Experimental Thermal and Fluid Science 82 (2017) 42–49

Contents lists available at ScienceDirect

Experimental Thermal and Fluid Science

journal homepage: www.elsevier.com/locate/etfs

Experimental heat transfer and pressure drop in a metal-foam-filled tube heat exchanger

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ARTICLE INFO

Article history:
Received 2 March 2016
Received in revised form 26 October 2016
Accepted 28 October 2016
Available online 31 October 2016

Keywords:
Heat transfer coefficient
Metal foam
Single-phase
Mini-tube

ABSTRACT

Heat transfer in small tubes is of particular interest in the heat exchanger industry for manufacturing shell-and-tube or concentric-tube heat exchangers. Metal-foam-filled tubes enhance the heat transfer mechanism by providing a high surface-area-to-volume ratio. This experimental study investigates the heat transfer and pressure drop in such tubes. Single-phase experiments were performed using copper tubes with an inner diameter of 4 mm and filled with copper metal foam. R245fa refrigerant was used as the working fluid with mass flux ranging from 200 to 1000 kg/m^2 s. The heat transfer coefficient and pressure drop data are reported and compared to a tube without metal foam. The experimental data are also compared to well-known correlations from the literature. Most of the correlations are unable to capture any data point since they were developed for much bigger channels. New correlations are proposed to predict the heat transfer coefficient and pressure drop in such small tubes with metal foam inside.

1. Introduction

A heat exchanger is any device that exchanges thermal energy between two media at different temperatures [1]. Devices that use tubes one one side of the heat transfer are of particular interest in manufacturing shell-and-tube, concentric-tube, and tube-and-fin heat exchangers. Many articles going decades back have investigated the thermal and hydraulic characteristics of fluids in such tubes. Recently, Mozafari et al. [2] studied the condensation in helical tube-in-tube heat exchangers. They used R-600a as the working fluid and reported pressure drop and heat transfer coefficient data for different inclination angles. Wang et al. [3] investigated the heat transfer characteristics of a tube bank and compared it to a shell-and-tube heat exchanger. They studied the flow characteristics under different inclination angles of the tubes.

Ho et al. [4] investigated the conjugated heat transfer in concentric-tube heat exchangers under sinusoidal wall fluxes. They analytically studied the Nusselt number for a double-pass heat exchanger and observed some improvements compared to a single-pass heat exchanger. Gomaa et al. [5] experimentally analyzed a triple concentric-tube heat exchanger. They experimented with different configurations such as counter-current and co-current flows with different fluids in triple-tubes, and they compared their experimental data with CFD analysis and double-tube data. They concluded that the triple tube heat exchanger is more effective than the double-tube exchanger. Quadir et al. [6] also investigated a triple-tube heat exchanger.

These studies looked at different aspects of tube heat exchangers and showed some improvements. However, they only cover conventional heat exchangers, for which the thermo-hydraulic behavior can be explained by conventional equations for flow inside empty channels. In contrast, high-porosity open-cell metal foams have been proposed for insertion inside the tubes to increase the heat transfer area between the fluid and solid media to increase the heat transfer coefficient. In some cases, the foams are installed on the outer surface of the tubes to act as a fin system. Metal-foam-filled channels usually have higher single-phase Nusselt numbers and pressure drops compared to empty channels. The thermo-hydraulic correlations for heat transfer and pressure drop differs from those of conventional heat exchangers with empty channels and are usually derived from correlations for porous media.

Due to their porous nature, the thermal conductivity of the metal-foam–fluid system differs from those of the foam and fluid individually. Determining the effective thermal conductivity has been a focus for many researchers. For example, Yao et al. [7] presented a new prediction model based on a tetrakaidecahedron model and considered the ligament orientation. Knowing the effective thermal conductivity is necessary for determining the Nusselt number in metal-foam-filled channels, as are the heat transfer

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http://dx.doi.org/10.1016/j.expthermflusci.2016.10.031
0894-1777/

Nomenclature

Q	heat rate (W)
q	heat flux (W/m^2)
h	enthalpy (kJ/kg)
$\dot{m}$	mass flow rate (kg/s)
v	voltage (V)
I	current (A)
G	mass flux (kg/m^2 s)
d	diameter (m)
μ	viscosity (Pa s)
Re	Reynolds number
Pr	Prandtl number
c_p	specific heat capacity (kJ/kg K)
k	thermal conductivity (W/m K)
T	temperature (°C)
α	heat transfer coefficient (W/m^2 K)
Nu	Nusselt number
L	length (m)
f	friction factor
P	pressure (Pa)
ΔP	Pressure difference (Pa)
V	velocity (m/s)
ε	porosity
PPI	pore density
δ	roughness (m)
ρ	density (kg/m^3)
d_h	metal foam hydraulic diameter (m)
d_f	metal foam strut thickness (m)
d_p	metal foam pore diameter (m)

Subscripts

i	inlet
o	outlet
f	fluid
H	heater
w	wall
MF	metal foam

coefficient and pressure drop data. Mancin et al. [8] experimented with channels filled with 5-PPI (pore per inch) metal foam and reported data for the single-phase heat transfer, two-phase heat transfer, and pressure drop of refrigerants R134a and R1234ze(E).

Most studies on single-phase heat transfer in metal-foam-filled channels used air as the fluid. For example, Sertkaya et al. [9] experimented with aluminum-fin and aluminum-foam heat exchangers using 10, 20, and 30-PPI aluminum foams. They concluded that the heat exchanger effectiveness has an inverse relation with the refrigerant velocity, whereas the pressure drop increases when increasing the velocity. Feng et al. [10] experimented with impinging jet cooling in metal-foam and fin-metal-foam heat sinks using 8-PPI metal foams. They concluded that the heat transfer rate of the fin-metal-foam structure is up to 2.8-times higher than that of the metal-foam-only structure. More recently, Chen and Wang [11] experimented with liquid-cooled metal foam heat sinks. They reported that metal foam excels over conventional heat sinks and that the thermal resistance was reduced by more than 62%.

The thermo-hydraulic characteristics of metal-foam-filled mini-tubes have not been sufficiently investigated. Therefore, this study focuses on an experimental investigation of the single-phase thermal behavior of R245fa refrigerant in a circular tube filled with 20 or 30-PPI metal foam. Heat transfer and pressure drop data are reported and compared with data acquired using empty tubes and with prediction methods from the literature.

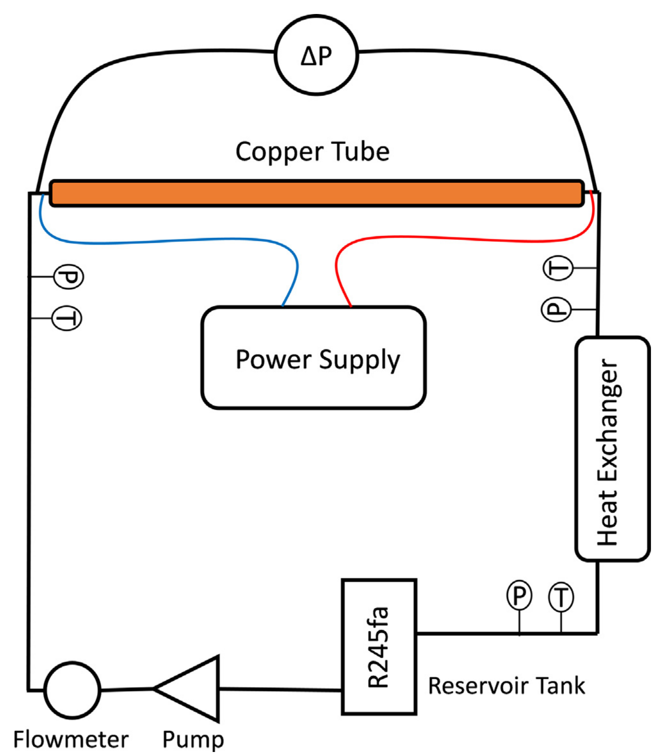

Fig. 1. Diagram of test rig.

2. Experimental apparatus

The experimental setup is shown in Fig. 1. A gear pump is used to deliver R245fa to the test section, and a positive-displacement flowmeter measures the volume flow after the pump. K-type thermocouples and pressure transducers are used right before and after each component so that the flow conditions are always known throughout the test setup. A heat exchanger cools down the refrigerant and returns it to the reservoir tank. The temperature of the refrigerant entering the test section is adjusted by controlling the cooling power of the heat exchanger. The pump then takes the refrigerant from the tank, thus completing one loop.

To apply the heat flux, a tape heater is tightly installed on the test section. The heat flux is controlled by varying the voltage applied to the tape heater, which is measured by a voltmeter. The heater and test section are electrically isolated from the rest of the setup. The pressure drop over the test section is measured separately using an accurate pressure difference transducer located on top of the test section. A data acquisition system is used to gather all the measured data and interfaced with a personal computer for constant monitoring and data storage.

A copper tube with an inner diameter of 4 mm and length of 500 mm is used as the test section. The test section is positioned horizontally and is long enough for the entrance effects to be