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An experimental investigation of the melting process of an ice bead in a hot shear flow

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ABSTRACT

In the present study, we report for the first time the observations of the melting process of an ice bead in a hot shear flow. During the experiment, a water droplet was first deposited onto a glass surface. Then, the surface temperature was cooled down to a desirable subfreezing value by a constant temperature bath circulator and the water droplet turned into an ice bead. After that, the ice bead was exposed to a hot shear flow and its melting process was recorded by two cameras. The results showed that, both the air flow speed and substrate surface temperature had significant effects on the melting process of the ice bead. The increase of the air flow speed resulted in a significant change of the runback phenomenon of the liquid water generated from the melting ice bead. Besides, as the decrease of the substrate surface temperature, the deicing time of the ice bead increased apparently. In addition, during the melting process of the ice bead, the temperatures of two characteristic points along the centerline demonstrated apparent differences.

1. Introduction

In nature, ice accretion is ubiquitous and poses hazards to many applications, such as wind turbines [1], aircraft [2], and power transmission lines [3], etc. Generally speaking, three deicing methods are widely used, which include mechanical deicing, chemical deicing, and thermal deicing [4]. Among the many technologies available, thermal deicing is the most commonly used method. Since the ice accretion in above-mentioned applications involves the formation of the ice beads from the freezing water droplets on a certain cold surface, the investigation of the melting process of the ice bead by using some kind of thermal deicing method could improve our understanding about the important microphysical processes pertinent to the deicing phenomena, which would be very desirable for researchers to develop more efficient thermal deicing devices.

Over the years, several studies have been carried out by utilizing thermal deicing methods. For example, Lanoie [5] developed a number of deicing techniques utilizing terrestrial heat power. Ryerson et al. [6] made a comparison of deicing performances for deicing fluids and infrared heater, and found that the infrared heater system was not as effective as deicing fluids system [7], and the efficiency of infrared deicing system for ice was greater than that for snow. Koenig and Ryerson [8] experimentally investigated the infrared deicing system and found that the infrared deicing was not suitable to adopt when the ice thickness was less than 1 mm. Liu and Han [9] studied the deicing method for trains using hot air, built the phase change heat transfer model of the ice, and proposed a steady-state calculation method of the melting ice time. Xie et al. [4] experimentally studied the melting process of an ice plate placed in a hot air flow. Their results showed that the increase of both velocity and temperature of the airflow resulted in the decrease of the deicing time.

In addition, Jin et al. [10] studied the melting process of an ice bead on a superhydrophobic surface. During their experiment, a water droplet was first deposited on a cold surface, the temperature of which was controlled by a bath circulator. Once the water droplet froze into an ice bead, the bath circulator was turned off and the ice bead melt gradually because the surrounding air was at room temperature. Moreover, Jin et al. [11] also used the similar experimental procedures to study the melting process of an ice bead on an inclined red cooper surface. They found that a solid-liquid interface appeared at the bottom of the melting ice bead and the liquid water stayed below the interface because of the relatively higher density of water than that of ice.

Even though some researches have been performed on the thermal deicing process [4–11], to the authors' best knowledge, the detailed measurement of the melting process of an ice bead in a

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hot shear flow has not yet been experimentally investigated. In addition, Battisti [12] recently developed an anti-icing technique to prevent or eliminate the accretion of ice on the external surface of the wind turbine blade, which permitted the hot airflow to the outside of the blades to fluid-thermodynamically interact with the wind hitting the part of the blade surface. In order to promote the practical application of this technique, a compressive understanding of the melting process of ice in the hot airflow under different conditions is needed. In this study, a water droplet was first deposited onto the surface of a quartz glass substrate. Then, the surface temperature was cooled down to a desirable subfreezing value by a constant temperature bath circulator and the water droplet turned into an ice bead. After that, the ice bead was exposed to a hot shear flow and its melting process was recorded by two cameras. A parameter study of the substrate surface temperature and the air flow speed was carried out. The present study is aimed to elucidate the underlying fundamental physics to improve our understanding about the important microphysical processes pertinent to the thermal deicing phenomena.

2. Experimental

2.1. Experimental setup

The schematic of the current experimental setup is shown in Fig. 1, which is similar to the previous work of Moghtadernejad et al. [13–16]. During the experiment, a deionized water droplet ($V = 9.47\ \mu L$) was first deposited on the surface of a quartz glass substrate by a home-made droplet generator. Then, the substrate surface was cooled down to a subfreezing temperature by a constant temperature bath circulator (AC150-A25, Thermo Scientific). The substrate surface temperature was monitored by a temperature acquisition unit (9211, National Instrument). The uncertainty of the temperature measurement was estimated to be within 0.05 °C. The cold surface caused the water droplet to freeze. Once the water droplet turned into an ice bead, a hot shear flow was introduced and the melting process of the ice bead was recorded by two cameras simultaneously. The side view of the melting process of the ice bead was obtained by a CCD camera (Sensicam, PCO) and then stored in computer 1 for later analysis. A delay generator (575, BNC) was adopted to trigger this CCD camera operating at a frequency $f = 10.0$ Hz. Besides, the top view of the melting process as well as the temperature distribution of the ice bead was recorded by an infrared camera (T650sc, FLIR) and then stored in computer 2. The infrared camera was operated at a frequency $f = 7.5$ Hz. In addition, a calibration for the infrared camera was done by using thermocouple and the emissivity coefficient of the water droplet and the quartz glass substrate was set at 0.97 and 0.75, respectively [17,18]. Air flow was introduced to the quartz glass substrate from a high pressure gas cylinder by using a tube with the inlet diameter of 9.8 mm. The tube was placed at the substrate leading edge and its length was 250 cm. The distance from the outlet of the tube and the location of droplet deposition was 10.0 mm. A pressure relief valve was used to control the air flow speed and the flow rate was measured by a flow meter (MF5700, Siargo). In the present study, the air flow speed varied between 11.0 and 20.0 m/s and was measured with a hot wire anemometer at the point that the droplet was deposited on the substrate. The air flow in the tube was heated up by an electric heating sleeve so that the temperature of the air flow (T_{air}) at the location of droplet deposition was increased up to 75.0 °C.

2.2. Experimental conditions

During the experiment, the relative humidity and temperature of the air in the laboratory were kept at 70.0 ± 4.0% and 26.0 ± 1.0 °C, respectively. The initial diameter of the water droplet (D) investigated in the present study was 2.63 mm. In addition, through adjusting the constant temperature bath circulator, three substrate surface temperatures (T_w) were tested, which were

Table 1
Some characteristics of the ice bead.

Surface temperature	$T_w = -3.0$ °C	$T_w = -6.5$ °C	$T_w = -10.0$ °C
Freezing time (s)	66.7 ± 0.6	33.9 ± 0.6	20.4 ± 0.3
Height (mm)	1.45 ± 0.02	1.44 ± 0.02	1.37 ± 0.01

Table 2
Ratio of the ice bead height to boundary layer thickness ($y^* = Z/\delta$).

	y^*		
	$U_{air} = 11.0$ m/s	$U_{air} = 15.5$ m/s	$U_{air} = 20.0$ m/s
$T_w = -3.0$ °C	2.17 ± 0.03	2.57 ± 0.04	2.92 ± 0.04
$T_w = -6.5$ °C	2.15 ± 0.03	2.56 ± 0.04	2.90 ± 0.04
$T_w = -10.0$ °C	2.05 ± 0.01	2.43 ± 0.02	2.76 ± 0.02

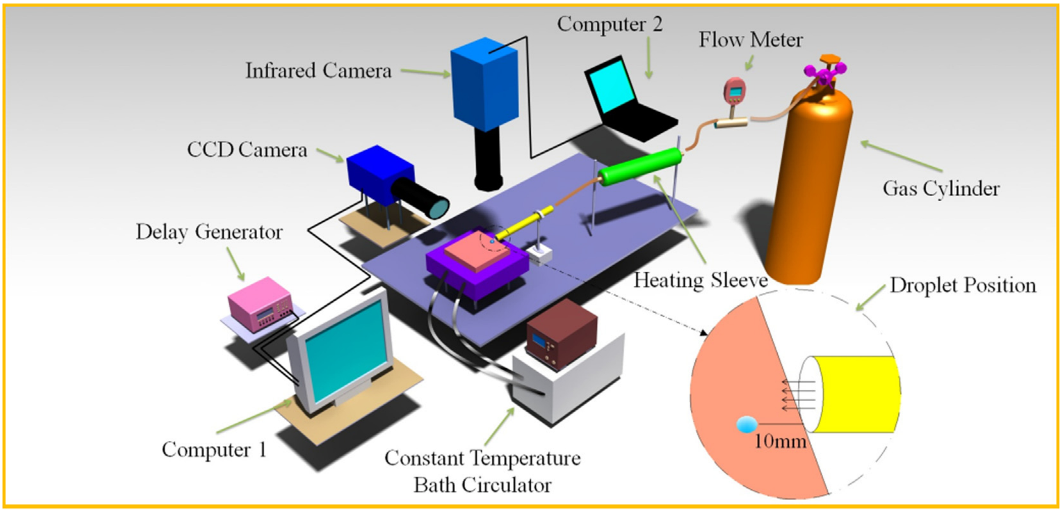

Fig. 1. Experimental setup.