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Flow boiling of refrigerant in horizontal metal-foam filled tubes: Part 2 – A flow-pattern based prediction method for heat transfer

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ABSTRACT

For enriching the heat transfer coefficient database of refrigerants flow boiling in metal-foam filled tubes, the heat transfer characteristics of two-phase flow in horizontal metal-foam filled tubes were investigated for flows in small diameter tubes and at higher mass fluxes. The results show that the heat transfer enhancement due to metal foam at lower mass fluxes is about 50% greater than that at higher mass fluxes. A flow pattern based prediction method was developed for a much wider range of working conditions than previous ones. The influence of the metal foam on the flow pattern and heat transfer area increase is both considered in the new prediction method. The heat transfer coefficients predicted by the correlation agree well with experimental data from the present and previous studies.

1. Introduction

In the past decade, flows through open-cell metal foams have been extensively investigated for thermal management applications. Due to their huge specific surface area, metal foams provide large contact surface area with the fluid. Most previous studies have focused on electronic cooling applications where a large amount of heat needs to be dissipated over a small volume [11]. In recent years, the growing demand for higher efficiencies in refrigeration systems has let to attempts to insert metal foams into heat exchanger tubes to improve the flow boiling heat transfer of refrigerants [13,15,16]. Excellent heat transfer enhancement has been obtained which indicates the potentials for metal-foam filled tubes in heat exchangers in refrigeration systems.

Heat exchanger design and optimization need detailed heat transfer characteristics of the refrigerant flow boiling inside the tubes for common refrigeration working conditions. Conventional refrigeration systems normally use 5–10 mm diameter tubes are widely used in the heat exchangers, with refrigerant mass fluxes in the tubes of up to 300 kg m^{-2} s^{-1} or more. However, previous research on refrigerant flow boiling heat transfer in metal-foam filled tubes has focused on larger diameter tubes (13.8–26 mm) and lower mass fluxes (up to 106 kg m^{-2} s^{-1}). Zhao et al. [13] experimentally investigated the heat transfer characteristics of R134a flow boiling inside metal-foam filled tubes with a 26 mm tube diameter and filled with 20 or 40 PPI copper foams and mass fluxes up to 106 kg m^{-2} s^{-1}. Zhu et al. [15,16] experimentally investigated the heat transfer characteristics of R410A–oil mixtures for flow boiling inside metal-foam filled tubes. The tube diameters were 23.4 and 13.8 mm and were filled with 5 or 10 PPI copper foams with mass fluxes up to 90 kg m^{-2} s^{-1}. These studies showed that the metal foams enhanced the flow boiling heat transfer by increasing the heat transfer area and promoting the formation of annular [16]. For smaller diameter tubes, the increased ratios of heat transfer area by metal foam are smaller, resulting in the weak effect of the heat transfer enhancement by metal foam. Moreover, at higher mass fluxes, the flow patterns in both metal-foam and smooth tubes are annular flow, resulting in the weak effect of the flow patterns on the heat transfer. Therefore, the heat transfer enhancement due to metal foams is less for refrigerant flow boiling in smaller diameter tubes at higher mass fluxes.

The design and optimization of heat exchangers using metal-foam filled tubes need a method to predict the local flow boiling heat transfer coefficients. The method should cover a wide range of working conditions, including the tube diameters and mass fluxes. Such goal has been achieved for flow boiling heat transfer predictions in plain tubes without metal foams inside. Abundant experimental data for plain tubes [4,5,9] was used to develop a flow pattern based phenomenological model for predicting the flow boiling heat transfer coefficients for all macro-scale tubes because of the similar flow and heat transfer mechanisms [10]. However, a universal heat transfer model is difficult to develop for metal-foam filled tubes due to the many geometric structural parameters of the metal foams which influence the

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two-phase flow and heat transfer in different ways. The metal foam promotes the formation of annular flow as the structure pushes the liquid towards the tube wall [13]. Metal foams with more fibers have stronger effect on the liquid and vapor flow, resulting in the formation of annular flow at lower vapor qualities and lower mass fluxes. Therefore, how to reflect various the influences of metal foams on the flow boiling heat transfer in one universal model is a challenge.

The present investigation considers two aspects needed to utilize metal-foam filled tubes in refrigeration systems. Firstly, enriching the database of flow boiling heat transfer coefficient in metal-foam filled tubes, especially for smaller diameter tubes and higher mass fluxes. Secondly, developing a general method for correlating all the heat transfer coefficients of pure refrigerant flow boiling in metal-foam filled tubes for a wide range of working conditions.

2. Previous studies of flow boiling heat transfer characteristics in metal-foam tubes

In order to develop a prediction method for heat transfer coefficients of refrigerant flow boiling in metal-foam filled tubes, a heat transfer coefficient database that covers common refrigeration working conditions should be firstly established.

The existing research on the heat transfer characteristics of refrigerant flow boiling in metal-foam filled tubes is summarized in Table 1. Two conditions should be extended to cover common refrigeration working conditions: tube diameter and refrigerant mass flux. The tube diameters in the existing studies are from 13.8 to 26 mm, while refrigeration systems often have tubes with diameters smaller than 10 mm. In addition, the refrigerant mass fluxes in the existing studies are from 10 to 106 kg m^{-2} s^{-1}, while the refrigerant mass fluxes in refrigeration systems are usually as high as 300 kg m^{-2} s^{-1} or higher.

The supplementary experiments conducted in the present study cover the working conditions of the tube diameters smaller than 10 mm and mass fluxes up to 300 kg m^{-2} s^{-1}, as also shown in detail in Table 1.

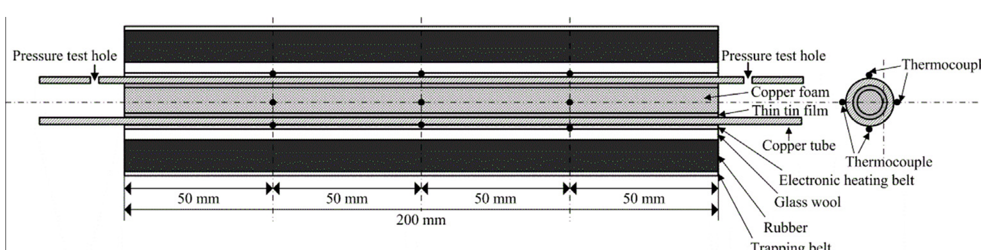
3. Experiments on flow boiling heat transfer characteristics in small diameter metal-foam tubes

3.1. Test sections and working conditions

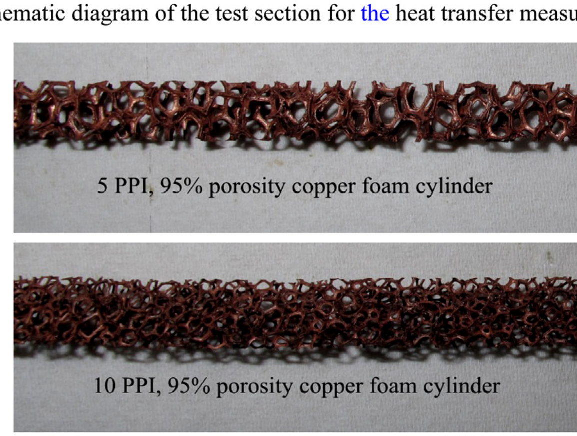
The test sections were 7.9 mm inner diameter horizontal tubes fully filled with 5 or 10 PPI copper foams (the specifications are listed in Table 1 in Part 1), their outside walls were tightly bound with electrical heating tapes for heating, as well as glass wool and double layers of rubber foam for reducing heat losses to the surroundings, as shown in Fig. 1a. The heat fluxes into the test sections were varied by adjusting the input power to electrical heating tapes, and tube wall temperatures were measured by

Table 1
Previous studies of the heat transfer for refrigerant flow boiling in horizontal metal-foam circular tubes for refrigeration applications.

Reference	Diameter (mm)	PPI	Refrigerant	Mass flux (kg m^{-2} s^{-1})	Heat flux (kW m^{-2})	Vapor quality
Zhao et al. [13]	26	20, 40	R134a	26–106	9–18	0–0.9
Lu and Zhao [7]	26	20, 40	R134a	26–106	9–350	0.1–0.8
Zhu et al. [15]	23.4	5, 10	R410A	10–30	3.1–9.3	0.2–0.8
Zhu et al. [16]	13.8, 23.4	5, 10	R410A	10–90	3.1–18.3	0.2–0.8
This work	7.9	5, 10	R410A	90–270	6.3–18.9	0.2–0.8



(a) Schematic diagram of the test section for the heat transfer measurements



(b) Copper foam cylinder photos

Fig. 1. Heat transfer measurement test sections.