A study on freezing of supercooled water droplet impacting on solid surfaces

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***Abstract*—An experimental study was performed to investigate the freezing characteristics of supercooled water droplets impacting on solid surfaces. Each water droplet was supercooled on a water-repellent guide-way in a cooled air environment, and then blasted horizontally by a jet of pressurized cooled air to impact on the vertical surface of a test block. The deformation and freezing of the droplets were observed using a high-speed camera. The droplets were frozen under various conditions of air temperature, wall temperature, blast velocity, and droplet volume. The experimental results indicate that the freezing time of the droplet is strongly affected by the degree of supercooling of the droplet. Furthermore, the experimental results revealed that the supercooling solidification consisted of two processes, the time scales of which differ greatly. Finally, the volumetric freezing velocity of the droplet has been expressed in terms of the changes in the droplet temperature and wall temperature.**

I. NOMENCLATURE

D	:	diameter[mm]
d_z	:	surface roughness[μ m]
T	:	temperature[℃]
t	:	time[ms]
U	:	velocity[m/s]
dV/dt	:	volumetric freezing velocity
V	:	volume[m^3]

Subscripts

a	:	air
d	:	droplet
0	:	initial

II. INTRODUCTION

Ice accretion of droplets in a cold airflow, may cause a variety of industrial problems such as icing on the wings or propellers of airplanes and atmospheric icing around the power-transmission lines. In particular, marine icing on the decks, handrails and antennas of boats in the northern sea increases the projected area and the weight of these boats. In this way, the phenomenon of ice accretion often causes serious delays and hazards in industrial work, and various structure-related accidents have been reported [1].

There have been several reports on the characteristics of ice accretion on the surfaces of structures. L. Makkonen [2], G.S.H. Lock et al. [3], and Horibe et al. [4] studied the mass and profile of ice accretion on a cylindrical surface. In addition, a number of studies on the de-icing and the anti-icing conditions have been carried out. From the point of view of heat transfer engineering, Horibe et al. [5] and Fumoto et al. [6] reported data on the minimum heat flux for anti-icing on a surface, and a number of methods for de-icing have been proposed in various studies [7]-[9].

There remains a need for further research into the fundamental mechanism of the freezing of droplets impacting on solid surfaces, which has not yet been conclusively determined. The freezing mechanism and the effect of various factors on ice accretion, for example, droplet temperature, air temperature, and air velocity have not yet been clarified. In addition, the freezing of an aqueous binary solution, such as seawater, is a markedly complicated phenomenon with the segregation of solute from the frozen layer. Thus, it may be necessary to investigate extensively the freezing characteristics of a droplet impacting on a solid surface. Recently, several experiments have been conducted using injected water spray droplets, in order to solve the mechanism of ice coating. However, spray freezing is a complicated dynamic and thermodynamic process. Moreover, sufficient conditions for icing or anti-icing on a solid surface have not yet been clarified, even through the use of a high-speed camera [10]. Therefore, a detailed understanding of icing behavior from a microscopic viewpoint is important.

A supercooled single droplet sticks and freezes rapidly when it touches a cooled object. The problem of solidification from a supercooled droplet has been discussed by Gao et al. [11] for a freely suspended cooled object and by Horibe et al. [12] and Fumoto et al. [13] for a cooled object installed on a wall. In addition, Matushima et al. [14] reported the impact on a solid surface by a single pure water droplet. However, the conditions of their experiment were limited.

The primary objective of the present study is to determine experimentally the effect of various parameters such as air temperature, wall temperature, droplet temperature, droplet velocity, and wall surface characteristics on the impact, and the freezing characteristics of both a pure water droplet and an aqueous binary solution droplet, and thus to provide fundamental information on ice accretion.

III. EXPERIMENTAL APPARATUS AND PROCEDURES

A. Experimental Apparatus

A diagram of the experimental setup used for icing a droplet in cold air is shown schematically in Figure 1. The main component of the experimental apparatus is a test box with a refrigeration system. The test box is made up mainly of an insulated box of 300 mm in height, 450 mm in width, and

350 mm in depth, the temperature of which is controlled in the range of 0 to -18ºC. The air temperature of the air stream and that near the droplet was measured by thermocouples (0.3 mm, C-A). The major components of the test box are a tent section, an evaporator, an air stirrer, a xenon light, and a high-speed imaging system.

The test section consists of a test block, an air nozzle, a water repellent guide, and a precision syringe. The test block is made from copper steel of three different surface roughnesses (d_z=0.61 and 1.08 μ m). The test block temperature is measured by thermocouples (0.3 mm, C-A) in the center of the block. The air nozzle is set up on one side of the water repellent guide. The air stream velocity injected from the nozzle is controlled by the air pressure of a compressor and the timing of an electric valve in range of 2.2 to 3 m/s.

The water repellent guide (length: 170 mm) was constructed from acrylic resin cut into a cylinder having a diameter of 300 mm in the direction of the circumference, and water-repellent paint (HIREC1550: NTT ADVANTEST Co., Ltd.) was applied to the inside of the cylinder. Water droplets are maintained in the state of the inside curvature part of the guide, as shown in Fig. 2. The droplet is injected from a precision syringe (resolution: 0.1 ml) from the top of the test box.

The high-speed imaging system was used to record the droplet impact process as a sequence of images. The specifications of the high-speed imaging system are listed in Table 1.

B. Experimental Procedures

The experiments were carried out under the steady state under a variety of prescribed air and test block temperatures. A droplet at room temperature of set volume is formed by the syringe. The water droplet is injected 2 minutes after leaving the syringe. The freezing and impact behavior on the solid surface was observed using the high-speed camera (Mothion Scope HR2000). The experiment was stopped when ice had formed on the test block surface. Air and block temperatures ranged between -8 and –15ºC. Droplet velocity ranged between 1 and 3 m/s, and the droplet volume ranged between 0.8×10^{-6} and 1.0×10^{-6} mm^3. Pure water was adopted as the test water.

The conditions of the tests are listed in Table 2.

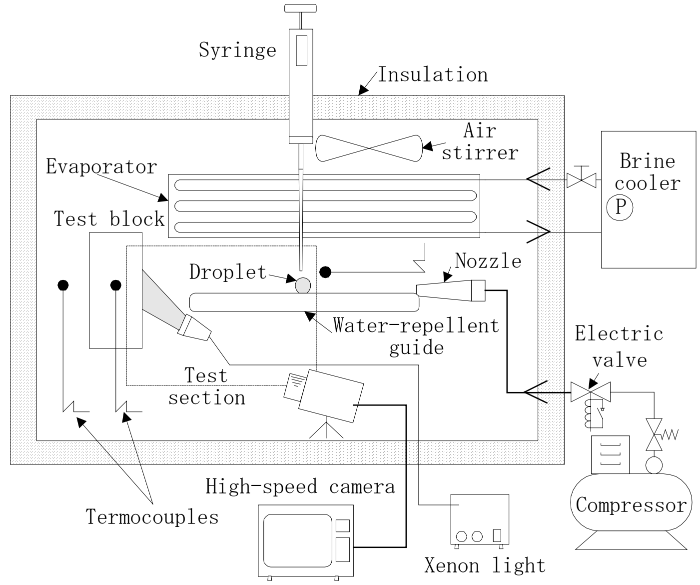
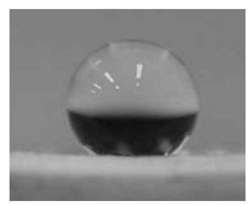


Fig. 1. Schematic diagram of the apparatus.



D=1.5mm
Pure water

Fig. 2. Droplet behavior on the water-repellant guide.

TABLE 1
FEATURE OF THE HIGH SPEED CAMERA

Screen	Monochrome
Frame rate	2000 frames/sec (Max:8000)
Exposure time	50 μ s (Max:6.25)

TABLE 2
EXPERIMENTAL CONDITION

Event number	T [deg C]	V [m^3]	D [mm]	U [m/s]	dz [μ m]
1	-8.8	1.0×10^{-8}	2.67	2.2	0.61
2	-11.7	1.0×10^{-8}	2.67	2.2	0.61
3	-15	1.0×10^{-8}	2.67	2.2	0.61
4	-8.7	0.8×10^{-8}	1.56	1.8	0.61
5	-11.5	0.8×10^{-8}	1.56	1.8	0.61
6	-15	0.8×10^{-8}	1.56	1.8	0.61
7	-8.5	1.0×10^{-8}	2.67	2.2	1.08
8	-11.6	1.0×10^{-8}	2.67	2.2	1.08
9	-15	1.0×10^{-8}	2.67	2.2	1.08

IV. EXPERIMENTAL RESULTS AND DISCUSSION

A. Freezing Characteristics of the Impacted Droplet on Block Surface

Droplet freezing process Figure 3 shows a sequence of photographs of the freezing of a droplet on the block surface. The experimental conditions are for the impact of pure water droplets (diameter: 2.67 mm) with a velocity of 2.2 m/s on a roughened surface (d_z = 0.61 μm) with air and block surface temperatures of -11.7 ºC. The photographs were taken using a camera inclined at an angle of 40º to the test block surface. The time shown in each picture is the lapse time after the first contact between the droplet and the block surface. Circular protrusions formed around the periphery of the droplet (Fig. 3(c)) as it spread. In the early stages of freezing, a dendritic ice structure was observed on the droplet surface (Fig. 3(d), indicated by an arrow). As the time progressed, the frozen layer in the droplet grew, stopping at 43 ms due to the freezing of the periphery of the droplet (Fig. 3(f)). However, the droplet profile continued to change. A planar ice layer in the droplet grew from the base toward the top of the droplet. The freezing of a supercooled water droplet occurred in two distinct stages, as follows. The first stage of freezing involves the formation of the ice shell. The total mass of water undergoing phase change causes the droplet temperature to rise rapidly to 0ºC due to the release of latent heat. During the second stage, the liquid interior gradually changes phase, and the latent heat of fusion must be transferred to the environment through the ice shell.

Effect of droplet temperature Figure 4 shows a sequence of photographs of the freezing of a pure water droplet with a velocity of 2.2 m/s, with air and block surface temperatures of -8.8 ºC. The experimental conditions were identical to those described for Fig. 3, except that the droplet temperature was raised to -8.8 ºC. This figure indicates that the formation speed of the ice shell in the early stages of freezing is reduced. This reduction in the formation speed occurs because the degree of supercooling of the droplet is small, and because the discharge of latent heat, which is transported from the impact droplet, is gradual. The tendency of this relationship between the freezing speed and droplet temperature was similarly observed for other conditions.

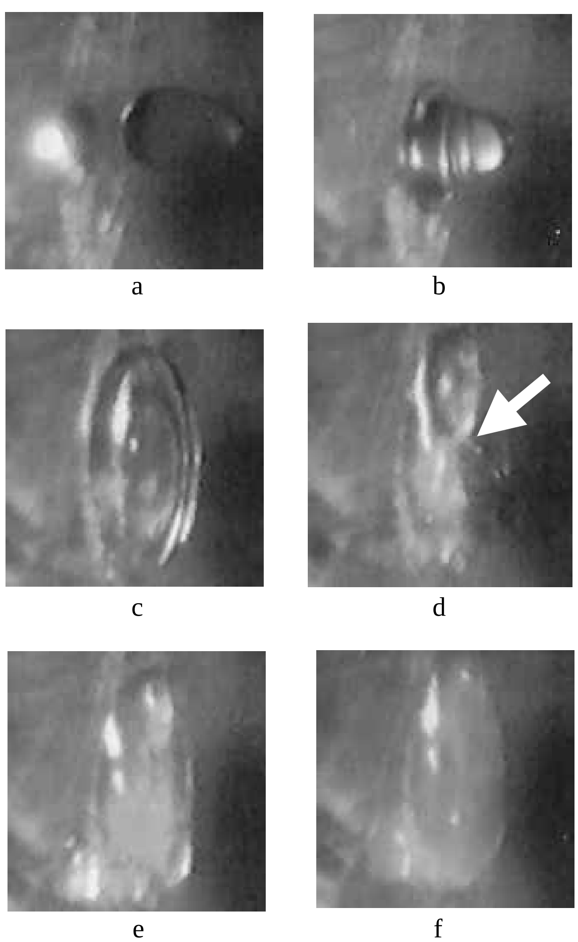


Fig. 3. Impact and freezing characteristics of supercooled droplet
T=-11.7 ℃, U=2.2 m/s, D=2.67 mm, dz=0.61 μm
Lapsed time; a: 0ms, b: 1ms, c: 3ms, d: 7ms, e: 13ms, f: 43ms

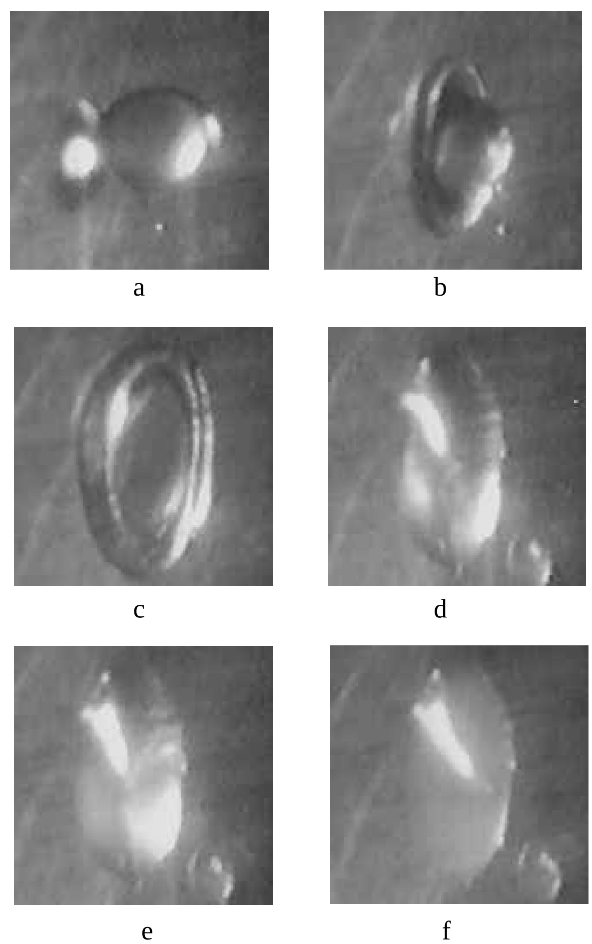


Fig. 4. Impact and freezing characteristics of supercooled droplet
T=-8.8 ℃, U=2.2 m/s, D=2.67 mm, dz=0.61 μm
Lapsed time; a: 0ms, b: 1ms, c: 3ms, d: 344ms, e: 467ms, f: 567ms

Effect of droplet diameter Figure 5 shows a sequence of photographs of the freezing of a pure water droplet with a velocity of 1.8 m/s, with air and surface temperatures of -11.5 ºC. The experimental conditions were identical to those described for Fig. 3, except that the droplet diameter was decreased to 1.56 mm. In the early stages of freezing, a dendritic ice structure was observed on the droplet surface as was the case for the conditions described for Fig. 3 (Fig. 5(b), indicated by an arrow). At this small droplet impact, splashing was not much more pronounced than for the 2.67-mm-diameter droplets (compared to Fig. 3), producing a large amount of debris ahead of the spreading rim (Fig. 5(c)).

Effect of block surface roughness Figure 6 shows a sequence of photographs of the freezing of a droplet that illustrates the effect of block surface roughness on the freezing characteristics. The experimental conditions are for the impact of pure water droplets (diameter: 2.67 mm) with a velocity of 2.2 m/s on a surface with air and block surface temperatures of -11.6 ºC. The experimental conditions were identical to those described for Fig. 3, except that the surface roughness was increased to 1.08 μm. As the block surface roughness was rough, the droplets were observed to smoothly spread over the block surface (Fig. 6(c)). Therefore, compared to the impact shown in Fig. 3, the freezing area due to the collision of the droplet was large. On the other hand, according to Matsushima et al. [2], the application of a water-repellent to the block surface will cause the water droplet to rebound after collision, thus preventing the droplet from freezing on the block surface.

B. Volumetric Freezing Velocity of Droplet

Figure 7 shows the measurement results of the volumetric freezing velocity using the high-speed camera. The vertical and horizontal axes show the mean volumetric freezing velocity and air temperature, respectively. The parameter is the droplet diameter. The volumetric freezing velocity was calculated by the following formula using droplet volume (V_d) and freezing time (t_f).

$$\left(\frac{dV}{dt}\right)=\frac{V_d}{t_f} \qquad \left[m^3/s\right]$$

The freezing time includes the first stage of freezing, which involves the formation time of the ice shell. Figure 7 shows that the volumetric freezing velocity increases linearly with the decrease of the droplet temperature.

V. Summary and Conclusions

Observations on the freezing of the impacting droplet revealed interesting and important phenomena. Basic information obtained concerning the freezing characteristics can be used in the design and optimization of a de-icing system. The conclusions drawn from the experimental observations are as follows:

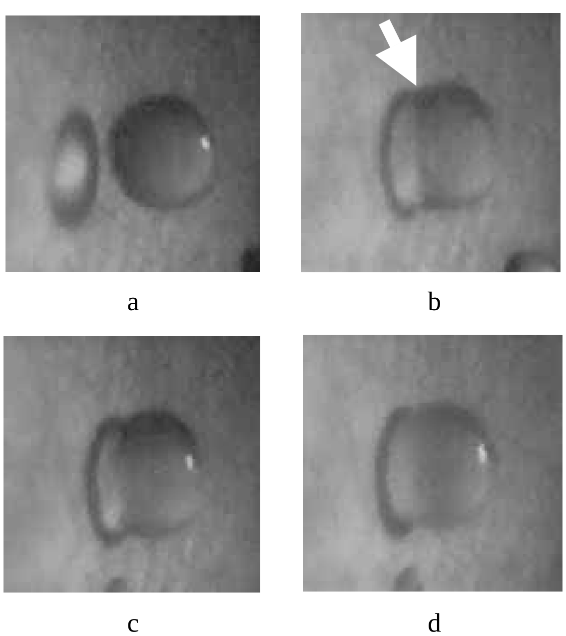


Fig. 5. Impact and freezing characteristics of supercooled droplet
T=-11.5 ℃, U=1.8 m/s, D=1.56 mm, dz=0.61 μm
Lapsed time; a: 0ms, b: 1ms, c: 6ms, d: 13ms

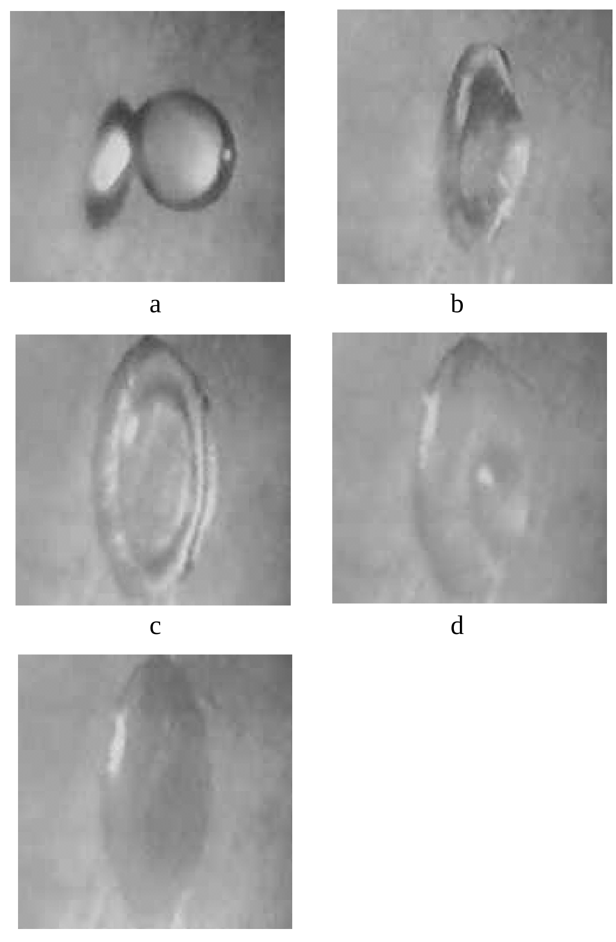


Fig. 6. Impact and freezing characteristics of supercooled droplet
T=-11.6 ℃, U=2.2 m/s, D=2.67 mm, dz=1.08 μm
Lapsed time; a: 0ms, b: 1ms, c: 3ms, d: 8ms, e: 77ms

(1) For the impacting droplet, freezing starts at the interface between the block and the surface of the droplet, after which dendrites grow along the surface of the droplet.

(2) Volumetric freezing velocity increases linearly with the decreases of the droplet temperature.

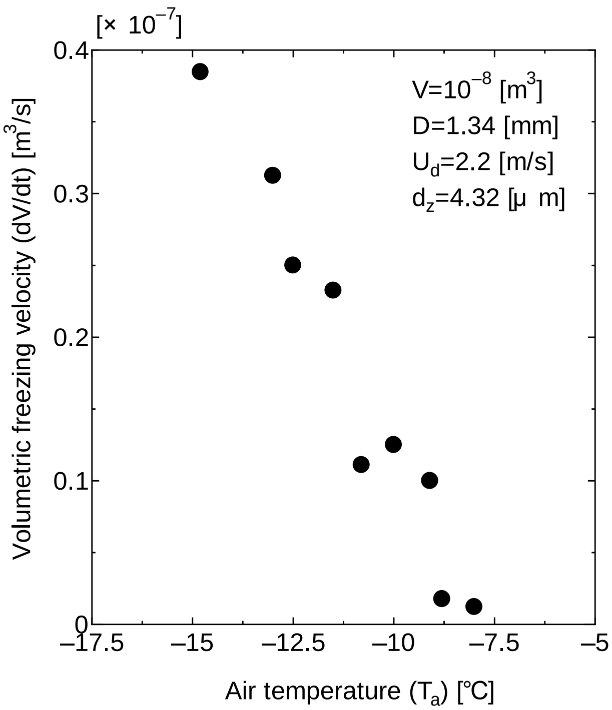


Fig. 7. Volumetric freezing velocity

VI. References

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