EXPERIMENTAL RESEARCH AND THEORETICAL ANALYSIS OF SURFACE CONTACT ANGLES OF DIFFERENT MATERIALS

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Abstract. Surface properties play an important role in the formation of frost crystals. The smaller the contact angle formed by droplets on the metal wall, the larger the contact area with the cold surface, thus accelerating the freezing process and making frost crystals easier to form. In this paper, the water droplets on the surface of zinc, aluminium, brass and red copper with the same specifications were observed microscopically. The images were binarized by Rising View software. The contact angles of the surfaces of different materials were measured, and the theoretical analysis and calculation were made by geometric method. It is found that the water droplets are spherical coronal on the horizontal surface. With the increase of the inclination angle of the specimen, the water droplets will incline downward, and the contact angle of the surface will be larger in front and smaller in back, and the difference between the two is equal to the inclination angle of the specimen. When the inclination angle exceeds the critical inclination angle, the water droplets will slip and no longer adhere to the metal surface.

1. Introduction

Frost phenomenon widely exists in air source heat pump, aerospace and other fields, and brings a series of hazards. For example, the frosting of heat exchanger will increase heat transfer resistance, hinder flow and deteriorate heat transfer[1]. Many scholars at home and abroad have done a lot of theoretical and experimental research on frost freezing and defrosting and deicing, and have also made a lot of academic achievements of great reference value. For example, some studies have shown that surface characteristics such as contact angle, surface roughness and surface energy have a great influence on frost suppression[2]; the mechanism of frost suppression on hydrophobic surface is to delay the time of frost formation on the surface as far as possible, reduce the accumulation of frost layer on the surface, and the larger the contact angle of water droplets on the surface, the better the frost suppression effect. Shin[3] conducted frosting tests on hydrophilic surfaces with contact angles of 23, 55 and 88 degrees respectively. The results showed that frost layer on surfaces with larger contact angles grew faster and frost layer density was smaller, while frost layer on surfaces with smaller contact angles grew slower, frost layer density was higher and frost layer deposition was larger[4]. Surface contact angle plays an important role in the initial stage of frost growth. In this paper, the surface contact angles of zinc, aluminium, brass and red copper sheets with the same specifications are studied experimentally and theoretically, and the relationship between the maximum front contact...
angle and the inclination angle of the sheets is studied[4,5].

2. Experimental System
The main experimental devices used in this study are mainly divided into four parts: constant temperature and humidity box, refrigeration system, data acquisition system and image acquisition system. The schematic diagram of the experimental device is shown in Fig. 1.

![Schematic diagram of experimental device](image)

1-Computer; 2-Rubber Cushion Control Line; 3-Semiconductor Refrigeration Table Temperature Controller; 4-Temperature Collector; 5-Semiconductor Refrigeration Table; 6-Rubber Cushion; 7-Constant Temperature and Humidity Box; 8-Body Microscope; 9-CCD Image Collector

In order to observe the morphology of water droplets on the surface of different materials more comprehensively, image data of surface materials were collected from top to bottom by stereo microscope and CCD camera, while horizontal video microscope was used to observe the water droplets from side. The device is shown in figure 2.

![Image Collection Device](image)

![Stereo microscope](image)  ![Horizontal microscope](image)

Figure 2. Image Collection Device

Table 1. Material Information

| Material type | Specification (long x wide x thick) | Surface roughness |
|---------------|-----------------------------------|-------------------|
| zinc          | 5cmx2cmx0.1mm                     | RZ25              |
| aluminium     | 5cmx2cmx0.2mm                     | 3.2               |
| brass         | 5cmx2cmx0.2mm                     | 3.2               |
| red copper    | 5cmx2cmx0.2mm                     | 3.2               |

3. Morphology of Water Droplets On Surfaces of Different Materials

![Zinc sheet](image)  ![Aluminium sheet](image)

(a) zinc sheet  (b) aluminium sheet
Figure 3. Morphology of water droplets on surfaces of different materials

Under the condition of ambient temperature $T_a=20^\circ C$ and relative humidity $RH=75\%$, we drip a droplet on different metal sheets by dropper. By observing the droplet from side by horizontal video microscope, we can find that the contact angles of droplets on different material surfaces are different, that is, different metal materials have different surface energy. In order to obtain the size of the surface contact angle, the image above is binarized and measured by Rising View software. The results are shown in Figure 4.

Figure 4. Binary Charts of Water Droplets on Different Material Surfaces

The results show that the surface contact angle of aluminium sheet is the largest and that of brass is the smallest. According to the theory of phase transformation kinetics, at a certain supercooling degree, the vapor molecule is continuously fluctuating and condenses into liquid nuclei on the cold wall, but only the liquid nuclei whose radius is larger than the critical radius can survive, and the vapor molecule can grow spontaneously. No liquid nucleus less than the critical radius can exist. The change of Gibbs free energy of the system caused by the formation of critical liquid nuclei is called the energy barrier for the formation of liquid phase, that is, the new phase nuclei can be formed and grow spontaneously only when the nucleation barrier is crossed. The surface contact angle directly affects the value of the nuclear barrier. In order to simplify the calculation, we assume that water vapor condenses on the cold wall, and the wall is smooth. Wet air is pure and does not contain suspended particles or dust. When spherical coronal liquid nucleation is formed on the cold wall, three interfaces are formed: solid-gas, solid-liquid and liquid-gas interfaces. The three interfaces are $A_{sv}$, $A_{sl}$, and $A_{lv}$ respectively, and the three-phase junction point is $O$. The surface tensions of these three interfaces are $\gamma_{sv}$, $\gamma_{sl}$, and $\gamma_{lv}$ respectively, as shown in Figure 5 [6].

Figure 5. Spherical coronal liquid nuclei formed by water vapor on the wall

When these three interfacial tensions are balanced, according to Young's equation, there are:

$$\gamma_{sv} = \gamma_{sl} + \gamma_{lv} \cos \theta$$
Formula (1) can be used to derive the expression for calculating the surface contact angle.

\[
\theta = \arccos \frac{\delta_w - \delta_d}{\delta_w}
\]

(2)

Formula (2) shows that the surface contact angle can be calculated as long as the interfacial tension is known. Because the interfacial tension is related to temperature and humidity, the existing experimental device cannot measure its value and \( \theta \) can be deduced from geometric knowledge.

\[
\theta = \arcsin \frac{4hl}{l^2 + 4h^2}
\]

(3)

The maximum height of spherical coronal liquid nucleus is \( h \), and the maximum chord length of spherical coronal liquid nucleus is \( l \). The value is shown in Fig. 4. The theoretical calculation value of surface contact angle can be obtained by introducing the value into formula (3). The value is shown in the following table:

| Material Information | Experimental measurement of contact angle (Unit Degree) | Theoretical calculation of contact angle |
|----------------------|--------------------------------------------------------|----------------------------------------|
| zinc                 | 65.2                                                   | 69.2                                   |
| aluminium            | 70.1                                                   | 70.2                                   |
| brass                | 57.3                                                   | 58.8                                   |
| red copper           | 62.6                                                   | 64.3                                   |

It can be found that the theoretical calculation of contact angle is larger than the experimental measurement of contact angle, because the liquid nucleus is actually ellipsoidal, not ideal spherical coronal.

4. Maximum Front Contact Angle and Critical Inclination Angle

A droplet is placed on the surface of different materials and observed under a horizontal microscope, and the inclination angle of the sheet is constantly changed. The experiment shows that the droplet is spherical-coronal on the horizontal surface. With the increase of the inclination angle of the sheet, the droplet will incline downward, and the contact angle of the surface will be larger in front and smaller in back. When the inclination angle of the sheet exceeds the critical inclination angle, the water droplets will slip and cannot adhere to the surface of the material. The difference between the front and back contact angles is approximately equal to the inclination angle of the sheet, and the maximum error is not more than 3%. The maximum front contact angle, minimum back contact angle and critical angle are shown in the figure below.

\[
\theta_{\text{MAX}} = 78.1^\circ, \theta_{\text{MIN}} = 41.8^\circ, \alpha = 37.1^\circ
\]

\[
\theta_{\text{MAX}} = 78.6^\circ, \theta_{\text{MIN}} = 48.3^\circ, \alpha = 29.9^\circ
\]
5. Conclusion

- In conclusion, the contact angle of water droplets on the surface of different metal materials will be different due to the different metal surface energy. Among the four materials mentioned above, the contact angle of aluminum surface is the largest and that of brass is the smallest. That is to say, under the same other conditions, liquid nuclei are more easily formed on the brass surface and the freezing process is easier.

- On the horizontal surface, the water droplets are ellipsoidal coronal. If the spherical coronal shape is used as geometric calculation, the calculated surface contact angle will be larger. With the inclination of the attached surface of the water droplets, the water droplets will incline downward, while the contact angle of the water droplets will be larger at the front and smaller at the back, and the difference between the two is equal to the inclination angle of the surface. There are maximum front contact angle $\theta_{\text{max}}$, minimum back contact angle $\theta_{\text{min}}$ and critical inclination angle $\alpha$. When the surface exceeds the critical inclination angle, the water droplets can not adhere to the surface and slip.

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