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Research paper

Experimental study of effective thermal conductivity of stainless steel fiber felt

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HIGHLIGHTS

- Matrix conduction, radiation and air convection were in the same order of magnitude.
- Air natural convection was suppressed by reducing operating pressure.
- Intensity of air convection was more sensitive to fiber diameter than porosity.
- Surface area and permeability was comparable in air convection as fiber diameter fixed.
- Interfacial area exerted dominant role in radiation and air convection as porosity fixed.

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ABSTRACT

An experimental apparatus was designed to measure the effective thermal conductivity of porous stainless steel fiber felt under different operating pressures. The total effective thermal conductivity was studied by analyzing matrix heat conduction, air natural convection, and matrix thermal radiation at ambient pressure. The contribution of air natural convection was experimentally obtained by changing the ambient pressure to vacuum condition and the solid matrix heat conduction was evaluated using a theoretical model. The ratios of the three mechanisms to the total effective thermal conductivity were approximately 40%, 37.9%, and 22.1%, respectively. In addition, the effects of fiber diameter and porosity on the three mechanisms and on the total effective thermal conductivity were studied. The air natural convection was found to gradually intensify when the operating pressure increases from vacuum condition (15 Pa) to ambient pressure (1.0×10^5 Pa). With an increase in fiber diameter under fixed porosity, the solid matrix heat conduction remained unchanged, and air natural convection and thermal radiation decreased, thereby resulting in reduced effective thermal conductivity. With an increase in porosity under fixed fiber diameter, the air natural convection was almost unchanged, and solid matrix heat conduction and thermal radiation were reduced, thereby resulting in reduced effective thermal conductivity.

1. Introduction

Porous metallic materials have attracted attention recently in the fields of aerospace transportation system, enhanced heat transfer, infiltration, and energy conservation because of several advantages, including light weight, high thermal conductivity, high mobility of inside fluid, and large interfacial area. A number of experimental, numerical, and theoretical studies have been conducted to characterize the heat transfer mechanisms of the porous material. Lee and Cunnington [1] briefly reviewed the heat transfer of the porous medium and developed the theoretical model for the conduction behavior of solids and gases in fibrous porous material. Phanikumar and Mahaja [2] conducted a numerical and experimental study to present the buoyancy-induced natural convection in metallic foam by adopting the Brinkman–Forchheimer extended flow model and the non-equilibrium energy model. Calmidi and Mahajan [3] explored the forced convection in metal foam within a range of porosities and pore densities. Thermal transport in compact porous media is considered as a complex process because of the inner-connected solid ligaments and multiple heat transfer mechanisms inside the structure. Zhao [4] summarized the thermal transport in high-porosity cellular foam. The terms of effective

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Nomenclature

A	surface area
a_{sf}	interfacial surface area (m^{-1})
d_f	fiber diameter (m)
d_p	pore diameter (m)
d_{eq}	effect pore diameter (m)
H	thickness (m)
h_{sf}	interfacial heat transfer coefficient ($W\ m^{-2}\ K^{-1}$)
K	permeability (m^2)
k	thermal conductivity ($W\ m^{-1}\ K^{-1}$)
k_e	effective thermal conductivity ($W\ m^{-1}\ K^{-1}$)
k_{ce}	contribution of solid matrix to k_e ($W\ m^{-1}\ K^{-1}$)
k_{ne}	contribution of air natural convection to k_e ($W\ m^{-1}\ K^{-1}$)
k_{re}	contribution of thermal radiation to k_e ($W\ m^{-1}\ K^{-1}$)
k_s	thermal conductivity of solid ($W\ m^{-1}\ K^{-1}$)
P	pressure (Pa)
q	heat flux ($W\ m^{-2}$)
Ra, Rb	parameters in Eq. (7)
T	temperature (°C)

Greek symbols

ξ	dimensionless ligament cylinder diameter
ε	porosity
λ	morphology parameter in Eq. (7)

Subscripts

in	insulation material

properties are usually employed to define the thermophysical characteristics of composite medium or a multiphase system. For instance, differing from the term of thermal conductivity which usually defines the conductive capability of single-phase material, the effective thermal conductivity is used to characterize the overall thermal conductivity of constituent phases of the porous material, i.e. solid matrix and internal fluids. In characterizing the thermal transport in porous material, the effective thermal conductivity is considered as the most important thermophysical property of the porous medium.

The most frequently used theoretical model in determining the effective thermal conductivity was derived from the work of Nield [5]. The effective thermal conductivity was calculated as the weighted arithmetic mean of the conductivities of the solid matrix and fluid under the assumption that heat conduction in the solid matrix and fluid occur in parallel. However, the effect of porous structure morphology was not considered. Calmidi [6] simplified the typical cell of metallic foam as a hexagon and the ligament of a cross-section as a square. The analysis of thermal transport inside the cell based on 1D thermal conduction yielded results that had good agreement with the experimental data. Using the work of Calmidi, Bhattacharya et al. [7] developed a similar physical model that presumed a circular shape at the cross section. In addition, Boomsma and Poulikakos [8] made a breakthrough on the calculation model and assumed a 3D tetrakaidecahedron cell; their findings showed good agreement with the findings of Calmidi [6] and accurate characterization of cell morphology.

Porous metallic fiber felt, as one kind of fibrous material, has the combined advantages of high interfacial area and thermal conductivity. The structure of the fiber felt is primarily characterized by two geometric parameters, namely, porosity and fiber diameter. The two parameters exert remarkable influence on the effectiveness of thermal conductivity. However, because of the structural complexity of the fibrous felt material, few models have been proposed to calculate effective thermal conductivity. For the fibrous material, Rayleigh [9] developed an analytical model to determine the effective thermal conductivity of fluid-saturated fibrous mesh. The flow in the typical fibrous mesh structure was simplified as stagnant fluid single-direction flow and the effective thermal conductivity was calculated by assuming the porous material to be isotropic. Li and Peterson [10] proposed an analytical model to predict the effective thermal conductivity of the screen mesh layers; their findings were dependent on the contact conditions, mesh number, and wire diameter. Qu et al. [11] developed an octet-truss lattice model to determine the effective thermal conductivity of fluid-saturated fiber felt with the assumption that the material was isotropic and that the natural convection inside the pores was neglected.

The theoretical models were simple and accurate in calculating the effective thermal conductivity. However, these models were applicable only in cases of ambient temperature and normal ambient pressure. In most thermal conditions, the porous material is exposed to a range of heating power and ambient pressures. Given that the theoretical models not applicable to such various conditions, experimental and numerical methods received further attention. Zhao et al. [12] experimentally studied the with effective thermal conductivities of steel alloy foams within the temperature range of 300–800 K under vacuum and ambient conditions. The results of their experiment indicated that the natural convection of air contributes to effective thermal conductivity. Mendes et al. [13] measured the effective thermal conductivity of fluids-saturated open-celled metal foam using an extremely simplified approach [14]. The experiment and numerical simulations were applied to predict the parameter in the model. The results showed that lower thermal conductivity working fluid was more suitable for determining the model parameter. Li et al. [15] experimentally measured the compressed expanded graphite and paraffin composite in various weight fractions. They also proposed a two-level scale model to compute the thermal conductivity of the composite. The results presented that numerical result agreed well with the measured data and the effective thermal conductivity was enhanced by 41 times compared with pure paraffin. For the porous fibrous material, Zhang et al. [16] built an apparatus to measure the effective thermal conductivity of high-alumina fibrous insulation under a temperature range of 300–973 K under the pressure of 10^{-2}–10^5 Pa. The results indicated that solid conduction and radiation contributions were independent of ambient pressure and that gas conduction increased with pressure. Numerical research [17] was further conducted to understand the conduction and radiation mechanism inside the fibrous insulation material that was formed by randomly-scattered alumina fibers. Wang et al. [18] presented a numerical method to determine the effective thermal conductivity of the general fibrous material using the lattice Boltzmann algorithm. The internal structure of the fibrous material was composed of stochastically generated fibers, and a random generation-growth method was applied to construct the microstructure of fibrous materials based on existing statistical macroscopic geometrical characteristics.

As stated above, a number of thermal conductivity studies have been conducted on porous materials, such as metal foam and fibrous insulation materials. However, few studies have been conducted on the influences of the operating pressure and the contributions of different heat transfer mechanism to effective thermal conductivity of stainless steel fiber felt. The objective of the present study is to establish the experimental setup for investigating the