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Study on sub-cooler based on the characteristics of the super-hydrophobic surface

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ABSTRACT

Nowadays, it is a growing need for energy shortage and environmental protection, and therefore the development of air conditioning and cooling system with ice slurry system has an important significance and broad application prospect. The ice-making using sub-cooling water has become one of the most stressed dynamic ice-making methods because of its simple structure, high heat transfer efficiency and high ice-making efficiency. However, the ice blockage occurs too frequently, resulting in a discontinuous ice-making and reducing the efficiency of the system. Aiming at dealing with the ice blockage, the experiment with the super-hydrophobic sub-cooler has been carried out, which provides theoretical and experimental basis for the optimum design of the ice-making system. It was found that a large sub-cooling degree and a long lasting time of sub-cooling state can be obtained with the super-hydrophobic sub-cooler, increasing the yield of ice slurry. As a result, the efficiency of the ice-making system is improved, achieving the purpose of energy saving.

1. Introduction

In today's fast-paced economy and unstable fuel market, energy conservation is becoming an important issue. As an environment-friendly medium of ice thermal storage, ice slurries can improve energy efficiency and reduce building energy consumption thanks to its thermo-physical advantages and its good fluidity. Meanwhile, the ice slurry exploit the latent heat of the ice, making them have more efficient heat carries than single-phase fluids, is often employed in the refrigeration and air-condition systems reducing the building energy consumption due to its high heat capacity and high heat transfer rate. Ice slurry has been successfully used in many fields [1–4], such as air-conditioning and refrigerating system, food storage, mine cooling and medical field [5–8].

In the past two decades, researchers have not only been attracted by these outstanding properties of ice slurries [9–17], but also investigated different type of ice slurry generators [18–22]. Using sub-cooling water is one promising method for ice generation because of its high efficiency and energy conservation. However, the key problem in this kind of ice generation is the ice blockage happened in the sub-cooler, which reduces the efficiency of the ice-making system. A great deal of endeavor has been made to avoid the ice blockage, categorized into three groups: adding additives, interfering externally and improving surface conditions [23]. While there is still no satisfactory report on avoiding ice blockage up to now.

In this paper, a sub-cooler with super-hydrophobic surface is presented, aiming at the development of a convenient and efficient ice-making system. In recent years, people have conducted more thorough research on the field of hydrophobic surface and phase change [24–26]. Kulinich and Farzaneh [27] investigated the ice adhesion strength on flat hydrophobic and rough super-hydrophobic coatings with similar surface chemistry. In this study, it was found that the contact angle hysteresis, along with the contact angle, also influences the ice–solid adhesion strength. Deschamps et al. [28] studied liquid water confined within nanopores which present a high level of hydrophobicity. They found that the liquid state persists down to temperatures much lower than in the bulk and in hydrophilic materials of comparable sizes, defining a thermodynamic limit for the melting/crystallization of water. In the study [29], the effects of these ZnO surfaces toward ice/frost formation were investigated. The results show that the time of condensed droplets maintaining the liquid state (t) increases with the decrease of the growth time of ZnO-nanorods which determines the surface wettability, clearly indicating the retardation of ice/frost formation. Heydari [30] found that the water freezing delay time is not significantly affected by the

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surface topography and discuss this finding within the classical theory of heterogeneous nucleation.

The objective of this work is to improve the performance of the sub-cooler, and to find an effective method to realize the continuous ice-making with sub-cooling water.

2. Characteristics of the super-hydrophobic surface

The polymer used in this study is a kind of high polymer that contains a fluoric binder and an organic solvent. The chemical name of the polymer is nitric derivate of perfluorpolyoxyalkyl carbonate. The organic solvent is a mixture of fluorinated hydrocarbon solvent and ethanol or isopropyl alcohol, which may guarantee a good dissolvability of the binder and a firmed coating of modifier on the surface. In reaction of fluorine to polymers with hydrogen, a fluorocarbon with special properties is produced by replacing the hydrocarbon chain with fluorocarbon one, and the polymer forms uniformly distributed protrusions on the surface when coated on the solid surface.

2.1. Surface wettability

Wettability, one basic property of a solid surface, is dependent on both the topographical structure and the chemical compositions. This typical parameter used to characterize surface wettability is the contact angle (CA). Furthermore, when a drop is placed on a surface, not only a single value (CA), but also the contact angle hysteresis. Contact angle hysteresis is the difference between the advancing angle θ_A and the receding angle θ_R. For a super-hydrophobic surface, a water contact angle is larger than 150° with a contact angle hysteresis of below 10°.

In the present study, one sample in size of 15 mm × 10 mm × 1.0 mm is prepared for investigating the wettability of the super-hydrophobic sub-cooler. The contact angle and the contact angle hysteresis of the sample were measured by a video-based contact angle measurement system (DCA, SL200B) with the accuracy of ±0.05°. The uncertainty is inevitable in the measurement of the contact angle. The reasons for the measurement uncertainty include the measuring instruments, the measuring conditions, the measuring procedures, and the processing methods of the person who measured and so on. To reduce the measurement uncertainty, the static WCAs were measured at least 3 times across the sample surface using the sessile drop by dispensing 2 μL drops of de-ionized water on the surfaces. All WCAs were measured at an ambient temperature 25 °C and relative humidity 50%. Based on the measurements (not shown here), the static CA on the surface is around 159.54°, the contact angle hysteresis is about 6.17°.

2.2. Flow and heat transfer characteristics

A prominent characteristic of the super-hydrophobic surface is the existence of slip-velocity. In [31], the authors pointed out that the main factor of velocity slip on super-hydrophobic surface is the surface wettability, and they believed that the larger the contact angle is, the larger slip-velocity can be produced. The velocity slip effects the flow and heat transfer characteristics, as following aspects:

(1) Flow capacity

On the basis of summarizing the previous studies, Lauga [31] obtained the equation of flow capacity with slip-velocity:

$$\delta = \frac{R}{4}\left(\frac{Q_{slip}}{Q_{non\text{-}slip}} - 1\right) \tag{1}$$

In Eq. (1), R is the radius of the pipe, Q_{slip} and $Q_{non\text{-}slip}$ respectively represent the flow capacity with slip-velocity and the flow capacity without slip-velocity. δ is the length of slip-velocity.

From Eq. (1), it can be seen that under the same condition, the flow capacity with slip-velocity is greater than that with no slip-velocity. Therefore, the flow capacity in the super-hydrophobic sub-cooler is greater than that of the non-super-hydrophobic sub-cooler.

(2) Flow velocity

The fluid flows in the pipe with slip-velocity, the distribution of velocity can be described as:

$$v_z = v_s + \frac{1}{4\mu}\frac{dP_d}{dz}(r^2 - r_i^2) \tag{2}$$

The maximum flow velocity at the center of the pipe can be expressed as:

$$v_{\max} = v_s - \frac{1}{4\mu}\frac{dP_d}{dz}r_i^2 \tag{3}$$

The average flow velocity is:

$$v_{av} = v_s - \frac{1}{8\mu}\frac{dP_d}{dz}r_i^2 \tag{4}$$

The ratio of the maximum velocity and the average velocity is expressed as:

$$\frac{v_{\max}}{v_{av}} = 2 - \frac{v_s}{v_{av}} \tag{5}$$

From the above equations, it can be known that: the velocity distribution in the pipe shows a parabola because of the slip-velocity; the ratio of the maximum flow velocity and the average velocity is not 2 but smaller than 2; with the increase of slip-velocity, the ratio will decrease.

(3) Pressure drop

The pressure drop of the fluid can be derived from the above expression of average flow velocity:

$$\Delta P_d = \frac{8\mu l v_{ar}}{r_i^2}\left|1 - \frac{v_s}{v_{av}}\right| \tag{6}$$

By Eq. (6), it can be seen that there is a linear relationship between pressure drop and slip-velocity. In other words, with the increase of slip-velocity, the pressure drop of the fluid decreases.

(4) Heat transfer characteristics

Based on various kinds of studies, Cassie and Baxter [32] proposed a gas cavity model for explaining the wettability of super-hydrophobic surface. According to the Cassie–Baxter model, most of the water contacts with the air on the super-hydrophobic surface. Due to the lower thermal conductivity of air, it reduces the heat transfer coefficient and the Nusselt number. The heat transfer of the super-hydrophobic surface is the result of the thermal convection and the heat conduction of the micro air layer. The surface heat conductivity coefficient can be expressed as:

$$\frac{1}{h_s'} = \frac{b}{\lambda_{air}} + \frac{1}{h_q} \tag{7}$$

In Eq. (7), b is the thickness of the air layer, λ_{air} is the thermal conductivity of the air, and h_q is the convective heat transfer coefficient of the fluid.