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Experimental investigation of the convective heat transfer coefficient for open-cell porous metal fins at low Reynolds numbers

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ABSTRACT

The heat transfer characteristics and convective heat transfer coefficient of porous metal fin are experimentally investigated. The pore density of the porous metal fin and frontal velocity of the working fluid are varied in the range of 20, 40, and 80 pores per inch, and 0.007–0.17 m/s, respectively. The porous metal fins are fabricated from nickel with different porosities and various pore densities. The geometrical parameters of the test samples are measured using an optical method. In this study, porous metals are considered as a fin and the heat transfer performances are experimentally evaluated. An equivalent diameter based on the permeability and porosity is used as the characteristic length to calculate the Reynolds numbers and Nusselt numbers. When the equivalent diameter is used as the characteristic length, the measured Nusselt numbers converge to a single curve regardless of the pore density. The Nusselt number variation appears to be very similar to previous correlations developed for convective heat transfers of turbulent pipe flows. Consequently, an empirical correlation of the Nusselt number for porous metal fins is proposed in the form of a Dittus–Boelter correlation.

1. Introduction

A heat exchange between working fluids is indispensable in various industrial and domestic energy systems. Because the heat exchange processes affect the overall performance of a thermal system, significant research results regarding compact heat exchangers have been presented over the past decade [1–4]. Porous metals have also garnered research interest for applications in electronic device cooling, fuel cell electrodes [5], compact heat exchangers [6], and so on. The diverse research areas in porous metals have been being investigated for more than 150 years [7–9]. Porous metals have high surface area-to-volume ratios as well as complex path structures. It is expected that enhancing the heat transfer area and flow mixing would increase the convective heat transfer capacity when applied to heat exchangers. Therefore, the heat transfer characteristics of porous metals have been investigated [10].

Rohsenow and Hartnett [11] and Nield and Bejan [12] considered forced convective heat transfers in rectangular ducts packed with porous materials and defined a convective heat transfer coefficient and Nusselt number based on the channel wall area. In their formulation, the overall porous medium thermal conductivity, i.e. the weighted mean of the fluid thermal conductivity and solid thermal conductivity, was used to consider the effect the porous medium on the heat transfer augmentation. Most previous research concerning porous metals has used the local thermal equilibrium (LTE) model [13–15]. The LTE model assumes a local thermal equilibrium between the solid and fluid. Dukhan et al. [16] presented a macroscopic lumped-parameter model that obtains the temperature distribution in a rectangular block of thin porous metal foam with a constant cross-sectional area. However, the validity of the LTE model is restricted to low Reynolds number applications [17]. Whitaker [18] and Quintard and Whitaker [19] presented the constraints that must be satisfied in order for the LTE assumption to be valid. They demonstrated that the LTE model is only applicable when the conductive heat transfer is dominant in a representative elementary volume that consists of a fluid and a solid of porous metal. However, in most practical applications, the heat transfer to the fluid flowing through porous metals is dominated by convective heat transfers.

When the temperature between the solid and fluid in the porous metal differs, the LTE assumption cannot be applied [20]. The local thermal non-equilibrium (LTNE) model can be used when the temperatures of the fluid and porous metals are known and the heat transfer area is measured. For these reasons, many researchers have used the LTE model without verifying the adequacy of the LTE assumptions. The LTNE model was recently

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Nomenclature

A_t	total heat transfer surface area of porous metal fin ($= \varepsilon A_b + aHA_b$)
A_b	base of porous metal fin ($= WL$)
A_f	fin surface area of porous metal fin
a	surface area density of porous metal ($= A_f/V$)
C_f	specific heat of working fluid
D_{eq}	equivalent diameter
d_f	diameter of ligament
d_p	diameter of pore
H	height of channel
h	convective heat transfer coefficient
k_f	thermal conductivity of metal
k_{fluid}	thermal conductivity of fluid
K	permeability
$\dot{m}$	mass flow rate of working fluid
Nu	Nusselt number
q_t	total heat transfer rate
q_b	heat transfer rate at the primary surface
q_f	heat transfer rate at fin surface
Re	Reynolds number
$T_{b,i}$	inlet temperature at the base surface of heater block
$T_{b,o}$	outlet temperature at the base surface of heater block
$T_{m,i}$	inlet temperature of working fluid
$T_{m,o}$	outlet temperature of working fluid
u	frontal velocity of working fluid
u_p	average pore velocity of working fluid

Greek symbols

ΔT_{lm}	logarithmic mean temperature difference
ε	porosity
η_f	fin efficiency
η_o	overall surface efficiency
μ	viscosity coefficient of working fluid
ρ	density of working fluid

introduced in order to consider the temperature differences between the solid and fluid in a channel filled with a porous metal. Lu et al. [17] used the LTNE model to obtain a functional relationship between the convective heat transfer characteristics and the geometrical shape of the porous metals. They developed an analytical model that assumes the porous metal to be a simple cubic structure that has unidirectional heat flow similar to a tube bundle in a cross flow. Hsieh and Lu [21] demonstrated the effect of the thermal diffusion coefficient in the entrance region. They illustrated that the Nusselt number predicted by the LTE model was higher than that predicted by the LTNE model. Calmidi and Mahajan [22] experimentally investigated forced convection in aluminum porous metals using air as a coolant; they also developed a numerical model through applying the LTNE model. Lee and Vafai [23] analytically characterized the forced convective flow through a channel filled with a porous medium and obtained the Nusselt number in terms of the Biot number and effective thermal conductivity. Ichimiya [24] investigated the thermal behavior in a ceramic porous medium channel through applying the LTNE model.

If a porous metal is attached to a heat transfer tube or a flat heat transfer surface, the ligament surface of this porous metal functions as an extended heat transfer surface attached to a primary heat transfer surface. That is, the ligament surface temperature changes with the distance from the primary surface, while a constant wall heat flux condition or a constant wall temperature condition is applied to the primary surface. In order to consider this effect, the porous metal attached to the heat transfer surface should be treated as a fin. However, there are few reports in the literature where a porous fin has been treated as a fin in order to obtain an average heat transfer coefficient on the primary and ligament surfaces. Kim et al. [25] measured the convective heat transfer coefficient of air flowing through an aluminum porous metal: they used the fin efficiency model of a louver fin to obtain the convective heat transfer coefficient of the porous metal surface because a more suitable fin model was not available. Recently, Ghosh [26] analyzed the convective heat transfer characteristics of a fluid flowing through a porous medium. In his work, Ghosh presumed that a porous metal with a high porosity had a simple cubic structure and proposed a fin efficiency model. In the present work, experiments were conducted to characterize the convective heat transfer of water flowing through a rectangular channel filled with an open-cell porous metal. The porous metal fins were fabricated from nickel, and tests were conducted using various pore densities. The average convective heat transfer coefficient of the channel filled with porous metal fins was obtained through applying a fin efficiency model.

2. Experiment

2.1. Experimental apparatus and test specimen

A schematic of the experimental setup is presented in Fig. 1. The experimental setup is composed of a constant temperature water bath, a pump, a flow meter, a differential pressure gauge, and a test section. Purified water was used as the working fluid, and it was held in a constant temperature water bath. Water was supplied at 20 °C to the test section using a gear pump or a centrifugal pump, and the pump speed was varied in order to control the water flow rate to be in the range of 0.0035–0.085 kg/s (0.007–0.17 m/s in terms of frontal velocity). A Coriolis' effect flow meter with an accuracy of ±0.1% of the reading was installed between the water pump and the test section in order to measure the mass flow rate of water, while a differential pressure transducer with an accuracy of 0.075% of full scale was installed in order to measure the pressure drop across the test section. Copper/Constantan (type T) thermocouples were used to measure the water temperature at the inlet and outlet of the test section. The uncertainty of the temperature measurement considering the combined effect of the thermocouple itself and signal converting electronics was 1.0 °C.

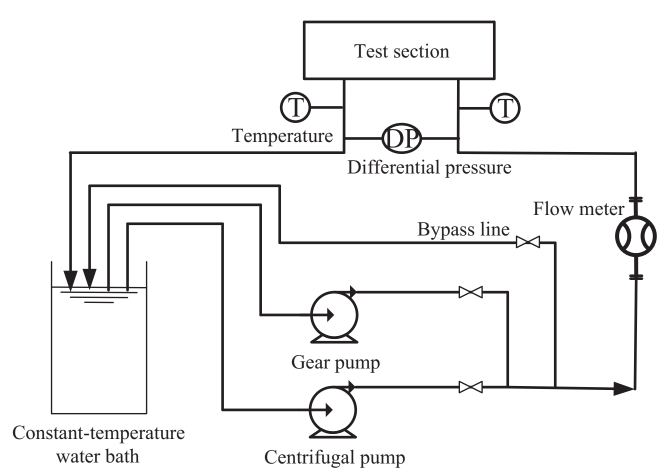

Fig. 1. Schematic of the experimental setup.