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Experimental investigation of convective heat transfer in an open-cell aluminum foams

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ABSTRACT

Experimental results of heat transfer and pressure drop for a three open-cell aluminum foam blocks are presented for turbulent forced convection. The aluminum foam samples are inserted in a rectangular channel in a staggered manner on its bottom and top walls. A constant heat flux of 2 W/cm^2 is maintained in the test section on the bottom wall. The wall temperatures along the flow direction as well as the average inlet and outlet temperatures of the air were measured. Measurements of pressure drop across the aluminum foam sample with a grade of 40 PPI and a porosity of 93% in a blower were used to determine the intrinsic properties of this foam and to allow the determination of its permeability and inertial coefficient. The air velocity was varied from 1 to 5 m s^{-1} while two heights of the porous blocks respectively 16 mm and 20 mm were used. Additionally a configuration of solid blocks made of aluminum was investigated.

The results show that inserting metallic foams in a turbulent air flow improves the heat transfer by approximately 300% compared with an empty channel with adopting lower velocity, which reduces the supplied power. This improvement is even more important as the sample height is great. Increasing the sample size of the metallic foam, accentuate the turbulent kinetic energy levels inside the porous matrix and into the inter-baffle space, which increased the heat dissipated in the wall. In addition, the use of metallic foam increased the thermal conductivity of the coolant. Finally, compared with solid baffles, the aluminum foam created lower pressure losses because of their permeability and dissipate 2 times more heat.

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1. Introduction

Open-cell aluminum foams are irregular structures belonging to the family of cellular materials. It is their inherent properties as high effective thermal conductivity (between 2 and 26 W/(m K)), high porosity (between 0.85 and 0.98), large surface area density and the tortuous flow path inside these media that make them useful materials for many industrial applications among them one can cite environment, thermal insulation, cooling systems. This explains the growing interest of these media in transport phenomena. In heat transfer, the foam ligaments normal to the flow direction cause boundary layer disruption and enhance flow mixing, while the solid struts enhance the heat transfer by conduction. Actually, the heat transfer properties of open-cell metal foams are so promising that such structures are used already as multifunctional heat exchangers [1], as compact heat sinks for cooling of microelectronic devices such as computer chips or power electronics. The electronic components performances, such as microprocessors, are influenced by the heat generated during the operating conditions of the component itself. Thus, in order to produce an efficient component with small size a cooling is necessary. Several fin types have been developed and optimized recently to obtain high heat transfer rates [1]. The use of open-cell metal foams as heat sinks could be a promising technique. Currently, the aluminum metal foams are widely used as heat exchangers because of their very high effective thermal conductivity and low flow resistance.

Jeng et al. [2] has experimentally studied the heat transfer and pressure drop in a 180-deg round turned channel fitted with aluminum foam blocks installed with different arrangements. The porosity and the grade of the samples used were 0.90 and 10 PPI respectively. They found that the average Nusselt number was

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Nomenclature

$C_{p,\text{air}}$	specific heat of air at constant pressure (J kg^{-1} K^{-1})
H	channel height (m)
K_f	fluid thermal conductivity of the fluid (W m^{-1} K^{-1})
$\dot{m}_{\text{air}}$	air mass flow rate (kg s^{-1})
$\overline{Nu}$	average Nusselt number
PPI	pore per inch
p	mean static pressure (Pa)
q_w	wall heat flux (W/m^2)
Re_{DH}	Reynolds number based on hydraulic diameter
$\overline{T}_w$	average wall temperature (K)
T_{in}	inlet temperature (K)
T_o	outlet temperature (K)
T_w	wall temperature (K)
T_b	bulk temperature
u_{in}	inlet velocity (m s^{-1})
w	width of aluminum foam (m)

Greek symbols

φ	porosity
ρ	air density (kg m^{-3})
ε	enhancement efficiency

Subscripts

e	effective
f	fluid
in	inlet
w	wall

from 74% to 140% higher than that obtained with an empty channel. Furthermore, the staggered configuration of the aluminum foam blocks was found to enhance the heat transfer capacity more efficiently with a lower pressure drop than the symmetric configuration. Kurtbas et al. [3,4] conducted experiments to study the heat transfer characteristics of the air flow mixed convection for Reynolds number from $6 \cdot 10^2$ to $3.3 \cdot 10^4$ through a horizontal rectangular channel in which aluminum foam plate of different grades is located. They found that if the grade increased from 10 PPI to 30 PPI, the average Nusselt number increased from 2% to 40% depending on the Reynolds number value. Ko et al. [5] carried out experiments to analyze the heat transfer and fluid flow through aluminum foam baffles installed on the top and on the bottom walls in a staggered way. Their experiments showed that the heat transfer enhancement ratio was increased with the baffle thickness and the grade, but the friction factor was slightly decreased with an increase of the Reynolds number, and increased with baffle thickness and grade. Mancin et al. [6–8] achieved an experimental study of the heat transfer and fluid flow in a horizontal channel fitted with twenty-one different aluminum and copper foams with 5, 10, 20 and 40 PPI. They found that for all aluminum foams samples, the global heat transfer coefficients increases with the air mass flow rate and are not depend on the imposed heat flux. They proposed two correlations which predict accurately the heat transfer coefficients and the pressure drops. Madani et al. [9] studied experimentally the pressure drop and heat transfer of an n-pentane single phase flow in a copper foam of a grade of 36 PPI. They found that when they brazed the foam on the channel wall, the pressure drop was not affected while the metal foam insert can clearly enhance the heat transfer during boiling process.

Lin et al. [10] conducted numerical study to predict the performance of graphite foams heat exchangers in vehicles. Four different configurations (baffle, pin–finned, corrugated, and wavy corrugated) of graphite foam fins are analyzed. The simulation results show that the wavy corrugated configuration of graphite foam presents high thermal performance and low pressure drop.

The above literature review revealed that experimental studies are limited to the forced convection of air through the cellular material in the turbulent regime. This work is devoted to turbulent forced convection through aluminum metallic foam samples of porosity 0.93 and grade 40 PPI inserted in a staggered manner in a rectangular channel. The air velocity at the channel inlet side is varied from 1 to 5 m s^{-1}. The influence of the metallic foam height on the heat transfer and pressure drop is analyzed as a function of a variable air velocity and a fixed heat flux of 2 W/cm^2. A comparative analyze will be also conducted with aluminum solid blocks configuration of 2 mm thickness and a variable height.

2. Experimental facility

A schematic diagram of the experimental apparatus installed at the Laboratory of Multiphase Flows and Porous Media of the University of Sciences and Technology Houari Boumedien, Algiers, is shown in Fig. 1.

The air is used as a coolant fluid in the channel. The working fluid was pulsed in the main channel made with 10 mm thickness Plexiglas, by a centrifugal fan mounted appropriately in front of the diffuser and was passed through a rectifier honeycomb to avoid severe turbulence in the test section inlet. The fan used in this system present a maximum flow rate of 450 m^3/h. The main channel has 100 mm wide, 20 mm high, and 1030 mm length is connected to a test section, where we inserted three metallic foam fixed in staggered manner. The thickness of the metallic foam is 6.35 mm and spaced 5 mm as shown in Fig. 2. The foam samples, which are 104 mm wide and variable high (max 20 m), were obtained using high pressure water jet. The inlet region is sufficiently long equal to ten times the channel height to ensure a fully developed turbulent flow upstream of the test section. The outlet region is also long equal to forty times the channel height. The test section was manufactured in low thermal conductivity PolyTetraFlur-oEthylène (PTFE) to minimize heat losses to the environment. The microscopic structure of the metallic foam sample used in this study is shown in Fig. 3 photographed with a Balayage Electron Microscope (MEB). It was made from aluminum alloy 6101, and has a porosity of 93% specified by the manufacturer, with a grade of 40 PPI. Table 1 gives the physical properties of aluminum alloy 6101. The air velocity was measured away from the test section by using a hot wire anemometer (AIRFLOW TA2) with precision of ±1.5 m/s. The air velocity range, from 1 to 5 m/s, was obtained by varying the speed of a centrifugal fan by an AC inverter (Altivar ATV312HU22M2).The pressure drop for the different blocks configurations was measured with two inclined liquid column manometer TX50 and MG60 Kimo type which were connected to pressure taps fixed at 2H upstream and downstream of the test section with 1 Pa accuracy as shown in Fig. 4. For each inlet velocity, differential pressure and temperatures under steady state were measured. Two cartridges heaters, each delivering a power of 100 W, are used to heat the bottom wall of the test section made with copper and are shown in Fig. 5. They were inserted into the heating plate in order to obtain a uniform heat flux density of 2 W/cm^2. An electrical power of 60 W which is measured with a power meter was adopted. To reduce heat loss, the test section enclosing the metallic foam blocks and the heater consists of 50 mm thick Teflon. The heat loss is estimated to be less than 10% for all experimental cases. The heat loss through the test section is estimated from the

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