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Experimental investigation on enhanced thermal performance of staggered tube bundles wrapped with metallic foam

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ABSTRACT

Tube bundles wrapped with metallic foam can be used in air-breathing engine as the compact heat exchanger due to its low density and high specific surface area. The enhanced thermal performance of metallic foam is crucial to design of staggered tube bundles with metallic foam fins. Previous studies have shown the effects of foam-structure on entire metallic foam, and discussed the influence of tube-bundle structure on the tube bundles qualitatively. However, the thermal and flow mechanisms on coupling of metallic foam and pure fluid which could expound enhanced heat transfer process of metallic foam fins are not yet fully explored. To address this, an experimental study was conducted to investigate the effects of structure parameters of metallic foam on thermal and flow characteristics in 2 mm outer-diameter staggered tube bundles wrapped with 2 mm thickness of metallic foam. This article reveals variation trend of heat transfer rate with change of key parameters: porosity and pore density. The results indicate that: 1, with increase of porosity, Nusselt number increases because of stronger penetrating ability, and heat convection dominates the heat transfer. 2, for variation of pore density, Nusselt number of high PPI samples is lower for thermal-insulation effect at low Reynold number. However, Nusselt number of high PPI samples is higher for greater amount of penetrating air at high Reynold number. 3, a new friction factor correlation of tube bundles is proposed to describe the pressure drop by dimensionless tube pitches, Reynolds number and Darcy number with maximum ±20% deviation. 4, a new Nusselt number correlation of tube bundles is given to reflect the heat transfer mechanism by Darcy number.
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1. Introduction

Tube-bundle is one of the simplest and the most effective heat exchanger forms in heat transfer industrial applications [1–11]. For air-breathing engine, high efficiency, light weight, and compactness have been the most important elements of air pre-cooler [11]. Although small diameter tube-bundle exhibits great thermal performance, the mass production of small diameter tube-bundle is confronted with the difficulty of welding and refrigerant leaks. Consequently, the application of new materials has received tremendous attention in the research of heat exchanger field. As a material of low density, high mechanical strength, high stiffness, and large specific surface area, metallic foam is widely utilized in industrial applications, such as heat exchangers, electronic cooling, fuel cells, catalytic reactors, and air coolers. In particular, with high permeability and thermal conductivity, metallic foam has been extensively studied as a means of heat transfer enhancement in recent years [12–24]. But little information on tube bundles wrapped with metallic foam is available. Therefore, it is essential to study the thermal and flow characteristics of tube bundles wrapped with metallic foam to guide the design of heat exchanger for industrial apparatus.

In the literature survey, most of the previous studies [12–21] focused on the thermal and hydrodynamic properties of metallic foam filled channels with different structures. Calmidi and Mahajan [13] and Zhao et al. [14] presented experimental and numerical results for the convection in metallic foam filled plated channels. The former study found that the transport enhancing effect of thermal dispersion depended on the relatively high conductivity of the solid matrix. The latter research revealed that the porosity, pore density, and different materials influence the pressure drop and heat transfer. A previous analytical study by Tamyol and Hooman [15] for metallic foam on the heated plate indicated that forced convection heat transfer coefficient was proportional to the PPI (pore density) and there was a nonlinear relationship between the height of metal foam and the overall heat transfer rate. Kamath [16] conducted a series experiments of the convection heat transfer in a vertical tunnel filled with metallic foam which indicated that metallic foam could enhance heat transfer while increasing

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Nomenclature

A	surface area (m^2),
c_f	inertial factor
c_p	specific heat at constant pressure (J/kg K)
Da	Darcy number
D	outer diameter of the tube (m)
D_{in}	inner diameter of the tube (m)
d_p	mean pore diameter (mm)
f	friction factor
h	average heat transfer coefficient (W/m^2 K)
k	thermal conductivity (W/m K)
K	permeability of the metal foam (m^2)
L	length (m)
N_L	the number of longitudinal tube rows
Nu	Nusselt number
p	pressure (Pa)
PPI	pore density – pores per inch
Pr	Prandtl Number $\mu c_p/k$
Q	heat transfer rate (W)
R_{bond}	bonding resistance (K/W)
R_f	fouling resistance (K/W)
Re	Reynolds number $\rho ud/\mu$
R_{ext}	exterior convective heat transfer resistance (K/W)
R_{int}	interior convective heat transfer resistance (K/W)
R_{tube}	tube wall resistance (K/W)
S_D	dimensionless diagonal tube pitch
S_L	dimensionless longitudinal tube pitch
S_T	dimensionless transversal tube pitch
T	temperature (K)
t_{foam}	thickness of metallic foam layer (m)
u	velocity (m/s)
X_L	longitudinal tube pitch (m)
X_T	transversal tube pitch (m)

Greek letters

ε	porosity
μ	dynamic viscosity (m^2/s)
ρ	density (kg/m^3)
ζ	geometric correction factor

Subscripts

air	air
in	inlet
m	mean value
out	outlet
water	water

the pressure drop in a range of lager Richardson number and Reynolds number simultaneously. Paek [17] experimentally studied the heat-transfer characteristics of aluminium foam and found that the effective heat transfer coefficient become higher with the decrease of the porosity, and it was not changed with the variation of pore diameter at a fixed porosity. Tzeng [18] conducted a further research of aluminium foam and found that the heat-transfer performance had an obvious increase with the decrease of pore diameter or the increase of the pore density. Moreover, the applications of metallic foam were extended based on the properties of metallic foam concluded by former researchers. A series of analytical studies was conducted by Lu and Zhao [19,20] on the applications of tube and tube-in-tube heat exchangers filled with metallic foam. Wang [21] conducted a further study of tube exchanger inserted sintering metallic foam by experimental method, and correlations of friction factor and Nusselt number were developed. These studies investigated thermal and flow characteristics in metallic foam and paid close attention to the heat transfer enhancement of channels filled with metallic foam at the cost of huge pressure drop. From another point of view, the coupling effect of metallic foam and pure fluid is a new research avenue to reduce the pressure drop.

As a consequence, the tube wrapped with metallic foam becomes a new approach to enhance the heat transfer. Odabaee [22] conducted a numerical study to examine the heat transfer from a solid cylinder wrapped metallic foam in a cross-flow. The results illustrated that the maximum heat transfer rate associated with a number of parameters, such as porosity, permeability, effective thermal conductivity of the metallic foam, and thickness of the porous layer. These findings provided suggestions to optimize the trade-off between the heat transfer and increases in the pressure drop. In another numerical simulation, Odabaee [23] investigated the heat transfer performance of a four-row tube bundles wrapped metallic foam and observed that the increase of the tube pitch improves the area goodness factor, and the converse is true for increasing the metallic foam layer thickness. T'Joen [24] conducted an experimental study of a single row heat exchanger covered with metallic foam to determine the thermo-hydraulic performance and found that the air could only penetrate the foam to a certain deepness at a fixed Reynolds number. In addition, the results indicated that a cost-effective and efficient brazing process is required to make metallic foam bond with the tube, and the influences of metallic foam height and tube spacing are discussed. All the previous experimental and numerical works focused on the influence of shape parameters of tube bundles (tube pitch, foam height, tube rows and so on). The thermal and flow mechanisms on the coupling of metallic foam and pure fluid, especially the foam structure, is not yet explored.

In view of the above, the previous studies predominantly focused on the effects of foam-structure properties on entire metallic foam and the influence of tube-bundle structure qualitatively. Few of them is systematically involved with the influence mechanisms of metallic foam structures on thermal and flow characteristics. Especially no attention is paid to the quantitative analysis of pressure drop in tube bundles wrapped with metallic foam. This paper presents an experimental investigation of forced convection of staggered tube bundles wrapped with metallic foam in cross-flow. The overall heat transfer rate and pressure drop of the heat exchanger are determined, and the effects of various parameters, including the Reynolds number, porosity, pore density, and Darcy number are examined. In the end, the friction factor and Nusselt number of tube bundles are discussed, and correlations of the friction factor and Nusselt number are presented for the tube bundles wrapped with metallic foam. The analysis of experimental data indicated the permeability and porosity of the metallic foam affect the heat conduction and the heat convection by the penetrating depth of fluid and the effective conductivity of metallic foam. The porosity and pore density PPI can also affect the permeability of metallic foam. So the influences of metallic foam microstructure on the thermal and flow characteristics are complexly under different conditions.

2. Experimental apparatus

Experiment was conducted in a test rig of an open-circuit wind tunnel with an air-water counter flow, which is schematically

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