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Experimental investigation on water drainage characteristics of open-cell metal foams with different wettabilities

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ABSTRACT

For optimizing the metal foam heat exchangers used in dehumidification apparatus, the influence of surface wettability on drainage characteristics should be explicit. In the present study, the water drainage characteristics of metal foams with different wettabilities were experimentally investigated. The experimental results show that the stabilization time of the water drainage process for the hydrophobic sample is the shortest among the tested metal foam samples, and the water retention mass in the hydrophobic metal foam is much smaller than that in the other samples; the wettability impact factors for water retention are within 0.78–1.1 and 0.40–0.77 for the hydrophilic and hydrophobic samples, respectively. The water retention mass in the copper foam is 9.5%–52.6% smaller than that in the aluminum foam. For the hydrophobic copper foam, the water retention mass per unit volume in metal foams with PPI of 5–20 is 45%–66% smaller than that in fin–tube heat exchangers.

Étude expérimentale sur les caractéristiques de drainage de l'eau des mousses métalliques à cellules ouvertes à différents niveaux de mouillabilité

Mots clés : Caractéristiques de drainage ; Déshumidification ; Hydrophile ; Hydrophobe ; Mousse métallique ; Mouillabilité

1. Introduction

Open-cell metal foam is one kind of porous media with high porosity, low weight, high effective thermal conductivity and high specific surface area, and is currently regarded as a highly promising material for constructing compact heat exchangers (Muley et al., 2012; Qu et al., 2014; Zhao, 2012). Using metal foam to replace the conventional fins in the heat exchanger would enhance the air side heat transfer characteristics under

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Nomenclature

h	height [mm]
M_1	mass of metal foam [kg]
M_2	mass of metal foam with retained water [kg]
M_{ret}	water retention per unit volume [kg m^{-3}]
ΔM	water retention [kg]
PPI	number of pores per inch
v	water removal rate [m s^{-1}]
t	time [s]

Greek symbols

β	wettability impact factor for water retention
θ	contact angle [°]

Subscripts

alu	aluminum foam
A	advancing
cop	copper foam
H	hysteresis
ret	retention
R	receding
sm	surface modification

the dry conditions (Boomsma et al., 2003; Dai et al., 2012; Ejlali et al., 2009; Han et al., 2012; Nawaz, 2014) and the dehumidifying conditions (Costa et al., 2014; Hu et al., 2016). As the heat exchangers operate under dehumidifying conditions (Wang et al., 2000; Zhang et al., 2010; Zhuang et al., 2016), the condensate accumulated on the surface may restrict the air flow and occupy heat-transfer area (Lin et al., 2002; Nawaz, 2011; Pirompugd et al., 2006; Yun et al., 2009), leading to a profound impact on the heat exchanger performance (Han and Nawaz, 2012; Korte and Jacobi, 2001; Liu and Jacobi, 2006; Xu et al., 2009). In order to decrease the negative effect of accumulated condensate on heat exchanger performance under the dehumidifying conditions, the condensate drainage characteristics should be improved to quickly drained out the condensate.

The condensate drainage characteristics rely on the surface wettability. The surface modification method to form hydrophilic or hydrophobic surface can change the surface wettability, and has been used for fin–tube heat exchangers to improve the condensate drainage performance (Kim et al., 2002; Liu and Jacobi, 2006, 2008; Liu et al., 2008; McLaughlin and Webb, 2000; Min and Webb, 2000; Wang and Chang, 1998; Wang et al., 2002, 2007; Wu and Webb, 2001). For metal foam heat exchangers, the condensate drainage characteristics may also be promoted by finding the suitable surface wettability. In order to optimize the metal foam heat exchangers under the dehumidification conditions, it is necessary to investigate the water drainage characteristics of metal foams with different wettabilities.

For the condensate drainage characteristics of metal foam, the existing research focuses on the influence of metal foam porosity through dynamic dip test (Han and Nawaz, 2012; Nawaz, 2011). The research results show that the water retention in metal foam increases as the porosity decreases (Han and Nawaz, 2012; Nawaz, 2011); the water drainage characteristics of the metal foam heat exchanger are better than that of the fin–tube heat exchanger (Han and Nawaz, 2012). The above existing research reveals the drainage characteristics of the metal foam, but the influence of surface wettability for different metal foams was not included.

For the condensate drainage characteristics of the surfaces with different wettabilities, the existing research mainly focuses on the fin–tube heat exchangers (Joardar and Gu, 2004; Kim et al., 2002; Korte and Jacobi, 2001; Liu, 2011; Liu and Jacobi, 2006, 2008; Min and Webb, 2000; Nawaz, 2011; Sommers et al., 2012; Xu et al., 2009; Yun et al., 2009; Zhong et al., 2005). The research results show that the hydrophilic fin surface will significantly promote the condensate drainage characteristics of the fin–tube heat exchangers (Liu, 2011; Liu and Jacobi, 2006, 2008), and shows better promotion effect than hydrophobic fin surface (Joardar and Gu, 2004); as the receding contact angle increases, the retained condensate initially increases and then decreases, showing a maximum at approximately 40° (Kim et al., 2002). The models for predicting the retained condensate mass (El Sherbini and Jacobi, 2006; Liu, 2011) and the drainage behavior (Zhong et al., 2005) were developed. However, due to remarkable difference between the conventional fins and metal foams, the existing research results for the fin–tube heat exchangers may not be extended to the metal foams with different wettabilities.

For the metal foam applied in enhancing the airside performance of the heat exchangers, the existing research mainly focused on the dry air (Ambrosio et al., 2016; De Schampheleire et al., 2013a; Dixit and Ghosh, 2016; Dukhan, 2006; Dukhan et al., 2015; Han et al., 2012; Hsieh et al., 2004; Huisseune et al., 2015; Kim et al., 2000; Mancin et al., 2010, 2012; Ribeiro and Barbosa, 2013; Ribeiro et al., 2012; Xu et al., 2011; Zhao, 2012), and there is only one published paper concerning the wet air flow through the metal foam (Hu et al., 2016). For the wet air flow through metal foam, as the relative humidity of inlet air increases, the heat transfer rate and pressure drop are increased by a maximum of 67% and 62%, respectively (Hu et al., 2016). In the exiting research for metal foam (Ambrosio et al., 2016; De Schampheleire et al., 2013a; Dixit and Ghosh, 2016; Dukhan, 2006; Dukhan et al., 2015; Han et al., 2012; Hsieh et al., 2004; Hu et al., 2016; Huisseune et al., 2015; Kim et al., 2000; Mancin et al., 2010, 2012; Ribeiro and Barbosa, 2013; Ribeiro et al., 2012; Xu et al., 2011; Zhao, 2012), the condensate drainage characteristics were not investigated, and should be specified experimentally.

The purpose of the present study is to experimentally obtain the data for the water drainage characteristics of metal foams with various surface wettabilities, and to analyze the influencing principles of surface wettability on the drainage characteristics of metal foams.

2. Design of experiment

2.1. Experimental method and apparatus

For analyzing the condensate drainage characteristics during the humidification process, the water retention in metal foams with different surface wettabilities should be measured.

For years dynamic dip testing has been working as a simple, fast and easy method to assess the condensate drainage behavior for dehumidifying heat exchangers (Zhong et al., 2005).