international journal of refrigeration 71 (2016) 1–7

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Defrosting on horizontal hydrophobic surfaces and the shrink angle

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ARTICLE INFO

Article history:
Received 22 January 2016
Received in revised form 31 July 2016
Accepted 9 August 2016
Available online 12 August 2016

Keywords:
Defrosting
Horizontal
Hydrophobic surface
Meltwater
Shrink angle

ABSTRACT

Defrosting of a frosted surface is a crucial part for system recovery in refrigeration and cryogenic engineering. The performances of defrosting on a horizontal surface can better reflect the defrosting and drainage characteristics of the surface itself, since the influence of gravity is almost eliminated. This work performed defrosting experiments on horizontal hydrophobic surfaces with the defrosting process divided into three stages including frost melting, meltwater breaking and meltwater shrinking. The meltwater on the hydrophobic surface finally shrinks into a droplet with a final contact angle which is called the shrink angle. A theoretical model was also developed to analyze the free energy change of the meltwater during defrosting with the shrink angle predicted and its influencing factors discussed. Based on the model, the shrink angle relates to the static contact angle, contact angle hysteresis and meltwater size. When the meltwater size is less than the capillary length, the shrink angle is only related to the surface wettability. With increasing static contact angle and reducing contact angle hysteresis, the shrink angle increases and approaches the static contact angle. The predicted shrink angles were consistent with the experimental results with a maximum difference of 7%.

Dégivrage de surfaces horizontales hydrophobes et angle de rétrécissement

Mots clés : Dégivrage ; Horizontal ; Surface hydrophobe ; Eau de fonte ; Angle de rétrécissement

1. Introduction

Frosting is a common phenomenon in refrigeration and cryogenic engineering systems. Since a frost layer reduces the heat transfer efficiency and blocks the flow channel, periodic defrosting is essential to maintaining the system efficiency. Therefore, the defrosting characteristics of a frosted surface need to be understood to improve the defrosting efficiency.

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http://dx.doi.org/10.1016/j.ijrefrig.2016.08.005

Nomenclature

Variables

A	interfacial area (m^2)
E	energy (J)
f	area fraction of the first component
F	force (N)
g	acceleration of gravity (m/s^2)
h	height of the center of gravity (m)
k	empirical constant
r_b	base radius (m)
r_w	roughness coefficient
R	characteristic volume radius (m)
V	meltwater volume (m^3)
β	length-to-width aspect ratio of the drop
γ	surface tension (N/m)
θ	contact angle (°)
ρ	water density (kg/m^3)

Subscripts

0	static contact angle
a	advancing contact angle
r	receding contact angle
s	shrink angle
C	Cassie
W	Wenzel
Y	Young
gs	gas-solid
lg	liquid-gas
sl	solid-liquid
gra	gravity
ret	retentive
sur	surface
tot	total

Previous studies have shown that hydrophobic surfaces reduce frost growth in the early stage (Huang et al., 2011; Liu et al., 2008; Wu et al., 2007a,b), but cannot entirely prevent frosting. Thus, defrosting is still essential even on hydrophobic surfaces and researchers have investigated the defrosting characteristics (Jhee et al., 2002; Jing et al., 2013; Kim and Lee, 2011; Liang et al., 2015, 2016; Wang et al., 2015). Jhee et al. (2002) conducted defrosting experiments on a fin surface with a 124° static contact angle on a tubular heat exchanger to show that the hydrophobic surface effectively drains the meltwater. Liang et al. (2015, 2016) and Wang et al. (2015) performed defrosting experiments on surfaces with different wetting properties and found that the defrosting and drainage characteristics are better as the static contact angle increases. Kim and Lee (2011). also performed defrosting experiments on a hydrophilic surface, a bare Al surface and a hydrophobic surface and compared their drainage efficiencies. Jing et al. (2013) found that the meltwater tended to become regular droplets on a hydrophobic surface instead of an irregular water film and that the hydrophobic surface more effectively drained the water.

All the above researchers concerned the defrosting on vertical surfaces with the drainage efficiencies measured. However, research on defrosting on horizontal surfaces is also essential, because the actual frosted surfaces, such as the heat exchangers surfaces, may be in various orientations. Moreover, the performances of defrosting on a horizontal surface can better reflect the defrosting and drainage characteristics of the surface itself, since the influence of gravity is almost eliminated. For example, if the meltwater finally shrinks into a droplet with a larger contact angle, which means a better meltwater film mobility and consequently improved surface defrosting and drainage characteristics.

Recently, Boreyko et al. (2013) concerned the dynamic defrosting process (unstable slush film composed of meltwater and frost crystal dewetted into mobile slush ball which can slide off the surface at low tilt angles ($\alpha < 15°$)) on horizontal superhydrophobic surfaces. Since their superhydrophobic surfaces had quite small contact angle hysteresis, they ignored the influence of the contact angle hysteresis on the dewetting. Compared with superhydrophobic surface with poor durability, hydrophobic surface has wider applications in industry; therefore, defrosting on horizontal hydrophobic surface is worth studying. Since hydrophobic surface has relatively large contact angle hysteresis which may greatly influence the meltwater dewetting process, the influence of contact angle hysteresis on the final contact angle of the shrinking meltwater also needs to be understood.

In this study, defrosting experiments were performed on four horizontal hydrophobic surfaces with the detailed defrosting process observed. A theoretical model was also developed to analyze the energy change during meltwater shrinking process and to predict the final meltwater contact angle which is defined as the shrink angle in this paper.

2. Experimental section

2.1. Surface fabrication and characterization

Aluminum hydrophobic surfaces were fabricated through chemical etching method (Lv and Zhang, 2014) with four hydrophobic surfaces (HS-A, HS-B, HS-C and HS-D) obtained by controlling the etching time. The surface wetting properties measured by a contact angle goniometer (JC2000C1, China. The accuracy is ±1°) include the static contact angle (θ_0), the advancing contact angle (θ_a) and the receding contact angle (θ_r). The advancing contact angle and the receding contact angle were measured by the tilting plate method (Pierce et al., 2008; Smedley and Coles, 2005) (place a 40 μL deionized water droplet on the surface and tilt the surface until the droplet just begins to move, then, measure the front angle and trailing angle of the droplet as the advancing contact angle and the receding contact angle). The measured surface contact angles are shown in Table 1.

2.2. Defrosting experiments

Before the defrosting experiments, frosting on the experimental surfaces were conducted first. The frosting experimental system included an air conditioning system, a semiconductor refrigeration system and a data/photograph acquisition