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Development of a device for the measurement of thermal and fluid flow properties of heat exchanger materials

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ABSTRACT

As yet, no standard equipment exists for the measurement of heat transfer through porous materials, such as metal foams (metals with a high volume fraction of porosity). Most research in this area has been carried out using bespoke test rigs. Here the creation of a test rig specifically developed for the measurement of the heat transfer of metal foams is reported. This method has been applied to laboratory made samples processed by replication and examples of commercially available aluminium foams (Duocel and Corevo), and should be suitable for the testing of all materials with comparable permeability. As this equipment is new and unique, the design will be discussed in detail, along with the various tests that were performed to ensure reliability and consistency with other methods and published data.

1. Introduction

Metallic foams are solid structures with a certain volume fraction of pores (free space). These pores could be what is described as open-cell or closed-cell, depending on whether they are connected together, allowing fluid to pass through the foam, or if they are isolated with the fluid in each cell being trapped. These materials can present a very attractive combination of physical and mechanical properties, and are potentially suitable for a number of applications. Metal foams can be manufactured from a wide range of pure metals or alloys, with typical pore fractions between 0.75 and 0.95 and pore sizes from around 5 mm to microns; these two characteristics, density and pore size, can be manipulated with the manufacturing processes that currently exist, increasing the potential for metal foams to serve in various applications [1–5]. For example, the high temperature resistance combined with good thermal conductivity and permeability to fluids of some porous metals makes them interesting candidates for use as heat exchangers where having good control over the size and connectivity of the pores is of central importance, because of their effect on the properties [6–9].

In the particular case of heat exchange, the foam would be required to show good properties for forced convection heat transfer (the thermal energy transferred when gas is forced to flow through the foam due to a pressure difference). As well as the macroscopic flow of the fluid implied in this process, heat will be transferred by conduction and there will also be a significant effect of dispersion processes (arising from the effects of flow separation and from the flow rate gradient created by the no-slip condition at the solid–liquid interface leading to wide dispersal of elements of the fluid). A recent review of methods to combine the various effects and predict the heat transfer between a fluid and various different porous materials is presented in [10].

To fully understand the relationships between the heat transfer and flow properties and the density and pore size

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of the foam, this behaviour must be explored in metal foam samples with different structural characteristics. For this an experimental technique is needed which can be applied to any open cellular structure. The essential principle of such a device is to be able to measure fluid flow and temperature changes when a sample of the open cellular structure, placed in contact with a heated block, is cooled by a fluid flowing through it. Several reports in the literature give examples of equipment that has been set up in the laboratory to perform such measurements. Calmidi et al. [11] used an experimental set up to characterise aluminium foams (alloy T-6201, processed by the investment casting method) with porosities from 0.89 to 0.97 and pore sizes between 5 PPI and 40 PPI under forced convection (PPI stands for pores per inch, and is one way the pore size of foams is characterised, particularly those with low density; at higher densities the mean pore diameter is often reported). The samples were heated by patch heaters, and the cooling air was passed through the sample by a fan/motor assembly, where the speed of the motor was adjusted to control the flow velocity, and this parameter was measured by the pressure drop across an orifice plate. The test duration was from 5 to 10 min depending on the flow velocity used. Temperature readings of the foam and the cooling air were taken, and using these results the heat transfer coefficient was calculated. The data collected in Ref. [11] were compared with results obtained from numerical simulations where the experimental conditions were reproduced, and the results were found to be comparable to a reasonable degree. This same system was used in further work [12] to measure the heat transfer of aluminium foams with a porosity of 0.9 and pore size of 20 PPI and 5 PPI, machined to incorporate longitudinal or pin-shaped fins, with the effect of the number of fins being investigated. Once again, the temperature of the air before and after the metal foam was measured, as well as the temperature of the metal foam itself and the flow rate. The results obtained demonstrated that the heat transfer coefficient increases at a given flow rate when dense metal fins are incorporated in the metal foams. This increment was not linear as expected, with the difference being explained by the interaction of the thermal boundary layers (non-free flowing fluid) formed on the adjacent finned surfaces.

Hsieh et al. [13] constructed different experimental apparatus to characterise the effects of the air velocity, porosity and pore size on the heat transfer of six different aluminium foam structures, having pore sizes from 10 to 40 PPI and pore fractions from 0.87 to 0.94. As in the experimental apparatus used by Calmidi et al. [11], the sample is cooled by air at different velocities, measured at the air inlet by a hot-wire anemometer, while being heated on the lower side through resistance heating controlled by a power supply. The samples tested were cylinders 60 mm in diameter and 65 mm in height. Hsieh et al. [13] measured the temperatures of the solid and gas phases in the system to understand the phenomenon of thermal equilibrium between them under flow conditions, finding that the temperature differences between solid and gas decrease with increasing foam porosity.

Mancin et al. also constructed a bespoke experimental apparatus, which they used to characterise the heat transfer and the permeability of aluminium [14,15] and copper foams [16]. The test rig was an open circuit tunnel with rectangular cross section in which the metal foam samples (the majority 100 mm long, 100 mm wide and 40 mm high), were tested. The sample was held within plates and heated from the lower face, which were instrumented with 12 thermocouples, of which 6 were installed in the top plate and 6 in the bottom of the test section. Where aluminium foams were tested, these were again foams produced by the investment casting method and had pore size of 5–40 PPI and porosity that varied between 0.89 and 0.97. The experimental results were compared with a model developed from the literature. Mancin et al. found that the heat transfer coefficient (h_c) calculated from the measured temperatures does not depend on the heat flux imposed and that it increases with increasing air mass flow rate. In tests with the same heat flux imposed, they found that, for a constant pore size, an increase in the global heat flux is obtained when the porosity is decreased.

2. Experimental rig design

In this work the development of a new device will be described. It will be shown that this device can measure a wide range of porous metals to monitor the performance of the foam at transferring heat. To gauge the suitability of a foam to act as a heat exchanger and its potential performance, the properties that need to be measured are the capability of transporting thermal energy between the solid and the fluid (through a parameter such as the heat transfer coefficient) and the resistance to fluid flow (measured by the pressure drop at a particular flow rate or the permeability). These parameters may be calculated from experimental measurements for steady state conditions of flow and heat transfer trough a sample of known dimensions of: the foam temperature; the pressure drop across the foam; the flow rate and temperature of fluid before and after flow through the foam.

The concept used here to obtain these parameters and characterise the heat transfer and the permeability performance of metal foams uses an open circuit design, with gas being supplied at a controlled pressure and measured flow rate from a compressed air bottle. A thick-walled cylinder of copper in which a cylindrical sample of foam is placed is heated by an electrical resistance heater, while the foam is cooled by forced convection by flowing air through it. The difference in temperature between the copper block close to the interface with the foam and the incoming air gives the driving temperature difference for the heat to be transferred. How effective the foam is at doing this can be found by measuring the temperature difference in the cooling air before and after the specimen. The apparatus, which is shown schematically in Fig. 1 and in the general view image in Fig. 2, consists of two steel chambers, one of which is connected to the cooling fluid (in this case air), between which is the copper cylinder. The chambers are the locations where the measurement of air temperature before and after the sample, and the pressure drop are