LATTICE FRAME MATERIAL GEOMETRY OPTIMIZATION FOR AIR HEAT TRANSFER

Giulia Righetti[1*], Giovanni A. Longo[1], Claudio Zilio[1], Simone Mancin[1]

[1]Department of Management and Engineering, University of Padova, 36100, Italy

ABSTRACT

Sometimes, for reason of space or functionality, a structural component must also be good for the heat transfer purpose. Lattice-frame materials are a class of cellular structured materials capable of fulfill to both requirements. However, there is still no comprehensive literature that optimizes these structures from the thermal point of view. This manuscript presents an experimental study on heat transfer and pressure drop of two aluminum single-layer lattice-frame materials with tetragonal structure obtained via additive manufacturing used as heat sinks, varying the air flow rate from 20 to 130 $m^3 h^{-1}$ and the electric power applied from 50 to 150 W. Two samples were compared: a round shape and an airfoil shape lattice-frame material. The second one was proposed to reduce pressure drops and improve the heat transfer performance. It was experimentally measured that pressure drop decreased on average by 5% maintaining almost constant the heat transfer coefficient. Then, the airfoil shaped heat sink can maintain the same junction temperature by lowering the pumping power per heat transfer area on average by 75%. This data encourages further research on geometry optimization in LFMs.

1. INTRODUCTION

Sometimes, for reason of space or functionality, a structural component must also be good for the heat transfer purpose. Lattice-frame materials (LFMs) are a class of cellular structured materials capable of fulfil to both requirements. Recently, numerous studies that investigate LFM structures have been published in the literature. Each paper numerically or experimentally evaluates the heat transfer performance of one or more structures. The pressure drops of LFM structures are quite high compared to the plain channel, even if they are lower than those of metal foams under the same working conditions. However, there are no comprehensive studies that discuss how to optimize these structures to obtain the best thermal performance coupled to reduced pressure drops.
Maconachie et al. [1] studied the main structural characteristics of LFMs, comparing the existing topologies, and indicating the most promising fields interested in this technology as aerospace, biomedical, automotive and underwater. As indicated by Son et al. [1], the LFMs use in aeronautics and aerospace is suggested since stringent space requirements. Coupling thermal and structural elements can save a lot of space. A further benefit is the greater stiffness and mechanical strength in relation to a light weight, obtained thanks to the high nodal connectivity of the lattices structures. So they give the possibility of reducing the heat exchangers volume and weight (Chaudari et al. [3].)
Recently, numerous studies that investigate LFM structures have been published in the literature. Each paper numerically or experimentally evaluates the heat transfer performance of one or more structures. However, there are no comprehensive studies that discuss how to optimize these structures to obtain the best thermal performance coupled to reduced pressure drops.
To give an example, Figure 1 reports some pressure drop data published in the literature by various authors on different LFM structures, all generated by an air velocity of 8 $m s^{-1}$. At a first glance, it can be seen that the data points are extremely scattered, even if all of them are lower than those obtained with metal foams (Bai et al. [4]). Hence, it can be stated that geometry has an extremely significant impact on the thermal results.
In detail, Figure 1 reports the data by:
-Tian et al. [5] who experimentally studied two copper lattice-frame materials, one generated by diamond wires and one by squared wires at different orientations. Friction factors and heat transfer coefficients were reported and discussed;

*Corresponding Author: giulia.righetti@unipd.it

-Yan et al. [6-7] who measured the thermal performance of a lightweight X-type lattice fabricated via the metal sheet folding;
-Chaudhari et al. [3] who experimentally assessed four octet-truss lattice structures having three different porosities;
-Bai et al. [4] who studied eight types of lattice materials using 3D simulations, including vertical lattices, slanted lattices, Kagome lattices, tetrahedral lattices and pyramidal lattices;
-Liang et al. [8] who experimentally and numerically investigated the effect of element shape of the face-centered cubic (FCC) lattice structure on the flow and heat transfer characteristics in a rectangular channel.

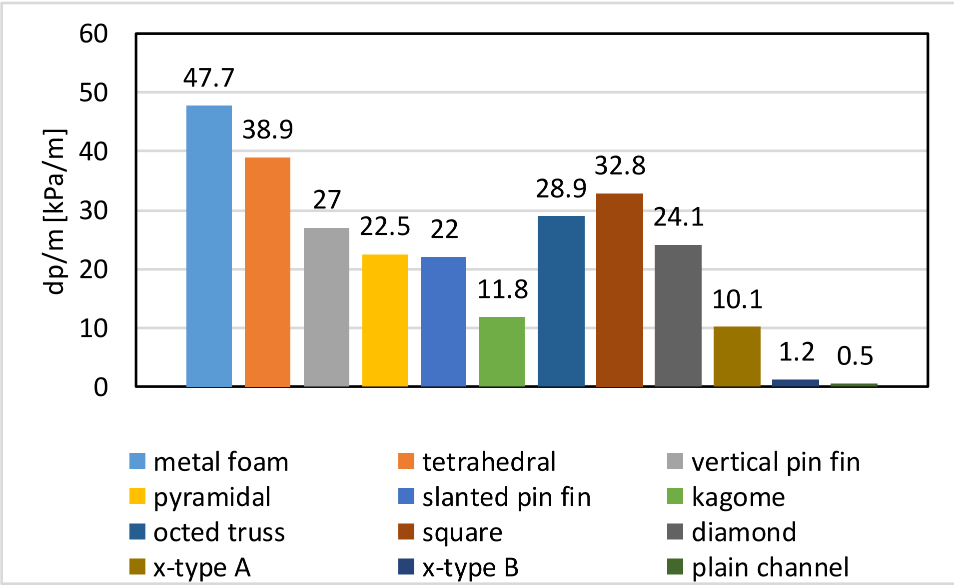

Figure 1. Schematic of the 3D aluminium structures and thermocouple locations.

Furthermore, from Figure 1, it can be seen that the pressure drops of LFM structures are quite high compared to the plain channel (0.5 kPa m-1), even if they are lower than those of metal foams (47.7 kPa m-1) under the same working conditions. Therefore, a scope of this work is to reduce pressure drops as much as possible without worsening the heat transfer coefficient. A scope of this work is to reduce pressure drops as much as possible without worsening the heat transfer coefficient. A possible solution is the use of airfoil shapes instead of round shapes. Currently, there are no studies analysing LFMs having airfoil ligaments. So, in this paper, thanks to a new experimental setup specially designed and built, the pressure drops and the heat transfer coefficients of two LFM structure-based heat sinks are measured and compared.

2. METHDOLOGY: TEST SAMPLES AND EXPERIMENTAL SET UP

The experimental set up consists of a rectangular cross-section air wind tunnel in which the test sample is housed. At the wind tunnel entrance there is a filter that homogenizes the air flow, then the air passes through the test sample, and at the wind tunnel exit there is a variable speed fan which regulates the air flow rate.
The volumetric air flow rate is measured with an uncertainty equal to ± 1% of the full scale, the sample pressure drops with an uncertainty of ± 0.075% of the full scale, and the temperature within ± 0.1 K.
Two 100x100x40 mm samples made of aluminium alloy AlSi7Mg0.6 via Direct Metal Laser Sintering were investigated (see Figure 1).

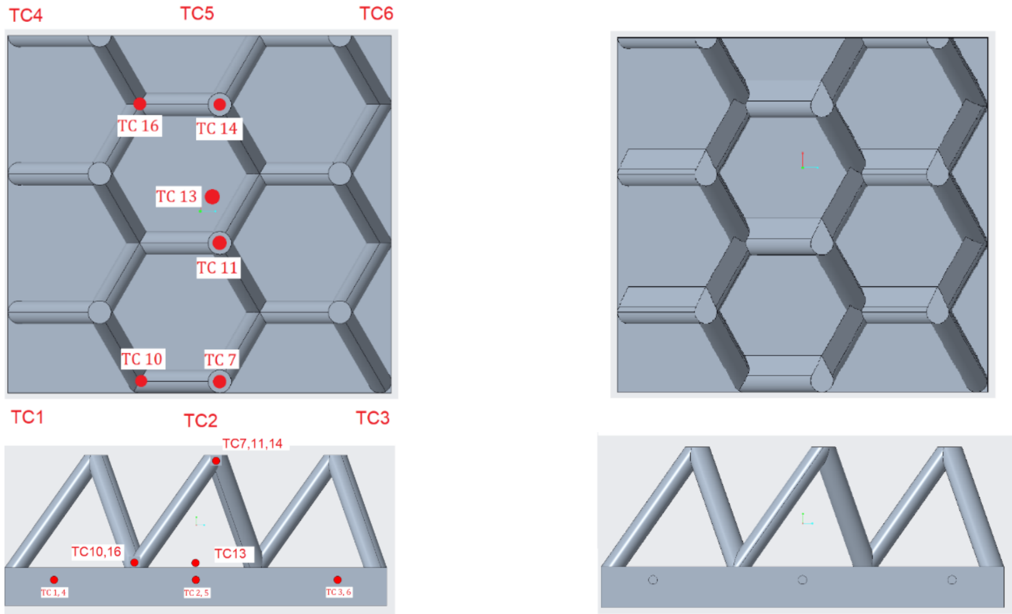

Figure 1. Schematic of the 3D aluminium structures and thermocouple locations.

The first one is a tetrahedral LFM structure, having an equilateral triangular basement and cylindrical ligaments arising from each basement vertex to the top. The tetrahedral height is 30 mm and the ligament diameter is 5 mm. The second sample, called airfoil LFM, is a lattice frame material designed to reduce the pressure drops of the previous case. The main sizes remain unchanged but the section of the ligaments was modified circular to a neutral airfoil shape. In all the ligaments, the airfoil tail edge was kept parallel to the flow direction.

The sample temperature was measured in 12 locations, as represented in Figure 1. Each sample was placed on a heating copper plate, necessary for the heat transfer tests. Also the copper plate temperature was monitored by a thermocouple, placed in a hole drilled in the copper plate centre. The heater is made up of twelve heating resistances connected in parallel which produce an equivalent resistance of 4.8 Ω. The copper plate which is 10 mm thick, 100 mm wide and 100 mm long is positioned between the resistances and the measurement sample to ensure a uniform distribution of the temperature field.
For each sample, pressure drops and heat transfer coefficients (HTCs) were measured by varying the air flow rate ranging from 20 to 130 $m^3 h^{-1}$ and electric powers from 50 to 150 W. Applying the Kline and McClintock [1] error analysis, that electric power uncertainty is always lower than ±0.15% of the reading. Furthermore, the uncertainty on the friction factor was always lower than ±2% of the calculated value and the HTC uncertainty lower than ± 8% of the calculated value

3. RESULTS

Figure 2 compares the experimentally measured pressure drops. The airfoil LFM sample has pressure drops on average 5% lower than the round LFM sample thanks to its more favourable shape. This data encourages further research on geometry optimization in LFM structures.
Figure 3 presents the HTC values of the two samples at 100 W power applied as a function of the air flow rate. The samples show very similar HTC values. In fact, the HTC should increase due to the reduction of the fluid stagnation areas but it should decrease due to the lower turbulence, and this effect should have a higher weight at lower flow rates.

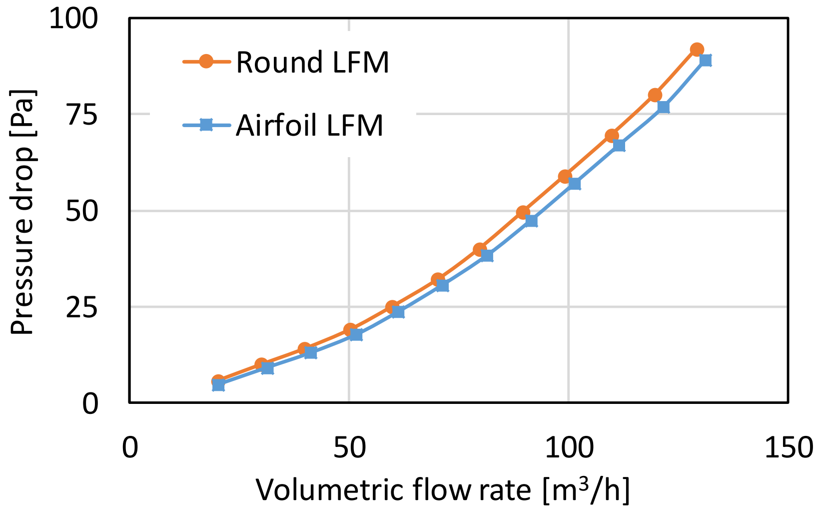

Figure 2. Pressure drops as a function of the volumetric flow rate

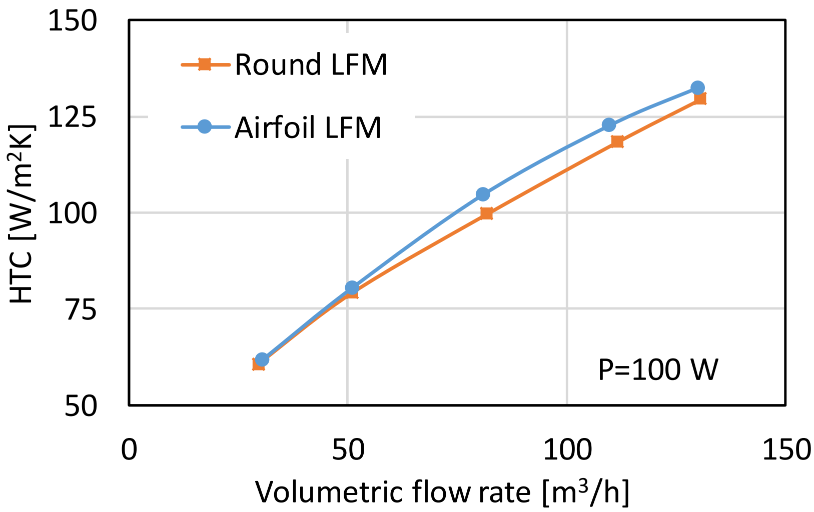

Figure 3. Heat transfer coefficients as a function of the volumetric flow rate, P_{el}=100 W.

The HTC does not depend on the applied electrical power, while it increases as the air flow rate increases. This is demonstrated by Figure 3, where the HTCs as a function of the volumetric air flow rate at five values of imposed electrical power in the airfoil sample are shown. The same results were already observed by other authors, for instance by Diani et al. [2] who studied a finned heat sink.
Another interesting data is the temperature of the copper plate which is installed below the samples. This plate is required to spread the heat, but it could be thought as an electronic component that must be cooled using the designed heat sink. This temperature is about 2% lower when the airfoil LFM sample is used at the same working conditions.
Furthermore, this copper temperature can be plotted as a function of the pumping power per unit of area transfer W (Eq. 1).

$$W = \frac{\Delta p \ \dot{V}}{A_{ht}} \quad \text{(Eq. 12)}$$

where Δp is the pressure drop, $\dot{V}$ the volumetric flow rate, and A_{ht} the heat transfer area.

This value can give an idea of the theoretical power consumed by a fan to move the fluid through the designed enhanced heat transfer area. In the case of thermal management, it should be desired to have the lowest as possible copper temperature by applying the lowest pumping power. The comparison, shown by Figure 4 demonstrates that the airfoil LFM globally over performed by 75% the round LFM one. Thus this result encourages a further shape optimization of this structural-thermal structures.

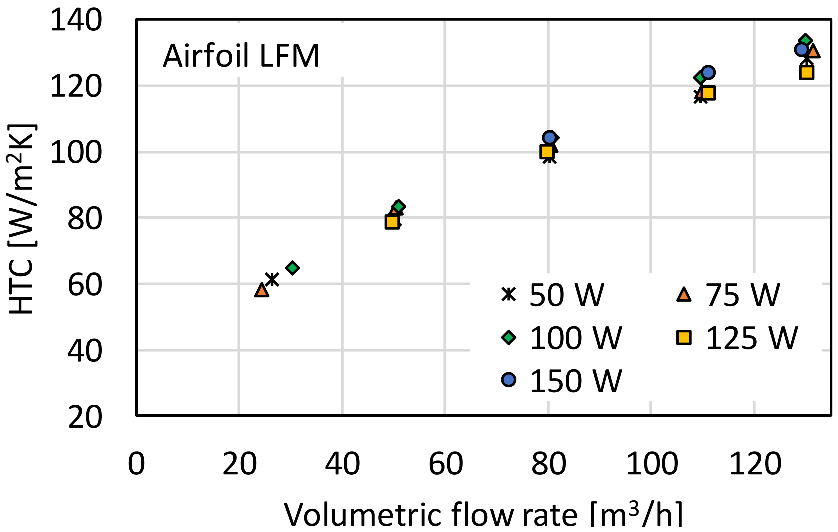

Figure 3. HTCs as a function of the volumetric flow rate and the electric power.

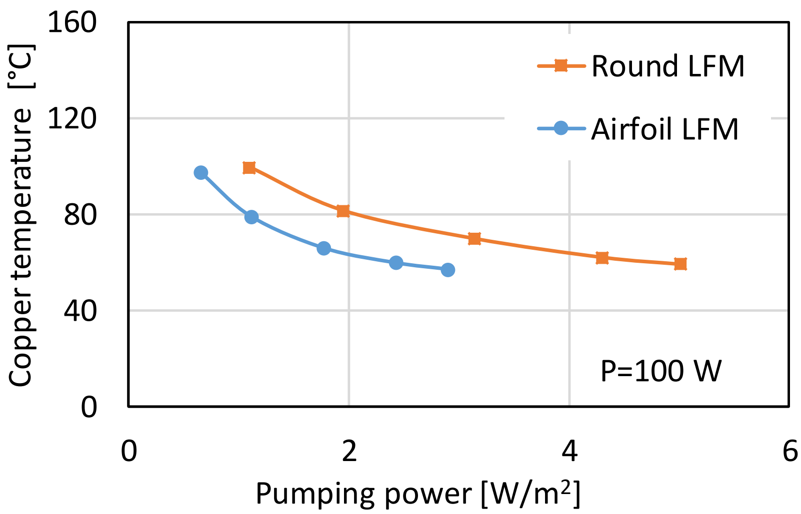

Figure 4. Copper temperature as a function of the pumping power per heat transfer area

4. CONCLUSIONS

The airfoil sample had pressure drops on average 5% lower than the round sample. The measured heat transfer coefficients did not depend on electric power, while they increased as the air flow rate increases. The two samples exhibited very similar HTCs.

The temperature of the copper plate installed below the sample was analyzed since it might represent the temperature of an electronic component that has to be cooled. This temperature was about 2% lower when the airfoil LFM sample was used at the same working conditions. Furthermore, by using the airfoil sample the copper temperature could be controlled by using a lower pumping power per unit of heat transfer area. All these results demonstrated that by using the airfoil LFM both pressure drops and heat transfer management can improve. This encourages further research on geometry optimization in LFMs.

5.ACKNOWLEDGMENTS

The research was supported by the “INTO-CSM: an INnovative methodology for Thermal performance Optimization of Cellular Structured Materials” Project under Grant: RIGH_SID19_01.

REFERENCES

[1] T. Maconachie, M. Leary, B. Lozanovski, X. Zhang, M. Qian, O. Faruque, M. Brandt, SLM lattice structures: Properties, performance, applications and challenges, Materials and Design 183 (2019) 108137.

[2] K. N. Son, J. A. Weibel, V.Kumaresan, S. V. Garimella, Design of multifunctional lattice-frame materials for compact heat exchangers, International Journal of Heat and Mass Transfer 115 (2017) 619–629.

[3] A.Chaudhari, P. Ekade, S.Krishnan Experimental investigation of heat transfer and fluid flow in octet-truss lattice geometry. International Journal of Thermal Sciences 143 (2019) 64–75.

[4] X. Bai, Z. Zheng, A. Nakayama Heat transfer performance analysis on lattice core sandwich panel structures. International Journal of Heat and Mass Transfer 143 (2019) 118525.

[5] J. Tian, T. Kim, T.J. Lu, H.P. Hodson, D.T. Queheillalt, D.J. Sypeck, H.N.G. Wadley The effects of topology upon fluid-flow and heat-transfer within cellular copper structures. International Journal of Heat and Mass Transfer 47 (2004) 3171–3186.

[6] H.B. Yan, Q.C. Zhang, T.J. Lu, T. Kim, A lightweight X-type metallic lattice in single-phase forced convection. International Journal of Heat and Mass Transfer 83 (2015) 273–283.

[7] H.Yan, X. Yang, T. Lu, G.Xie Convective heat transfer in a lightweight multifunctional sandwich panel with X-type metallic lattice core. Applied Thermal Engineering 127 (2017) 1293–1304.

[8] D. Liang, W. Bai, W. Chen, M. K. Chyu. Investigating the effect of element shape of the face-centered cubic lattice structure on the flow and endwall heat transfer characteristics in a rectangular channel. International Journal of Heat and Mass Transfer 153 (2020) 119579

[9] S.J. Kline, and F.A. McClintock, Describing uncertainties in single-sample experiments *Mech. Eng.* vol. 75, pp. 3–8,1954.

[10] A. Diani, S. Mancin, C. Zilio, and L. Rossetto. An assessment on air forced convection on extended surfaces: Experimental results and numerical modeling *International Journal of Thermal Sciences*, vol. 67, pp. 120-134, 2013.