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Experimental investigation on flow condensation in horizontal tubes filled with annular metal foam

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ABSTRACT

This work studies the heat transfer and pressure drop of water vapor flow condensation in horizontal tubes filled with annular metal foam of three different sizes (10, 15 and 20 PPI). The range of vapor mass flow rate is 20–100 kg/h and cooling water flow rate is 1–3 m^3/h. The flow condensation characteristic in metal foam tubes is presented and compared with corresponding micro-fin tubes by using unit mass efficiency coefficient method. The effects of metal foam size, inlet vapor pressure, vapor mass flow rate, and cooling water temperature on heat transfer and pressure drop are examined and analyzed. Heat transfer and pressure drop correlations for horizontal tubes with annular metal foam are obtained by curve-fitting of the experimental values. The results indicate that the introduction of metal foam enhances the heat transfer although resulting in a larger pressure drop. Metal foam of 10 PPI size exhibits the superior performance. The average heat transfer coefficient is also observed to increase with higher inlet vapor pressure, higher vapor mass flow rate and higher cooling water temperature.

1. Introduction

Heat transfer enhancement for HVAC&R applications has always been a topic of interest for engineers. The most common way of achieving such enhancement is by increasing the heat transfer area [1,2]. Although fins were the commonly employed for increased area, metal foams were considered to have greater advantage from an enhanced heat transfer-area perspective. Due to the high surface area to volume ratio, high thermal conductivity, and strong flow-mixing capability, metal foams were regarded as one of the most promising materials for high performance compact heat exchangers [3,4].

Prior work on heat transfer of metal foam was mainly focused on single-phase convective heat transfer. Calmidi et al. [5], Kim et al. [6] and Mancin et al. [7,8] investigated convective heat transfer and pressure drop performance of copper and aluminum metal foams in air flow condition. They developed new correlations according to experimental values. Wang et al. [9] investigated air flow heat transfer in metal-foam tubes. They found Nusselt number was depended on air flow velocity and increased with the increase of the pore density of metal foam. Du et al. [10] applied two-equation numerical model to study the conjugated heat transfer in double-pipe filled with metal foam. The model could effectively display the real physical heat transfer process. The study of single-phase convective heat transfer in metal foam revealed that metal foam significantly improves heat transfer efficiency. The study of heat transfer in the two-phase flow of metal foam was mostly focused on flow boiling heat transfer. Diani et al. [11] and Mancin et al. [12] investigated flow boiling heat transfer in tubes with 5 PPI metal foam. Zhao et al. [13] investigated the flow boiling heat transfer in horizontal tubes filled with metal foam. They found that the heat transfer was nearly doubled when decreasing the cell size from 20 PPI to 40 PPI at the same porosity. Abadi et al. [14–15] performed experiments on the flow boiling inside a circular copper mini tube. The flow pattern was visualized through glass tubes. They proposed correlations on heat transfer coefficient and pressure drop based on previous works and experimental data. For flow boiling heat transfer, the heat transfer coefficient increased significantly due to the existence of metal foam.

In comparison to single-phase heat transfer in metal foam, there is relatively few published research on the flow condensation heat transfer in metal foam. During flow condensation heat transfer, the heat transfer resistance increases with the generation of condensate liquid. In order to reduce the film thickness and increase the heat transfer surface area, many scholars investigated flow condensation in micro-fin tubes and helically dimpled tubes etc. Hartnett et al. [16] investigated the two-phase heat transfer coefficients of HFC-134a flow condensation in smooth and

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Nomenclature

A	area, m^2
a_{sf}	metal foam specific surface area, m^2/m^3
c	specific heat capacity, J/kg·K
d	internal diameter of tube, m
d_w	average window diameter of metal foam, m
G	vapor mass flow rate, kg/h
h	average heat transfer coefficient, $W/m^2 \cdot K$
h_{fg}	latent heat, J/kg
h_n	local heat transfer coefficient, $W/m^2 \cdot K$
h_o	smooth pipe heat transfer coefficient, $W/m^2 \cdot K$
L	Total length of experimental section, m
l_n	distance from the entrance of experiment section,m
m	mass flow rate, kg/s
M	weight, g
Nu	Nusselt number
PPI	pores per inch
Pr	Prandtl number
ΔP	pressure drop, Pa
$\Delta P_{r,L}$	theoretical pressure drop, Pa
Q	heat transfer rate, W
q	heat flux, W/m^2
Re	Reynolds number
T_c	average cooling water temperature, °C
T_{ci}	inlet cooling water temperature, °C
T_{co}	outlet cooling water temperature, °C
T_v	vapor temperature, °C
T_{vn}	local vapor temperature, °C
T_{wn}	local wall temperature, °C
T_w	average wall temperature, °C
V	vapor flow rate, m/s
x	vapor quality

Greek symbols

α	metal foam influence coefficient
β	heat balance error
ρ	density, kg/m^3
ε	porosity
θ	thickness of metal foam
Φ	pressure drop multiplier
μ	dynamic viscosity, Pa·s
η_h	mass efficiency coefficient of heat transfer
η_p	mass efficiency coefficient of pressure drop

Subscripts

c	cooling water
i	inlet
o	outlet
v	vapor
l	liquid
w	wall
f	metal foam
$smooth$	smooth tube
z	metal foam/micro-fin

micro-fin tubes. The fin height was 0.2 mm and the diameter of tube was 9.52 mm. They found that the average heat transfer coefficient of micro-fin tube was 10–85% higher than that of smooth tube. Miyara et al. [17] investigated the flow condensation heat transfer and pressure drop in herringbone micro-fin tubes. They found that heat transfer coefficient was about 2–4 times higher than that of the helical micro-fin tube. However the pressure drop increased with the fin height. Sarmadian et al. [18] conducted experiments on flow condensation heat transfer in helically dimpled tubes. The heat transfer coefficient of dimpled tube was 1.2–2 times of the corresponding smooth tube. Moreover they found the best vapor quality for increasing heat transfer coefficients. Micro-fin and helically dimpled tubes can significantly improve the performance of flow condensation heat transfer.

Metal foam has great potential in strengthening condensation heat transfer due to complex foam matrix and high specific surface area. Ribeiro et al. [19] compared metal foam with louvered fins in miniaturized condensers. Hu et al. [20] investigated the wet air flow condensation in metal foam tube and compared with louvered fin-and-tube. They found that the flow condensation heat transfer characteristic in metal foam tubes was superior to that in louvered fin tubes. This enhancement in heat transfer may be attributed to the increase in the effective heat transfer area. Xie et al. [21] studied on condensation heat transfer in tubes with and without lyophilic porous-membrane-tube insert. They found the heat transfer coefficient of modulated heat transfer tube was about 1.85 times compared to the corresponding smooth tube. Xu et al. [22] investigated condensation heat transfer and pressure drop performance of 40 PPI annular metal foam tube. They analyzed the effects of mass flow rate and vapor quality on the condensation heat transfer. Flow pattern was predicted by wall temperature distribution and fluctuation. However, effects of metal foam structures, vapor pressure and cooling water temperature were not discussed in detail.

In summary, a majority of investigations on metal foam are on single-phase or boiling enhancing heat transfer. Comparatively, only a few research work on flow condensation heat transfer has been reported. Therefore the purpose of this paper is (i) to experimentally investigate heat transfer and pressure drop performance of horizontal tubes filled with annular metal foam, (ii) to analyze flow pattern by wall temperature distribution and fluctuation, (iii) to develop new correlations by curve-fitting of the experimental data, (iv) to find metal foam heat transfer potential application by comparing with micro-fin.

2. Design of experiment

2.1. Experimental system

The schematic of the experimental system is shown in Fig.1(a). Water is used as working fluid in this study. The saturated vapor is produced by boiler. The water vapor flows through the condensate tube. At the inlet of the condensate tube, the water vapor is at saturated state. In the condensate tube, the water vapor condensates by the cooling water. Fig.1(b) is the p - h diagram of working fluid in the condensate tube.

The experimental section is a horizontal double-tube heat exchanger with effective length of 1 m. The inner tube (condensate tube) is made of copper, which has a diameter of 22 mm. The schematic of condensate tube is shown in Fig. 2. The thickness of metal foam is 2 mm. The metal foam is made of copper with porosity of 90%. The PPI value is 10, 15, and 20 respectively. The thermocouples are welded in groove on the surface of condensate tube with spacing of 100 mm.

The vortex flow meter is used to measure vapor mass flow rate. The quartz glass tube is installed at the inlet and outlet of the condenser tube to observe the flow pattern. Differential pressure transmitter is used to measure pressure difference between the