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Flow boiling visualization and heat transfer in metal-foam-filled mini tubes – Part I: Flow pattern map and experimental data

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High-porosity open-cell metal foams are well known to enhance the heat transfer mechanism in rectangular or circular channels. Their high surface area to volume ratio makes them a great candidate for manufacturing high-performance small-scale heat exchangers. This two-part experimental study investigated the two-phase flow boiling inside a circular copper mini tube. In Part I, the flow pattern was visualized by high-speed imaging in glass tubes. Flow pattern maps, the heat transfer coefficient, and pressure drop are presented for mean vapor quality of 0.1–0.7, heat flux of 20–40 kW/m^2, and mass flux of 400–700 kg/m^2 s. The experiments were also performed without the metal foam in the mini tube for comparison to the original data. In this range of experimental conditions, the metal foam increased the heat transfer coefficient up to 3.2 times. Also, as expected, the metal foams adversely affected the pressure drop inside the tubes.

1. Introduction

Enhancing heat transfer has always been a topic of interest for engineers. New technologies are enabling the manufacture of designs that were previously only conceptual, with which comes the need to modify the traditional components of different cycles. The importance of mini-scale heat exchangers has been realized recently after the introduction of new concepts such as mini organic Rankine cycles, mini refrigeration cycles, and electronic cooling devices. One promising method for enhancing the heat transfer mechanism in channels is inserting high-porosity metal foams, which have a high surface area to volume ratio that leads to higher heat transfer area in a very small volume. This allows for compact designs and increases the heat transfer coefficient [1].

The last decade has seen many single-phase and flow boiling experiments with channels that are fully or partially filled with metal foam. Calmidi and Mahajan [2] investigated single-phase forced convection in aluminum metal foams. They used air as the fluid and foams with high porosities of up to 0.97. Their model showed good agreement with experimental results. Mancin et al. [3] performed experiments on convective heat transfer in metal foams with different pore densities ranging from 5 to 40 pores per inch (PPI). They studied the pressure drop and heat transfer coefficient for heat fluxes between 25 and 40 kW/m^2 and compared their data with prediction methods, which showed good agreement. They later performed similar studies for copper metal foams [4].

Lu et al. [5] and Zhao et al. [6] thermally analyzed heat exchangers with metal-foam-filled channels. They used the Brinkman-extended Darcy momentum model and two-equation heat transfer and obtained the velocity and temperature distributions in metal-foam-filled pipes. They concluded that a metal-foam heat exchanger has better thermal performance than a finned tube heat exchanger. Kim et al. [7] presented one of the first experiments for convective heat transfer in metal-foam channels with air flow. Advances in computational fluid dynamics methods and software later enabled new types of simulations. Ranut et al. [8,9] used an accurate microtomography-based CFD method to simulate the heat transfer mechanism in metal foams with air flow. Their X-ray CT method is a powerful tool for capturing the shape of the metal foam and creating an acceptable mesh.

A more interesting aspect of the heat transfer mechanism is the phase changes inside the metal-foam-filled channels. There is competition between nucleate boiling and convective boiling inside the channels on the wall or struts, and different flow patterns occur with the introduction of metal foam. The different pressure field completely changes the heat transfer coefficient compared to empty tubes. Recently, the number of articles regarding the flow boiling in metal foam channels has increased. Diani et al. [10] and Mancin et al. [11] investigated the phase change phenomena of R134a, R1234yf, and R1234ze(E) in a

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Nomenclature

A	area, m^2
A_{total}	total surface area of the metal-foam-filled tube
A_{tube}	surface area of the copper tube
c_p	specific heat, J/kg K
D_h	hydraulic diameter, m
G	mass flux, kg/m^2 s
g	gravitational acceleration, m/s^2
h	enthalpy, kJ/kg
h_{fg}	latent heat of evaporation, J/kg
k	thermal conductivity, W/mK
L	distance, m
M	molecular mass, kg/kmol
$\dot{m}$	mass flow, kg/s
P	pressure, bar
Pr	Prandtl number
P_r	reduced pressure
q	heat flux, kW/m^2
Q	heat, W
Re	reynolds number
T	temperature, K
x	quality

Greek symbols

α	heat transfer coefficient, W/m^2 K
β	pressure drop factor
δ	liquid film thickness, m
ε	void fraction
ε_0	porosity
μ	viscosity, Pa s
ρ	density, kg/m^3
σ	surface tension, N/m

Subscript

Cb	convective boiling
F	friction
H	heater
l	liquid
MF	metal foam
nb	nucleate boiling
pre	preheater
sat	saturation
tp	two phase
v	vapor
w	wall

channel filled with 5-PPI metal foam. The heat transfer was enhanced by up to 4.8 times in their experiments at low mass flux, low heat flux, and high vapor quality. In all cases, the pressure drop increased with the vapor quality or mass flux.

Zhu et al. [12] performed nucleate pool boiling experiments on mixtures of R113 refrigerant and VG68 oil. They used copper foam with 10 and 20 PPI and porosity as high as 0.98. The metal foam cover increases the heat transfer coefficient up to 160% compared to a flat plate, and the addition of oil decreases the heat transfer coefficient by up to 15%. Hu et al. [13] investigated the effect of tube diameter and compared the pressure drop data for 7.9, 13.8, and 26.0-mm tubes. When the tube diameters decreased from 13.8 mm to 7.9 mm with the same PPI, the pressure drop decreased due to the incomplete cells in the metal foam.

Zhu et al. [14,15] visualized the flow boiling of R410A refrigerant inside 7.9-mm glass tubes and presented a flow map based on their data. The enhancement of the heat transfer coefficient by the foam was 50% greater at low mass fluxes than at higher mass fluxes. Slug flow, plug flow, and annular flow were observed in the experiments, and the metal foam promoted the formation of annular flow. This effect was stronger with higher PPI.

The study of flow boiling inside metal-foam-filled tubes is just beginning, and the phenomenon is not fully understood yet. The experimental conditions and thus the validity of the correlations have been limited. Thus, more experimental data are needed to understand the heat transfer mechanism inside such tubes. Therefore, the focus of this study is the flow boiling of refrigerants in small tubes at medium mass fluxes. Part I of this experimental study looks at the flow boiling of R245fa refrigerant inside a 4-mm copper tube filled with 20-PPI and 30-PPI copper metal foam. The flow patterns were visualized inside identical glass tubes by high-speed imaging. The mass flux ranges from 400 to 700 kg/m^2 s, and the maximum heat flux is 40 kW/m^2. The mean vapor quality ranges from 0.1 to 0.7, and the experiments were performed at the saturation temperature of about 62.75 °C. Experiments were performed under the same experimental conditions using tubes without metal foam for comparison and to understand the effect of the foams. In Part II [16], the experimental data are compared to previous correlations, and new predictive correlations are proposed for the heat transfer coefficient and pressure drop.

2. Test rig

2.1. Cycle

A closed loop was prepared for the experiment, as shown in Fig. 1. The main part of the loop is a refrigerant cycle where a 170-W gear pump is used to deliver refrigerant to the test section. A positive-displacement flow meter is installed after the pump. The volume of flow entering the test section is controlled by adjusting the pump frequency. The pump speed is adjustable from 0 to 3600 RPM corresponding to 0–4 LPM.

Before the test section is a preheating section. The inlet quality of the refrigerant entering the test section is controlled at the preheater, which is a long electrically heated copper tube (through the Joule effect). The heater and preheater are electrically isolated from

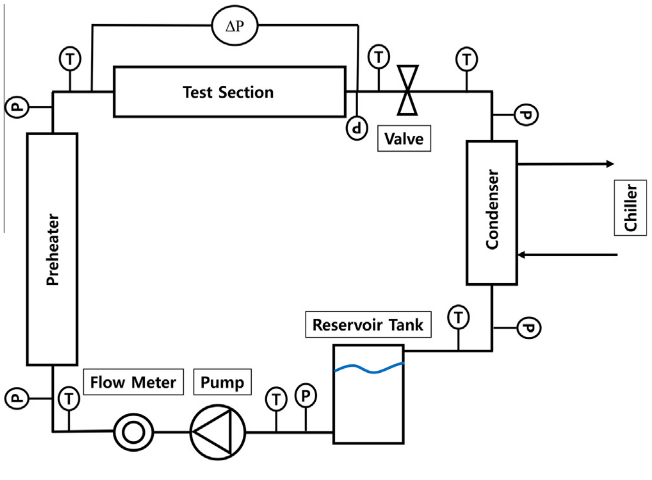

Fig. 1. Diagram of experimental loop.

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