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Experiment on the convective heat transfer from airflow to skeleton in open-cell porous foams

Xin-lin Xia [*], Xue Chen [*], Chuang Sun, Zhen-huan Li, Bo Liu

School of Energy Science and Engineering, Harbin Institute of Technology, 92, West Dazhi Street, Harbin 150001, PR China

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ABSTRACT

In order to understand the heat transfer behavior of forced airflow in open-cell porous foam, a tubular device filled with porous foam is built to conduct the experimental measurement. Three kinds of porous foams of Cu, Ni and SiC with various pore diameters and high porosity from 0.87 to 0.97 are used in the experiment, respectively. The tested sample is heated transiently by the hot airflow with an inlet velocity varying from 2.0 m/s to 9.0 m/s. And the transient temperature data of airflow are measured to determine the volumetric heat transfer coefficients by an inverse analysis. The experimental results are compared with those predicted by seven groups of experimental correlations available at present. Furthermore, an improved correlation of volumetric heat transfer coefficient is presented, which has two independent structure parameters of porosity and pore diameter and is valid for a wide range of Reynolds number $20 \leqslant \mathrm{Re_d} \leqslant 10^3$. By comparing with all of the available experiment data, the proposed correlation shows an error of ±40%.

1. Introduction

The open-cell porous foams with unique structural properties have been widely used in engineering applications such as compact heat exchangers [1,2], porous radiant burners [3,4], catalyst supports [5,6] and volumetric solar receivers [7,8]. There are two major mechanisms causing heat transfer enhancement for the porous foams [9]. One is the tortuosity of the three dimensional pore structure which makes the flow more turbulent, the other is the extended exchange surface area. A detailed understanding of heat transport within the foams is crucial for the thermal performance analysis and optimal design.

In the study of flow and heat transfer within the porous foams, two primary models are widely utilized, local thermal equilibrium (LTE) and local thermal non-equilibrium (LTNE) models [10]. The temperature difference between the fluid and solid phases is neglected in the LTE model, while it is taken into consideration in the LTNE model. Moreover, when a substantial temperature difference exists between the two phases, the LTE model does not hold. Some investigations have revealed that the LTE model is not valid for some problems, such as storage of thermal energy, heat transfer with internal heat generation, transient heat transfer and the coupled radiative and convective heat transfer at high temperature [11–13]. In these situations, the volumetric heat transfer coefficient (VHTC) is used to represent the internal heat exchange between the two phases. The energy equations of the fluid phase and the solid phase are coupled by the VHTC between these two phases. Therefore, the VHTC is a key input parameter for the thermal analysis of porous foams using the LTNE model.

Several studies have been done to predict the VHTC between the fluid phase and the solid phase numerically and experimentally. Moreover, only few empirical correlations are proposed for the porous foams. The numerical approach to compute the VHTC is usually carried out with a simplified geometric model or a microstructure obtained by employing computer tomography (CT) [14–16]. The aforementioned structures are used as a geometrical representation of the real solid skeleton of porous foam. On the other hand, two kinds of experimental methods have been developed in the literature: steady state and transient methods [9,17]. The transient method also called a single-blow method is mostly used, due to that more reliable values can be obtained than those attained by the former one, as pointed out by Fuller et al. [9]. For the steady state method, the thermal conduction has a significant effect because of the heat source located at the side surface of the channel. The VHTCs from the steady state method are inherently affected by the thermal conductivity of porous foam. While for the transient method, it is assumed that the foam has a uniform temperature in the transverse direction. Therefore, the conduction effect is not an issue [9]. In addition, the main advantage of the

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[*] Corresponding authors.
E-mail addresses: xiaxl@hit.edu.cn (X.-l. Xia), hit_chenxue@163.com (X. Chen).

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Nomenclature

a_{sf}	specific surface area, m^{-1}
c	specific heat, J kg^{-1} K^{-1}
d_c	cell diameter, m
d_h	hydraulic diameter, m
d_n	nominal diameter, m
d_p	pore diameter, m
d_s	strut diameter, m
d_{par}	particle diameter, m
h_v	volumetric heat transfer coefficient, W m^{-3} K^{-1}
h_{sf}	interstitial heat transfer coefficient, W m^{-2} K^{-1}
k	thermal conductivity, W m^{-1} K^{-1}
L	length of foam specimen, m
$\mathrm{Nu_v}$	volumetric Nusselt number
Pr	Prandtl number
$\mathrm{Re_d}$	Reynolds number based on the pore diameter
$\mathrm{Re_{par}}$	Reynolds number based on the particle diameter
T	temperature, K
T_0	initial temperature, K
u	velocity in x direction, m s^{-1}
V	volume, m^3
x, r	coordinates in flow region, m

Greek symbols

μ_f	dynamic viscosity, kg m^{-1} s^{-1}
ρ	density, kg m^{-3}
ρ_b	relative density
τ	time, s
ϕ	porosity
Γ	temperature deviation

Subscripts

e	effective
in	inlet
f	fluid
out	outlet
s	solid

transient method is that only the fluid temperature has to be measured. However, the related experimental study can be rarely found so far. Ichimiya [18] adopted the steady state method to evaluate the VHTCs in an alumina foam with the porosity $\phi = 0.87$ by comparing the measured and predicted Nusselt numbers on the heated wall of a porous channel. The transient method is adopted in the other researches. There exists two different test procedures with respect to the transient method in the previous studies: (1) a cold fluid to cool down the hot porous foam, (2) a hot fluid to heat up the cold porous foam. In the first test procedure, the porous foam is firstly heated up to a temperature and then instantaneously cooled by the fluid stream. In the second test procedure, a perturbation in the inlet fluid temperature is produced and then the foam is heated by the fluid stream. Using the two test procedures, the VHTCs are both determined employing an inverse analysis with the outlet fluid temperature response as a main input condition.

Using the first test procedure, the FeCrAlloy and Cu foams of 10 and 20 pores per inch (PPI) were experimentally investigated by Giani et al. [19] in a range of flow superficial velocities from 1.2 to 5.7 m/s. A prismatic cell model was adopted to estimate the average strut diameter which was used as the characteristic length. Experiments were performed by Ando et al. [20] to obtain the VHTCs for ceramic foams of 6–20 PPI, nevertheless, the porosities of the tested foams were not given. The second test procedure is adopted in the other experimental investigations. The VHTCs were determined experimentally by Younis and Viskanta [21] for ceramic foams (alumina and cordierite) with $0.83 \leqslant \phi \leqslant 0.87$ and the pore diameters in the range of 0.29–1.52 mm. Fu et al. [22] conducted exhaustive measurements to obtain the VHTCs between five different cellular ceramics and a stream of air, and the effects of pore length-scale and specimen thickness were discussed. Aluminum foams of $0.7 \leqslant \phi \leqslant 0.95$ were experimentally explored by Hwang et al. [23] to analyze the combined effects of porosity and flow Reynolds number on the VHTCs. The VHTCs measurements of SSiC, CBSiC and cordierite ceramic foam materials used as open volumetric solar receivers were performed by Fend et al. [24]. Three ceramic foams (Alumina, Mullite and Oxidic-Bonded Silicon Carbide) with the structure parameters of $0.75 \leqslant \phi \leqslant 0.85$ and 10–45 PPI were measured by Dietrich [25] and a Nusselt–Hagen correlation was developed.

From the literature survey, it can be seen that experimental studies of the VHTCs inside the porous foams are rather limited. No universally applicable correlation exists so far. Moreover, the empirical correlations have been rarely established, compared with each other and experimentally validated. Besides, the VHTCs of Ni foams have not been reported. Among the porous foams, Cu foam has been widely used in the heat exchangers design. Additionally, the application of porous foams at high temperature has attracted a great deal of interest recently. For example, SiC and Ni foams have been used in the solar thermal utilization [26,27]. In this study, a series of tests are performed to obtain the VHTCs of three porous foams (Cu, Ni and SiC). Then, some correlations available in the literature are compared with the experimental results in this study. A new VHTC correlation is finally proposed and validated against different experimental data points presented by other independent research groups.

2. Experiment and analysis

2.1. Experimental setup and test procedure

The transient method is used to determine the VHTCs between the fluid and solid phases of the porous foams [21,25]. A schematic diagram of the experimental setup for the VHTC measurement is shown in Fig. 1. The air stream is steadily supplied by the compressor with a constant flow rate controlled by the valves. The volumetric flow rate is measured by a flowmeter with an accuracy of ±1.0% rdg. The heater is used to realize the change of inlet air temperature. The test specimen is equipped with several thermocouples (type T, 0.5 mm sheath diameter and exposed tips) and placed in the test section. The thermocouples are calibrated to an accuracy of ±0.5 °C. The signals of thermocouples are recorded using a data acquisition system. The diameter of the test section is 50 mm. The outside of test section is insulated and the pressure drop is measured with a differential pressure transmitter with an uncertainty of ±0.0375% F.S. (Full Span is 0–100 kPa).

The desired volumetric flow rate is firstly obtained by adjusting the control valves. When the flow reaches steady state, the mean temperature measured by the thermocouples located at the inlet and outlet is recorded and used as the initial temperatures of the fluid and solid phases. Then, turn on the air heater. The inlet air