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Effect of porosity on heat transfer and pressure drop characteristics of wet air in hydrophobic metal foam under dehumidifying conditions

Zhancheng Lai, Haitao Hu*, Guoliang Ding

Institute of Refrigeration and Cryogenics, Shanghai Jiao Tong University, Shanghai 200240, China

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ABSTRACT

In order to evaluate the performance of the hydrophobic metal foam heat exchangers under dehumidifying conditions, the effect of porosity on the heat transfer and pressure drop characteristics of wet air in hydrophobic metal foam was experimentally investigated and compared with that in uncoated ones. The test results show that, as the porosity decreases from 95% to 85%, the heat transfer coefficient and pressure drop in hydrophobic metal foams are increased by 6%–18% and 56%–162%, respectively. The heat transfer coefficient of wet air in metal foams is increased by the hydrophobic coating at most experimental conditions except for the porosity of 85% and relative humidity of 70%–90%, and the maximum increment is 33%. The pressure drop of wet air in hydrophobic metal foams is 3%–139% larger than that in uncoated ones. The comprehensive performance of hydrophobic metal foam is better than that of uncoated foams at porosity of 95% and relative humidity of 30%–50%, and it becomes worse than that of uncoated ones with the decreasing porosity and increasing relative humidity.

1. Introduction

In the air conditioning system, the evaporator mostly operates under dehumidifying conditions. Metal foam has great advantages of high thermal conductivity and large specific surface area [1–3], and it provide 56%–196% higher heat transfer capacity compared with the conventional fins [4,5]; therefore, metal foam has shown a great potential in the heat transfer enhancement under dehumidifying conditions. During the dehumidifying process, the water vapor in wet air would condense on the cold surface of metal fibers, and the condensate droplets could be accumulated in the metal foams, which may block the flow path of wet air and occupy the heat transfer area in metal foams. To reduce the negative effect of accumulated condensate, the hydrophobic coating on metal foam can be used for promoting the drainage of condensate [6–10], and may have a great potential for enhancing the heat transfer under dehumidifying conditions. In order to optimize the hydrophobic metal foam heat exchangers, the influence of metal foam structure on the heat transfer and pressure drop characteristics of wet air in the hydrophobic metal foam must be experimentally investigated.

Among the influencing factors, the porosity has a great effect on the heat transfer and pressure drop performance of metal foam [11–14]. As the porosity decreases, the specific heat transfer area of metal foam and the condensate sites on fiber surface are increased [11–14], but the drainage of the condensate under dehumidifying conditions is deteriorated [6], leading to the increment of pressure drop and the decrement of heat transfer coefficient [15–17]. The existing researches for the effect of porosity only focus on the dry air flow convection [11–14] and solid-liquid two phase flow [18], and there is no published paper on the hydrophobic metal foam. The existing research results show that, for the dry air flow convection, both the heat transfer coefficient and pressure drop increase with the decreasing porosity due to the thicker fibers with smaller thermal resistance and larger flow resistance [11–14], and the optimal porosity based on the balance between pressure drop and heat transfer varies from 0.85 to 0.95 [11]; for the two-phase flow, the increment of porosity improves the heat transfer performance and shorten the completely melted time, but it has no negative effect on solidification [18]. However, for the wet air in hydrophobic metal foam, the water vapor in wet air would condense on the cold surface of metal fibers, and the accumulated condensate may occupy the heat transfer area and block the flow path, resulting in a significant effect on the heat transfer and pressure drop characteristics. It can be imaged that, due to the effect of accumulated condensate, the effect of porosity on the heat transfer and pressure drop characteristics must be different from that for dry air flow and solid-liquid two phase flow, and should be investigated.

For the heat transfer and pressure drop characteristics of wet air in metal foam under dehumidifying conditions, the existing research is focused on the influence of experimental conditions [4,19], and there is

* Corresponding author.
E-mail address: huhaitao2001@sjtu.edu.cn (H. Hu).

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Nomenclature

A	area (m^2)
b	slope of saturated enthalpy line ($kJ{\cdot}kg^{-1}{\cdot}K^{-1}$)
Cp	specific heat at constant pressure ($kJ{\cdot}kg^{-1}{\cdot}K^{-1}$)
D	hydraulic diameter (m)
F	flow configuration factor, non-dimensional
f	friction factor, non-dimensional
h	heat transfer coefficient ($W{\cdot}m^{-2}{\cdot}K^{-1}$)
HA	heat transfer coefficient based upon enthalpy difference ($kg{\cdot}s^{-1}$)
i	enthalpy ($kJ{\cdot}kg^{-1}$)
IF	influence factor, non-dimensional
j	Colburn j factor, non-dimensional
k	thermal conductivity ($W{\cdot}m{\cdot}K^{-1}$)
L	length (m)
m	mass transfer rate ($kg{\cdot}s^{-1}$)
Nu	Nusselt number, non-dimensional
PPI	number of pores per inch
Pr	Prandtl number, non-dimensional
Δp	pressure drop (Pa)
Q	heat transfer rate (W)
Re	Reynolds number, non-dimensional
T	temperature (K)
ΔT	temperature difference (K)
u	velocity ($m{\cdot}s^{-1}$)

Greek symbols

δ	copper plate thickness (m)
ρ	density ($kg{\cdot}m^{-3}$)
ε	porosity of the metal foam

Subscripts

a	air
c	copper
w	water
v	vapor
in	inlet
out	outlet
LM	logarithmic mean
s	saturated
dehumid	dehumidified water

no published paper on the influence of porosity for hydrophobic metal foam. The results on the influence of experimental conditions show that, the total heat transfer rate in metal foam increases with inlet air humidity and temperature [4]; the heat transfer coefficient increases with increasing face velocity [19]. However, the existing research was conducted with only one certain porosity, and the influence of porosity on the heat transfer and pressure drop characteristics of wet air in metal foams was not revealed.

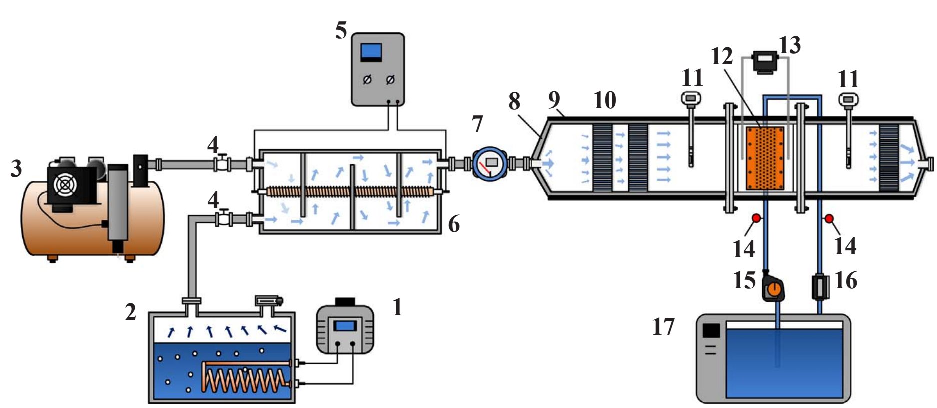
For the wet air in heat exchangers with hydrophobic coating, the existing research mainly focuses on the traditional fin-and-tube heat exchangers, and there is no reported research on the metal foam heat exchangers. The experimental results on the hydrophobic fin-and-tube heat exchangers under dehumidifying conditions show that, the hydrophobic coating on fin surface is effective to enhance the dropwise condensation [20–24] and can increase the heat transfer coefficient and pressure drop by 25% and 43%, respectively [7,9,10,25–27]. However, for the metal foam heat exchangers, the condensate droplets formed on the fiber surface may remain or roll down, and some droplets could accumulate on the nodes of the interconnecting fibers, leading to the different heat transfer and condensate characteristics from that on the traditional fins [4]. Therefore, the existing researches for fin-and-tube heat exchangers cannot be extended to metal foams.

The purpose of the present study is to experimentally investigate the heat transfer and pressure drop characteristics of wet air in hydrophobic metal foams under dehumidifying conditions, and to analyze the influence of porosity on the performance of metal foams.

2. Design of experiment

2.1. Experimental apparatus

The experimental apparatus for investigating the heat transfer and pressure drop characteristic of wet air in hydrophobic metal foams consists of wet air side system, cooling water system and data acquisition system, as shown in Fig. 1. The experimental apparatus was introduced in detail in the literature [4] (see Fig. 2).



1 Power regulator 2 Humidifier 3 Air compressor 4 Valve
5 PID controller cabinet 6 Air conditioner box 7 Volume flow meter
8 Wind tunnel 9 Thermal insulation foam 10 Air deflector
11 Temperature and humidity transducer 12 Test sample
13 Differential pressure transducer 14 Thermocouple 15 Micro water pump
16 Magnetic flow meter 17 Thermostatic water tank

Fig. 1. Schematic diagram of experimental rig.