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Fabrication and Characterization of an Innovative Heat Exchanger with Open Cell Aluminum Foams

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Abstract

The present study deals with the design, the fabrication and the characterization of an innovative heat exchanger manufactured by using open cell aluminum foams. The cooling performances of the heat exchanger, working in low temperature difference were measured. Open cells aluminum foams, produced via polymeric foam replication method, have been assembled to manufacture the cooling elements. The wettability of the aluminum foam surface was improved through a surface treatment, in order to enhance the joining between the pipes and the metal foam. In a first phase, preliminary experimental tests on aluminum metal foam samples were used for an estimation of the overall cooling performance. The experimental test was also aimed to understand the basic mechanisms involved in the heat transfer process. In a second phase, the full heat exchanger was assembled, and an experimental setup was designed in order to determine the performance of the heat exchanger. The heat exchanger revealed its high potentiality in terms of thermal performance, showing also a remarkable behavior in terms of energy saving, assembly and endurance.

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Keywords: Aluminium Foams, Heat exchanger, Cooling, Energy efficiency

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1. Introduction

Recently, metal foams, due to their unique structural and functional properties have been stimulating interest in many research and technological domains [1-3]. The mechanical characteristics of such class of materials are function of pore size, distribution and density [4-7]. One of the advantages, in using metal foams, is the possibility to combine interesting mechanical properties and lightness to functional properties [4-5].

The metal foams can be produced with different morphologies and may have structures with open or closed cells. This last feature will inevitably define the field of application [1], [8]. In particular metal foams with closed cells are produced with several common used methods like powder compact melting method [1], [6] or dissolution and sintering process [8]. The replication processes, casting or coating processes etc., can be used for the production of open-cell cellular material [1]. The cost linked with the production of cellular materials is still too high, due to process complexity and hazard although all the efforts to develop a cheaper procedure [1], [3] and [5]. Moreover, in many production approaches several problems of replicability of the final product are highlighted [1], [6-7]. Some researchers to solve the replicability problems of the process adopted with satisfactory results the neural networks, [8-9]. Open cells metal foams present structures randomly oriented and mostly homogeneous in size and shape. They are distinguished mainly for their attractive functional properties. The particular inner structure of these foams permits the application of these materials in many technologies domains like heat exchangers, cryogenics, combustion chambers, cladding on buildings, strain isolation, geothermal operations, petroleum reservoirs, catalytic beds, compact heat exchangers for airborne equipment, air-cooled condensers for air conditioning and refrigeration systems, and compact heat sinks for power electronics [10-13]. Most commercially available foams are produced in different metals such as aluminum, copper, nickel and metal alloys. One of the critical constructive aspects which restrict the use of these materials is related to the difficulty in joining them with other components, limiting the ability in heat transfer from the bulk to the foam [14-16]. In the past years, many researchers have investigated on the thermal transport in metal foams for practical applications. Calmidi et al. experimentally investigated the effective thermal conductivity of high-porosity fibrous metal foams [17]. Hsieh et al. carried out an experimental study to characterize the heat transfer behavior of several heat sinks made of aluminum metal foams with different porosity (0,87-0,96) and PPI (10-40) [18]. Boomsma and Poulikakos developed a one-dimensional heat conduction model for use with open-cell metal foams, based on idealized three-dimensional cell geometry of the foam. Only open-cell metal foams appear to have interesting future in constructing heat exchangers [19]. Bhattacharya et al. proposed an analytical and experimental investigation for the determination of the effective thermal conductivity, the permeability and inertial coefficient of high porosity metal foams [20]. Lu et al. analyzed the forced convection problem in a tube filled with a porous medium subjected to constant wall heat flux [21]. K. Nawaz and Guarino et al. studied the fluids flow inside the open-cell metal foams and stated the these materials have high specific surface area, relatively high thermal conductivity, and a tortuous flow path to promote mixing [22-23].

Many studies related to the thermal characterization of metal foams were made, but much less on their actual application in industrial or domestic components. In particular, the information that can be used to evaluate a real application of metal foams in heat exchangers, are currently scanty in the scientific literature. In this context, in this paper, the authors have designed, manufactured and characterized a metal foam heat exchangers The performance of a heat exchanger, working in low temperature difference, is evaluated. The novel heat exchanger was assembled and used for experimental tests aimed at understanding the basic mechanisms involved in the heat transfer process and to establish the thermal performance.

2. Materials and methods

The 10 pore per inch Aluminum foams used for the heat exchanger (Hex) manufacturing, and provided by M-PORE (Germany), were produced via the replication method of polymeric pattern. The aluminum foams were cut in the dimension of (350x400x12.5) mm^3 and assembled to obtain panels with dimension (700 x 400 x 12.5) mm^3 (mid HEx), fig. 1a. Subsequently two panels were milled in order to obtain the seat of the coil. In order to obtain a good joining between the aluminum foam and copper pipes, the wettability of the aluminum foam surface was improved through a thin copper coating (about 10 μm) by electro-deposition process. The copper coating allowed the use of commercial and low cost brazing media (tin-based). The electro-deposition was carried out in an electrolytic cell at

25 °C [24]. Preliminary test on small foam samples, has been implemented in order to get, at least, a first approximate computation of the overall cooling performance of the HEx. The implemented procedure has been designed to estimate the thermal resistance of a square sample of aluminium foam, with the same porosity and thickness of the two mid HExs equipping the main HEx. The experimental tests were focused to correlate the heat transfer rate, P_s, to ΔT_b, i.e., the difference between the sample base temperatures, T_b, and the ambient temperature T_a, by means of a constant thermal resistance. The assembly of the HEx was obtained according to the following steps: (i) milling of the foams to obtain the two half-seats for the insertion of the copper pipes, (ii) electro-deposition of milled foam panels; (iii) deposition of brazing paste on the tubes, (iv) realization of the sandwich foam-pipe-foam, (v) oven treatment and brazing in air.

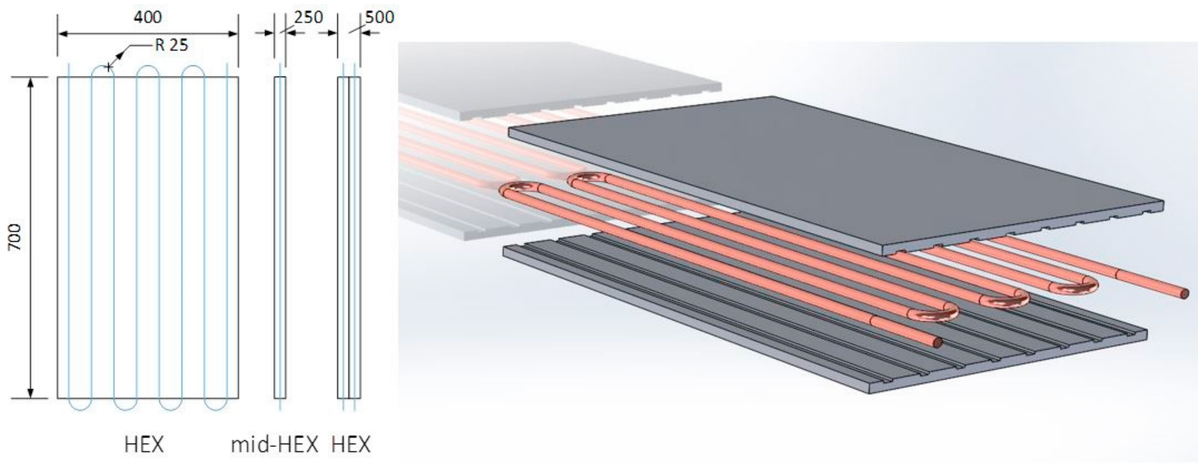


Fig. 1. (a) Section of the full appliance: detail of the heat exchanger, (b) Exploded view.

Fig 1a and Fig. 1b depicts the section and the exploded view and the final prototype of the HEx. The HEx is composed of two identical single-foam HExs, named mid-HExs in the follows. The two mid-HExs are connected each other as showed in Fig. 1b. The cooling circuit consists of two copper coils with a total length of 6.15 m, external radius 6 mm, and thickness 1.15 mm. The coils was connected in parallel in order to not increase the overall pressure drops, Fig. 2a.

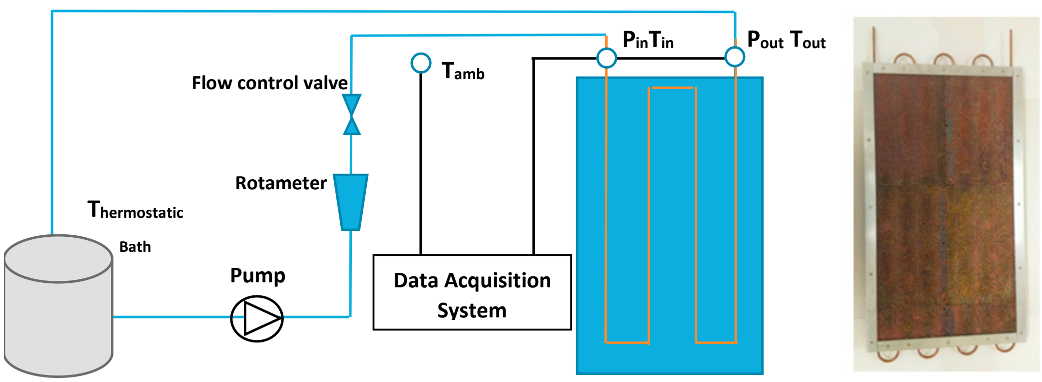


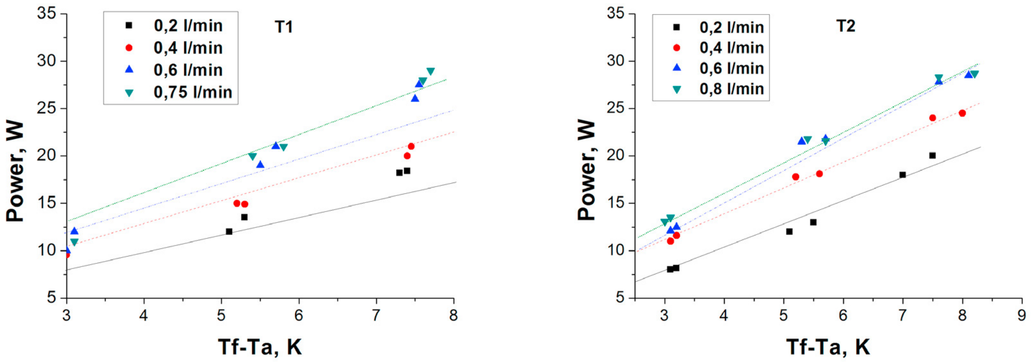
Fig. 2. (a) HEx experimental evaluation: Experimental setup. (a) HEx Prototype.

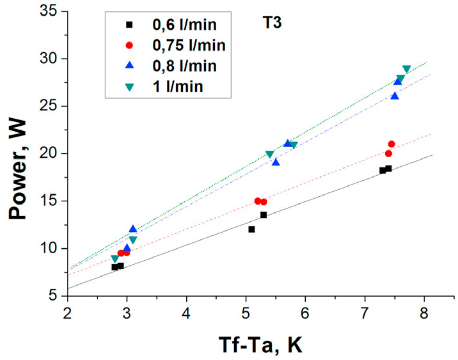
The ambient temperature was monitored by an additional RTD PT100 sensor, placed two meters away from the

HEX. The experimental set-up was used for implementing three different tests:
T1) mid-HEx positioned vertically with the main side close to a wooden board, with an air gap of 10 mm;
T2) HEx positioned as in the previous point;
T3) HEx positioned in the middle of a chamber 60 mm wide, with an air gap of 5 mm.
Test T1 was performed at four flow rates: (0.2, 0.4, 0.6, 0.75) l min^{-1}; test T2 at six flow rates: (0.2 to 1.2) l min^{-1}, step of 0.2 l min^{-1}; test T3 was performed at five flow rates: (0.4 to 1.2) l min^{-1}, by step of 0.2 l min^{-1}. The test T3 was conceived in order to evaluate the reduction of performance with the HEx working in a limited environment. In figure 2b is reported the Hex prototype realized.

3. Results and Discussion

Results concerning the three tests T3 are reported in Fig. 3, where the heat flow rate is plotted as a function of ΔT_f and v. As regard the test T1, the heat rejection increased with the temperature difference.





T1) mid-Hex positioned vertically with the main side close to a wooden board, with air gap of 10 mm
T2) Hex positioned as in the previous point
T3) mid-Hex positioned in the middle of a chamber 60 mm wide, with air gap of 5 mm, with air gap of 10 mm

Fig. 3. Test T1, T2, T3, Power vs ΔT, varying v.

Results also showed that P_H increased in general with the flow rate, and that the increase was more evident in the range of (0.2 0.4) l min^{-1}. That phenomenon was probably due to the flow regime into the coil duct, where the flow rate 0.2 l min^{-1}, corresponding to a Re number of 1430, indicates a laminar flow. At 0.4 l min^{-1}, instead, the Re number was 2860, which corresponded to a transitional flow. The changing from laminar to transitional flow influences the Nusselt number, which could justify the greater increment of heat transfer in the mentioned flow rate range. By interpolating data at $\dot{v}$=0.4 l min^{-1} and ΔT_f =5 K, the heat rejection rate results 18 W, therefore, the cooling power resulted about 13 % greater than the estimated one. Data related to the test T2 was similar to the ones obtained in test T1. Heat rejection, in fact, increased with both ΔT_H and $\dot{v}$. In the range of (0.2 - 0.4) l min^{-1}, the dependence of the heat rejection on the flow rate was more evident. In Test T2, however, the total flow was divided in each mid-HEx, obtaining an actual flow rate of only 0.2 l min-1, which corresponded, differently to test T1, to a laminar condition (Re=1430). For the HEx, a total cooling power of 32 W was expected at $\dot{v}$=0.8 l min^{-1}. In the present case, however, the estimated value of the power, obtained by interpolating experimental data at the same flow rate condition, resulted in an actual heat flow rate of 23 W. The under-estimation of about 30 % was probably due to two main issues: 1) the simplifying assumption that the foam temperature was uniform; 2) the 20 mm foam layer, enclosed by the two coils, poorly contributed to the overall cooling efficacy, in comparison with the rest of the foam facing the ambient air. As concerns the test T3, the HEx efficacy in term of heat rejection decreased of about the 26 %, compared to the one measured in Test T2. That reduction was due to the low ventilation in the chamber. Actually, the pressure drop due to the metal foam matrix, under buoyancy-induced convection, did not allow a sufficient air flow through the HEx. The average thermal resistances, clustered by the two flow rate conditions $\dot{v}$=0.2 l min^{-1} and $\dot{v}$>0.2 l min^{-1} are reported in Fig. 4. In both the fluid rate clusters, a reduction of 0.03 K W^{-1} for R_H occurred from test T1 to test T2. The reduction was of about 10 % in both the flow rate cases, but only the latter case can be statistically confirmed. On the contrary, moving from configuration T2 to T3, at $\dot{v}$>0.l min^{-1}, R_H increased significantly of about 30 %.

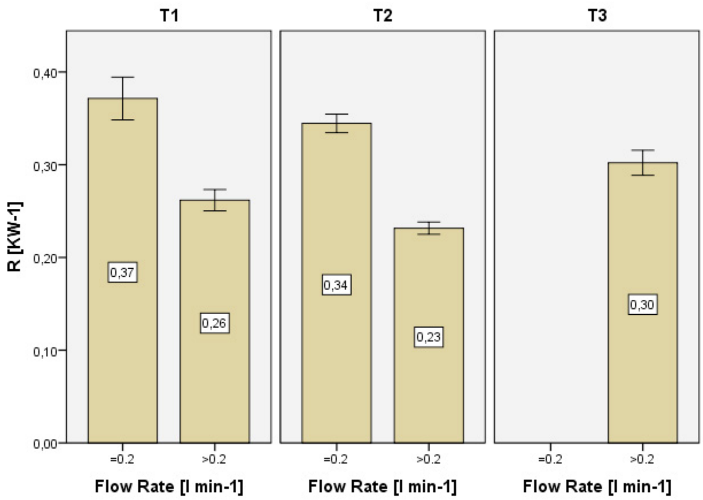


Fig. 4. Average thermal resistances.

4. Conclusions

A metal foam heat exchanger was realized. A computation of the overall cooling performance of the mid-HEx and HEx was provided by preliminary experimental tests on aluminum metal foam samples, with the same characteristics of the foam used in the heat exchangers.

The tests performed on mid-HEX showed that the heat rejection increases with ΔT_f and the flow rate, with a major improvement moving from 0.2 l min^{-1} to 0.4 l min^{-1}. A reduction of 13% between the estimated heat rate rejection and the experimental one was observed at the operating point. The performance estimation obtained by the proposed method, therefore, resulted sufficiently accurate, and could be implemented for a first dimensioning of a HEx of similar characteristics and size.

The heat rate dissipated by the HEx decreased of about 30 %, when the heat exchanger was positioned in the middle of a narrow chamber. Therefore, further studies are required to optimize the HEx geometry in case of confined spaces, by achieving a trade-off between the air gap and the heat transfer surface.

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