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Experimental study on frosting/defrosting characteristics of microgrooved metal surfaces

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ABSTRACT

Effect of microgroove geometry on the frost formation and frost melt-water drainage is experimentally investigated on a number of aluminum surfaces. Condensation and frost formation processes are also examined on a set of microgrooved copper surfaces for which the dimensions of the microgroove geometry are varied in a cyclic manner. These metal surfaces are studied because of their technical importance as working materials and are fabricated by two different techniques, photolithography and wet etching, respectively. The morphology, distribution and growth pattern of the condensed and frozen water droplets are found to be considerably different on the microgrooved surfaces from that on the flat baseline surfaces. While the amount of frost melt-water retention on the flat surfaces is found to increase in the subsequent refrost cycles and is highest in the last frost cycle, the microgrooved aluminum surfaces consistently exhibit improved frost-water drainage in all frost cycles and under different operating conditions. Findings of this study will be useful in designing microgrooved metal surfaces operating under frosting/defrosting conditions to have improved frost-water drainage properties.

Etude expérimentale des caractéristiques de givrage/dégivrage de surfaces métalliques à micro-rainures

Mots clés : Formation de givre ; Dégivrage ; Surface à micro-rainures ; Evacuation d'eau de dégivrage ; Pénalités dues au givrage ; Mouillage anisotropique

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1. Introduction

For any surface operating under frosting/defrosting conditions, a portion of the frost melt water is retained on the surface after defrosting which refreezes again in the next frost cycle. High retention of frost melt-water on the surface is disadvantageous for any heat exchanger since defrosting is required more frequently and an increase in the defrosting energy expenditure further increases the operational cost. Minimization of frost melt-water retention on a surface operating under frosting/defrosting condition is, therefore, of tremendous importance in a wide range of air conditioning and refrigeration applications.

There has also been increasing interest in understanding and manipulating the effects of surface wettability on the condensation and frosting processes, to minimize water retention and frosting penalties, and to promote effective defrosting (Hoke et al., 2004; Jhee et al., 2002; Shin et al., 2003; Lee et al., 2004; Liu et al., 2008; Varanasi et al., 2010; Karmouch and Ross, 2010; Min and Webb, 2001; Korte and Jacobi, 2001; Furuta et al., 2012; Yin et al., 2012; Rykaczewski, 2012; Enright et al., 2012; Feng et al., 2012). The effects of surface wetting characteristics on the frosting/defrosting behavior and thermal-hydraulic performance of an aluminum fin-tube heat exchanger were examined experimentally by Jhee et al. (2002), who found that frost of higher and lower density grows on the hydrophilic and hydrophobic surfaces, respectively, compared to that on the bare aluminum heat exchanger. Shin et al. (2003) found that frost formed on the surface with lower dynamic contact angle had higher thermal conductivity and density during the initial stages of the frost formation. A detailed description of the effect of surface wetting characteristics on the early and mature stage of frost formation was given by Hoke et al. (2004). They reported that denser and more thermally conductive frost layer forms on a higher energy surface. However, this trend was observed to reverse in the mature frost growth period. A lower frost thickness and higher frost density on a hydrophilic aluminum surface than the same on a more hydrophobic surface under the operating conditions of household refrigerators was reported by Lee et al. (2004).

Furuta et al. (2012) examined the effects of condensation on the surface wettability of two different fluoroalkylsilanes and found that the change in the interfacial free energy of the solid–gas interface due to the water adsorption and an increase of the condensed water on the surface result in the decrease of contact angle and a mode transition from Cassie to Wenzel. In a similar study on superhydrophobic aluminum surfaces fabricated by a chemical etching method, Yin et al. (2012) examined the effect of substrate temperature and relative humidity on the superhydrophobicity under condensation conditions. They also cited the increase in the solid–liquid contact area with condensation as the primary reason for the observed decrease in the contact angle and droplet mobility and a transition from Cassie to Wenzel state.

Rykaczewski (2012) and Enright et al. (2012) studied, both theoretically and experimentally, the condensation and droplet growth mechanisms on nanostructured superhydrophobic surfaces with the help of ESEM imaging. Enright et al. (2012) emphasized the importance of local energy barriers on the growth of the condensed droplets and explained how the wetting states are affected by the length scale which in turn is influenced by the nucleation density of the droplets.

Condensate formation and drainage behavior on a number of vertical copper and coated and uncoated aluminum fin surfaces was studied by Min and Webb (2001), who reported the amount of condensate retention on the surface to be a function of the receding contact angle. Korte and Jacobi (2001) examined the effect of condensate retention on the thermal performance of plain fin, round-tube heat exchangers. They developed a model for predicting the mass of retained condensate and found that the size of the largest droplet retained significantly affects the amount of condensate retention.

Water drainage behavior of various microchannel and fin-and-tube heat exchangers was experimentally investigated by Zhong et al. (2005) using the method of dynamic dip testing. After examining a number of fin-and-tube and microchannel heat exchangers with hydrophobic and hydrophilic surface coatings, Liu and Jacobi (2008) reported that hydrophilic coating on the fin-and-tube coils increases the amount of water retention, while microchannel coils with hydrophilic coating reduces it. Liu and Jacobi (2009), in a later study on the thermal-hydraulic performance on four slit-fin-and-tube heat exchangers found that heat exchangers with a hydrophilic coating retain significantly lower amount of condensate than heat exchangers with hydrophobic coatings.

Xia et al. (2006) examined the thermal-hydraulic performance of louvered-fin, flat-tube heat exchangers for frost/defrost/refrost conditions and found that the water retention significantly affects the pressure drop and heat transfer in the refrost cycles. In a germane study, Moallem et al. (2012) reported the effects of surface coating and frost-water retention on the cycle time and thermal-hydraulic performance of louvered-fin microchannel heat exchangers under frosting conditions. Li et al. (2014) reported a very recent experimental study on the effect of frost melt-water retention on the performance of an air source heat pump for 16 frost–defrost cycles. They suggested that the water retention during defrosting undergoes three different stages and that a ‘permafrost’ area forms at the lower part of the evaporator surface after about 10 frost–defrost cycles, which remains there in the subsequent frost–defrost cycles. A decrease of about 10% in the heat transfer efficiency and large fluctuations in the operating conditions have also been reported.

Drainage behavior of condensed water droplets from surfaces with microgroove topography has been studied because of the potential of these surfaces in promoting water drainage (Yoshimitsu et al., 2002; Morita et al., 2005; Chen et al., 2005). The unique characteristics of the wetting pattern of condensed droplets and four stages of droplet growth on microgrooved surfaces were identified and reported by Narhe and Beysens (2004). Liu et al. (2009) studied the water retention behavior of microgrooved aluminum surfaces and compared that to the same on flat surfaces. A