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Flow boiling visualization and heat transfer in metal-foam-filled mini tubes – Part II: Developing predictive methods for heat transfer coefficient and pressure drop

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High-porosity metal foams are proposed for insertion into heat exchanger channels to enhance the heat transfer mechanism in evaporators that are mainly used in organic Rankine cycle applications. This two-part experimental study investigates the two-phase flow inside a circular copper mini tube. Part I visualized the flow pattern and presented flow pattern maps, heat transfer coefficient data, and pressure drop data. Part II compares experimental data to recent correlations developed for metal-foam-filled mini tubes. The experimental conditions of the present study fall outside the valid range of the correlations, so none of them can predict the heat transfer coefficient or pressure drop accurately. Therefore, both the heat transfer coefficient and pressure drop are correlated using new approaches based on previous works and the present experimental data. Good agreement is observed between the experimental data and the new correlations in these experimental conditions.

1. Introduction

Heat exchangers play an undeniably large role in refrigeration and power generation cycles. Single-phase and two-phase heat transfer in heat exchangers have always been treated as important issues. High-porosity metal foams have high surface area to volume ratio and are proposed for insertion into heat exchanger channels to improve the heat transfer coefficient and overall heat transfer mechanism of evaporators and condensers while maintaining small size. Many experiments have been performed on metal-foam-filled channels, and many more numerical simulations have been conducted, especially in the last decade. However, there is no reliable correlation for predicting the heat transfer coefficient and pressure drop in metal-foam-filled tubes in a wide range of experimental conditions.

Single-phase flow has gained more attention because of its simplicity for developing a predictive correlation. Calmidi and Mahajan [1], Mancin et al. [2,3], and Kim et al. [4] investigated single-phase forced convection in aluminum and copper 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 a range of heat and mass fluxes and compared their data with prediction methods, showing good agreement.

Two-phase flow inside metal-foam-filled channels has been studied experimentally by many others recently. Diani et al. [5] and Mancin et al. [6] investigated the flow boiling of R134a, R1234yf, and R1234ze(E) in 5-*PPI* metal-foam-filled channels but did not propose any predictive correlation for their data. Zhu et al. [7] extended previous pool boiling experiments to flow boiling heat transfer in 5 and 10-*PPI* metal foams and reported an enhancement factor of up to 185% for metal-foam-filled tubes in comparison to empty tubes. They proposed a correlation that captured 98% of their experimental heat transfer coefficient data with ±30% deviation.

Zhu et al. [8] found similar results for higher mass fluxes and observed an enhancement of up to 220% in the heat transfer coefficient. They reported that the heat transfer coefficient decreased with increasing vapor quality at low mass fluxes, but it increased with vapor quality at high mass fluxes. Compared to an empty tube, metal foam has been reported to promote the annular flow and change the flow pattern from stratified to stratified-wavy and from stratified-wavy to annular. Hu et al. [9] compared their pressure drop data for inner diameters of 7.9, 13.8, and 26.0 mm with some correlations and proposed a new correlation for predicting the pressure drop inside metal-foam-filled tubes. Zhu et al. [10,11] proposed a correlation for the heat transfer coefficient based on the flow pattern map and data acquired from the flow visualization.

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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/m K
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

This short review along with that in Part I [12] of this article list the most influential recent studies regarding metal-foam-filled channels. Although many experimental studies have been conducted, there is still a knowledge gap in this field. The predictive correlations for two-phase heat transfer in metal-foam-filled channels are not universal, and the experiments cover limited conditions. 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. In Part I, the flow pattern was visualized and experimental data was presented. In Part II, predictive correlations are proposed based on the experimental data at mass flux of 400–700 kg/m^2 s and heat flux of 20–40 kW/m^2. The inlet quality ranges from 0.1 to 0.7, and the saturation temperature is about 62.75 °C. Original experimental data for metal-foam-filled tubes and an empty tube have been used to develop the correlations.

2. Test rig

A closed loop was prepared for this experiment. The experimental setup is explained in detail in Figs. 1 and 2 in Part I of this article [12]. Before the test section is a preheating section where the inlet quality of the refrigerant entering the test section is controlled by adjusting the voltage input of the preheater. The test section for this experiment is a copper tube with an inner diameter of 4 mm and outer diameter of 6 mm. This section is followed by a quartz glass tube with the same size as the copper tube.

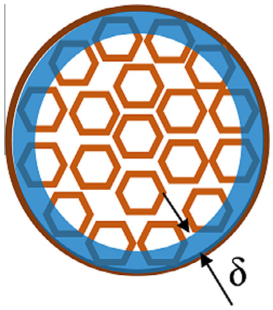

Fig. 1. Cross-sectional view of metal-foam-filled tube showing the liquid film thickness with a dry angle of zero.

There are four thermocouples installed on the outer surface of the copper tube at every 50 mm. A tape heater is tightly installed on the copper tube, and the whole system is thermally insulated by wool glass insulation around the tube. The heat flux is controlled by the voltage applied to the tape heater. Copper metal foams with porosity of 0.9 and 20 and 30 *PPI* were prepared. The working fluid in this experiment was R245fa refrigerant, which have been studied extensively in previous flow boiling experiments and organic Rankine cycle applications [13–15].

3. Results and discussion

The experimental data presented in Part I are compared to predictive correlations from the literature. Heat transfer coefficient and pressure drop data for metal-foam-filled tubes and an empty tube have been calculated based on original experiments. The experimental conditions of this study are listed in Table 1.

3.1. Heat transfer coefficient predictive correlations

3.1.1. Comparison of the experimental results to existing correlations

There are only a few studies on prediction methods for the two-phase heat transfer coefficient in metal-foam-filled tubes. Presently, there is only one approach for predicting the heat transfer coefficient in metal-foam-filled tubes with pure refrigerants [7,10,11]. This method is based on the dry angle θ_{dry} obtained from visualization and flow pattern maps and on the improvement factor IF [7,8,11]. In this approach, the heat transfer coefficient of the metal-foam-filled tube is predicted by first predicting the heat transfer coefficient of the refrigerant in an empty tube and then multiplying it by the predicted improvement factor [11]:

$$\alpha_{MF} = IF \times \alpha_{Empty} \tag{1}$$

It is crucial to predict the heat transfer coefficient of the empty tube accurately to decrease the error by further introducing the IF into the equation.

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