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On the Rebound of Supercooled Droplets Colliding with Ice Plate (II)

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Abstract

Water droplets ranging from 60 to 160 μm and from 200 to 300 μm in size were collided with an ice shell covered with the brass pipe of 1.5 cm in diameter. The experiments were carried out in the environment temperature of -10 to -25°C .

The rebound was observed in the droplets ranging from 200 to 300 μm and at the temperatures of -20 and -25°C at the rate of about 2%. When the rebounded droplets were taken on a sampling tray, they were almost all frozen. The rate of rebound was greatly dependent on the impact angle of droplets in that this rate increased to about 5% at the collision approaching to the grazing incidence.

It was found that the occurrence of rebound of supercooled droplets was restricted within the certain ranges of Weber number of colliding droplets and the environment temperature. For example, according to the considerations given so far, the convenient Weber number is about 0.15 to 0.8 at the temperature of -15°C . This condition is sufficiently satisfied on the collision of rimed snow crystals or graupel particles with natural cloud droplets.

1. Introduction

It has been emphasized by Mason¹⁾ that the rebound of cloud droplets from hail pellets during the growth process is very important for the charge separation in thunderstorms. As one of the phenomena which show the possibility of rebound, the rolling or sliding of droplets under 5 μm in diameter on ice surface was observed by Nakaya et al.²⁾ for the first time.

Aufdermaur and Johnson³⁾ found that a rime pellet acquired the appreciable charge due to the rebound of supercooled droplets ranging from 20 to 100 μm in diameter at grazing incidence. In their experiments, the rate of rebound was about 0.1 to 1% of accreted droplets and the droplets leaving from the rime pellet remained liquid. However, it is quite possible that the nucleation of collided droplets will start at the contact part on rime pellet and

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soon after the some rebounded droplets freeze, under certain different conditions from those of their experiments.

In order to confirm the possibility of this idea, a preliminary experiment was performed by one of the authors⁴⁾. According to this experiment, when the supercooled droplets ranging from 120 to 200 μm in size collided with an ice plate at their terminal velocities and in the temperatures of -15 to -20°C , the rate of rebound was 2 to 3% and the rebounded droplets were frozen. On the other hand, Aufdermaur and Larsen⁵⁾ reported the result of experiments in which the collisions at grazing incidence between the simulated hailstone of 7 mm in diameter and water drops of 1.4 mm in diameter produced the splash products of ice with the rate of 22% at the temperature of -10°C and with the impact velocity of 2 $\text{m}\cdot\text{sec}^{-1}$. Although the impact angle on the phenomenon of rebound is a very sensitive factor, it seems that there still remains a problem that the diameter of drops was considerably larger than that of natural cloud droplets in their experiments.

The purpose of this experiment reported here is to clarify the effects of size, impact velocity, impact angle and environment temperature of supercooled water droplets on the phenomenon of rebound, taking into account the previous results of experiment⁴⁾.

2. Experimental apparatus and method

The apparatus for this experiment is shown in Fig. 1. Water droplets were made by an atomizer which contained the distilled water along with tiny pellets of ice at temperature about 0°C . The metal of exit of atomizer was earthed to remove electrical influences.

The droplets were allowed to fall at their terminal velocities through the inside of metal cylinder, which was covered with cloth to prevent the growth of frost. Then these droplets collided with an ice shell covering over an earthed brass pipe (1.5 cm in outer diameter), which was fixed in the wooden observation chamber. It can be considered from the calculation based on the method of Hobbs and Alkezweeny⁶⁾ that the droplets were close to the thermal equilibrium state with their environment prior to the collision to ice shell. The smooth surface of ice shell (about 200 μm in thickness) was produced by soaking the cooled brass pipe into supercooled distilled water during several seconds.

The trajectories of falling droplets illuminated by a stroboscope and a tungsten lamp were photographed with a close up camera from the direction

of axis of pipe. In order to ensure the correspondence of droplets to trajectories and to reduce the temperature change of ice shell owing to the latent heat of riming droplets, the number of colliding droplets was restricted within about twenty at one time utilizing a slit. At the collision of droplet, the fresh parts of ice shell were selected by means of the rolling pipe on its axis.

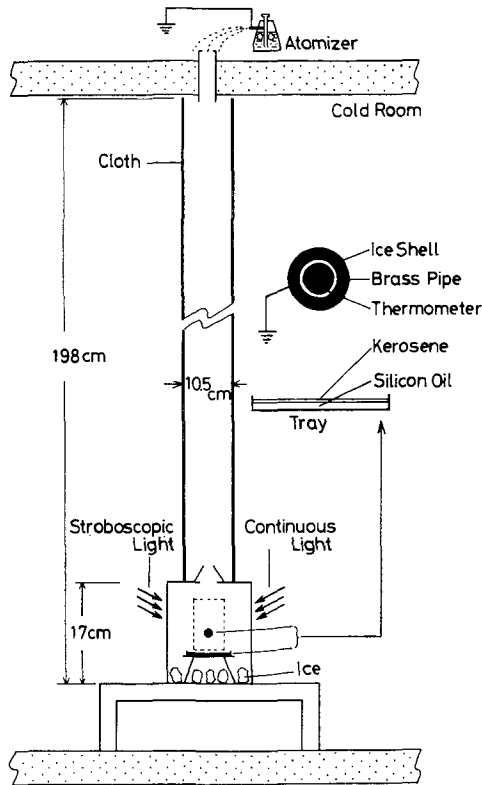


Fig. 1 Experimental apparatus with details of collision plane.

The diameters of collided droplets were decided by the values of falling velocities, which were calculated from the trajectories of droplets on photographs with time marks through the stroboscopic light. The impact angle was decided from the collided points on ice shell in the photographs. The impact angle of 0° means the grazing collision of droplets with ice surface.

The observation chamber was made airtight in order to diminish the turbulent motion of air in it. Moreover, some ice blocks were placed in its bottom

so that it might assume the condition of ice saturation as closely as possible. When the brass pipe was removed, the fallen droplets were sampled by a shallow tray containing kerosene and silicone oil. And then it was checked strictly by means of a polarizing microscope that the droplets were not frozen prior to the collision with ice shell.

The environment temperature was measured by a thermometer inserted to the brass pipe, as shown in Fig. 1. The fluctuation of temperature in the observation box was in the range of $\pm 1^\circ\text{C}$, because the cold room temperature was controlled automatically at a fixed value. Therefore, it can be considered that the temperature of ice shell was approximately equal to the environmental value.

3. Results

The two types of atomizers (Atomizer A and Atomizer B) were used in this experiment to prepare the water droplets of different size. The size distribution of fallen and collided droplets is shown in Fig. 2.

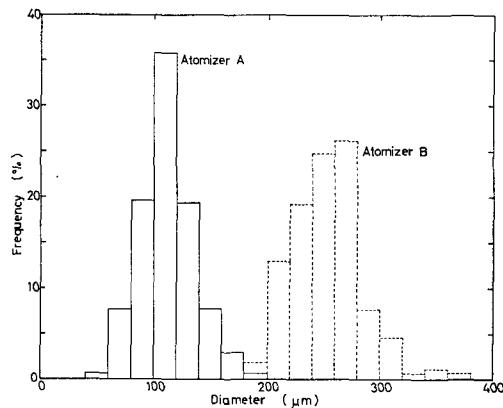


Fig. 2 Size distribution of supercooled water droplets.

Although the experiments were performed at the environment temperatures of -10 , -15 , -20 and -25°C (only Atomizer B), the rebound of droplets collided with ice shell was observed in the case of Atomizer B at the temperatures of -20 and -25°C . Examples of rebounding droplets are shown in Fig. 3. The photographs of rebounded droplets taken by polarized light are shown in Fig. 4. As seen these photographs, the rebounded droplets

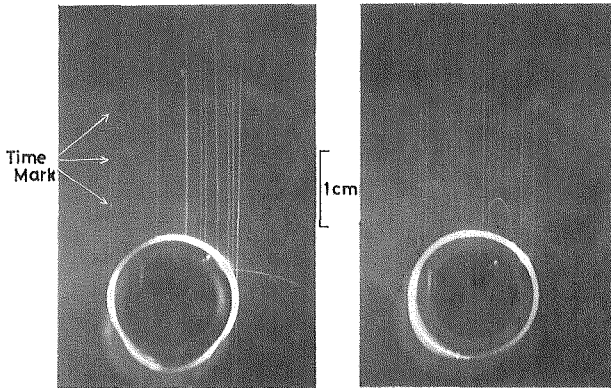


Fig. 3 Photographs of rebounding droplets. Time interval of stroboscopic light is $1/100$ sec.

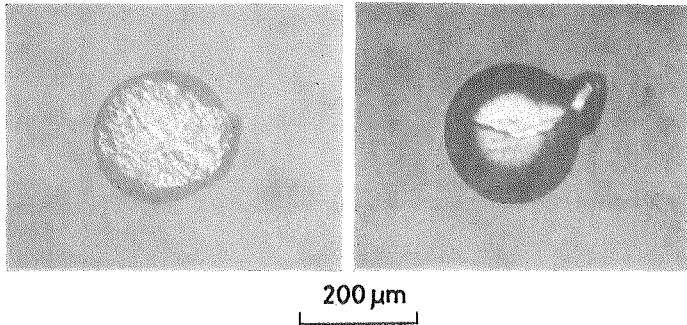


Fig. 4 Photographs of rebounded droplets taken by polarized light.

were almost all frozen, which state is the same as that of the result of the previous experiment⁴⁾.

Table 1 is the result of collision and rebound of droplets, in the case of Atomizer B. From a viewpoint of the number of colliding droplets, the calculation of the rate of rebound was restricted to a definite ranges of diameters. Unfortunately the terminal velocities of about one third of collided droplets could not be decided, because their trajectories on photographs were not accompanied with the distinct time marks (see Fig. 3) through the stroboscopic light. Therefore, the number of droplets (N) with fractions was estimated by considering the diameters of droplets with uncertain time marks to be the same frequency (Fig. 2) of droplets, which had the distinct time marks

Table 1. The result of collision of supercooled droplets with ice shell at their terminal velocities.

Diameter of droplet (μm)	Environment temperature					
	-20°C			-25°C		
	Number of droplet (N)	Number of rebound (n)	Rate of rebound $n/N \times 100(\%)$	Number of droplet (N)	Number of rebound (n)	Rate of rebound $n/N \times 100(\%)$
181-200	14.3	0	—	12.7	0	—
201-220	96.3	2	2.1	86.1	3	3.5
221-240	142.7	1	0.7	127.5	4	3.1
241-260	183.8	1	0.5	164.2	2	1.2
261-280	194.4	1	0.5	173.7	1	0.6
281-300	57.1	0	0	51.0	1	2.0
301-320	33.9	0	—	30.2	0	—
321-340	5.3	0	—	4.8	0	—
341-360	8.9	0	—	8.0	0	—
361-380	5.3	0	—	4.8	0	—
Unknown		3			5	
Total	742	8	1.1	663	16	2.4

on photographs. For the same reason described above, the diameters of several rebounded droplets were unknown.

It can be seen from Table 1 that the rebound of droplets in the range of 201 to 280 μm was observed at the rate of about 1% at the environment temperature of -20°C. On the other hand, the rate of rebound increased to about 2% at the temperature of -25°C in the range of 201 to 300 μm .

The effect of impact angle is shown in Table 2. It is worthwhile to note that the rate of rebound increased violently with the decrease of impact

Table 2. The rate of rebound at various impact angles.
The angle 0° means the grazing collision.

Impact angle (deg.)	Environment temperature (°C)					
	-20			-25		
	Number of droplet (N)	Number of rebound (n)	Rate of rebound $n/N \times 100(\%)$	Number of droplet (N)	Number of rebound (n)	Rate of rebound $n/N \times 100(\%)$
0-30	81	3	3.7	51	3	5.9
31-60	208	2	1.0	242	7	2.9
61-90	453	3	0.7	370	6	1.6
Total	742	8	1.1	663	16	2.4

angle. A reason of this change of rate is considered to be the increase of tangential component of the kinetic energy of collision.

4. Discussion

It was the same result as that of the previous experiment⁴⁾ that no rebound was observed at the temperature of -10°C . In this temperature of ice surface, the existence of liquid-like layer^{7),8)} could be considered to be one factor affecting the rebound of droplets. Namely, the collided droplets will spread and adhere easily to ice surface under these experimental conditions; size of droplets, impact velocities and radius of curvature of ice surface.

Although the rebound of droplets in the range of diameters from 121 to 180 μm was observed in the previous experiment at the temperature of -15°C , no rebound was occurred in the range of diameters 201 to 300 μm and 61 to 160 μm in this experiment. This fact suggests that the suitable size range for the rebound of droplets existed under one temperature condition. As the environment temperature rises, the suitable range of size for rebound becomes smaller to some extent as seen in Table 3. This table contains the results of impact angle from 60° to 90° selected from Table 1 as well as the results of previous experiment⁴⁾.

The reason of existence of this suitable size at fixed temperature may be considered mainly as follows. When the smaller droplets contact with ice surface, they will freeze rapidly in their whole volumes. Therefore the de-

Table 3. The rate of rebound under the various conditions of diameter and temperature at the impact angles of 60° to 90° .

Diameter of droplet (μm)	Environment temperature ($^{\circ}\text{C}$)			
	-10	-15	-20	-25
61- 80	0 (%)	0 (%)	0 (%)	(%)
81-100	0	0	0	
101-120	0	0	0	
121-140	0 (0)	0 (2.5)	0 (0)	
141-160	0 (0)	0 (3.5)	0 (1.3)	
161-180	(0)	(2.0)	(2.1)	
181-200	(0)	(0)	(1.8)	
201-220	0	0	1.7	2.1
221-240	0	0	1.1	1.4
241-260	0	0	0	1.1
261-280	0	0	0.8	1.0
281-300	0	0	0	0

() Kajikawa⁴⁾

formation and following recovery of droplets required in their rebound is insufficient. On the other hand, when the size of droplets is larger than the suitable diameter at one temperature, the deformation becomes greater and also freezes rapidly before the sufficient recovery of their shapes, because the area of contact of the collided droplets with ice surface increases. When the environment temperature decreases, because of the acceleration of freezing speed, the suitable size for rebound of droplets slightly shifts to the larger size range.

In general, the results of the collision and rebound dynamics can be expressed in terms of the Weber number (We)^{9),10)},

$$We = \frac{\rho d v^2}{\sigma}$$

where ρ , d , v , σ are the density, diameter, impact velocity and surface tension respectively. The Weber number is proportional to the ratio of the kinetic energy to the surface energy of droplets. Accordingly, the smaller We is the less is deformation of colliding droplets and hence the less likely occurrence of rebound. When the rebound of droplets was observed, because We was nearly 1 in this experiment, both effects of the surface tension and inertia are not negligible. In addition to these effects, it can be considered that the freezing velocity or probability of supercooled droplets and the curvature of ice surface are concerned with the rebound of them.

Fig. 5 shows the ranges of We and the environment temperature for rebound at the impact angles of 60° to 90°. There is a trend toward larger We with descending temperature, although the rebound of droplets occurred in We range of about 0.15 to 3. It is evident from this figure that the droplets smaller than 60 μm in diameter also have the possibility of rebound, if the impact velocity increases beyond their terminal velocities. For example, We is 0.3 as the droplets of 30 μm in diameter collide with the impact velocity of 89 $\text{cm}\cdot\text{sec}^{-1}$ at the temperature of -15°C . From the point of view of their falling velocity^{11),12)}, the collisions of the rimed snow crystals or the graupel particles with the supercooled cloud droplets sufficiently satisfy this condition.

According to the experiment of grazing collision by Aufdermaur and Larsen⁵⁾ the probability of freezing of splashed droplets is concerned to the curvature of ice surface. In connection with this subject, it is assumed that the rebound of droplets is also affected by the curvature of ice surface.

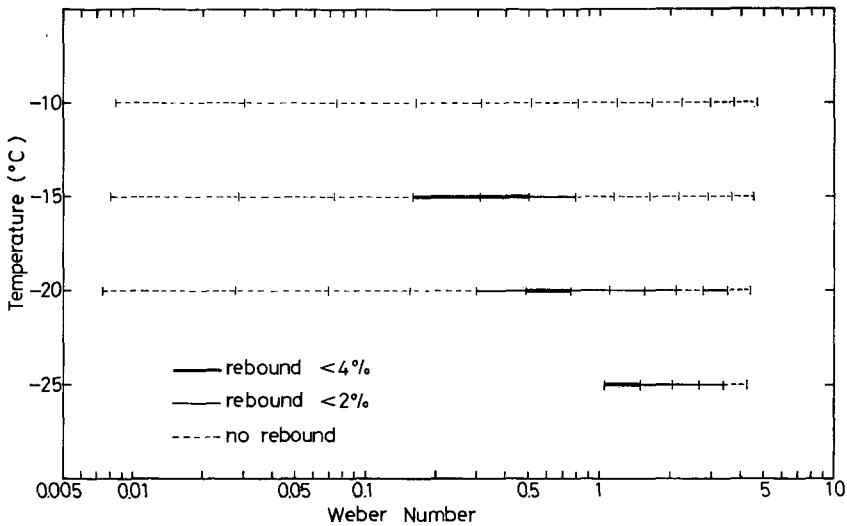


Fig. 5 The ranges of Weber number and environment temperature for the rebound of droplets at the impact angles of 60° to 90° .

Therefore, the rebound of droplets seems to be probable in the case of the ice surface with larger curvature, such as the rough surface of rimed snow crystals or graupel particles, than in the case of this experiment (7.7 mm in radius of curvature of ice shell) even at the temperature of -10°C due to the effect of impact angle.

5. Concluding remarks

When the supercooled water droplets collided with an ice surface at their terminal velocities, the rate of rebound was about 1 to 2% at the impact angle of nearly 90° and size range of 200 to 300 μm and the rebounded droplets were almost all frozen. The rate of rebound was affected by the various conditions as shown in Tables 1 and 2. For example, this rate increased to 5% as the impact angle approached to the grazing incidence of 0° .

It has been found that the ranges of occurrence of rebound can generally be described by the Weber number and the temperature condition of ice surface, as seen in Fig. 5. These results indicate that there is a possibility of rebound and subsequent freezing of supercooled cloud droplets colliding with the rimed snow crystals or graupel particles, although the present experiment is insufficient in the sense that the diameters of droplets were larger than that

of natural snow clouds and impact velocities were also smaller than natural cases.

The phenomenon of freezing of rebounded droplets can be applied to explain the multiplication of the number of ice particles in cumulus clouds.

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