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Visualization study of the effect of surface contact angle on frost melting process under different frosting conditions

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A B S T R A C T

Frost melting is closely related to solid surface characteristics and initial frost layer. In this paper, visualization study of frost melting processes on different surfaces, from hydrophilic to superhydrophobic, was carried out under different frosting conditions. On the hydrophilic and hydrophobic surfaces, the whole frost layer is divided into several blocks accompanying with melting, and the frost-water mixed blocks finally shrink into water droplets because of the surface tension and surface free energy. However, frost layer directly sheds from the superhydrophobic surface and only several spherical water droplets remain on the surface. The surface coverage ratio and frost-melting water mass all decrease with the increase in surface contact angle, which are smallest on the superhydrophobic surface. The frosting time and multiple frosting cycles show significant effects on frost melting of the hydrophilic and hydrophobic surfaces while frosting time and multiple frosting cycles have no influence on that of the superhydrophobic surface.

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Étude de visualisation de l'effet de l'angle de contact de surface sur le processus de fusion du givre sous différentes conditions de givrage

Mots clés : Fusion de givre ; Angle de contact de surface ; Surface superhydrophobique ; Étude de visualisation

1. Introduction

Frost formation is a common phenomenon which exists in the fields of aviation, refrigeration, cryogenics, air conditioning and so on (Amini et al., 2014; Jiang et al., 2013; Zhang and Lv, 2015). The growth of frost layer heavily impacts on the operating efficiency and security of these equipments under frosting conditions, for example, air source heat pumps, which are widely used as cooling and heating sources for heating, ven-

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Nomenclature

θ	contact angle [°]
h	thickness [m]
f	surface coverage ratio [%]
A	area [m^2]
m	frost-melting water mass [g]
σ	surface tension [N m^{-1}]
r	radius [m]
ρ	density [kg m^{-3}]
V	volume [m^3]
w	specific work [J kg^{-1}]
W	work [J]
M	heavy torque [J]

Subscripts

f	frost layer
w	frost-melting water
s	surface

tilation and air conditioning. When the air source heat pump is used for heating in winter, frost formation may occur on the surface of its outdoor heat exchanger. The frost layer acts as a thermal resistance between the heat exchanger and air, causing the heat transfer efficiency to decrease and the pressure drop to increase, and even resulting in the shutdown of the heating unit (Hwang and Cho, 2014; Wang et al., 2015a). Therefore, developing an effective anti-frosting technology is very important to improve the heating efficiency of air source heat pumps.

With the development of surface treatment technology, there is a considerable interest on the study of anti-frosting by using surface-treated materials. The anti-frosting method has advantages of high efficient, low cost and environmental protection. Researchers (Highgate et al., 1989; Huang et al., 2009; Okoroafor and Newborough, 2000; Wang et al., 2005) carried out frosting experiments on hydrophilic surface and their investigations indicated that the reduction in frost growth rate and frost thickness lied in the range of 10–30% compared with that of the bare surface. Rahman and Jacobi (2013, 2015) investigated the frosting/defrosting characteristics on microgrooved metal surface. The specific surface showed good anti-frosting performance and drained up to 70% more condensate than the flat baseline did. Wang et al. (2015b, 2015c) and Cai et al. (2011) all experimentally compared the frost formation on hydrophobic and bare surfaces. In their experiments, the frost deposition on hydrophobic surface was obviously delayed. In addition, Kim and Lee (2011), and Jhee et al. (2002), based on single surfaces or fin-tube heat exchangers, respectively, both systematically studied the frosting characteristics on different surfaces from hydrophilic to hydrophobic according to the contact angle.

Superhydrophobic surface, inspired by lotus effect, was recently used for anti-frosting research. Being different from hydrophilic surface, superhydrophobic surface has very weak wettability with contact angle bigger than 150° (Oberli et al., 2014). Scholars (He et al., 2013; Jing et al., 2013; Kietzig et al., 2009; Xu et al., 2012) prepared superhydrophobic surfaces by various methods, such as wet chemical etching, sand blast, micro-EDM machining and chemical oxidation. The superhydrophobic surface was observed to delay the freezing time of condensate droplets by Huang et al. (2011). Boreyko and Collier (2013) investigated frost formation on superhydrophobic surface, and reported that the condensate droplets showed self-propelling and jumped off the surface before it turned into solid phase. Liu et al. (2008) prepared a superhydrophobic surface whose contact angle was 162° and the frost layer on the surface was delayed for 55 min compared with a plain copper surface. Jing et al. (2013) investigated the frosting/defrosting behavior on various surfaces having differing wetting properties, ranging from superhydrophobicity to superhydrophilicity, and showed that the rigid superhydrophobic surface was most effective in both defrosting and against frosting.

Although the surface treatment is an effective anti-frosting technology, frost formation is unavoidable sometimes under frosting conditions. It is therefore of great significance to implement periodical defrosting to maintain the normal operation of air source heat pumps. The defrosting process consumes large amounts of energy and time to melt the frost layer, which leads to the reduction in heating efficiency. The efficiency improvement in frost melting is significant to save defrosting energy and time. Some studies (Boreyko and Collier, 2013; Boreyko et al., 2013; Jing et al., 2013; Liang et al., 2015; Wang et al., 2015a, 2015b, 2015c) indicated that the superhydrophobic surface reduced the frost-melting water retaining on the surface and saved time in frost melting through comparing superhydrophobic surface with other surfaces. However, visualization experiments on frost melting processes of surface-treated surfaces are lacking to fully understand the mechanism of frost melting and the effect of surface characteristics on its behavior. In addition, since the frost melting process is closely related to the initial frost layer before melting, it is significant to study the frost melting characteristics under different frosting conditions.

In this paper, different surfaces were prepared according to the surface contact angle, from hydrophilic to superhydrophobic. Visualization study of frost melting processes was carried out on prepared surfaces under different frosting time and multiple frosting cycles. All the results will provide foundation for the efficiency improvement of frost melting of air source heat pumps.

2. Visualization experiments

Fig. 1 shows the schematic diagram of the cold platform and visualization apparatus. The cold platform with semiconductor thermoelectric refrigeration was used to implement frosting and frost melting processes on the surfaces of prepared samples. The surface temperature of the cold platform could be regulated from −20 to 150 °C by using a temperature controller. The cold platform was placed vertically in the experiments and the samples were fixed on its surface by using heat-conducting silicone grease. The heat-conducting silicone grease has a high thermal conductivity, which makes the temperature difference between the cold platform surface and sample surface be less than 1 °C. An image acquisition system, which included a CCD video camera, an asana microscope and

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