Thermo-Fluid Dynamic Modeling of Cu Based Metallic Foams for Heat Exchanger Applications

Carlo A. Biffi[*,1] and Ausonio Tuissi [1]
[1] National Research Council CNR, Institute for Energetics and Interphases, Unit of Lecco, C.so Promessi Sposi 29, 23900 Lecco (Italy).
*Corresponding author: carlo.biffi@ieni.cnr.it

Abstract: In this work the innovative concept is the use of a Cu based metallic foam, characterized by open cell structure, as active element for heat exchangers. The metallic foam, produced by liquid infiltration method, was introduced inside a Cu tube, as base element for the exchanger. In the configuration under investigation, an moist air flow at few hundreds of degrees passes through the metallic foam and the heat is transferred to the water, flowing in the opposite direction, at room temperature in an external coaxial tube. Modeling of this complex system was done using Comsol software; conduction and convection for the modeling of the heat transfer as well as the fluid-dynamic field were considered for the evaluation of the performances of the heat exchanger. Results show how the contribute of the Cu based foam can provoke the heat transfer, mainly localized in the foam.

Keywords: Cu based alloy, metallic foam, heat exchanger, thermal modeling, fluid-dynamic modeling.

1. Introduction

Cellular materials, as innovative and challenging class of materials, are able to offer interesting and almost unique combination in terms of morphology and material performances. This can be associated to an interesting set of physical, chemical and mechanical properties, which makes these materials very attractive both for structural and functional applications. Different processes can be adopted for the production of cellular materials. One of the most interesting ones is related to the infiltration of a molten metallic alloy in a particular leachable bed of solid particles [1-4]. In open literature, the most studied metallic foams, obtained by liquid infiltration of leachable space holders, are usually Al based alloys because their offer lightness, high stiffness, good thermal stability and quite low manufacturing cost. The relative quantities and distribution of the metal, the relative density, the pore size and interconnection are the most important parameters, affecting stiffness, permeability and thermo-physical properties from the point of view of the material, and the reliability and reproducibility of the process from the technological point of view [5,6].

More recently, an attractive possibility is the production of open-cell metal foams by means of the use of SiO_2 beads, as space holders having high melting point, from the production of open cell structures [7-9]; moreover, results in cellular metals with a very homogeneous arrangement of almost spherical cavities. In these works, Cu base shape memory alloys were produced, having functional properties, such as the shape memory effect as well as the pseudo-elasticity. Additionally, because of the high chemical stability of SiO_2, reactions between the space holders and the molten metal tend to be minimal or inexistent, even at high temperatures.

Due to these potentialities, the adoption of foams in Cu based alloys, thanks to their high thermal conductivity, can be considered an interesting challenge in heat exchanger applications [10]. In fact, combining the alloy properties with the cellular structure ones can be a suitable task for improving the efficiency during the heat transfer of fluids, as the transfer surface can be significantly enlarged. In this context, the present work proposes the adoption of such cellular material as an active element in a new prototype of heat exchanger. The numerical modeling, performed by means of Comsol 4.3b version, has been considered because of the necessity of different physics, which have to be simultaneously approached. In the proposed model the effect of the presence of the metallic foam, in function of different values of relative porosity, was studied in terms of performances during the heat transfer from an high temperature moist gas to a water flow. The geometry of the heat exchanger has been strongly simplified in order to focalized the attention on the foam performances.

2. Experimental

In this paragraph the description of the foam preparation and the definition of the model, representative of the heat exchanger, are reported.

2.1 Material Preparation

The method adopted for the production of the foam, in commercial brass (chemical composition: $CuZn_{39}Pb_3$ in atomic percentage) has been presented in literature by the authors [7-9]. Briefly, ingots (60mm in diameter) of the desired composition were melted in a an Aseg Galloni VCMIII induction melt casting system, under pure Ar flow. Then, the material was foamed, by using amorphous SiO_2 spheres (Sigma S7500 Type II), as space holders. The schematic of the foaming process is represented in Figure 1 and the process details were already described in previous papers [7-9]. The space holder size (2.5 mm ± 0.2 mm) was selected through some steps of sieving for the selection of the dimensions, required by the application under investigation.

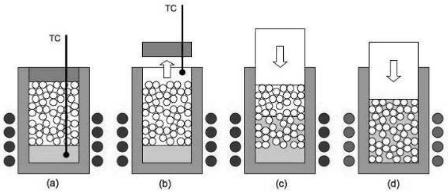

Figure 1. Schematic of the infiltration process: a) alloy melting, b) cap removal, c) pressing of the space holders in liquid metal d) infiltration completed.

After foaming and SiO_2 leaching processes, the foams were sectioned in order to evaluate the void distributions and characteristics. A typical section is shown in Figure 2: almost round and interconnected pores are clearly visible. An average pore fraction of 70% was calculated from image analyses as well as weight/volume measurements. Before its use, compositional control was considered and no significant change from the nominal composition of the alloy has been noticed.

Figure 2. Representative samples of Cu based foam

2.2 Definition of the FE model

A schematic of the prototype of the heat exchanger is shown in Figure 3. The produced foam, whose dimensions are 30 mm in diameter and 30 in length, was introduced inside an external Cu tube. In the configuration under investigation, a moist air flow at few hundreds of degrees passes through the metallic foam and the heat is transferred to the water, flowing in the opposite direction, at room temperature in a coaxial tube, external to the previous one, as shown in Figure 3.

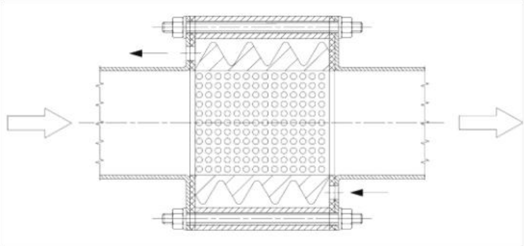

Figure 3. Schematic of the heat exchanger prototype

The spatial domain, which was used for the modeling of the heat exchanger, is depicted in Figure 4; because of the axial-symmetry of the problem, the problem was studied on a semi-transversal section of the domain (see on the bottom of Figure 4). In Figure 4 the presence of different elements, made of different materials, is shown using different colors: the moist air at high temperature, as input, is shown in blue; the porous medium is shown in blue-light, placed in the middle of the heat exchanger; the air at lower temperature, after the heat transfer in the porous medium, is shown in yellow; the tube, in brass, is depicted in red. The numerical simulation has been performed in Comsol 4.3b, coupling the following physics:

- heat transfer in solids: modeling of heat conduction, because of the massive elements, from which the temperature of the Cu solid can be calculated;
- heat transfer in fluid: modeling of convection, because of the air and water flow, from which the temperature of the fluid can be calculated;
- free and porous media flow: modeling of the foam presence from the point of view of the thermo-fluid problem, from which both the fluid velocities (axial and radial) and the pressure can be calculated;

- transport of diluted species: modeling of the moist air by means of a concentration term.

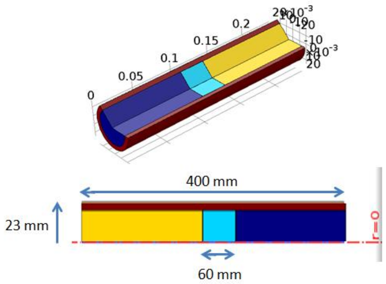

Figure 4. Geometrical model, implemented in Comsol, in a tridimensional (top) and in a bidimensional (bottom) representation

The inlet and the outlet sections were characterized by transport of mass, momentum and energy in free flux. It was solved using Navier-Stokes for the calculation of the fluid velocities and pressure and using the energetic balance for the fluid temperature. In the inlet section the fluid velocity profile was fixed parabolic, having the value on the axis equal to 50 cm/s, which corresponds Reynolds of 1,000 (laminar flow). On the contrary, at the outlet section atmospheric pressure was fixed.

In the external tube of copper, a pure heat conduction can be modeled while the water flow (20°C) is imposed using a convective coefficient in the boundary condition.

The porous medium is modeled using the Brinkman equation, giving just the relative porosity coefficient (0.7) and the permeability coefficient (10^{-6} m^2).

The fluid has to be considered as moist air at high temperature (120°C), having a reactive term as function of the water concentration, expressed as follows:

$C= 0.05*p_{sat}(T_{inlet})/(R_{const}*T_{inlet})$ [mol/m^3]

where p_{sat} is the pressure of saturation, T_{inlet} is the temperature at the inlet section and R_{const} is the universal constant of the gases. The pressure of saturation is considered as function of the temperature T_{inlet}. The initial value of the water concentration has been fixed equal to 3 mol/m^3.

3. Analysis of Results and Discussion

The main results, associated to the heat exchanger performances, are the fluid velocity, the percentage of water in the moist air, the pressure of the fluid as well as the fluid and solid temperatures.

In Figure 5 it is plotted the distribution of the fluid velocity in the heat exchanger; it can be seen that the velocity is significantly decreased, mainly in the axis of symmetry of the tube where the velocity is maximum, just inside the foam. This means that the fluid-dynamic resistance of the foam can make slower the moist air from 0.5 mm/s to 0.25 m/s. After that the fluid has passed through all the foam, no significant variation of its velocity can be seen. So, the greatest pressure loss can be associated to the cellular structure.

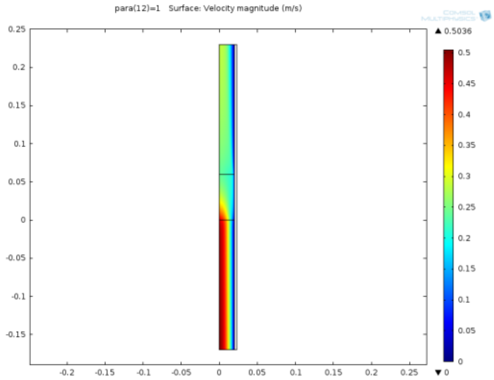

Figure 5. Distribution of the fluid velocity in the heat exchanger

For this fact, the fluid pressure distribution inside the foam is plotted in Figure 6; A sensible reduction of the fluid pressure has been evaluated only in the foam; after the foam, no variation of the pressure is visible.

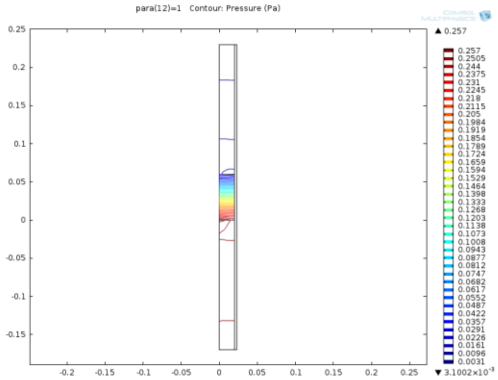

Figure 6. Distribution of the fluid pressure in the heat exchanger

According to the study of the fluid-dynamic behavior of the heat exchanger, the thermal field was also investigated. In Figure 7 the solid and fluid temperatures are plotted along the axial direction. The blue line shows the temperature of the fluid in the center of the heat exchanger; it can be seen that the fluid does not transfer its heat to the Cu tube before the foam. On the contrary, inside the foam the fluid allow the heat transfer significantly, reducing its temperature from about 120°C to 45°C. Then, in the second part of the Cu tube, the fluid reduces more its temperature; this should be due to its condensation. Here, the reduction of its temperature down to the water temperature at 20°C is not realistic but it is a artificial of the numerical model. However, it has to be underlined that almost 75°C are exchanged in the foam.

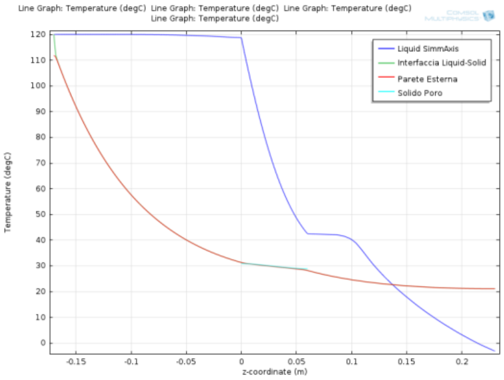

Figure 7. Distribution of solid and fluid temperatures along the axial direction in the heat exchanger

The red line of the Figure 7 is representative of the external surface of the Cu tube. Above the foam, this temperature is reduced down to about the water temperature.

This means that the presence of the Cu base foam can improve in a sensible way the heat transfer between the moist air and the solid elements, made in Cu alloy, for increasing the water temperature.

Finally, Figure 8 shows the distribution of the water concentration of the moist air in the heat exchanger.

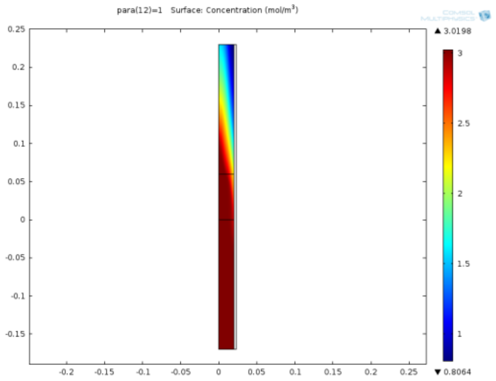

Figure 8. Distribution of concentration of water in the fluid in the heat exchanger

The water concentration does not change until the foam, above which it starts to fall down. In fact, it is reduced down from 3 mol/m^3 to 1 mol/m^3 in half of the radius of the heat exchanger at the outlet section. This means that water condensation, coming from the moist air, happens; after its condensation, the proposed model does not consider how to model its presence. In particular, it has been modeled in a way, such as it disappears when it becomes water.

4. Conclusions

In this work a multi-physical approach has been proposed for the evaluation of the performances of a metallic foam, made of commercial brass, as additional element in a prototype of heat exchanger for improving the efficiency in heat transfer. The use of Comsol allowed to combine different physics for the modeling of heat conduction, convection, fluid-dynamic of moist air in a porous element. The main results has shown that:

- The fluid-dynamic field is strongly influenced by the presence of the foam; otherwise, the fluid pressure and velocity are not significantly changed immediately before and above the foam.
- The heat transfer is favorable in the porous medium while it can be considered negligible in the other part of the heat exchanger.
- More than 60% of the maximum temperature gap is transferred inside the cellular element, showing how much it can improve the heat transfer efficiency.
- The water condensation has been also taken into account; it was shown that a relevant amount of water could be generated in the heat exchanger.

As future developments, experimental tests would be required for the calibration of some coefficients (i.e. the permeability coefficient) as well as for the validation of the numerical model. Moreover, the evaluation of the temperature variation of the water, outside the Cu tube, has to be taken into account, too.

5. References

1. M.F. Ashby, A. Evans, N.A. Fleck, L. Gibson, J.W. Hutchinson, H. Wadley, Metal Foams: A Design Guide, Butterworth-Heinemann, Boston, (2000).

2. J. Banhart, Manufacture, characterisation and application of cellular metals and metal foams, *Progr. Mat. Sci.* **46**, 559 (2001).

3. H.N.G. Wadley, Cellular metals manufacturing, Adv. Eng. Mat. **4**, 726 (2002).

4. J.F. Despois, A. Marmottant, L. Salvo, A. Mortensen, Influence of the infiltration pressure on the structure and properties of replicated aluminium foams, *Mat. Sci. Eng. A* **462**, 68 (2007).

5. F.J. Gil, J.M. Guilemany, Effect of cobalt addition on grain growth kinetics in Cu-Zn-Al shape memory alloy, *Intermetallics* **6**, 445-450 (1997,).

6. J. Banhart, Manufacture, Characterization and Application of Cellular Metals and Metal Foams, *Prog. Mater. Sci*., **46**, 559-632 (2001).

7. E.M. Castrodeza, C. Mapelli, M. Vedani, S. Arnaboldi, P. Bassani, A. Tuissi, Processing of shape memory CuZnAl open-cell foam by molten metal infiltration, *JMEPEG* **18**, 484-489 (2009).

8 S. Arnaboldi, P. Bassani, F. Passaretti, A. Redaelli, A. Tuissi, Functional Characterization of shape memory CuZnAl open-cell foams by molten metal infiltration, *JMEPEG* **20**, 544-550 (2011).

9. A. Tuissi, P. Bassani, C.A. Biffi, CuZnAl Shape Memory Alloys Foams, *Advances in Science and Technology*, **78**, 31-39 (2013).

10. S. Mavridou, G.C. Mavropoulos, D. Bouris, D.T. Hountalas, G. Bergeles, Comparative design study of a diesel exhaust gas heat exchanger for truck applications with conventional and state of the art heat transfer enhancements, *Applied Thermal Engineering*, **30**, 935–947 (2010).

6. Acknowledgements

The authors wish to thank Eng. Andrea Panzeri, Mr. Marco Pini, Mr. Nicola Bennato and Mr. Giordano Carcano for their technical support in the experimentation. This work was development in the framework of ‘‘Nuovi Materiali e nuove tecnologie per un cogeneratore prototipo a combustion interna (Matec)’’ project and sponsored by Mise.