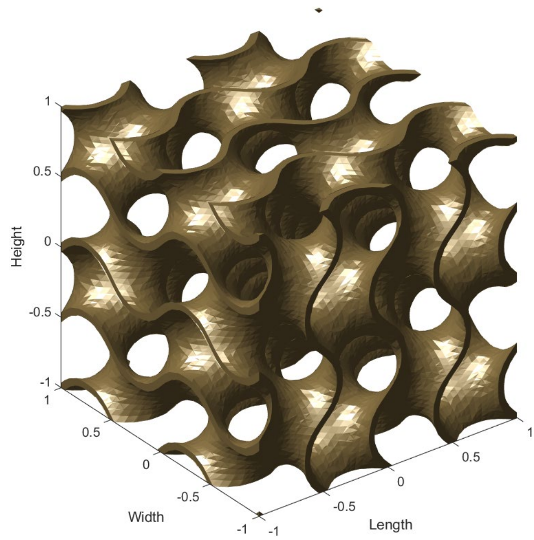

Fig. 1. Gyroid TPMS model.

There are different ways to manipulate the geometry of TPMS in heat exchangers – to change the porosity, wall thickness, cell sizes, as well as to make gradually changing porosity structures. To improve heat transfer, studies have investigated the degree of porosity of TPMS-based structures. For gradual TPMS, the porosity can be varied along the length, width or height of the channel while keeping the overall porosity of the structure the same.

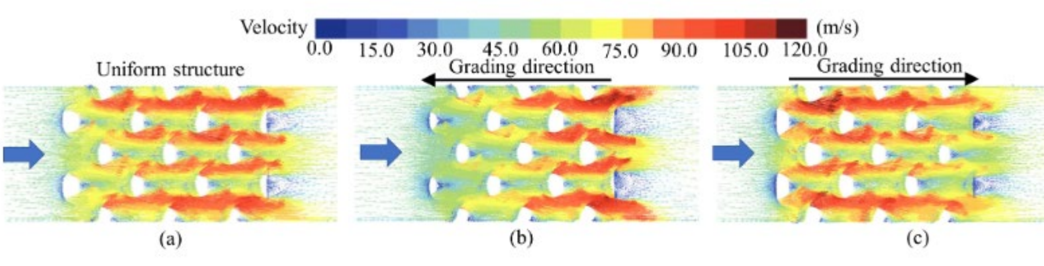

Fig. 2. Velocity vectors in proportional and gradient TPMS structure at high Re flow [2].

Gradually increasing the porosity in the flow direction can show better results than uniform porosity or gradually decreasing porosity sheet TPMS models (see Fig. 2). For example, at high Reynolds number flow and Schwarz-d structure, by increasing the porosity by 2.5 %, pressure loss in channels was reduced by 27.6 %, while reducing the heat transfer coefficient only by 15.7 % [2]. This implies that by reducing the overall porosity of the structure and using gradually increasing porosity channels, it is possible to increase the heat transfer at the same pressure loss, compared to a uniform model. Such manipulations with TPMS geometry could create an opportunity to improve the flow parameters without changing the overall size of the heat exchanger.

By reducing the overall uniform porosity, channel dimensions are decreased, which increases the flow speed. That increases the convective heat transfer coefficient in the channels (see Fig. 3), while also increasing the pressure loss significantly. The heat transfer coefficient is also affected by the surface area changes in the same volume, which increases by reducing the porosity [3].

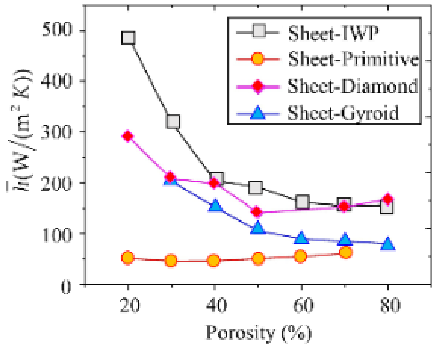

Fig. 3. Effect of porosity on convective heat transfer coefficient at Re = 40 [3].

There are studies performed on various gyroid wall thicknesses at constant cell sizes and porosity, which conclude, that increasing the wall thickness in TPMS structures, there can be an increase in a convective heat transfer coefficient. Although the convective heat transfer coefficient increases, thick walls can interfere with flow, creating regions of backflow (Fig. 4), which reduces the thermal efficiency of the system. Because of both good thermal efficiency and low-pressure loss, thin walled TPMS heat exchangers show better results [4].

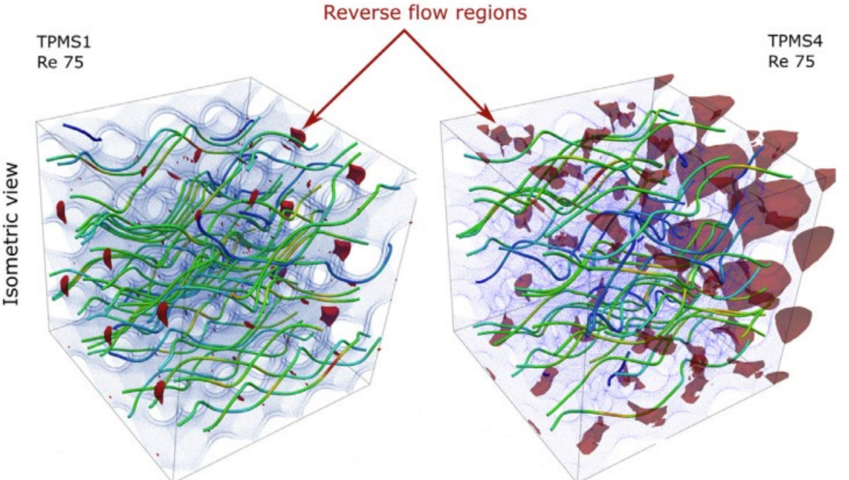

Fig. 4. Backflow regions in thin walled and thick walled Schwarz-d model [4].

Results from cell size studies imply that TPMS with larger cell sizes produce lower pressure loss in the system, while smaller cell sizes significantly increase the pressure loss, especially at higher Reynolds number flow. It can be concluded that gyroid and primitive strictures with smaller cell sizes produce the largest pressure losses compared to other types of TPMS, which can be explained by their relatively complex geometry and lower porosity (see Fig. 5) [5].

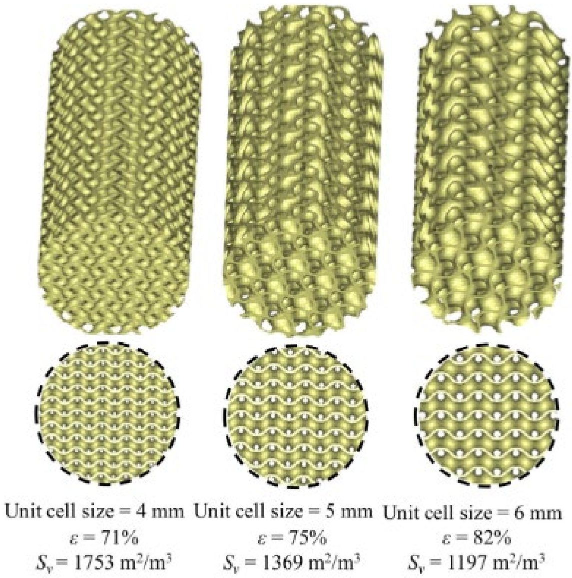

Fig. 5. Gyroid structure cell size, porosity and specific surface area [5].

Comparing the flow regimes in the previously mentioned TPMS heat exchangers, it can be concluded that in the lowest pressure systems Schwarz-d structure has the better thermal performance [6], while at turbulent flows and high flow speeds, gyroid can perform better [7].

Using the information collected from previous studies, gyroid heat exchanger was modelled, test printed for numerical flow simulations, in order to review the effect of cell sizes and cell proportions on thermal efficiency as well as pressure loss.

2. MODEL DESIGN AND BOUNDARY CONDITIONS

Using previously mentioned Eq. (1), base model of gyroid structure was modelled in SolidWorks 2020 CAD software. The base surface model, used for all following numerical simulations, was a gyroid cell surface (Fig. 6) with dimensions of 20x20x20 mm. Using this model, the geometry could be patterned as required, as the structure is periodic in any given direction.

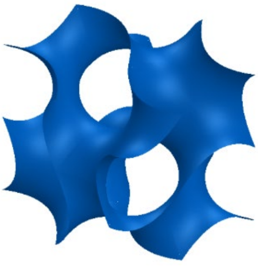

Fig. 6. Gyroid surface model cell.

To better observe flow parameters similarly to a cell of a real life-sized air-to-air heat exchanger, numerical model geometry size of 40x40x180 mm was chosen. This way a full-length counter flow channels can be simulated, while not using excessive computational capacity. Enlarging the TPMS structure models significantly increases the computational resources needed to perform flow calculations, so it is necessary to create geometric models of the smallest possible size.

By applying a thickness to the surface model, a solid model of structure was acquired. To create flow channels for SolidWorks Flow Simulation 2020, a heat exchanger body was created (Fig. 7). The model consists of a body with two inlet and two outlet channels and gyroid surface core. Both cold air (blue) and hot air (red) inlets and outlets were placed in 40 mm distance from the gyroid structure to help with flow steadiness before entering the structure, as well as decreasing the possibility of flow vortexes across pressure boundaries. In order to avoid the influence of the auxiliary geometry on the results, the body and lids in the model were defined as ideal walls with a friction coefficient = 0, as well as a heat transfer coefficient of 0 W/m*K.

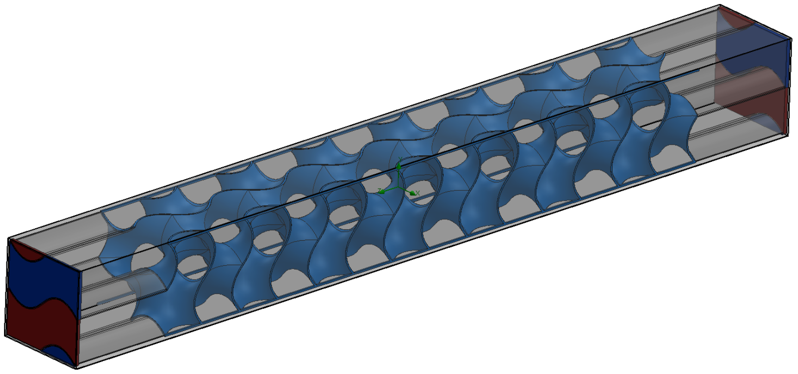

Fig. 7. Simulation model.

In order to study different geometric parameters, it was necessary to completely remodel each heat exchanger, since triply periodic surface modelling is not a built-in feature in the SolidWorks environment. Given the time consumption of modelling computationally complex structures, it was not possible to perform a large number of calculations. Since these patterns and flow channels are repeated periodically in all 3 axis directions, it is not possible to create a 2D model to simplify the CFD calculation.

Plastic with a heat exchange coefficient of 0.2 W/m*K was defined as heat exchanger material, and the chosen wall thickness of 0.6 mm was chosen. To choose a wall thickness several test prints were made, using a Prusa MK3S FFM/FDM 3D printer, 0.4 mm nozzle, and Prusament PETG filament. While trying to reach the smallest wall thickness (around 0.6 mm), stringing, holes in walls and rough surface texture were observed. While these deformations could be eradicated by fine tuning the print settings, such as temperature of the nozzle, print speed, retraction of the nozzle, ambient temperature, very small wall thicknesses were not likely to be reached. As the material heat transfer coefficient is very low, bigger wall thickness for TPMS heat exchangers can significantly decrease the heat transfer between channels.

While larger scale heat exchanger printing using a FFM printer could be feasible, especially if specific thermally conductive plastic filaments were used, an UV LCD resin 3D printer Creality Halot Mage Pro was tested for thin wall gyroid structure printing. Resulting prints (Fig. 8) had much better surface quality, no stringing and completely intact walls. Even lower wall thicknesses could be printed with good results; however, finalized prints always had slightly bigger wall thickness than modelled, so 0.6 mm was chosen as more realistic dimension for large scale printing.

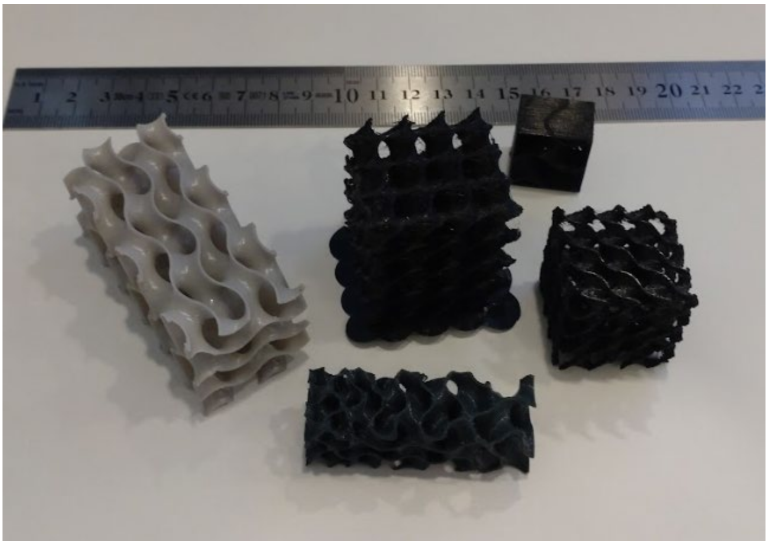

Fig. 8. Gyroid structure samples printed with FFM 3D printer (black) and UV LCD printer (white).

After the initial CAD geometry development, modelling of different cell size structures was carried out.

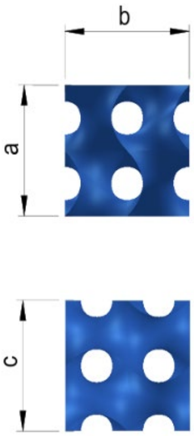

Fig. 9. Gyroid cell.

To compare gyroid cell size effect on heat transfer and pressure drop, three different gyroid structure variants were created, changing the size of the cell (Fig. 9) in each iteration, but keeping the overall model dimensions and wall thickness (0.6 mm). Specific surface area and porosity were determined by SolidWorks mass properties tool, but the hydraulic diameter for porous structures was calculated using the following formula [8]:

$$D_h = \frac{4\varepsilon}{S_s}, \qquad (2)$$

where ε is the porosity (a ratio of volume of flow channels for fluid flow to total volume of structure), S_s is the specific surface area (a ratio of gyroid surface area to the total volume of structure). Resulting hydraulic diameter for each cell size study is shown in Table 1.

Table 1. Cell Size Study Geometric Parameters

Cell size, [mm]	Specific surface area, S_s [m^2/m^3]	Porosity, ε	Hydraulic diameter D_h [m]
20x20x20	314.9	90.6 %	0.0115
30x30x30	213.7	95.1 %	0.0178
40x40x40	155.7	95.5 %	0.0245

Similarly, more studies were conducted on disproportionate gyroid cells, with different cell dimension in flow direction (Table 2). The obtained porosity values are over 90 % for all studies, which results from thin gyroid walls used – the cell length has little to no impact on structure porosity.

Table 2. Cell Length in Flow Direction Study Geometric Parameters

Cell size, [mm]	Specific surface area, S_s [m^2/m^3]	Porosity, ε	Hydraulic diameter, D_h [m]
20x20x20	314.9	90.6	0.0115
20x20x25	295.7	90.8	0.0123
20x20x30	283.8	90.8	0.0128
20x20x40	271.0	90.8	0.0134
20x20x50	264.4	90.8	0.0137

The gyroid solid model was assigned properties presented below.

Table 3. Material Properties Assigned

Material properties	Value
Average density [$kg.m^{-3}$]	1270
Specific heat [$J.kg^{-1}$ K^{-1}]	1000
Thermal conductivity [$W.m^{-1}.K^{-1}$]	0.2

The defined flow medium is air, with inlet volume flow values of 0.5, 1.875. 3.25, 4.625. 6 m^3/s. In all simulations, the temperature at the hot inlet is 20.05 °C, the temperature at the cold inlet is 0 °C, and the atmospheric pressure is set to 101325 Pa. The value of the inlet volume flow in the channels is variable to evaluate the influence of different flow parameters on the results. To solve K-ε transport equations for the turbulent kinetic energy, its dissipation rate was used, as it is the only turbulence model available by SolidWorks Flow simulation solver. Solving of 3-dimensional flow – pressure, velocity and other values – was done using Navier-Stokes equation system. Detailed mathematical model is defined in SolidWorks Flow Simulation 2020 Technical Reference [9].

To describe the effect of cell sizes on flow characteristics, temperature difference in cold and hot channels, and pressure drop in cold and hot channels were collected. The temperature difference was obtained by subtracting the average calculated outlet temperature from the inlet temperature in one channel. Pressure drop values were obtained analogously.

3. RESULTS AND DISCUSSION

The results provided in this study are pressure loss of air flowing through heat exchanger channels and temperature difference between each channels inlet and outlet. A total of 15 simulations were performed to study the effects of cell sizes on heat exchange and pressure drop, as well as 25 simulations on cell length effects.

In order to determine the flow characteristics in porous channels in each study case, Reynolds number was calculated [8]:

$$Re = \frac{D_h v \rho}{\mu \varepsilon}, \tag{3}$$

where D_h is the hydraulic diameter, v is the flow velocity, μ is the viscosity and ρ is the density of the flowing fluid. Density and viscosity were chosen as an average of inlet and outlet values. Calculation of hydraulic diameter for porous structures was discussed in the previous paragraph.

The obtained Reynolds number values from hydraulic diameter and flow parameters (Table 4) indicate flow being in transition region (10–200) and fully turbulent flow region (Re > 200), given that the Reynolds number values are reviewed as for flow through porous media [10]. Only the lowest volume flow rate value used in simulation covers a transitional flow, where there is either not fully developed turbulent flow or a combination of laminar and turbulent flow. The highest volume flow rate studies reach highly turbulent flow values.

Table 4. Reynolds Number Values for Each Numerical Study

Gyroid cell size	Volume flow rate, [m3/h]	Re	Gyroid cell size	Volume flow rate, [m3/h]	Re
	0.5	77.26		0.5	92.03
	1.875	289.74		1.875	345.10
20x20x20	3.25	502.22	50x20x20	3.25	598.18
	4.625	714.69		4.625	851.25
	6	927.17		6	1104.32
	0.5	85.75		0.5	156.25
	1.875	321.58		1.875	585.94
30x20x20	3.25	557.41	40x40x40	3.25	1015.63
	4.625	793.23		4.625	1445.33
	6	1029.06		6	1875.02
	0.5	89.78		0.5	82.28
	1.875	336.69		1.875	308.55
40x20x20	3.25	583.59	25x20x20	3.25	534.81
	4.625	830.49		4.625	761.08
	6	1077.40		6	987.35
	0.5	113.84			
	1.875	426.90			
30x30x30	3.25	739.96			
	4.625	1053.02			
	6	1366.08			

Figure 10 presents the obtained pressure loss and temperature difference between channels results of cell size study.

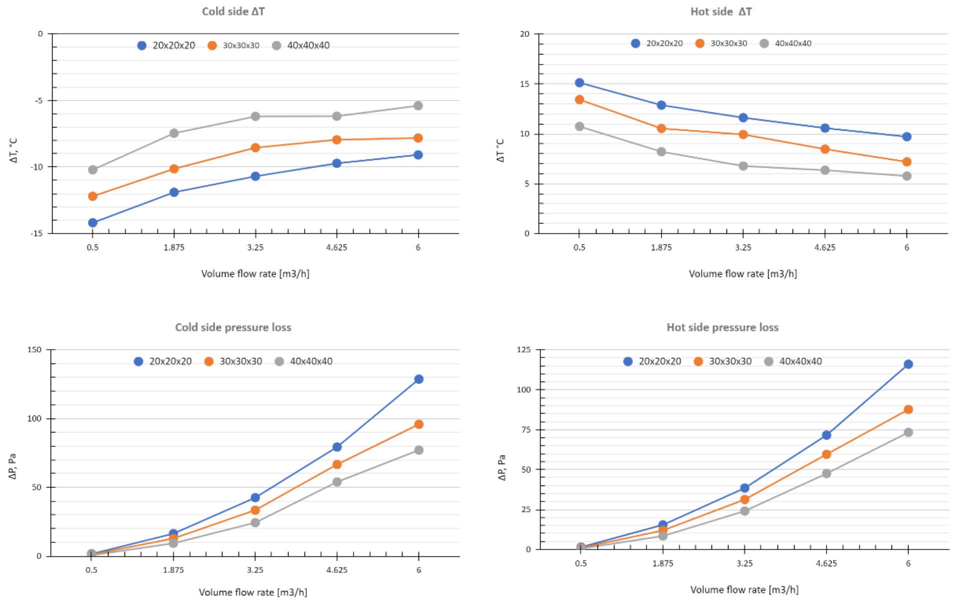

Fig. 10. Cell size study ΔT and pressure loss.

The obtained data indicate that by increasing the cell size the temperature difference between both hot and cold side channel inlets and outlets decreases similarly in the entire range of flow rates, being around 30–40 % lower when increasing cell size from 20x20x20 to 40x40x40. It can be concluded that the relationship between temperature difference and flow rate is consistent across all three studies. However, pressure loss values are close within lower flow rates of each study, but indicate a more rapid rise in pressure loss with a flow rate for each respective study. Thus, it can be concluded that the heat exchanger structure is the most efficient at low flow rates, with less internal friction in the flow, and by increasing the flow rate exponentially the pressure loss increases in the flow channels. Decreasing the cell size has a bigger effect on pressure loss in high volume flow regimes.

The obtained results of cell length in flow direction study are presented in Fig. 11. Cell length in flow direction is defined in the legend in mm. Cell width and height are 20 mm in all studies.

By increasing the length of the gyroid cells in the flow direction, it could be possible to significantly reduce the pressure loss in flow channels, while having a minimal effect on heat transfer. This could imply that gyroid structure can be improved for heat exchanger use, by increasing the length proportion of cells. In this study, by increasing the cell length two times (from 20 to 40 mm), pressure loss in each channel can be reduced from 71 % to 76 % in most of the volume flow rate range. At the same time, ΔT and, subsequently, the heat transfer between opposite flow channels is reduced by 6.6 % to 9.4 % in low volume flow rates, while achieving around 21.5 % reduction in higher flow rate ranges. Relations of graph lines of each study are similar to cell size study, but the results show bigger disproportionality between temperature difference and pressure loss results. Results show that proportional cells (20 mm in length) produce the steepest pressure loss curve while increasing the flow rate. By slightly increasing cell length, all further curves have a slower exponential increase, indicating a less pronounced rate of growth in pressure loss as the flow rate increases.

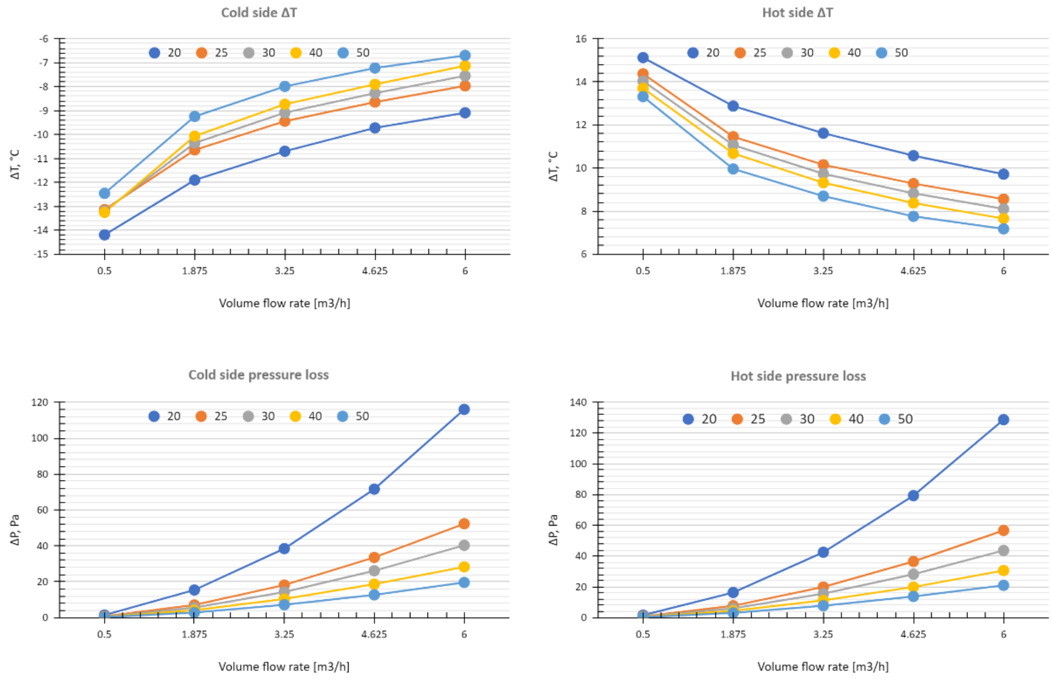

Fig. 11. Cell length in flow direction study ΔT and pressure loss.

4. CONCLUSIONS

TPMS air-to-air heat exchangers provide high design freedom for reaching compact sizes with a high surface area, low back pressure and high heat transfer. One of the main advantages is the production method used – 3D printing. While gyroid structure can be impossible to produce by traditional methods, printing can be used to manufacture even adjusted geometries, such as disproportionate cells, gradient TPMS structures and more. The main limitation is material used, as cheaper technologies can only use low heat transfer coefficient plastics, while metal printing can be too expensive to justify the cost. However, given that flow pressure for air-to-air heat exchangers in residential recuperators is relatively low, it can be bypassed by producing thin-walled heat exchangers, where the material conductive heat transfer coefficient does not play a huge role in heat transfer between the flow channel.

As discussed before, some cell sizes work well at low air flows, but can decrease the heat transfer efficiency at higher flow rates. Each of the studies had pressure loss rising exponentially by increasing the air flow rate and Re number, which means that the gyroid cell sizes must be carefully chosen for each heat exchanger application. The structure of flow channels creates transitional or turbulent flow regimes even with relatively low air flow speeds, which increases the heat transfer as well as pressure loss.

It can be concluded that disproportional gyroid heat exchanger, with cells longer in the flow direction, could achieve significantly lower pressure loss values, without losing much of the heat transfer characteristics. This can be very important for compact size air-to-air heat exchanger design for residential ventilation, as lower pressure loss means smaller and slower fans, which uses less power and produces less noise.

Although the manufacturability for complex TPMS structured heat exchangers is achievable by SLA, SLS, UV LCD printing or similar technologies, mass production of such parts can have its own problems. Printing one whole heat exchanger for a compact air recuperator with UV LCD printer requires multiple hours of printing, whereas traditional plate heat exchangers can be manufactured much faster. This would require large print farms for increasing the production output, which might hinder the ability to scale the manufacturing.

ACKNOWLEDGEMENTS

The present reasearch has been conducted by WeMPS Ltd. with the financial support from the Recovery and Resilience Facility (Project No. 5.1.1.2.i.0/1/22/A/CFLA/006), within the framowork of the project of Competence center for mechanical engineering (Mašīnbūves Kompetences centrs).

REFERENCES

1. von Schnering, H.G., & Nesper, R. (1991). Nodal Surfaces of Fourier Series: Fundamental Invariants of Structured Matter. *Zeitschrift* für *Physik B – Condensed Matter., 83* (3), 407–412.
2. Al-Ketan, O., Ali, M., Khalil, M., Rowshan, R., Khan, K. A., & Abu Al-Rub, R. K. (2021). Forced Convection Computational Fluid Dynamics Analysis of Architected and Three-Dimensional Printable Heat Sinks Based on Triply Periodic Minimal Surfaces. *Journal of Thermal Science and Engineering Applications, 13*, 1–14. DOI:10.1115/1.4047385
3. Cheng, Z., Li, X., Xu, R., & Jiang, P. (2021). Investigations on Porous Media Customized by Triply Periodic Minimal Surface: Heat Transfer Correlations and Strength Performance. *International Communications in Heat and Mass Transfer, 129*, 11–12. DOI:10.1016/j.icheatmasstransfer.2021.105713
4. Attarzadeh, R., Rovira, M., & Duwig, C. (2021). Design analysis of the "Schwartz D" Based Heat Exchanger: A Numerical Study. *International Journal of Heat and Mass Transfer, 177,* 6–7. DOI:10.1016/j.ijheatmasstransfer.2021.121415
5. Al-Ketan, O., Pelanconi, M., Ortona, A., & Abu Al-Rub, R. K. (2019). Additive Manufacturing of Architected Catalytic Ceramic Substrates Based on Triply Periodic Minimal Surfaces. *Journal of the American Ceramic Society, 102*, 6176–6193. DOI:10.1111/jace.16474
6. Femmer, T., Kuehne, A. J. C., & Wessling, M. (2015). Estimation of the Structure Dependent Performance of 3-D Rapid Prototyped Membranes. *Chemical Engineering Journal, 273,* 438–445. DOI:10.1016/j.cej.2015.03.029

7. Li, W., Yu, G., & Yu, Z. (2020). Bioinspired Heat Exchangers Based on Triply Periodic Minimal Surfaces for Supercritical CO2 Cycles. *Applied Thermal Engineering, 179*, 9–10. DOI:10.1016/j.applthermaleng.2020.115686.
8. Reynolds, B.W., Fee, C.J., Morison, K.R., & Holland, D.J. (2023). Characterisation of Heat Transfer within 3D Printed TPMS Heat Exchangers. *International Journal of Heat and Mass Transfer, 212*, 2–3.
9. Flow Simulation. (2020). *SolidWorks Flow Simulation 2020 Technical Reference.* Available at: https://www.cati.com/wp-content/uploads/2021/04/swflow2021-technical-reference.pdf
10. Rhodes, M. (2017). *Introduction to Particle Technology* (2nd ed.). Chichester, UK, John Wiley & Sons, Ltd. 30–42.