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Research Paper

Experimental study on single-phase heat transfer and pressure drop of refrigerants in a plate heat exchanger with metal-foam-filled channels

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HIGHLIGHTS

- Heat exchanger with metal-foam-filled channels is manufactured.
- Single-phase experiments are performed.
- The effect of metal foam configuration and pore density is analyzed.
- With 60 PPI metal foam the overall HTC increased by 5.1 times.
- With 60 PPI metal foam the pressure drop increased by 5.7 times.

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ABSTRACT

Metal-foam-filled channels are proposed to increase the heat transfer area between hot and cold flows in plate heat exchangers. This experimental study focuses on the single-phase heat transfer mechanism of R245fa refrigerant in a metal-foam-filled plate heat exchanger instead of more commonly used air or water in single-phase experiments. The refrigerant-side heat-transfer coefficient and pressure-drop data are reported. Different metal foams with various pore densities of values of 20, 30, and 60 pore per inch (PPI) were examined. Cases were studied with uniform PPI and with two different PPI along the flow direction. A complete heat exchanger test section with an overall volume of 0.001 m^3 that is able to generate 1–2 kW heat duty in this range of experimental conditions is manufactured. The result shows that inserting 60-PPI metal foam increases the refrigerant-side heat transfer coefficient by up to 5.1 times compared to the plate heat exchanger without the metal foam insert. As expected, the pressure drop penalty is huge. The 60-PPI metal foam had the greatest pressure drop, which was 5.7 times that of an empty-channel heat exchanger.

1. Introduction

Heat exchangers have various applications ranging from small-scale heat sinks in electronic cooling to medium-sized heat exchangers in organic Rankine cycles (ORC) and industrial heat exchangers in power plants. Wherever there is a heat source, there is a form of heat exchanger. Compact-sized heat exchangers are especially of interest because they offer high heat duty and take up less space. The last century has seen myriad of new ideas and inventions in heat transfer engineering and energy management related to the size of heat exchangers.

Corrugated plates, twisted tape inserts, integral fins, and dimples are among the enhancements that have proved useful for improving the single-phase heat transfer mechanism in pipe flows. The enhancement ratio of experimental Nusselt numbers over predicted values is 2–4 for an integral finned tube, 1.5–6 for a twisted tape insert, 1.5–4 for a corrugated tube, and 1.5–4 for a dimpled tube [1]. On the other hand, compared to a normal unenhanced tube, the experimental friction factor increases by 1–4 for tubes with integral fins, 2–13 for inserted twisted tape, 2–6 for corrugated tubes, and 3–5 for a dimpled tube.

Plate heat exchangers are mainly appealing because of their compactness. Amalfi and Thome [2,3] studied the single-phase thermal and hydraulic performance of a compact plate heat exchanger. In their experiment, the Reynolds number ranged from 34 to 1615 and the Prandtl number ranged from 4.9 to 6.5. The friction factor was a strong function of the Reynolds number. They performed an infrared temperature measurement to obtain the local heat transfer coefficient. The local Nusselt number was a

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Nomenclature

A	area, m^2
c_p	specific heat capacity, kJ/kg K
D_h	hydraulic diameter, m
d_h	metal foam hydraulic diameter, m
d_f	metal foam strut thickness, m
d_p	metal foam pore diameter, m
f	friction factor
G	mass flux, kg/m^2 s
g	gravitational acceleration, m/s^2
h	enthalpy, kJ/kg
k	thermal conductivity, W/mK
L	length, m
$LMTD$	logarithmic temperature difference, °C
$\dot{m}$	mass flow rate, kg/s
N	plate number
Nu	Nusselt number
P	pressure, Pa
Pr	Prandtl number
$\dot{Q}$	heat rate, W
Re	Reynolds number
T	temperature, °C
U	overall heat transfer coefficient, W/m^2 K
V	velocity, m/s
v_m	mean specific volume, m^3/kg

Greek symbols

α	heat transfer coefficient, W/m^2 K
ΔP	pressure difference, Pa
ε	porosity
ε_0	roughness
μ	viscosity, Pa s
ρ	density, kg/m^3

Subscripts

c	cold side
f	fluid
h	hot side
i	inlet
o	outlet
p	plate
r	refrigerant
w	wall

function of the Reynolds and Prandtl numbers for heat flux ranging from 74 to 3478 W/m^2.

Plates with a rough surface have a higher heat transfer coefficient compared to smooth ones. Nilpueng and Wongwises [4] studied the single-phase heat transfer and pressure drop in plate heat exchangers with rough surfaces. They used water as the working fluid inside the heat exchanger and compared their experimental data with similar plate heat exchangers made with smooth plates. Their experimental Reynolds number was between 1300 and 3200. Increasing the surface roughness resulted in an increase in the heat transfer coefficient by between 4.46% and 17.95%, but it also increased the pressure drop by between 3.90% and 19.24% compared to a smooth surface.

High-porosity open-cell metal foams also improve the heat transfer mechanism in different channel types and various applications. As an example, air-cooled heat sinks could be improved by using metal foam structures or a combination of metal foam and finned structures. Feng et al. [5] investigated these two structures experimentally and numerically using heat sinks under air-jet cooling. They chose aluminum metal foams with more than 96% porosity and 8 pore per inch (PPI). The heat transfer coefficient of the metal foam heat sinks decreased when increasing its height, but it increased for the fin and metal foam structure. The heat transfer of the fin and metal foam structure was 1.5–2.8 times higher than that of the metal foam structure with the same height.

Many studies have looked at single-phase heat transfer in metal-foam-filled channels. Kim et al. [6] studied heat transfer enhancement using aluminum metal foam. Their experimental data show that the pressure drop and Nusselt number are affected by the permeability and porosity. Hamadouche et al. [7] also experimented with aluminum metal foams and investigated the heat transfer and pressure drop mechanism. They reported an increase of up to 300% in the heat transfer coefficient using 40-PPI aluminum metal foam with porosity of 0.93 and air as the fluid compared to an empty channel.

Dyga and Płaczek [8] focused on the effective thermal conductivity of metal foam in a channel and subjected to a fluid flow. They used aluminum foams with air, water, and oil as the fluid. The effective thermal conductivity was strongly dependent on the fluid. In a recent study, Liu et al. [9] conducted an experiment to analyze the convective heat transfer and pressure drop of supercritical CO_2 in metal-foam-filled tubes. They used 20, 40, and 60-PPI metal foams and reported that the heat transfer coefficient decreases at first and then increases with increasing the porosity. The heat transfer coefficient decreased with decreasing PPI. They also measured the pressure drop and reported that the pressure drop increases with decreasing porosity.

Recent numerical studies have used microtomography, X-ray, and computer tomography (CT) scans to make an accurate mesh of the metal foam for computational fluid dynamics analysis. Diani et al. [10] used such techniques to generate a metal foam mesh and simulated the heat transfer of air flow in copper metal foams with different PPI ranging from 5 to 40. They compared their pressure drop and heat transfer simulation results with predicted values obtained by previous correlations and with experimental results. There was good agreement between the experimental data and simulations.

Most single-phase studies in the literature use air or water as the working fluid and only consider an isolated channel with limited heat duty. The single-phase flow of refrigerants in metal-foam-filled channels is particularly of interest in applications where lower pressure drops at higher Nusselt numbers is preferred. Therefore, this study focuses on plate heat exchangers that utilize R245fa refrigerant on the cold side and water on the hot side. A complete compact heat exchanger is manufactured that is able to generate 1–2 kW heat duty in this range of experimental conditions. It has a total of five channels that are filled with metal foam sheets. Experiments were performed with mass flux ranging from 24 to 76 kg/m^2 s and different metal foam configurations with different pore densities of 20, 30, and 60 PPI.

2. Experimental setup

The experimental setup is shown in Fig. 1 and is similar to that used in a previous study [11]. The setup consists of three loops. Hot water is generated in the first loop, which is used on the hot side of