Supercooled Cloud Tunnel Studies on the Growth of Snow Crystals between -4 and -20°C

By Tsuneya Takahashi* and Norihiko Fukuta

*Department of Meteorology, University of Utah,
Salt Lake City, Utah 84112,
U.S.A.*

(Manuscript received 2 June 1988, in revised form 2 September 1988)

Abstract

Snow crystal growth in free fall by vapor diffusion under water saturation and riming was studied up to 30 min in a supercooled cloud tunnel.

The results showed that: 1) the growth rates were pronouncedly highest along a -axis at -15°C and along c -axis at -5.5°C . Each peak coincided with the growth of dendrites and needles, respectively; 2) polycrystalline snows, consisting of spatial dendrites and spatial plates, were observed very frequently below -15°C ; 3) the variation of fall velocity with growth time could be expressed by two straight lines, except for the temperature zone of dendritic crystal growth, where a curve and straight lines were fitted; 4) the empirical relations between crystal fall velocity and growth time under constant temperatures were divided into two groups. In the higher fall velocity group, isometric crystals grew and were rimed; in the lower fall velocity group, shape enhancement occurred during continuing vapor diffusional growth. The crystals in the former group dropped from 700 to 800 m, and those in the latter only 300 to 400 m in 30 min; 5) isometric crystals grown at around -10°C changed into graupel. The growth mode was represented by three stages: vapor diffusional, transitional and graupel growths. The crystal mass was roughly proportional to $t^{1/2}$, t^2 and t^6 in each corresponding stage. In the vapor diffusional and graupel growth stages, the particles followed Stokes' and Newton's laws of resistance, respectively.

1. Introduction

It is a prerequisite to understand the growth processes of snow crystals for studying the natural snowfall mechanism as well as the seeding effects of supercooled clouds in weather modification. In order to obtain the necessary knowledge, reproduction of the processes in the laboratory under clearly controlled conditions is highly advantageous.

In pursuit of the origin of snow crystal shape variation, Nakaya (1954) grew for the first time a few snow crystals on rabbit hair in a convection-

type chamber, which resulted in a successful growth habit reproduction. Subsequently, Hallett and Mason (1958) used fiber-held ice crystals in a diffusion-type cloud chamber, whereas Kobayashi (1961) exposed them to supersaturated air, obtained by mixing two ice-saturated air streams, to study the growth of individual snow crystals. Unfortunately, the free-fall behavior of a snow crystal during the growth could not be obtained from these experiments due to the fact that the processes of heat dissipation from the static crystal and the diffusion field of water vapor to it were different from those of natural snow crystals. On the other hand, Schaefer (1946) generated artificially a large number of ice crystals in a supercooled cloud; the growth in

*Present affiliation: Institute of Low Temperature Science, Hokkaido University

this experiment took place under free-fall conditions, although the crystal diameters attained were only of the order of several tens of micrometers, and the crystal growth apparently happened below water saturation due to growth competition among them. Fukuta (1969) made the first attempt to determine quantitatively and simultaneously the growth and fall parameters of ice crystals under free-fall conditions at water saturation without competition for available water vapor; the growth period was only about 1 min. Ryan *et al.* (1974 and 1976) and Michaeli and Gallily (1976), extended the growth period to about 3 min, but they did not investigate the crystal fall velocity.

Fukuta (1980) considered the development of fast-falling ice crystals at -10°C and predicted that by applying a simple treatment to them, there would be a high probability of them growing into graupel and hail embryos. Later, Fukuta *et al.* (1982) succeeded in suspending and growing ice crystals for 10 min using a newly devised vertical, supercooled cloud tunnel, which applied an aerodynamical mechanism for horizontal stability of ice crystal suspension, and determined ice crystal growth parameters in it. In this case, the crystal size attained was almost that of typical natural snow crystals (*e.g.* 2 mm in diameter for a dendritic crystal). Fukuta *et al.* (1984) extended the crystal growth time further and experimentally showed that the isometric crystals grown at around -10°C have indeed a tendency to develop appendages and become graupel. Furthermore, the difference in growth-mode switch from vapor diffusion to riming of graupel and hail type under different temperatures was discussed; due to the long time period needed for each measurement, the amount of systematic data obtained was rather small. On the other hand, the modeling study of Bruintjes *et al.* (1987) revealed that crystals grown at around -10°C are potentially important as graupel embryos in initiating precipitation in growing cumulus congestus clouds. These crystals were actually observed in natural graupel (Takahashi and Fukuta, 1988).

In this paper, we report the results of snow crystal growth measurement that extended to 30 min of growth time using an improved super-

cooled cloud tunnel: the maximum sizes of dendrites and needles grown were 5 mm in diameter and 2 mm in length, respectively, which are almost equal to the maximum sizes of natural snow crystals (Pruppacher and Klett, 1978). We also describe the results of experiments on graupel growth at around -10°C .

2. Experiment

The present study was carried out in the vertical supercooled cloud tunnel, in which a snow crystal can be suspended freely and grown by applying aerodynamical mechanisms for horizontal stability, similar to that described in detail by Kowa (1981) and Fukuta *et al.* (1982, 1984). This apparatus has the following advantages: 1) the snow crystal growth in free fall can be simulated for desired periods of time under different temperatures; 2) there is no competition for water vapor between adjacent snow crystals because only one snow crystal is grown at a time; 3) temporal variation of fall velocity due to the growth of the snow crystal can be measured continuously.

Figure 1 illustrates the supercooled cloud tunnel. It consists of seven sections: steam generator, fog chamber, 1st suction chamber, working/observation section with a honeycomb, 2nd suction chamber, velocity control valves and air suction device. The steam generator is a specially modified pressure cooker containing a heater with the carrier compressed air bubbling through it. The fog is generated by uniformly mixing the steam laden air disbursed from the holes on a 90 cm copper pipe, which is wrapped by a heat insulator, into the cold air, which is introduced by the suction device using a vacuum cleaner.

To make the fog uniform, three vertical partitions are used to divide the fog chamber (120 cm long, 150 cm high and 90 cm wide) into four sections. While the fog moves through these sections, turbulence is damped, and the fog becomes uniform both in temperature and droplet concentration. The fog is rectified by a honeycomb made of plastic soda straws (6 mm in diameter, 10 cm in length) and then is introduced into the working/observation section, where the snow crystal is to be suspended freely.

Fig. 1. The vertical supercooled cloud tunnel.

A conical clear cylinder, 94 cm long and convergent, i.e. 17 cm in bottom diameter and 10.2 cm in the top, is used as the working/observation section. The suspending position of ice crystal is 45 cm above the honeycomb top. This convergent configuration of the section provides excellent horizontal stability for the crystal suspension.

Figure 2 shows an example of upward wind

Fig. 2. Example of upward wind velocity profile across the working/observation section at 35 cm above the honeycomb.

velocity profile across the cylinder 35 cm above the honeycomb; it is flat in the center and higher near the wall due to the convergent effect. By operating velocity control valves constantly in order to keep the position of the crystal, the upward wind velocity in the middle is adjusted to the terminal fall velocity of the floating snow crystal. To observe the snow crystal, the dark-field illumination method is using a quartz-halogen automobile light beam from the side.

The air velocity control valves fractionate the flow into the working/observation section and into the 1st suction chamber without changing the total flow rate, thus preventing a fog condition change. The excess supercooled droplets are removed from the fog by icing while passing through the two suction chambers. The crystal growth time has been extended to 30 min by improving these functions. If a radiator with fins spreading out radially in the 1st suction chamber became iced up, it was removed and the ice was melted at room temperature for reuse. In the 2nd suction chamber, supercooled droplets of the fog also caused icing in the rotated foam rubber sheet, but the ice was continually removed by melting with a heater and being sucked up by the bypassed tunnel air.

A typical experiment proceeds as follows:

first, the cold room air is introduced into the tunnel by the air suction device and stabilized while passing through the honeycomb. Then, compressed air is applied to the hot water in the steam generator. The generated steam is led to fog chamber and mixed with the cold air to form supercooled fog droplets. After a stable condition is attained with the supercooled fog in the tunnel, ice crystals generated by adiabatic expansion/cooling of air in a separate small chamber are supplied to the tunnel by a large ice-lined squirt. To suspend a snow crystal freely at a particular point in the working/observation section, the upward wind velocity is adjusted to the terminal fall velocity of the snow crystal by the velocity control valves. The velocity increases gradually as the crystal grows. The crystal is sampled on a cover glass coated with motor oil. Its removal from this section is done by placing the glass in the upstream side at each temperature after the desired growth time (growth time of snow crystals is measured from the time when ice crystals are supplied to the wind tunnel). The sampled snow crystal is then sandwiched between two immiscible oils, motor oil and silicone, the former being lighter than ice and the latter (DC 550) heavier than water. Under the microscope, the snow crystal is rotated by applying shear to the liquid through lateral movement of the cover glass and photographed from the top as well as from the side, except for needles and dendrites. The snow crystal is melted by applying a soldering iron from below, and the diameter of the formed drop is measured to determine the crystal mass.

Experiments were carried out under the following conditions: 1) temperature ranging from -4 to -20°C ; 2) water saturation and liquid water content below 0.5 g m^{-3} over the entire experimental temperature range except 2 g m^{-3} at around -10°C ; 3) growth time up to 30 min in 5 min increments. The latter value of the liquid water content is comparable to that in cumulus congestus or cumulonimbus (Mason, 1971). The fog temperature and crystal fall velocity were measured by a copper-constantan thermocouple and a hot-wire anemometer, respectively, and monitored continuously by a strip-chart recorder. The air temperature rise during a 30 min

crystal growth time ranged from 0.4 to 1.6°C , 0.8°C being on the average. The temperature rose gradually due to the thermal load from the steam generator with the liquid water content of 2 g m^{-3} : the rise being 0.9°C at 10 min after injection of seed crystals to the wind tunnel, and 3.7°C after 27.5 min. Wind velocity was measured in the plastic pipe leading to the air suction device. By multiplying the pipe velocity by a predetermined factor, the actual wind velocity to suspend a snow crystal, i.e. the fall velocity of the snow crystal, was estimated. The hot wire anemometer was compared with the Pitot tube method of determining the air velocity: the difference of wind velocities obtained by the two methods was less than 4 percent. The liquid water content of the fog was inferred from the temperature and the dew point of air obtained by evaporating the fog, which was measured by a mirror-type dew point hygrometer after the snow crystal was sampled.

An example of the cloud droplet size distribution, measured simultaneously by an FSSP (Forward Scattering Spectrometer Probe, Particle Measuring System, Boulder, Colo.) and an impaction method, is shown in Fig. 3: the peak diameter measured by the FSSP was $11\text{ }\mu\text{m}$ and was about $5\text{ }\mu\text{m}$ larger than that obtained by the impaction method. This may be because systematic oversizing of cloud droplets occurred due to

Fig. 3. Comparison of cloud droplet size distributions for fogs with liquid water content of 0.4 and 2 g m^{-3} respectively, obtained by the FSSP and the impaction method.

the coincidence of particles in the laser beam of FSSP (Baumgardner, 1983). Peak diameter measured by the FSSP was $25\text{ }\mu\text{m}$ for a liquid water content of 2 g m^{-3} . There were no noticeable changes in the size distribution throughout the experiment.

Experiments were carried out at the University of Utah, Salt Lake City, whose altitude is about 1300 m above mean sea level and pressure at about 860 mb.

3. Results

a. Crystal habit

Figure 4 shows examples of the snow crystals obtained in these experiments: the photographs shown for the same temperature are different crystals grown for respective periods of time. Habit variation with different temperatures was observed: columns ($-4\sim-10^{\circ}\text{C}$) and plates ($-10\sim-20^{\circ}\text{C}$). Shape enhancement occurred at around -5.5°C and between -14 and -16°C : needles grew at around -5.5°C . Between -14 and -16°C , the crystal shape changed in time

Fig. 4. Snow crystals grown at different temperatures. The growth time of each snow crystal is shown in each photograph.

from sectors (or hexagonal plates) to dendrites. In the plate growth region, most of the crystals were double plates; especially, corners on one of the plates grew in the case of dendrites, and in some cases, six branches grew in two separate planes. It was inferred from the displacement between both plates determined under the microscope that the crystal fell with the smaller plate oriented downward, as pointed out by Iwai (1983).

At temperature below -15°C , polycrystalline snows consisting of spatial dendrites and spatial

plates, were frequently found to grow. This polycrystalline form may have occurred by capturing and freezing cloud droplets on the crystal surface, because single-crystalline crystals were expected in the early growth stage of ice crystals produced by the "popping bubble" technique (Ryan *et al.*, 1976). This result agreed qualitatively with the experimental result in which supercooled droplets were captured at different temperatures on the plate surface of a single ice crystal (Magono and Aburakawa, 1968) and on the ice crystal surface (Takahashi, 1979). In the

latter experiment, polycrystalline frozen droplets of 20 – 100 μm in diameter appeared on a basal plane when accreted at temperatures below -13°C , and all of the accreted droplets were polycrystalline at temperatures below -19°C . When a polycrystalline ice particle grew large, its suspension became difficult because it moved erratically.

It was observed with the naked eye that a planar crystal fell with its a -axis horizontal while a columnar crystal fell with its c -axis in that position. At -4°C and from -8 to -11.5°C , isometric crystals grew. At 10 to 20 min after the seed crystal introduction, riming growth commenced and subsequently graupel-like crystals were formed. Riming began from the basal plane of the plate as well as from the prism face of the column. Rime droplets were formed with the same orientation as that of isometric crystals and grew by vapor deposition: columns grew on the basal plane of a plate, and plates developed on the prism face of a column to the same extent. As the riming progressed, droplets began to be captured on both basal (plate) and prism faces (column); this result was most likely due to either crystal tumbling (rotation) or change of the aerodynamic status of the crystal. After this, the riming portions on the crystal edges developed further. Figure 5 shows the snow crystals

grown at around -10°C with the liquid water content of 2 g m^{-3} . Only a few water droplets were captured by the isometric crystal in 5 min of growth. However, subsequent riming on the crystal edges became markedly faster. This indicated the presence of onset conditions for riming. The isometric crystal eventually turned into graupel, which was nearly spherical in shape probably owing to crystal rotation.

b. Crystal dimension, mass and density

Figure 6 shows the variation of axial dimensions of the crystal with temperature. The c -axis length of the dendritic crystal was obtained by dividing the crystal mass by the basal plane area assuming the bulk density of ice for the crystal. The dashed portions of the lines indicate where the crystal dimensions were uncertain because of riming. The growth rate was maximum along the c -axis at -5.5°C and along the a -axis at -15°C . Each peak coincided with the growth of needles and dendrites, respectively.

Figure 7 shows the variation of crystal masses with temperature in a semi-log scale. The crystal mass curve reached a maximum at around -15°C . This maximum corresponded to the highest growth rate along a -axis shown in Fig. 6, whereas the maximum at around -5.5°C was obscure. After 10 min of growth, another

Fig. 5. Snow crystals grown around -10°C at a liquid water content of 2 g m^{-3} .

Fig. 6. Variation of crystal axial dimensions with temperature. The dashed lines indicate where crystal dimensions were uncertain due to riming.

Fig. 7. Variation of crystal masses with temperature. The areas filled with open-circles show where rimed crystals were observed.

maximum appeared at around -10°C . This was because marked riming growth commenced at around -10°C .

To connect ice crystal growth parameters thus measured, apparent crystal density (ρ_c) was defined by dividing the mass by the volume of the circumscribing hexagonal cylinder as:

$$\rho_c = \frac{8m}{3\sqrt{3}a^2c}, \quad (1)$$

where m is the crystal mass, a the length along the a -axis and c the length along the c -axis. Figure 8 shows the variation of apparent crystal density with temperature at the growth time of 10 min. The values at around -5.5 and -15°C were small owing to shape enhancement, *i.e.* needle or dendritic growth. At these temperatures, the crystal densities were smaller than those obtained for the growth time of 2.5 min by Ryan *et al.* (1976).

Fig. 8. Variation of apparent crystal densities with temperature at the growth time of 10 min. Also shown is the result of Ryan *et al.* (1976).

c. Crystal fall velocity

Figure 9 shows the variation of crystal fall velocity with temperature. The data below -16°C were scattered due to the varying spatial branch development. The crystal fall velocity was higher at around -10°C and became more pronounced with time. This was because the aerodynamic drag of the isometric crystal grown at around -10°C was small. Thus, riming growth

Fig. 9. Variation of crystal fall velocity with temperature.

was superior to vapor growth at around -10°C . The crystal fall velocity showed two minima, one at around -5.5°C and the other at around -16°C because the aerodynamic drag at these temperatures became large due to shape enhancement caused by the growth habit.

Fig. 10. Variation of crystal fall velocity with time at -10.5°C . Each measurement is shown by a different symbol; it was analyzed at 1 min intervals from the recorder chart.

Figure 10 shows the variation of the crystal fall velocity with time at -10.5°C . It appears that two straight lines fit the obtained data best rather than a smooth curve: the straight line

showed a sudden bend at the growth time of 8 or 9 min. The error in this fall velocity data was about 3 cm s^{-1} . The average slope of the early growth stage was $0.056 \pm 0.003\text{ cm s}^{-2}$.

Fig. 11. Variation of crystal fall velocity at different temperatures.

Figure 11 shows the variation of the crystal fall velocities with time at different temperatures for a growth time of 30 min. The fall velocities at temperatures between -4 and -11.5°C can be expressed by two straight lines, those at -13.5 and -15.5°C with a curve convex upwards and a straight line, and those at -16°C with two straight lines and a curve convex upwards. The velocity data lines were divided into two groups except for that at -4°C : in the higher fall velocity group, isometric crystals grew and subsequently rimed. In the lower fall velocity group, vapor diffusional growth continued and shape enhancement occurred. The acceleration rate of isometric crystals growth at -4°C was lower, corresponding to the lowest growth rate (see Fig. 7). Unlike Nakaya and Terada (1935), the fall velocity did not become constant when a dendrite grew large.

d. Riming on isometric crystal

Variation of crystal mass with growth time at the temperature of -10.5°C is plotted on a log-log scale in Fig. 12. The figure also gives the

Fig. 12. Variation of crystal masses with growth time for a temperature of -10.5°C . Also shown are the results by Fukuta (1969), Ryan *et al.* (1976), Michaeli and Gallily (1976) and Fukuta *et al.* (1982).

results reported by Fukuta (1969), Ryan *et al.* (1976), Michaeli and Gallily (1976) and Fukuta *et al.* (1982). The variation of crystal mass with time in our present experiment was represented by three straight lines: $d(\log m)/d(\log t) = 1.6$, when the growth time was between 0 and 6 min (hereafter referred to as Stage I); 2.3 between 6 and 20 min (Stage II) and 6.2 over 20 min (Stage III). Data reported by Michaeli and Gallily appear to be unreasonably low apparently due to moisture exhaustion during the experiment.

Snow crystals grew predominantly by vapor diffusion in Stage I because very few rime droplets were observed on them. The vapor-growth phase continued up to 10 min when the liquid water content was below 0.5 g m^{-3} .

The crystal mass suddenly began to increase with time when Stage III was reached; this stage existed only with the liquid water content of 2 g m^{-3} . The slope is nearly equal to the theoretical value of graupel growth [$(d \log m/d \log t) = 6$], estimated by Fukuta (1980). Stage III, therefore, can be considered as the graupel growth stage. The variation of fall velocities of individual snow

crystals with growth time at -10.5°C at a liquid water content of 2 g m^{-3} is represented by three straight lines, similar to those of crystal masses, as shown in Fig. 13. The variation of fall velocity was the same regardless of the liquid water content during the early growth stage (growth time $< 8\text{--}12 \text{ min}$) because the growth mechanism was by vapor diffusion. The velocity increased suddenly after a growth time of about 20 min under the liquid water content of 2 g m^{-3} . This was equivalent to Stage III. The velocities in this stage increased linearly with time, which agreed with the theoretical prediction of Fukuta (1980).

Fig. 13. Variation of crystal fall velocity with time at -10.5°C at a liquid water content of 2 g m^{-3} . Each measurement is shown by a different symbol; it was analyzed at 1 min intervals from the recorder chart. The dashed line shows the case with the liquid water content below 0.5 g m^{-3} .

4. Discussion

a. Crystal mass

The following mass growth rate of a crystal can be formulated using the diffusion equations for water vapor and heat together with the Clausius-Clapeyron equation at the surface (Mason, 1971). The ventilation and fog effect as

well as the effects of deposition and thermal accommodation coefficients (Fukuta and Walter, 1970) are ignored in this treatment.

$$dm/dt = 4\pi C(S_i - 1) \left(\frac{L_d^2}{KR_v T_\infty^2} + \frac{1}{\rho_{is\infty} D} \right)^{-1}, \quad (2)$$

where L_d is the latent heat of deposition, K the thermal conductivity of air, R_v the specific gas constant for water vapor, T_∞ the temperature of the environment, $\rho_{is\infty}$ the saturation vapor density with respect to ice at T_∞ , D the diffusivity of water vapor in air, C the electrostatic capacitance of the crystal and S_i the ambient saturation ratio with respect to ice ($\rho_{s\infty}/\rho_{is\infty}$), and $\rho_{s\infty}$ is the saturation vapor density with respect to water at T_∞ .

For a spherical crystal (Fukuta, 1969), this equation can be integrated into

$m =$

$$\frac{8\sqrt{2}\pi}{3\rho_i^{1/2}} \left[(S_i - 1) / \left(\frac{L_d^2}{KR_v T_\infty^2} + \frac{1}{\rho_{is\infty} D} \right) \right]^{3/2} t^{3/2}, \quad (3)$$

where ρ_i is the density of ice. The 1.5 power of t agreed approximately with the slope in Stage I (see 3.d.). Figure 14 shows the mass variation in our experiment and by Eq. (3) for the growth time of 10 min. Both results coincided roughly at

Fig. 14. Comparison of the observed crystal mass with the calculated result using Eq. (3) and that of Miller and Young (1979) for the growth time of 10 min at different temperatures.

around -10°C , where isometric crystals were grown. That is, an isometric crystal can be regarded as a spherical crystal.

The numerical result by Miller and Young (1979) is also shown in Fig. 14. The discrepancy between our experimental data and their numerical result is especially large at around -5 and -15°C , which seems to be due to their assumptions regarding ventilation factor and crystal dimensions.

b. Fall velocity

The fall velocity (w) of an isometric crystal is expressed as follows using Eq. (3) and Stokes' equation of fall velocity, the latter being satisfied by the crystal (see 4.d.):

$$w = \frac{4g(S_i - 1)}{9\eta \left[\frac{L_d^2}{KR_v T_\infty^2} + \frac{1}{\rho_{is\infty} D} \right]} t, \quad (4)$$

where η is the dynamic viscosity of air and g the gravitational acceleration.

The proportionality constant of t in Eq. (4) is equal to 0.086 cm s^{-2} at -10°C ; this value is 1.5 times larger than the experimental value (see 3.c.). This is probably related to the difference of the drag coefficient between the sphere and the actual ice crystal. When riming had started, the drag coefficient changed, and this was followed by a sharp bend in the time variation of the fall velocity.

In the case of dendritic crystals, a curve convex upwards fitted well for the fall velocity variation with time at the early growth stage. This was probably because the drag increased by the gradual change of the crystal shape or density. When a dendrite continued to grow, a straight line became sufficient to represent the changing fall velocity. Figure 15 shows the variation of crystal density at around -14°C with time: the apparent crystal density decreased with time till 10 min point in growth time, and thereafter remained constant. This indicates that the crystal shape remained the same after the growth time of 10 min. In the early stage of growth, straight line was fitted for the fall velocity at -16°C ; this may correspond to the growth of hexagonal plate (see Fig. 4). Dendritic growth was observed thereafter.

Fig. 15. Variation of apparent crystal density around -14°C with time. The result of Ryan *et al.* (1976) is also shown.

c. Fall distance

The equivalent fall distance (z) in a cloud is derived by integrating the fall velocity of the snow crystal. The relationship is summarized in Table 1. The formulae can be applied to crystals growing by vapor deposition or riming in supercooled clouds whose liquid water content is below 0.5 g m^{-3} . Figure 16 shows the variation of fall distances with time at constant temperatures. After 10 min of growth, the curves separated into two groups due to the behaviors of crystal fall velocities (see 3.c.). Without updraft in the supercooled cloud, solid precipitates of the isometric or near spherical crystal group dropped from 200 to 250 m in 15 min and 700 to 800 m in 30 min. Particles of the non-spherical crystal group dropped from 125 to 150 m in 15 min and 300 to 400 m in 30 min.

d. Three stages of isometric crystal growth

The growth of an isometric crystal may be represented by the following three stages as

Table 1. Empirical relationships of the crystal fall velocity (w) and the fall distance (z) with growth time (t)

TEMPERATURE	t	$w-t$ relationship	$z-t$ relationship
-4°C	$t \leq 17 \times 60$	$w = 0.03t$	$z = 1.5 \times 10^{-4}t^2$
	$t > 17 \times 60$	$w = 0.02t + 10.2$	$z = 10^{-4}t^2 + 10^{-1}t - 50$
-6	$t \leq 19 \times 60$	$w = 0.027t$	$z = 1.4 \times 10^{-4}t^2$
	$t > 19 \times 60$	$w = 0.017t + 11.4$	$z = 8.5 \times 10^{-6}t^2 + 1.1 \times 10^{-1}t - 54$
-8	$t \leq 12 \times 60$	$w = 0.051t$	$z = 2.6 \times 10^{-4}t^2$
	$t > 12 \times 60$	$w = 0.03t + 15.1$	$z = 1.5 \times 10^{-4}t^2 + 1.5 \times 10^{-1}t - 51$
-10	$t \leq 12 \times 60$	$w = 0.056t$	$z = 2.8 \times 10^{-4}t^2$
	$t > 12 \times 60$	$w = 0.03t + 18.7$	$z = 1.5 \times 10^{-4}t^2 + 1.9 \times 10^{-1}t - 69$
-11.5	$t \leq 19 \times 60$	$w = 0.047t$	$z = 2.4 \times 10^{-4}t^2$
	$t > 19 \times 60$	$w = 0.023t + 27.4$	$z = 1.2 \times 10^{-4}t^2 + 2.7 \times 10^{-1}t - 152$
-13.5	$t \leq 12 \times 60$	$w = 0.82t^{0.6}$	$z = 5.5 \times 10^{-3}t^{1.5}$
	$t > 12 \times 60$	$w = 0.017t + 9.8$	$z = 8.5 \times 10^{-6}t^2 + 9.8 \times 10^{-2}t - 8$
-15.5	$t \leq 11 \times 60$	$w = 0.82t^{0.6}$	$z = 5.5 \times 10^{-3}t^{1.6}$
	$t > 11 \times 60$	$w = 0.016t + 10.5$	$z = 8 \times 10^{-6}t^2 + 1.1 \times 10^{-1}t - 14$
-16	$t \leq 12 \times 60$	$w = 0.024t$	$z = 1.2 \times 10^{-4}t^2$
	$12 \times 60 < t \leq 24 \times 60$	$w = 0.29(t - 12 \times 60)^{0.6} + 17.3$	$z = 1.9 \times 10^{-3}(t - 12 \times 60)^{1.6} + 1.7 \times 10^{-1}t - 60$
	$t < 24 \times 60$	$w = 0.015t + 3.5$	$z = 7.5 \times 10^{-6}t^2 + 3.5 \times 10^{-2}t + 16$

t : s, w : cm s^{-1} , z : m

Fig. 16. Variation of fall distances with time at various temperatures.

before:

- Stage I : vapor diffusional growth
- Stage II : transitional growth
- Stage III: graupel growth

Stage II is transitional from vapor diffusional growth to graupel growth: that is, the stage begins with the acceleration of riming growth and ends with the commencement of graupel growth. This stage is characterized as riming on crystal surfaces perpendicular to flow in contrast to riming on all surfaces in Stage III.

A simplified expression for Stage II may be given as

$$dm/dt = S\bar{E}W_Lw, \quad (5)$$

where S , $\bar{E}$, and W_L are the cross-sectional area of the particles presented to the flow, the average collection efficiency of droplets on the snow crystal and the liquid water content of the cloud, respectively. Since w is proportional to t (see 3.c.), integration of Eq. (5) with constant S , $\bar{E}$ and W_L yields

$$m \propto t^2. \quad (6)$$

The expression is in agreement with the experimental result described in 3.d.

Figure 17 shows the relationship between drag

coefficient (C_D) and Reynolds number (Re) of double plates, rimed particles and graupel grown between -10 and -12°C . C_D and Re are defined as follows, respectively:

$$C_D = 2mg/\rho_a w^2 S, \quad (7)$$

$$Re = \rho_a w d / \eta, \quad (8)$$

where ρ_a is the density of air, and d the diameter of the crystal. In the case of riming-free crystals in Stage I, C_D and Re was constant. That is, these crystals behaved as Stokes' particles. Riming began when Reynolds number exceeded about 5, which is approximately the outer border of Stokes' region. C_D of rimed particles varied inversely with the liquid water content. The reason for this relationship appears to be as follows. At low liquid water contents, riming occurs only at the corners and edges due to the relatively small droplet size and results in lower apparent density. In contrast to this, particles exposed to high liquid water contents, which rime almost at any position due to the large droplet size, develop a nearly spherical shape with higher density. Therefore, larger sizes and m , i.e. larger C_D , are probably required to reach the given level of Re in the case of lower liquid water content. C_D tended to become independent of Re when the crystals changed

Fig. 17. Drag coefficient of snow crystals grown between -10 and -12°C as a function of Reynolds number for liquid water content below 0.5 g m^{-3} and at 2 g m^{-3} .

into graupel, *i.e.* Re was close to 100; this indicates that the crystals followed Newton's law of resistance; w is proportional to $r^{1/2}$, where r is the radius of graupel. This result supports the assumption Fukuta (1980) made in his theoretical treatment.

5. Conclusion

Snow crystals were suspended freely and grown in a vertical supercooled cloud tunnel under the following conditions: 1) temperature ranging from -4 to -20°C at about 2°C intervals; 2) water saturation with liquid water content below 0.5 g m^{-3} over the entire temperature range and at 2 g m^{-3} at around -10°C ; 3) growth time up to 30 min at 5 min intervals. Under these conditions, growth parameters of snow crystals were measured. The main findings are summarized below:

1) Crystal habits showed the well-known transition of columns ($-4 \sim -10^{\circ}\text{C}$) to plates ($-10 \sim -20^{\circ}\text{C}$). Shape enhancement occurred at -5.5°C (needles) and $-14 \sim -16^{\circ}\text{C}$ (dendrites). Polycrystalline snows were observed very frequently below -15°C . An isometric crystal grew at -4°C and between -8 and -11.5°C ; riming growth began to dominate the vapor diffusional growth after a certain time even when the liquid water content was below 0.5 g m^{-3} , and the crystals actually changed into graupel when the liquid water content was 2 g m^{-3} within the time range of the present experiment.

2) The growth rate was pronouncedly highest along the c -axis at -5.5°C , and along the a -axis at -15°C , respectively. The crystal mass had a remarkable maximum at around -15°C . After 10 min of growth, another maximum appeared at around -10°C due to riming.

3) The time variation of crystal fall velocity was expressed by two straight lines between -4 and -11.5°C , or by a curve convex upward and one or two straight lines between -14 and -16°C . The straight line changed its slope when riming commenced or a needle grew. Between -14 and -16°C , the curve convex upward and fitted when the crystal shape or density changed, and the straight line was fitted when a dendrite grew. Crystal fall velocities were separated into

two groups: the group of higher fall velocities and the group of lower fall velocities. In the former, an isometric crystal grew and in the latter, shape enhancement, *i.e.* dendritic or needle growth, occurred except at -4°C . For the growth time of 30 min in the present measurement, the fall distance was 700 to 800 m in the former and 300 to 400 m in the latter.

4) The growth mode of isometric crystals was represented by three stages: vapor diffusional growth, transitional growth and graupel growth. It was confirmed that the mass was roughly proportional to $t^{3/2}$, t^2 and t^6 in each growth stage. In the vapor growth stage, the crystals behaved as Stokes' particles. Transitional growth stage was characterized by riming to surfaces perpendicular to the flow. The particles tended to follow Newton's law of resistance for fall in the graupel growth stage.

Acknowledgements

This work was supported in part by the Division of Atmospheric Sciences, National Science Foundation, under Grant ATM-82-18966.

One of authors (T.T.) is most grateful to Prof. G. Wakahama and Dr. T. Endoh of Hokkaido University for valuable discussion and hearty advice while finishing this research and preparing the manuscript at his present affiliation.

References

- Baumgardner, D., 1983: An analysis and comparison of five water droplet measuring instruments. *J. Climate Appl. Meteor.*, **22**, 891-910.
- Bruintjes, R.T., A.J. Heymsfield and T.W. Krauss, 1987: An examination of double-plate ice crystals and the initiation of precipitation in continental cumulus clouds. *J. Atmos. Sci.*, **44**, 1331-1349.
- Fukuta, N., 1969: Experimental studies on the growth of small ice crystals. *J. Atmos. Sci.*, **26**, 522-531.
- , 1980: Development of fast falling ice crystals in clouds at -10°C and its consequence in ice phase processes. *Proc. 8th International Conf. on Cloud Phys.*, Clermont-Ferrand, France, 15-25 July 1980, 97-100.
- , N.H. Gong and A.S. Wang, 1984: A microphysical origin of graupel and hail. *Proc. 9th International Conf. on Cloud Phys.*, Tallinn, USSR, 21-28 Aug. 1984, 257-260.
- , M.W. Kowa and N.H. Gong, 1982: Determina-

- tion of ice crystal growth parameters in a new supercooled cloud tunnel. *Preprints Conf. on Cloud Phys.*, Chicago 15-17 Nov. 1982, 325-328.
- , and L.A. Walter, 1970: Kinetics of hydrometeor growth from a vapor-spherical model. *J. Atmos. Sci.*, **27**, 1160-1172.
- Hallett, J. and B.J. Mason, 1958: The influence of temperature and supersaturation on the habit of ice crystals grown from the vapour. *Proc. Roy. Soc. London*, **A247**, 440-453.
- Iwai, K., 1983: Three-dimensional structure of plate-like snow crystals. *J. Meteor. Soc. Japan*, **61**, 746-755.
- Kobayashi, T., 1961: The growth of snow crystals at low supersaturations. *Phil. Mag.*, **6**, 1363-1370.
- Kowa, M.W., 1981: *Determination of ice crystal growth parameters in a supercooled cloud tunnel*. M.S. Thesis, Dept. of Meteor., Univ. of Utah, 127pp.
- Magono, C. and H. Aburakawa, 1968: Experimental studies on snow crystals of plane type with spatial branches. *J. Fac. Sci., Hokkaido Univ., Ser. VII*, **3**, 85-97.
- Mason, B.J., 1971: *The physics of clouds*, 2nd ed., Oxford Univ. Press, 671 pp.
- Michaeli, G. and I. Gallily, 1976: Growth rates of freely falling ice crystals. *Nature*, **259**, 110.
- Miller, T.L. and K.C. Young, 1979: A numerical simulation of ice crystal growth from the vapor phase. *J. Atmos. Sci.*, **36**, 458-469.
- Nakaya, U., 1954: *Snow crystals*. Harvard Univ. Press, 510 pp.
- and T. Terada, 1935: Simultaneous observations of the mass, falling velocity and form of individual snow crystals. *J. Fac. Sci., Hokkaido Univ., Ser. II*, **1**, 191-201.
- Pruppacher, H.R. and J.D. Klett, 1978: *Microphysics of clouds and precipitation*, D. Reidel Publishing Company, 714 pp.
- Ryan, B.F., E.R. Wishart and E.W. Holroyd, 1974: The densities and growth rates of ice crystals between -5°C and -9°C . *J. Atmos. Sci.*, **31**, 2136-2141.
- , ——— and D.E. Shaw, 1976: The growth rates and densities of ice crystals between -3°C and -21°C . *J. Atmos. Sci.*, **33**, 842-850.
- Schaefer, V.J., 1946: The production of ice crystals in a cloud of supercooled water droplets. *Science*, **104**, 457-459.
- Takahashi, C., 1979: Formation of poly-crystalline snow crystals by riming process. *J. Meteor. Soc. Japan*, **57**, 458-464.
- Takahashi, T. and N. Fukuta, 1988: Observation of the embryos of graupel. *J. Atmos. Sci.*, **45**, 3288-3197.

鉛直過冷雲風洞中での雪結晶の浮遊成長実験

高橋 庸哉*・福田 矩彦

(ユタ大学気象学科)

雪結晶を浮遊成長させることができる鉛直過冷雲風洞を使って、 $-4 \sim -20^{\circ}\text{C}$ で結晶成長時間30分までの実験を行い、雪結晶の水飽和下での気相成長および雲粒捕捉成長を調べた。

得られた結果は以下のようである；1)樹枝状結晶及び針状結晶の成長に対応して、a軸方向には -15°C 、c軸方向には -5.5°C で成長が著しく速かった；2) -15°C 以下では多結晶（立体樹枝・立体角板）になることが多かった；3)雪結晶の落下速度の時間変化は、樹枝状結晶では曲線と直線、その他では2本の直線で表せた；4)各温度での落下速度の時間変化は2グループに分類できた。落下速度の速いグループでは、等方的な結晶が成長し、雲粒捕捉を起こした。一方、落下速度の遅いグループでは、気相成長を続け、樹枝状結晶や針状結晶が成長した。30分間に前者では700～800m、後者では300～400m落下した；5) -10°C で成長した等方的結晶は霰に変化した。その過程を‘気相成長期’・‘遷移成長期’・‘霰成長期’の3段階に区分することができ、結晶質量はそれぞれ $t^{1/2}$ 、 t^2 および t^0 に比例した。降水粒子の落下は、気相成長期ではストークスの抵抗法則、霰成長期ではニュートンの抵抗法則に従った。

* 現所属：北海道大学低温科学研究所