

Analysis of Minute Water Droplet's Freezing Process on Coated Surface

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ABSTRACT

Unlike the conventional bleed-air method, using electro-thermal anti-/de-icing methods to completely evaporate all of the supercooled water droplets that collide with the leading edge wing surface of aircraft flying in a freezing environment is not easy in terms of technical feasibility and energy efficiency[1]. If the leading edge is warm enough to stay free from frozen water droplets, the water moves backward while still maintaining the liquid phase. The droplets may freeze somewhere on an unheated surface after being halted for some reason and stick on the surface. Ice gradually accumulates as this process is repeated. Therefore, liquid water must be removed from the surface as soon as possible if the electrothermal method is employed for icing prevention. One answer to this problem is coating the surface with a superhydrophobic paint. Since the contact angle of a minute water droplet on a superhydrophobically coated surface becomes higher than 150° according to the definition, the water droplet becomes spherical. If the surface is inclined or the droplet receives an external force, the droplet moves along the surface with a rotational motion. When the electrothermal method is employed to prevent aircraft icing, the surface of the body of interest should be superhydrophobic in order to quickly remove liquid water. This type of icing prevention is called the electrothermal-coating method. To mechanize this concept into a device, correctly determining droplet behavior is important. In the present study, the freezing process of a minute water droplet moving on a hydrophobically coated surface in a sub-zero environment was analyzed experimentally. A simplified two-dimensional numerical droplet model was developed to calculate the temperature change inside the droplet.

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INTRODUCTION

Several methods to prevent aircraft in-cloud icing have recently been proposed. A promising approach is the electrothermal method, which employs an electric heating system embedded in the leading section of an airfoil. In order to make this method more effective, improving the anti-/de-icing capability of the system and reducing fuel consumption by more efficient power use are important. A superhydrophobic paint is a potential answer to these requirements.

The authors conducted an icing wind tunnel test to confirm the effectiveness of a novel electrothermal-coating method to prevent aircraft in-cloud icing (Figure 1.) [2].

In the test, the super-hydrophobic paint FHI-AIS (Fuji Heavy Industry, Ltd.) and a conventional polyurethane paint were used for coating. To heat the airfoil, an electric heating system was installed in the leading edge section of an airfoil model. The effectiveness of the heating and coating combination was examined by changing the heating area, power supply, and icing conditions. In the heating mode of the FHI-AIS coated model, the impinging supercooled water

droplets became spherical small water droplets after agglomeration through a heating-melting process and moved backward along the airfoil surface. When the power supply was insufficient or only the narrower area at the leading edge was heated, these droplets froze on the unheated surface even in the leading edge section. Ice deposits accreted, and the area grew with incoming droplets. The deposits separated from the surface when the ice attained a certain size and the acting aerodynamic force surpassed the adhesion force, which was weakened by the FHI-AIS characteristics. As long as the superhydrophobic airfoil model for which only the leading edge was heated was exposed to the icing environment, this type of ice formation was repeated. Since the test was focused on the capability of the new method to prevent icing, the temperatures of the airfoil surface and droplets on the surface were not measured. Based on these results, research was conducted to analyze droplet behavior in horizontal motion on a super-hydrophobically coated surface. As a first step of the research, tests on a coated flat plate were carried out in a sub-zero environment in order to determine the dynamic behavior of a minute droplet and measure the temperature of the droplet. Sturb et al. [3], Hindmarsh et al. [4], Kostinski and Cantrell [5], and Kawakami et al. [6] conducted the research for the characteristics of a droplet in a freezing process by various experimental and/or numerical approaches. However the droplet tested was at rest on a coated surface or on a suspended thermocouple. Therefore some problems accompanied by the rolling motion as considered in the present research were not dealt with. For the second step, numerical analysis was carried out using a simplified droplet model in order to numerically measure the temperature inside the droplet and evaluate the applicability of the simplified model.



Figure 1. Icing on a superhydrophobically coated test model Airspeed: 90 m/s Ambient temperature: -10 deg. C LWC: 0.42 g/m³ MVD: 20 microns Duration: 5 min.

EXPERIMENTAL APPROACH

For the surface of an actual in-flight wing designed based on the electrothermal-coating concept under icing conditions, water droplets can be assumed to travel by aerodynamic force along the surface very rapidly. Observing these droplets can be difficult because of the small droplet size and high-speed motion. Thus, the present test used larger droplets that were 2

mm in diameter and instilled by a micro-syringe to substitute for the actual smaller droplets. The droplets were moved slowly in a sub-zero environment and observed with a thermograph and high-speed camera to record the images in order to analyze the behavior and temperature changes of a droplet traveling on a superhydrophobically coated surface. The droplets were moved in two different ways: the gravity fall method, where a droplet falls down freely on an inclined coated plate, and the forced roll method, where a droplet is fixed at the same position in space and then forced to rotate while in contact with the coated plate. These methods are described below.

Gravity Fall Method

The gravity fall method reduces the number of external factors with regard to movement of a droplet by as much as possible. In this method, a droplet is dropped on the edge of an inclined plate that is coated with superhydrophobic paint.

Apparatus and test procedure

Figure 2 shows a device comprising a micro-syringe and heating unit for instillation of a single minute water droplet. An injection needle (0.4 mm outside diameter and 0.22 mm inside diameter) was used. This particularly thin needle produces droplets with a diameter of approximately 2 mm. The micro-syringe was set up on the test stand and positioned just a little above the inclined test plate. The heater unit was used to regulate the temperature of water inside the syringe in the sub-zero environment of the test chamber. The temperature of the syringe was measured and regulated at the prescribed value by the controller. During instillation, the temperature of the droplet coming out of the tip of the needle was monitored by a thermograph (FLIR SC655). If the droplet temperature was not at the prescribed value, all data for the test run was deleted from the record.

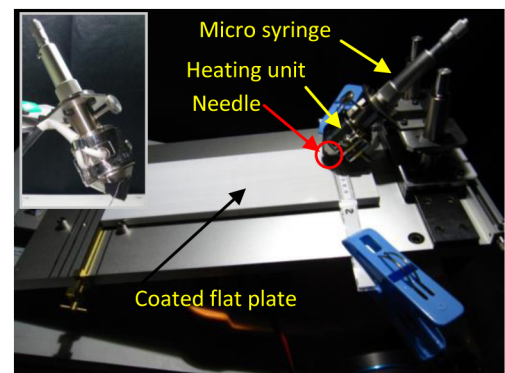


Figure 2. Test stand for the gravity fall method

The test piece (flat plate on which a superhydrophobic paint was coated) was made of 7075 aluminum alloy and had dimensions of 300 mm $\times$ 100 mm $\times$ 10 mm. One flat surface was manually coated by HIREC450 with extreme caution in order to produce a constant and smooth surface condition. HIREC450 is a superhydrophobic paint produced by the

Japanese manufacturer NTT-AT. The basic properties of HIREC450 are summarized in Table 1. The test stand upon which the test piece was placed was set up in the test chamber.

Table 1. Properties of HIREC

Property	Evaluation	Value
Repellency	Contact angle	> 150 deg
Coating strength	Bending	No crack
	Impact	No peeling
	Pencil stiffness	< 6B
Adhesion	Crosscut	10/100
Weathering	Water-resistance	not affected

The measurement system is shown in Figure 3. The droplet movement was monitored by a high-speed camera (Photron FASTCAM-APX RS). A thermograph was installed beside the test stand. An LED-based lighting system was used in order to not warm the whole test system.

The test conditions are shown in Table 2. The ambient temperature was constant at -15°C for all test runs. The droplet temperatures were 5, 10, 15, and 30°C . The speed of the droplet moving along the surface depended on the inclination of the plate. Lower inclinations were desired in order to observe the droplet motion as slow as possible. However, since the droplet did not start to move at all when the inclined angle was below 20° , the test was begun by setting the angle above this value.

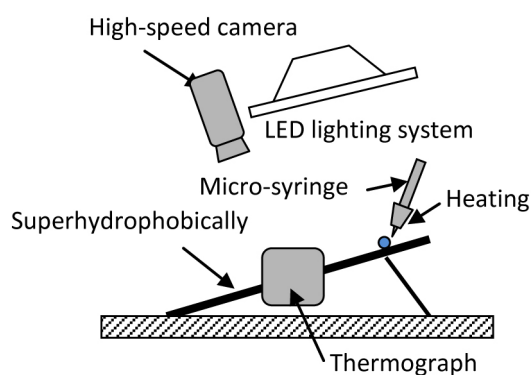


Figure 3. Measurement system

Table 2. Test and observation conditions

Item	unit	Set value
Ambient temperature	deg. C	-15
Droplet temperature	deg. C	5,10,15,30
Inclination	deg.	20
H.S. Camera	fps	1000
Thermograph	fps	200

The test was carried out in accordance with the following procedure.

1. The micro-syringe was set in a prescribed spot on the test piece. The spots for instillation are indicated in Figure 4.
2. The micro-syringe was warmed and maintained at the temperature set before the test.
3. The thermograph and high-speed camera were activated.
4. A water droplet was dropped onto the spot on the test piece surface.
5. Data from the thermograph were examined in order to confirm the correctness of the droplet temperature at the needle tip. If the temperature deviated from the target value, the collected data were deleted from the dataset.

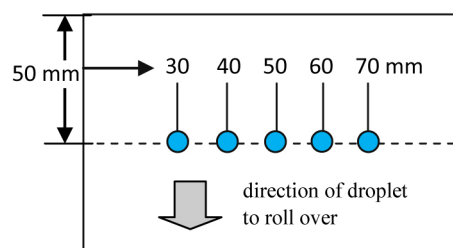


Figure 4. Position of the instillation from the needle

Test results and discussion

First, the state of motion of a droplet (e.g., sliding and/or rotating) was analyzed by close examination of the images from the high-speed camera. Particles were thus mixed into the water for instillation; the properties of the particles are given in Table 3. Water was then dropped onto the surface of the inclined test piece. When the droplet started to move, the motion was recorded by the high-speed camera. In the analysis, a single particle inside the droplet was tracked. Successive tracking of the particle, as shown in Figure 5, showed that the droplet rolled downward as if it were a rigid body.

Table 3. Property of the tracer particle

Material	Polyamid12 powder/white	
Density	1.0 – 1.2 g/cm ³	
Particle size	Median	145 microns
	Range	60 – 250 microns