CONVECTIVE HEAT TRANSFER CHARACTERISTICS OF FLOW THROUGH OPEN-CELL METAL FOAM CONSIDERING REAL STRUCTURAL GEOMETRY

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ABSTRACT

This study demonstrates numerical prediction of temperature and velocity field when fluid flows through the real 40 PPI metal foam structure extracted by the 3-D μ-CT method. The results are compared to those obtained using structured model and experimental data. The effects of the hollowness of a metal foam ligament on the heat transfer characteristics are presented, and an empirical correlation is suggested for estimating the corresponding Nusselt number. The numerical results clearly show that the hollowness directly affects the heat transfer characteristics, and the Nusselt number for hollowness of 0.79 was about 40% lower than that for a solid ligament. An extended correlation was derived through thermodynamic analysis and numerical results. The experimental data verified that the proposed correlation is appropriate for estimating the Nusselt number for open-cell metal foam with hollow ligaments.

INTRODUCTION

Open-cell metal foam has been attracting attention as a heat transfer medium in recent years due to its outstanding surface volume density (790–2740m^2/m^3) and high porosity (ε>0.9) [1–6]. These characteristics improve the ratio of the heat transfer surface area to the volume, which is one of the key variables in determining the performance of heat exchanger [3, 5, 7–10]. Previous studies have reported that this material can potentially enhance heat transfer performance and make heat exchangers more compact [3, 5, 10–13].

The effects of metal foam geometry on heat transfer characteristics have been studied widely using experimental, analytical, and numerical approaches. Paek et al. [4] experimentally examined the effects of porosity and ligament diameters on the effective thermal conductivity. Shin et al. [14] observed the effects of the height of a metal foam heat sink on the cooling performance. Lu et al. [3] and Zhao et al. [5] reported the heat transfer performance of a metal-foam-filled pipe and metal-foam-filled tube-in-tube heat exchanger. Bhattacharya et al. [15] analytically and experimentally determined the effective thermal conductivity, permeability, and inertial coefficient of metal foams and reported a theoretical model and empirical correlation for effective thermal conductivity.

NOMENCLATURE

A	[m^2]	Heat transfer area of heat source
Bi	[-]	Biot number
C	[-]	Geometrical constant
d	[m]	Outer hydraulic diameter of ligament
d'	[m]	Inner hydraulic diameter of ligament
H	[m]	Height of channel filled with metal foam
h	[W/m^2K]	Averaged heat transfer coefficient
k	[W/mK]	Thermal conductivity
m	[kg/s]	Mass flow rate
Nu	[-]	Nusselt number
Pr	[-]	Prandtl number
Red	[-]	Prandtl number
T	[K]	Temperature

Special characters

ε	[-]	Porosity
η	[-]	Hollowness
μ	[Pa·s]	Viscosity
ξ	[-]	Thermal conductivity factor
ψ	[-]	Solidity
y^+	[-]	Wall unit

Subscripts

f	Fluid
in	Inlet
out	Outlet
p	Pore
s	Solid
w	Wall

Lu et al. [10] estimated the overall heat transfer coefficient of metal foams by proposing an analytical model with simple cubic unit cells using existing heat transfer data on convective crossflow through cylinder banks. Kopanidis et al. [16] employed a Weaire-Phelan model for three-dimensional numerical simulation of the flow and heat transfer through high-porosity open-cell metal foam and verified the model experimentally. However, only solid ligaments have been considered in most previous studies [1–4, 10, 14, 15].

Open-cell metal foam ligaments are categorized into solid, precursor-filled, and hollow ligaments [11, 17], as shown in Figure 1. A precursor-filled ligament is manufactured by a metallic deposition method, which is widely used due to the relatively high uniformity and the exceptional porosity of the metal foam products [11, 17]. Solid ligaments are made using a powder metallurgy method [11], while precursor-filled ligaments are hollowed and filled with air after a pyrolysis process [11, 17]. The hollowness of a ligament could vary with the electroplated thickness, precursor material, and precursor ligament thickness [11, 17]. According to the literature, up to 77% of the ligament volume could be hollow [17].

According to Fourier's conduction law [9], the ligament hollowness should be closely related to the heat performance. However, the ligament hollowness has not been considered in previous studies [4, 10, 14-16, 18, 19]. Thus, the aim of this study is to investigate the effects of hollowness in open-cell metal foam ligaments on the heat transfer characteristics and to develop an empirical correlation for the corresponding Nusselt number. Numerical simulations were conducted for various hollow ligaments, and then an empirical correlation was derived based on a previous correlation for a circular fin array proposed by Zukauskas [5, 8, 10, 20]. Experimental verification was carried out using an open-cell metal foam block with hollow ligaments.

For this investigation, hollowness and solidity should first be defined. The cross-sectional shape of a ligament is simplified as a circular tube using hydraulic diameters, as shown in Figure 1. An irregular foam ligament has been considered as a circular fin in previous studies [1, 2, 10, 15]. The hollowness η is defined as the ratio of the inner empty area to the total area of the cross-section, d'^2/d^2, where d and d′ are the hydraulic outer and inner diameters of a hollow ligament, respectively. The solidity ψ can be defined as $\psi = 1- \eta$.

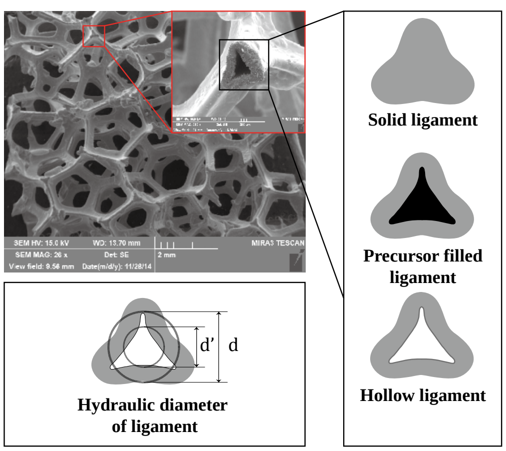


Figure 1 Cross-sectional shapes of metal foam ligament

NUMERICAL METHODS

Figure 2 shows a schematic diagram of the computational domain with open-cell metal foam that has hollow ligaments. The computational domain consists of a flow channel, metal foam structures, heat transfer medium block, and heat source plate. A conjugate heat transfer module was used to calculate the heat transfer from the heat source to the fluid flow through the heat transfer medium and metal foam structures. The metal foam was modeled with a Weaire-Phelan structure that has been widely used in previous studies [16, 19, 21]. The metal foam is positioned in the middle of a straight rectangular duct with inlet and outlet regions as shown in the figure. The applied thermal properties of the metal foam domain were the same as those of copper, which has a thermal conductivity of 401W/mK. The heat source domain has a constant temperature of 328K.

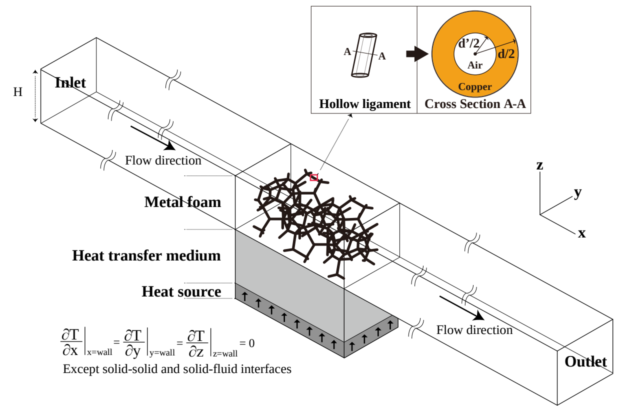
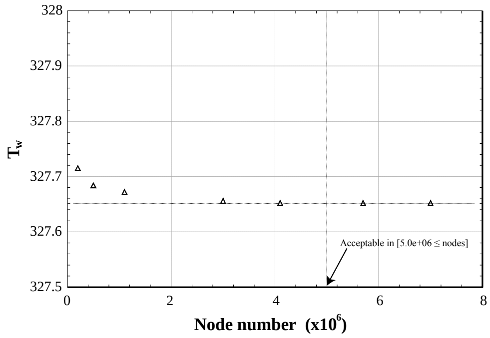


Figure 2 Schematic diagram of computational domain with open-cell metal foam structure

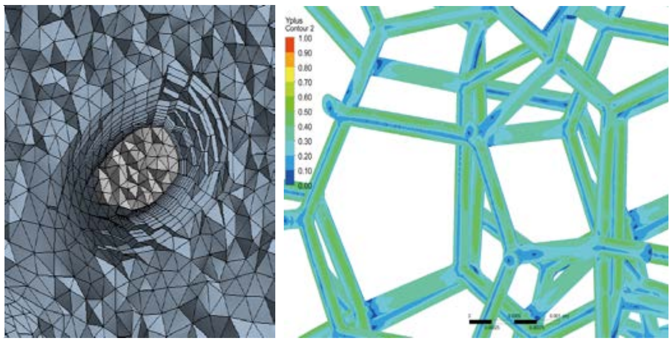
For the fluid domain, air flows with an inlet temperature of 300K under gravitational acceleration of -9.81 m/s^2 along the z axis. Open conditions with a relative pressure of 0 Pa was employed at the channel inlet, and a constant mass flowrate condition was set at the channel outlet. Adiabatic and no-slip boundary conditions were applied to all walls.

Under steady-state conditions, three-dimensional RANS (Reynolds-averaged Navier-Stokes) equations with continuity, momentum, and thermal energy equations were solved using the commercial code CFX 16.1 from ANSYS Inc. Double-precision, higher-order advection, and the turbulence numerical scheme were used. An SST (shear stress transport) turbulent model was applied to compute the Reynolds shear stress of RANS equation. This model is based on the BSL *k-ω* model, which is frequently used to predict adverse pressure gradients and separating flow. To observe the laminar boundary layer in the transition region, a Gamma-Theta transition model was employed in the SST model.

The model had more than 5 million nodes determined by the grid independency test, as shown in Figure 3 (a). At η=0.60, the computational domain consists of 2.8 million elements comprising 1.7 million wedge elements, 420 thousand hexahedron elements, and 450 thousand triangular prism elements. All the nodes are directly connected to each other. The aspect ratio, skewness, and orthogonal quality of the grid were 6.15, 0.23, and 0.86 respectively, and the values indicated good quality. The y^+ values were set to less than 0.5, and the values at the fluid-ligament interfaces are presented in Figure 3 (b).



(a)



(b)

Figure 3 Grids of computational domain: (a) grid independency test result and (b) y^+ value

EFFECTS OF LIGAMENT HOLLOWNESS ON HEAT TRANSFER PERFORMANCE

The Reynolds number is defined as:

$$Re_d = {}^{\rho u d}/_{\mu} \tag{1}$$

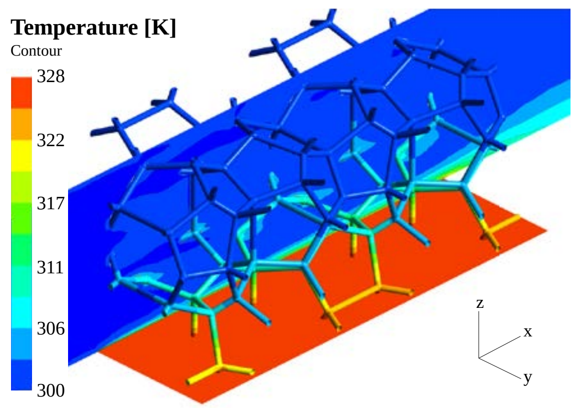
where u is the mean velocity of the channel flow, and d is the hydraulic diameter of a ligament associated with geometrical parameters such as PPI (pores per inch) and permeability [1, 2, 10, 15].

Figure 4 shows the calculated temperature distributions for the case of Re_d=266.2 with different ligament hollowness: (a) η=0.79, (b) η=0.60, (c) η=0.33, and (d) η=0.00. As the hollowness decreases, the temperatures of the downstream air flow and metal foam surfaces increase. The ligament temperatures on the bottom surface are similar at about 328K, but the ligament temperature at the top surface for hollowness of 0.79 (solidity, ψ=0.21) is about 8K less than for hollowness of 0.00 (solidity, ψ=1.00). The downstream air temperature passing through metal foam structures increases as the ligament hollowness decreases (and the solidity increases). Therefore, the results clearly show that the ligament hollowness of the metal foam affects the heat transfer characteristics.

A thermal conductivity factor can help to understand the effects of the ligament hollowness on heat transfer. Assuming that the hollow ligament is filled with air and that the natural convection and radiation of the confined air and hollow ligament are negligible due to the low-temperature heat source [9, 10], the thermal conductivity factor ξ for a ligament can be expressed as:

$$\xi = {}^{[k_s\psi + k_f\eta]}/_{k_s} \tag{2}$$

where k_s and k_f are the thermal conductivities of the ligament surface and the confined air, respectively.



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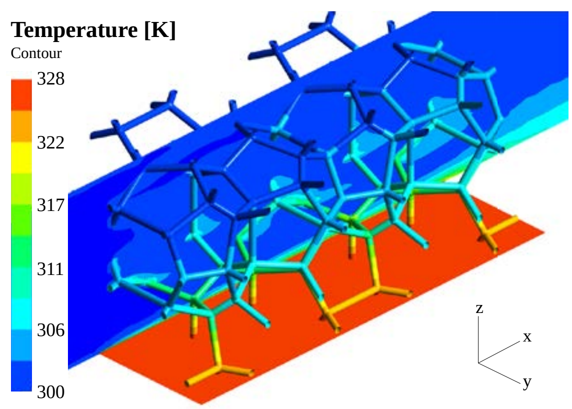

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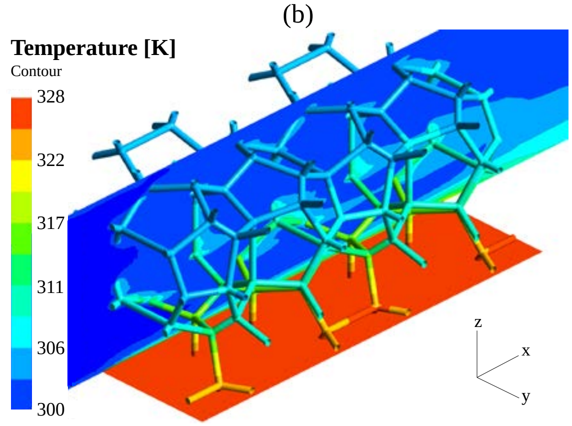

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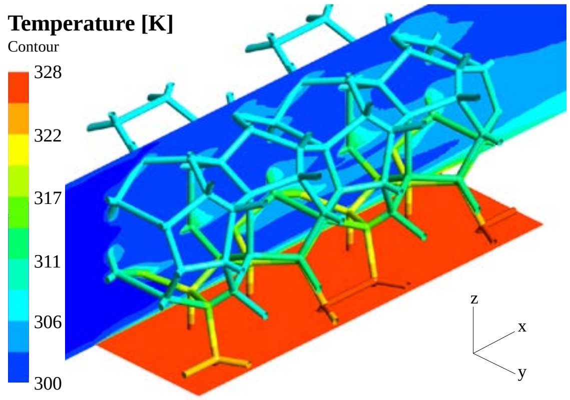


(d)

Figure 4 Temperature distributions for Re_d = 266.2; (a) η=0.79, (b) η=0.60, (c) η=0.33, and (d) η=0.00

Figure 5 shows the variation of the Biot number with the ligament hollowness and Reynolds number. Heat is transferred here mainly by two means: the forced convection between air and the foam ligament and the conduction through the metal foam ligaments. Thus, the Biot number can be expressed as:

$$Bi = h / \left(k_s\xi / H \right) \quad (3)$$

where H is the channel height filled with metal foam structures. The Biot number is defined by considering a metal foam ligament as a single straight hollow tube, as in previous studies [1, 2, 10, 15]. The averaged ligament thermal conductivity can be expressed with the thermal conductivity factor as $k_s\xi$. The averaged heat transfer coefficient h is defined as [9]:

$$h = \left[\dot{m}c_p (T_{out} - T_{in}) \right] / (A\Delta T_{LMTD}) \quad (4)$$

where ΔT_{LMTD} for a constant-temperature heat source is [9]:

$$\Delta T_{LMTD} = (T_{out} - T_{in}) / \ln\left[(T_w - T_{in}) / (T_w - T_{out}) \right] \quad (5)$$

where T_w is wall temperature at the hot side. As shown in Figure 5, the Biot number increases as the thermal conductivity factor decreases (and the hollowness increases) due to the increased conduction resistance from the enlarged cross-sectional area of the confined air, which has quite low thermal conductivity. The Biot number also increases with the Reynolds number for a specific hollowness because the averaged heat transfer coefficient h increases with the Reynolds number, while the conduction resistance is fixed.

In addition, the figure shows larger Biot number variation with respect to the Reynolds number at a lower thermal conductivity factor (higher hollowness). This implies that the heat conduction rate is directly affected by the ligament hollowness and that the heat transfer through metal foam structures is closely related to the ligament hollowness. For Re_d=343.6, the Biot number at ξ=0.21 is about 2.9 times higher than that at ξ=1.00 and about 2.6 times for Re_d=46.9.

In this study, the Nusselt number is defined as:

$$Nu = h / \left(k_f / d \right) \quad (6)$$

where the characteristic length, d is the hydraulic outer diameter of a ligament. Figure 6 presents the Nusselt number versus the Reynolds number for various values of ligament hollowness. The figure shows that the Nusselt number decreases as the hollowness increases with a linear relationship on a natural logarithmic scale for each hollowness case.

Zukauskas's correlation is widely used to estimate the Nusselt number for a circular rod bundle [8, 9, 20]. The correlation is expressed in Eq. (7) and has been employed in previous studies to predict the Nusselt number for open-cell metal foam with non-hollow ligaments [3, 6, 10]:

$$Nu = C Pr^{0.36} \left(Pr / Pr_w \right)^{1/4} Re_d{}^n \quad (7)$$

where the constants C and n are determined by the geometrical shape of the heat transfer medium and the Reynolds number range [5, 8–10, 20], and Pr (=$C_p\mu/k_f$) is the Prandtl number [9]. Pr_w is the Prandtl number based on the wall temperature [8, 9]. Eq. (7) can be rewritten in a logarithmic form as:

$$\ln Nu = \ln C + \ln Pr^{0.36} + \ln \left(Pr / Pr_w \right)^{1/4} + n(\ln Re_d) \quad (8)$$

In Eq. (8), the Prandtl numbers are constant when the inlet fluid temperature and the wall temperature are fixed for single-phase flow, making ln Nu linearly proportional to ln Re_d for a solid ligament (η=0), as shown in Figure 6. Since the Nusselt number and Reynolds number have a linear relationship for hollow ligaments, as shown in Figure 6, Eq. (8) can be extended for any hollowness value as:

$$\ln Nu = f(\xi) + g(\xi) \ln Re_d \quad (9)$$

Figure 7 presents the values of $f(\xi)$ and $g(\xi)$ extracted from fitted curves in Figure 6. The figure shows that $f(\xi)$ and $g(\xi)$ have a linear relationship with lnξ. Thus, Eq. (9) can be expressed as:

$$ln\, Nu = (\alpha\, ln\, \xi + \beta) + (\gamma\, ln\, \xi + \delta)\, ln\, Re_d \quad (10)$$

where α, β, γ, and δ are constants.

Eq. (10) can be rewritten as:

$$Nu = e^{\beta} \xi^{\alpha} Re_d{}^{\gamma \ln \xi + \delta} \quad (11)$$

Using the numerical results, α, β, γ, and δ were obtained as 0.5, 0.069, -0.03, and 0.34, respectively. The difference in Nu calculated by Eq. (11) is up to 3.98% from the numerical results.

Considering two different hollow ligaments, the Nusselt number ratio Nu_1/Nu_0 is expressed as:

$$Nu_1/Nu_0 = \left(\xi_1/\xi_0\right)^{\alpha} \left(Re_{d,1}{}^{\gamma \ln \xi_1 + \delta} / Re_{d,0}{}^{\gamma \ln \xi_0 + \delta} \right) \tag{12}$$

The equation implies an interrelation between Nusselt numbers for two different hollow ligaments. For ξ_0=1 (η=0, solid ligament) and $Re_{d,0}$=$Re_{d,1}$, Eq. (12) can be simplified as:

$$Nu_1/Nu_0 = \xi_1{}^{\alpha} Re_{d,1}{}^{\gamma \ln \xi_1} \tag{13}$$

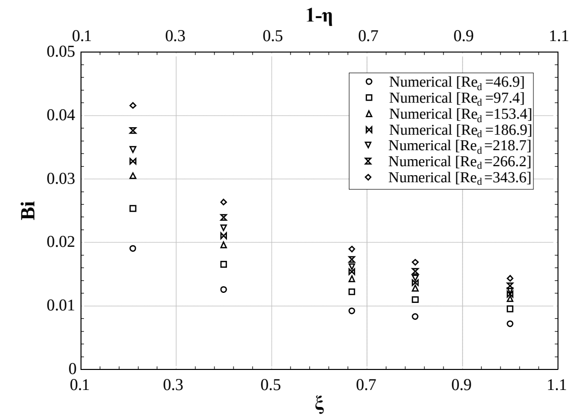


Figure 5 Effects of hollowness on Biot number

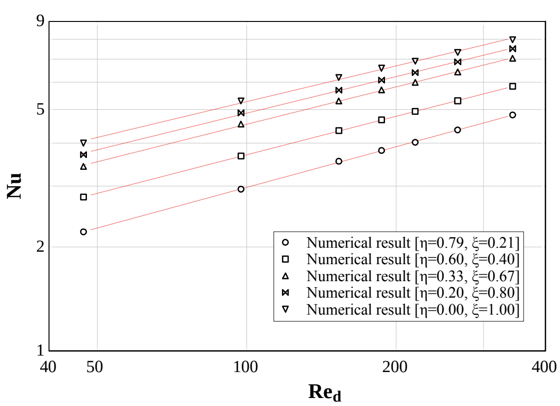
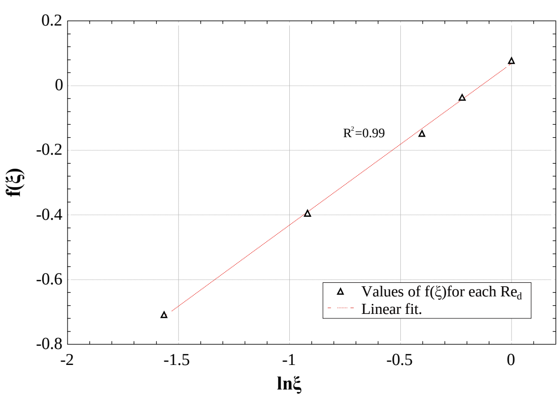
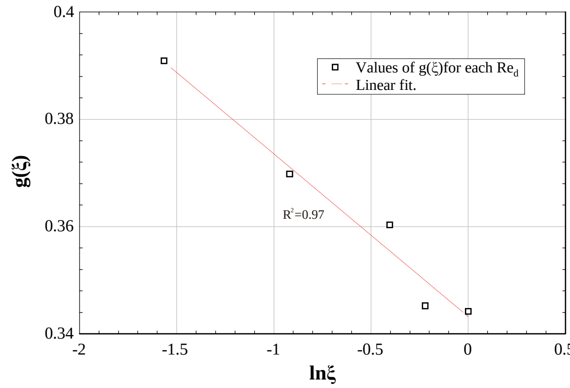


Figure 6 Effect of hollowness on Nusselt number; superimposed red lines are linear fitted curves.



(a)



(b)

Figure 7 Values of $f(\xi)$ and $g(\xi)$ extracted from fitted curves in **Figure 6**

Figure 8 shows the Nusselt number ratios Nu_1/Nu_0 for ξ_0=1. The Nusselt number for ξ=0.21 (η=0.79) is 40% lower than that for a solid ligament (ξ=1, η=0). From Eq. (7) and (13), the final equation for various hollowness values is:

$$Nu = C\xi^{\alpha} Pr^{0.36} \left(Pr/Pr_w\right)^{1/4} Re_d{}^{n+\gamma \ln \xi} \tag{14}$$

where α and γ are 0.5 and -0.03, respectively, and C and n are constants obtained from the literature [8, 9, 20]. If the thermal conductivity factor is 1 (solid ligament), the equation is identical to Zukauskas's correlation (Eq. (7)) [8, 9, 20].

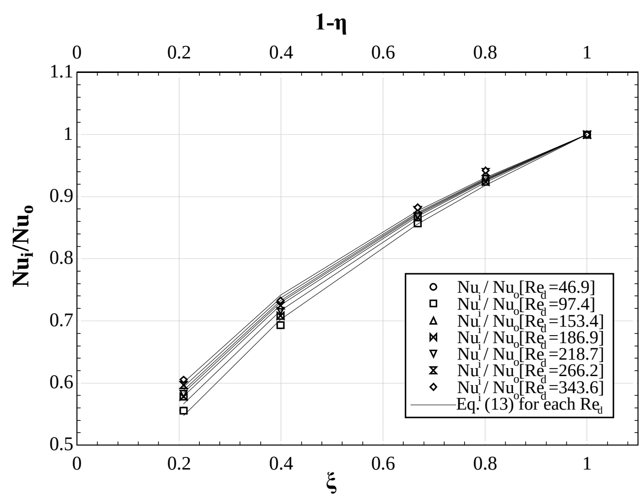


Figure 8 Nusselt number ratios, Nu_1/Nu_0 for ξ_0=1.

An experimental investigation was conducted using an open-cell metal foam with hollow ligaments (ξ=0.67), and the results were compared with Eq. (14). The setup consists of a rectangular flow channel with 60-mm width and 5-mm height, an open-cell metal foam block, a plate heater, and a suction blower. A test section is positioned at 300 mm downstream from the channel entrance with a copper metal foam block placed on a 200W electrical plate heater. The metal foam block (60-mm width, 200-mm length, and 5-mm height) has a manufactured pore density of 30 PPI. The geometrical specifications of the ligament structure were measured by SEM (scanning electron microscope). The measured ligament hydraulic diameter (*d*) was 0.181 mm, the inner hollow hydraulic diameter (*d'*) was 0.104 mm, and the pore diameter (d_p) was 2.31 mm. The permeability K was calculated as 7.79e-08m^2.

In Figure 9, the experimentally obtained Nusselt numbers for ξ=0.67 (η=0.33) are compared to those estimated by Eq. (14). The values of *C* and *n* in Eq. (14) were determined as 0.81 and 0.4 respectively [8, 9]. As shown in the comparison, the Nu estimated by Eq. (14) is in a good agreement with that acquired from the experiment. The difference between the tested and the analytical values is less than 4.82 % of the experimental value.

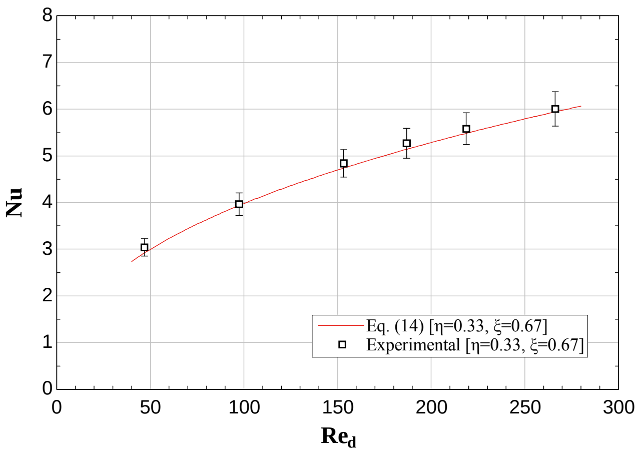


Figure 9 Nusselt number obtained by experiments and Eq. (14); measurement uncertainty is about 6.1%.

CONCLUSION

The effects of hollowness of a metal foam ligament on the heat transfer characteristics have been investigated by numerical simulation, and an extended correlation of Nu has been derived for various ligament hollowness values. The proposed equation was then verified experimentally. The numerical results clearly showed that the hollowness directly affects the heat transfer characteristics, and the Nusselt number for hollowness of 0.79 was about 40% lower than that for a solid ligament.

The extended correlation (Eq. (14)) was derived through thermodynamic analysis, and the constants α and γ were found to be 0.5 and -0.03, respectively. The experiment verified that the proposed correlation is appropriate for estimating the Nusselt number for open-cell metal foam with hollow ligaments. Due to the thermal conductivity factor, the correlation might have potential for use in predicting the Nusselt number for metal foam ligaments filled with a different material.

ACKNOWLEDGEMENT

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