Freezing of Freely Suspended, Supercooled Water Drops in a Large Vertical Wind Tunnel

John D. Spengler[1] and Narayan R. Gokhale

Dept. of Atmospheric Science, State University of New York at Albany

ABSTRACT

The design and operation of a large vertical wind tunnel (1.8 m diameter updraft) are described, together with the associated special photographic equipment and techniques required for studies of the interactions and freezing of freely suspended water drops.

During the first two winters of operation several new and important observations have been made while freezing freely suspended, large supercooled water drops. The terminal velocity of the frozen pellet was found to be very different than that of the liquid drop. If individual drops freeze at −6C and colder they often exhibit a marked decrease (up to 4 m $\sec^{-1}$) in terminal velocity. Coalescence of a frozen pellet and a liquid drop produces an elongated ice pellet (8–15 mm horizontal axis) with a terminal velocity of 9 m $\sec^{-1}$. When an ice pellet becomes unstable and spins about a horizontal axis, it can obtain a rapid horizontal velocity. Two ice pellets frozen together display the same erratic tumbling. These observations indicate that some ice pellets have greatly increased distances and residence times to grow in the supercooled region of a cloud.

1. Introduction

This paper describes the design and construction of a large vertical wind tunnel for studying the interactions of freely suspended water drops and frozen pellets in a steady updraft. The reasons for using vertical wind tunnels in the study of our atmosphere are well documented in scientific literature. However, with the advent of the accumulation zone concept to cloud physics (Bowen, 1950; Bibilashvili *et al.*, 1959; Douglas, 1963; Atlas *et al.*, 1965; Gokhale and Rao, 1969), the effects of high concentrations of cloud and precipitation particles have become increasingly more important (List and Lozowski, 1968; Gokhale and Rao, 1969; Iribarne, 1968).

While some vertical wind tunnels have small updraft diameters and, as a result, are more suited to study the behavior of single drops or ice particles, the large vertical wind tunnel reported in this paper, with its order-of-magnitude increase in dimensions over its now dwarfed prototype vertical wind tunnel (Cotton and Gokhale, 1967), is capable of studying the behavior of a multitude of droplets simultaneously suspended in the updraft of the tunnel. Now, instead of just 2 drops, up to 2000 drops can be simultaneously suspended in the updraft of the vertical wind tunnel, thus facilitating the study of interactions of high concentrations of freely suspended hydrometeors.

2. The construction of a large vertical wind tunnel

This large vertical wind tunnel is similar in basic design to the smaller (6 inch cross section) vertical wind tunnels built by Blanchard (1950) and by Cotton and Gokhale (1967). The entire tunnel is made of seven components: the inlet section, the fan and motor, the plenum, the vertical section with straighteners, the screens and honeycomb, the working volume, and the back-pressure screen canopy. Except for the inlet section, which is open to ambient air, all other components of the vertical wind tunnel can be seen in Fig. 1. Another view of the entire wind tunnel is shown in Fig. 2.

An essential factor in any investigation with a vertical wind tunnel is a knowledge of the velocity profiles, both vertical and horizontal. Plotting of these profiles at various levels in the wind tunnel can be used to determine the size of suspended drops, their location, and most important, their stability in terms of lifetime in the working area of the tunnel. Moreover, accurate plotting of the velocity profiles demonstrates the effect that mechanical variables such as baffles, screens and honeycomb have on the airflow.

Only a few basic features of the tunnel will be described in this section. The description of the other components and the exact dimensions can be obtained from the drafted specification drawing of the vertical wind tunnel on file with the Department of Atmospheric Science, State University of New York at Albany.

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[1] Present affiliation: Environmental Health Sciences Department, Harvard University School of Public Health, Cambridge, Mass.

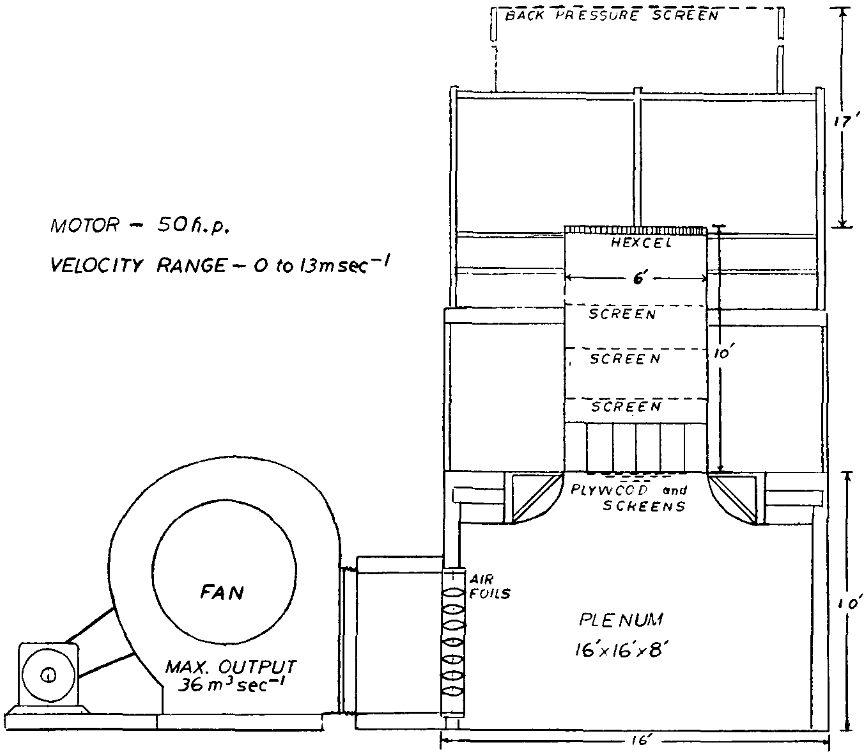

FIG. 1. Vertical wind tunnel of the Department of Atmospheric Science and Atmospheric Sciences Research Center of the State University of New York at Albany.

a. Fan and motor

The fan is driven by a 50-hp motor through a hydraulic transmission. The fan speed can be varied and updraft velocities from 0 to 13 m sec^{-1} can be obtained with the 6-ft (1.8 m) diameter vertical shaft. The fan and motor are mounted on a vibration absorbing spring base. The entire fan is attached to the inlet tunnel and to the plenum chamber with a rubberized cloth. These precautions separate the fan-motor system from the rest of the wind tunnel.

b. Vertical cylinder

The most important section of the tunnel is the vertical cylinder. It is in this section that airflow is straightened and most of the turbulence removed. The vertical cylinder, 1.8 m in diameter and 3 m in length, was made from two 1.5 m sections of formed fiberglass and polyester resin. In the first 60 cm of the vertical tunnel, 0.65-cm plywood was fixed in 30-cm cross hatching to straighten the flow as it leaves the plenum.

Three screens were placed across the tunnel at 1-, 3- and 5-ft levels above the plywood. The screens damp-out large eddies and even-out the airflow across the tunnel. By comparing hot wire anemometer recordings for different positions in the tunnel system it was found that the greatest reduction of turbulence occurred in the screen section of the tunnel. Because of the lack of rigidity of a 1.8 m diameter metal screen, the resistance to the airflow was not uniform across the vertical section. The air stream was deflected as a result of the screens not being exactly perpendicular to the flow. By applying screens to the lower side of the plywood, the greatest resistance to the airflow was produced in the center of the vertical cylinder. A screen 0.9 m in diameter was centrically attached underneath the plywood. The velocity profile above the tunnel indicates that the highest velocity occurs in an annulus whose outer perimeter is approximately 15 cm from the edge and whose inner perimeter is approximately 45 cm from the edge. The profile also indicates that the velocity decreases gradually to a minimum in a region near the center. The difference between the maximum and the minimum velocity is ~ 0.75 m sec^{-1}.

With the intention of reducing turbulence and straightening the airflow, 1.8 m diameter, 7.5 cm thick honeycomb Hexcel core was placed on wires over the opening of the tunnel (Fig. 3). It was made of 0.68 cm equivalent diameter hexagonal cells with each cell having a length-to-diameter ratio of 8. The addition of the honeycomb core did reduce turbulence. The level of turbulence, $100[(u'^2)^{\frac{1}{2}}/U]$, where u' is the perturbation from the mean flow velocity (U), in the test volume was between 2 and 3%. Under these conditions large drops could be suspended for long periods of time.

c. *Test volume*

For a more complete understanding of the structure of the airflow, the entire 2.62 square meters area above the opening of the tunnel has been mapped at four levels. Fig. 4 shows the horizontal traverses at these levels and Fig. 5 is a vertical profile through the center of the updraft. Many interesting features are immediately apparent. One is that the velocity profile changes with height above the orifice. However, the velocity in the center region of the updraft remains almost constant with height up to the 2.2 m level. Vertical profiles demonstrate that the velocity in and near the center of the updraft decreases slowly with an average rate of 0.008 sec^{-1} to 2.3 m, then decreases with a rapid rate of 1.5 sec^{-1} to 3.0 m. The updraft is being eroded at the edges by entrainment of environmental air (Fig. 4).

3. Instrumentation

Air temperature was monitored at four positions in the tunnel: at the inlet, in the plenum, in the working volume, and in the ambient air. The temperatures were continuously recorded on a multichannel recorder. For experiments on the freezing of supercooled drops, in order to determine the actual drop temperature, it became necessary to know the temperature of the water reservoir and the ambient wet-bulb or ice-bulb temperature.

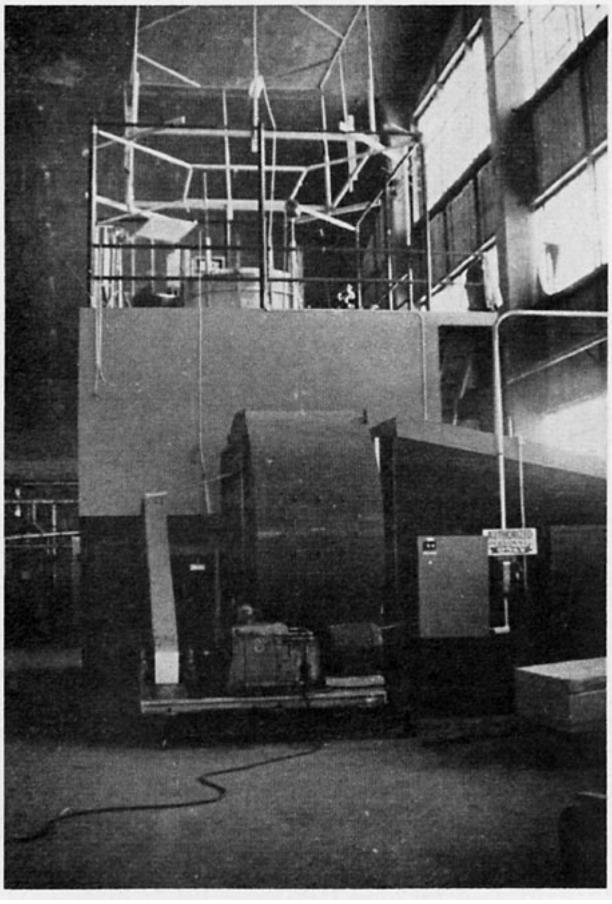

Fig. 2. Vertical wind tunnel of the State University of New York at Albany.

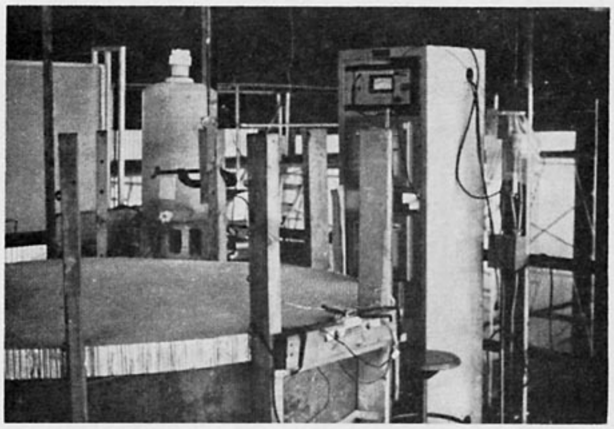

Fig. 3. Test area of vertical wind tunnel. Hexcel core and drop generator are in foreground, hot wire anemometer and temperature recorders on right.

Using a vibrostaltic pump to pulsate a stream of water, uniform-sized drops were produced at a rate of 120 sec^{-1}. In 10 sec over 1000 drops could be injected into the vertical wind tunnel. The drops formed by the vibrostaltic pump originally had a narrow size distribution around 5.5 mm as determined by the methylene blue dye and filter paper method.

4. Photographic technique and equipment

In the study of drop interactions, a special set of requirements must be fulfilled. During investigations of impactions of small droplets of sizes 200 μm to 3 mm on larger suspended drops 5 mm in diameter, velocities

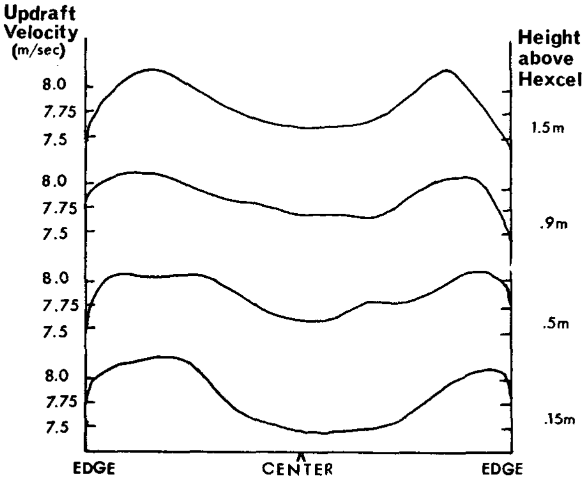

Fig. 4. Horizontal updraft velocity profiles at four levels. (Profiles are similar for different velocity settings.)

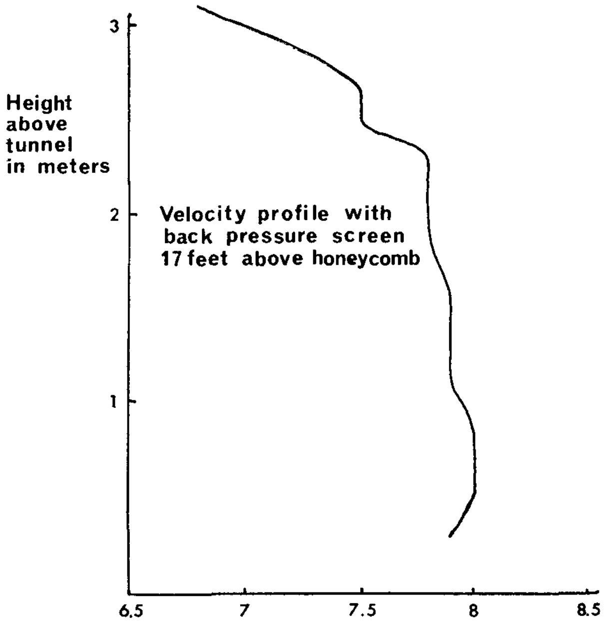

FIG. 5. Updraft velocity (m sec^{-1}) through center region of tunnel.

are encountered that vary between a few cm sec^{-1} and 10 m sec^{-1}. The size of drops studied range between 200 μm and 8 mm. Ice pellets which originate from a frozen 5-mm drop can grow by coalescence, either with supercooled water drops carried in an updraft or with accretion of ice crystals, to 1–2 cm in diameter, yet particles used to nucleate ice growth may be as small as a few microns to 10 μ. Contact times between impacting drops, particle-drop interactions, and capillary waves propagating on the surface of the drops are of the order of 1–100 msec. Wake effect, the process which increases the collision efficiencies between drops of equal sizes, drop break-ups, and propagations of ice crystal growth on a drop surface vary over a range of 100 msec to a few seconds. Thus, time requirements vary over four orders of magnitude.

There were two objectives in conducting these experiments: first, to study the phenomena of drop impactions, wake effects, and freezing of supercooled drops in order to obtain physical knowledge about them and about their relative importance in precipitation growth process; second, to produce high-magnification photographs of individual events. Therefore, to optimize the conditions of the experiments, a high-speed camera and a lens affording a high degree of variability were selected. Using high-speed cameras with 400- and 2000-ft film capacities and a 12 to 120 mm zoom lens with diopters, droplet interactions could be recorded at full framing rates of 10 to 10,000 frames sec^{-1}, and at half-framing rates of 20 to 20,000 frames sec^{-1}.

To obtain a sharp boundary definition, drops were silhouetted against a frosted glass illuminated from behind with a medium floodlight. A "white card" light-meter reading was used to determine correct exposures. A very narrow spotlight was situated at right angle to the camera-subject axis to illuminate the drops in the volume to be photographed. This second spotlight was sometimes needed to highlight the drops and make surface waves and oscillations more apparent. Most events were filmed at a distance of ~2.5 m with either a 90-, 100- or 120-mm lens at framing rates of 500 to 4000 frames sec^{-1} depending on the requirements of the interactions being studied.

To achieve the second goal of photographing individual events, a 120-mm lens with close-up attachments was used to cover an area of approximately 6 cm by 4 cm and 3 cm by 2 cm. Spatial resolution of drop impactions and drop oscillation experiments were achieved with two high-speed cameras oriented at a right angle to each other. Grids similarly oriented aligned the cameras and a common recorded event synchronized the film.

5. Observations on freezing of supercooled drops

Other than Blanchard's (1957) investigation of supercooled drops in a wind tunnel and that by Gokhale and Spengler (1972), very little attention has been given to the freezing of freely suspended water drops. The present observations indicate that several previously undescribed phenomena can occur when large supercooled drops freeze. Phenomena such as the type of freezing, change in terminal velocity upon freezing, coalescence between frozen pellets and supercooled drops, and coagulation between frozen ice pellets may be playing important roles in hail-embryo formation or hailstone growth.

During the winters of 1969 and 1970 many thousands of large drops were supercooled and frozen while suspended in the updraft of the wind tunnel (Spengler, 1971). Through careful observation with high-speed film, the following qualitative results were obtained

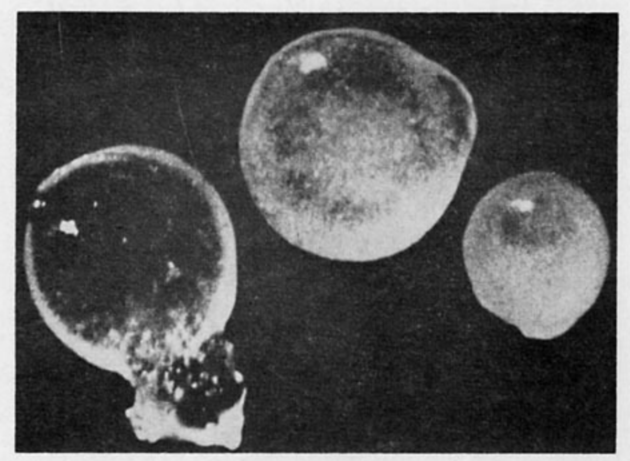

FIG. 6. Examples of ice pellets frozen in the updraft of the wind tunnel. Air temperature was −17C, but the freezing temperatures of the drops were warmer. The clear drop on left froze at −5C or warmer. Center pellet is 11 mm in diameter.

on the freezing of supercooled drops at various air temperatures between 3 and −27C. The water for these and all experiments was filtered tap water. Since the wind tunnel draws in unfiltered outside air the use of distilled water seemed unnecessary.

6. Freezing characteristics

Observations on the freezing temperatures of large water drops are very similar to those made by Blanchard (1957). In his work Blanchard showed the manner of freezing to be a function of drop temperature. He confirmed earlier work indicating that −5C was the approximate dividing temperature between clear ice, which forms at warmer temperatures, and opaque ice, which forms at colder temperatures. Present observations confirm these results (Fig. 6). In describing freezing at temperatures warmer than −4C Blanchard stated that ice would originate on the bottom of the drop and then proceed to form a thin shell of clear ice around the entire drop. In these experiments we have observed this same occurrence between 0 and −3C.

7. Terminal velocities of frozen pellets

It immediately became apparent that frozen large drops displayed interesting and varied patterns of fall.

1) A drop, freezing slowly with an ice disc originating at the bottom of the drop, may encounter heavy turbulence, possibly in the wake of another drop. Under such conditions, the unfrozen portion of the hydrometeor could "spill" from the drop. Upon losing this liquid mass the ice disc had a greatly reduced terminal velocity and was accelerated upward in the tunnel, often in a zigzag manner.

2) It has been filmed and observed that a partially frozen drop may rotate about a vertical axis with sufficient angular velocity to shed water by centrifugal force. The remaining ice structure behaves as described above.

3) Some pellets have the same terminal velocity as the unfrozen drop (Fig. 7). They may also have an aerodynamically stable position in the flow. When this type of freezing occurs at slight supercooling, it may be quite difficult to actually detect the presence of ice. This type of stable ice pellet occurs less frequently as the temperature of supercooling decreases.

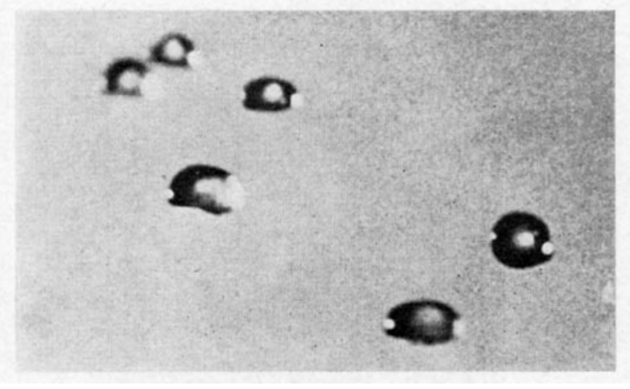

Fig. 7. Drops of 5.5 mm equivalent diameter: left center drop frozen, far right drop still liquid.

Fig. 8. Large frozen pellet with horizontal axis approaching 10 mm rocking back and forth in the updraft.

4) Some pellets exhibit modes of instability. Frozen pellets have been filmed rocking back and forth in the updraft (Fig. 8). If an ice pellet encounters some heavy turbulence, such as that produced by passing in the wake of another hydrometeor, the pellet can start to spin about a horizontal axis. When this happens the pellet continues to spin and can obtain a considerable horizontal velocity and may either rise or fall in a zigzag path.

5) Some large ice pellets which either froze clear or opaque were observed to fall upside down to their liquid shape (flat side up and rounded side down). This inverted position of fall was anticipated by McDonald (1954) and Blanchard (1957). The center of drag forces of a liquid drop is below the center of gravity. Upon freezing, the shape of the drop is fixed and it can no longer adjust to this coupled force. Therefore, the drop may change to a more stable and faster fall position (Fig. 9).

6) When drops froze opaquely it was often observed that the ice pellet would instantly accelerate upward in the tunnel. The number of frozen drops that exhibited this behavior increased as the temperature of supercooling decreased. An attempt was made to explain this intriguing observation. Large liquid drops oscillate about a mean drop shape. It is this mean drop shape that determines the terminal velocity of the liquid drop. As temperature decreases, the rate of ice crystal

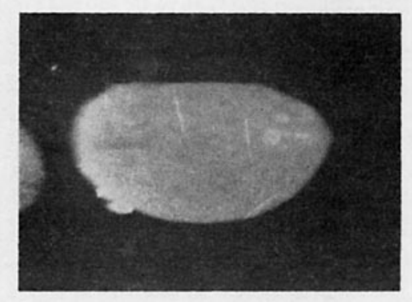

Fig. 9. Inverted fall position of some frozen pellets. Resulting fall velocity is greater than terminal velocity of original liquid drop.

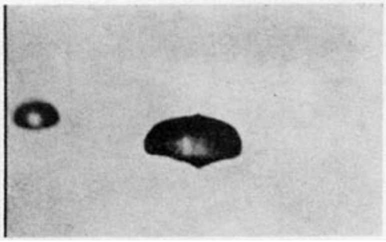

FIG. 10. Elongated ice pellet with a minor to major axis ratio of 0.4. Note irregular spike on bottom.

growth increases. Gokhale and Lewinter (1971) measured the rate of ice crystal growth in the surface of a supercooled 2-mm diameter drop. They found that the surface crystallization propagates radially from the point of nucleation. Large drops are oscillating with a frequency of 10–20 times per second. Therefore, to capture a particular state of oscillation there must be sufficient ice crystal growth in 0.1 sec to cover the lower surface of the drop. A 6-mm diameter drop has a bottom surface area (nearly flat) of approximately 38 mm^2. Applying Gokhale and Lewinter's data, ice crystallization in 0.1 sec could cover 50 mm^2 at -7C, 80 mm^2 at -8C, and 155 mm^2 at -9C. This indicates that sufficient growth can occur to freeze a drop in some state of oscillation. The crystallization rate measurements of Gokhale and Lewinter were not carried out in a ventilated airflow. The actual crystallization rate on the surface of a well-ventilated, freely suspended drop may have a greater value. In any case, a state of larger amplitude would be favored in freezing, because of increased surface area which results in increased ventilation and removal of latent heat from the drop. Therefore, one would expect more oblate than prolate ellipsoids. A drop frozen in an elongated state inevitably would attain a terminal velocity lower than the original unfrozen drop.

This phenomenon of change in terminal velocity upon opaque freezing of drops may have important implications in the microphysics of hailstone growth. Depending on the existing updraft profile and the actual change in terminal velocities, the frozen pellets might rise in an updraft. The result is that these pellets with initial decrease in terminal velocity will have an increased lifetime in the region of supercooled water, and therefore greater growth.

Unfortunately, the frozen pellets that accelerated upward from an area where the velocity was 9 m sec^{-1} would impact on the back pressure screen over the tunnel, where the vertical velocity was only 5 m sec^{-1}, or they were thrown out of the updraft and smashed on the floor. However, this does indicate that the decrease in terminal velocity of the large frozen drops was as much as 3–4 m sec^{-1}.

7) On the other hand, some drops upon freezing would increase in terminal velocity. These pellets fell slowly to the Hexcel core on top of the tunnel, apparently only increasing their terminal velocities by a few centimeters per second. This phenomenon would only occur at temperatures -6C and warmer. An explanation for this slight increase in fall velocity is not apparent.

8. Other observations

While conducting freezing experiments, many other interesting observations were made that are worthy of mention.

1) Coalescence occurred during the freezing of drops. Many frozen pellets having a diameter $\geqslant 10$ mm were collected and photographed. Several sequences of high-speed film show ice pellets coalescing with supercooled drops either permanently or temporarily. The liquid water coated the surface of the ice pellet but appeared most concentrated around the edges and top of the pellet (Figs. 7 and 10). Because of this distribution of collected water, the horizontal axis of the ice pellet grew preferentially. The result was that 10-mm frozen pellets can have the same terminal velocity as 5-mm liquid drops. This implies a longer lifetime in the region of supercooled water.

2) Two ice pellets frozen together were observed many times at various degrees of supercooling. Visual observation and high-speed film give some insight into the actual mechanism of fusing two ice pellets. Frozen pellets have been photographed coalescing with supercooled drops forming a liquid layer on the surface of the ice pellet. Such an ice pellet contacting another "dryer" ice pellet at a colder temperature could cause freezing at the point of contact and fuse the pellets together. Close inspection of Fig. 11 gives this appearance. A second possible mechanism involves the cracking of the thin ice shell shortly after the commencement of freezing. This could provide the water necessary to freeze the pellets together.

Coagulated frozen pellets had a very erratic fall behavior. Usually they began to tumble very rapidly and shot horizontally across the updraft. This may be an explanation for some very irregular shaped hailstones. L. N. Rogers of the Alberta Research Council (1971) has photographed cross sections of a natural

FIG. 11. Coagulated pellets, total horizontal length 19 mm.

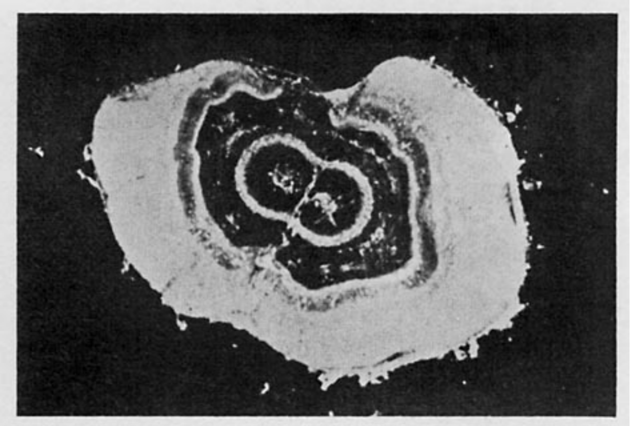

Fig. 12. Hailstone with two approximately 2-mm diameter drops as embryo. (From Rogers, 1971.)

hailstone which appears to have two frozen coagulated millimeter size drops as an embryo (Fig. 12).

9. Conclusions

This large vertical wind tunnel with its 1.8 m diameter updraft and its ability to simultaneously suspend thousands of liquid drops and frozen ice pellets has improved the laboratory simulation of natural conditions of drop interactions in an updraft with a high liquid water content. Phenomena such as drop impactions, wake effects, freezing of drops, and drop oscillations, which occur too rapidly for visual observations, can be studied with high-speed photography to obtain a better understanding of the precipitation growth processes in clouds. The results of these studies are described in separate papers.

The observations on the freezing of large water drops has revealed some interesting and important phenomena. Changes in terminal velocity can accompany freezing of supercooled water drops. When opaque freezing occurs at temperatures below −6C the ice pellet may suddenly have a terminal velocity several meters a second lower than the terminal velocity of the original liquid drops. Through the subsequent collection of supercooled water, ice pellets exceeding 10 mm in horizontal dimension can grow and remain suspended at 9 or 10 m $\sec^{-1}$. Ice pellets that become unstable or two coagulated pellets can spin about a horizontal axis and move very rapidly in a horizontal direction.

The importance of these phenomena concerns hail growth. By these observations it has been shown that ice pellets can have 1) a greatly increased growing distance over that distance calculated from just a simple vertical sweep of supercooled water, and/or 2) a prolonged existence in the region of supercooled water.

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