Air Bubbles in Artificial Hailstones

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ABSTRACT

Icing experiments are described in which artificial hailstones have been grown in a vertical wind tunnel at a relative speed of 18 m sec^{-1}, at temperatures between −5 and −20C, and with liquid water contents of 2 and 4 gm m^{-3}. The results show that air bubbles can be characterized by log-normal distributions of their diameters with the mean sizes primarily dependent on the liquid water content. Doubling the liquid water content led to larger but fewer bubbles, while lowering the air temperature led to smaller but more numerous bubbles. Thus, it is expected that bubble size distributions and concentrations may be the key to the interpretation of hailstone history.

1. Introduction

The interpretation of hailstone structure is still a key issue of laboratory hail research. Many attempts have been made to decipher specific properties of hailstone shells. Aufdermaur *et al.* (1963), Kidder and Carte (1964), Bailey and Macklin (1968), Levi and Aufdermaur (1970), and List *et al.* (1970) worked on the structure and crystallographic properties, some of whom also worked on crystal size and *c*-axis distributions, as well as shell densities. These studies considered artificially grown ice and/or natural hailstones. Macklin *et al.* (1970) followed a different line of attack by investigating the isotope content of different hailstone shells. The understanding of hail growth was improved somewhat by this method but no clear-cut identifications of icing conditions like air temperature and liquid water content which lead to given shells can be made on that basis.

After the discovery that air bubbles in drops, frozen while floating in a vertical wind tunnel (Murray and List, 1972), showed log-normal size distributions (i.e., the logarithm of the bubble diameter is linearly related to the cumulative percentage of bubble occurrence when the latter is plotted on probability paper), with the mean diameter increasing with increasing freezing temperature, a successful search was made for similar size distributions in hailstone shells (List *et al.*, 1972). This study gave the justification for new experiments on the growth of artificial hailstones in an icing tunnel in Toronto. The preliminary results are quite exciting because they confirm that the knowledge of air bubble size distributions and their mean sizes and concentrations can improve the interpretability of hailstone history immensely. In making this statement, it is not forgotten that our knowledge on hailstone aerodynamics has to be improved too. But the progress in that area will be discussed in other papers.

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2. Experimental arrangement and procedures

The basic apparatus used for the icing experiments was a wind tunnel with a closed circuit and a vertical measuring section. It had a radial fan driven by a variable speed motor (5 hp) which was set for the pilot experiments reported here, at an air speed of 18 m sec^{-1}. The cylindrical measuring section had a diameter of 15.8 cm and a length of 25.4 cm. There was also a cooling element in the air flow allowing a variation of temperatures to as low as −20C. The whole tunnel [which is described in a somewhat different setup by Murray and List (1972)] was located in a cold room with an independent temperature control with a lowest temperature of −28C.

The water was injected through a nozzle (of the type used in the Swiss hail tunnels) together with a variable amount of air. Two liquid water contents were achieved: 4.0±0.5 gm m^{-3} (series B) and 2.0±0.5 gm m^{-3} (series C), with log-normal drop size distributions and mean volume diameters of 57 and 47 μm, respectively. The liquid water content calibrations followed procedures as used by List (1960). Checks using Macklin and Bailey's (1968) data on collection efficiencies of growing hailstones showed reasonable agreement between the calibrated liquid water content and the measured growth rates of growing artificial hailstones. The original artificial particles were ice spheres with a diameter of 2 cm. They were rotated around a horizontal support rod at a speed of 1 Hz. A Barnes Infrared Radiometric Microscope (IRM) Model RM-2B allowed continuous monitoring of the surface temperature of the growing ice particles. Since the instrument was used in a cold room, it had to be specially calibrated (Agnew, 1972). The temperature-indicating signal was averaged over 1 sec by a Dymec Digital Voltmeter Model 2401C and measurements were typed out every 10 sec. The lens of the radiometer had a working distance of 53 cm, and the horizontally pointing radiometer viewed an area of 0.27 cm^2 on the particle equator, just before that area re-entered the droplet stream (Fig. 1). It measured the temperature at a location where the major part of the (quite homogeneous) accretion occurred. Due to this arrangement, the IRM indicated the lowest temperature of the equatorial deposit during one revolution cycle, because the accretion had time to cool somewhat while being shaded from the droplet cloud of the air stream. However, rotation in the opposite direction did not show deviations beyond the measurement accuracy of ±1C.

After finishing an experiment an icing specimen (Fig. 2) was frozen (when necessary) and moved into another cold room for bubble (List *et al.*, 1972; Agnew, 1972) and crystal size measurements with a Projectina projection microscope. For the smallest bubbles, measured magnifications of up to 500× had to be used. Sizes of 128 to 396 bubbles per shell were grouped in classes differing by $\sqrt{2}$, and areas containing 150–850 crystals per shell were measured and used to calculate the average planar crystal area.

3. Experimental results

In the B series (liquid water content ≈4 gm m^{-3}) each icing experiment had a duration of 7-9 min, with growth rates of the equatorial radius of 0.11–0.34 cm min^{-1}. This produced stones with diameters between 4.2 and 7.5 cm. While the air temperature varied between −5 and −20C, the IRM indicated surface temperatures of 0C throughout the series. This is in agreement with the observation of a liquid film which covered the surface and gave the stones a smooth glassy appearance. Because cracking was observed during cooling after the experiment, spongy growth is indicated. Observation showed that the particles remained essentially spherical during growth. Their appearance would be classified as bubbly, but transparent rather than opaque.

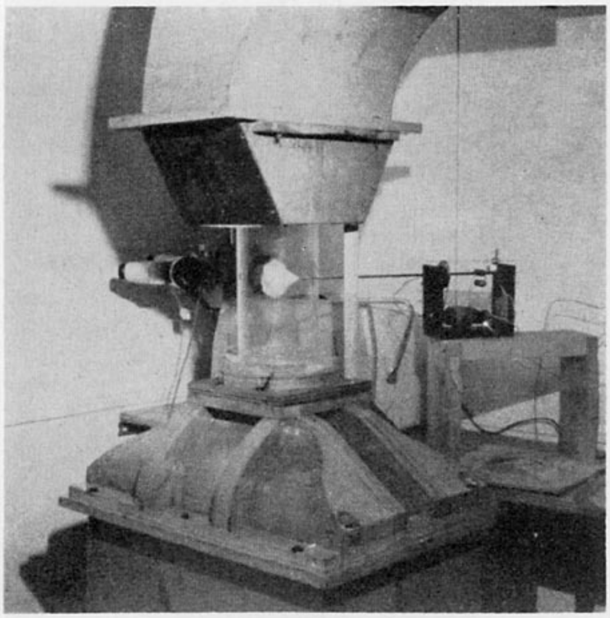

FIG. 1. Measuring section of vertical wind tunnel depicting the artificial hailstone growing while rotating counterclockwise in a updraft with supercooled droplets, its surface temperature being monitored by an Infrared Radiometric Microscope on the left of the stone.

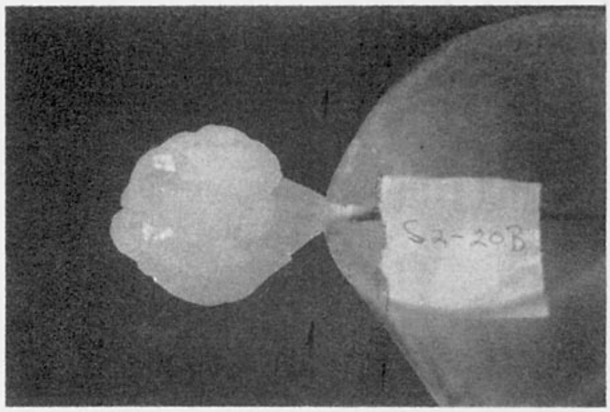

FIG. 2. Typical ice specimen (diameter 7.5 cm) of series B grown at −20C with a liquid water content of 4 gm m^{-3}.

For the C series (liquid water content ≈2 gm m^{-3}), accretion rates between 0.06 and 0.11 cm min^{-1} during 10–15 min led to ice particles with sizes between 3.8 and 4.6 cm. The stones in this series developed more lobes and a more knobby structure than in the B series, particularly at the lower temperatures. There was visual evidence of a liquid water film on the particles produced at −5, −7, −9, −11 and −13C, and within measurement accuracy the IRM indicated surface temperatures of 0C. The stones were markedly opaque in contrast to those of the B series. It is suspected that the stone at −15C grew essentially at the transition between spongy and non-spongy ice. In its first growth period the stone grown at −17C did not have an even layer of liquid water; while the surface temperature was 0C, ice dendrites protruded from the thin water film giving the surface a rough pitted appearance. This was probably caused by the rapid dendritic growth (which is faster than the stone growth rate) during the initial stage of droplet freezing due to the supercooling, with the non-frozen water then draining off into the liquid film. The IRM indicated that the average stone surface temperature fell below 0C during the last few minutes of growth. [It may be added here, that the presence of a *continuous* water film does not necessarily require surface temperatures of 0C because the system is not in equilibrium; but the temperature cannot deviate very much from 0C (generally <1C). At air temperatures of −20C, the surface of a growing hailstone can still be *partly* wet because freezing of accreted water requires time.] The hailstone grown artificially at −20C was completely opaque and nearly all the outer shell was white indicating high density ice with many tiny air bubbles (List *et al.*, 1970). The IRM readings were below 0C all the time. (This case is discussed later in detail.)

Except for the stones of the C series grown at −15, −17 and −20C, all ice particles definitely did grow spongily because cracking was visible after allowing the trapped water to freeze. Two of the three mentioned exceptions may also have grown slightly spongy or just wet. (Frozen spongy ice does not always show cracks, particularly if the liquid water fraction is small and/or when the freezing is slow and plasticity can adjust to the volume expansion.)

The *formation of air bubbles* can occur by various mechanisms. Air dissolved in the accreted water is liberated in the form of bubbles by an advancing ice-water interface. At 0C 28.6 cm^3 of air is dissolved in 1000 cm^3 of water, while at −20C about 70 cm^3 are expected on the basis of extrapolation. It would be unrealistic, however, to assume that all the air coming out of solution would remain in the growing particle by becoming engulfed by ice; most of the air bubbles escape through the liquid particle surface (an effect which may have consequences for electrification by bubble bursting during the growth phase). The trapping of air bubbles is enhanced by more numerous growing dendrites; in the case of so-called dry growth, environmental air may also be trapped between accreted droplets. It may be added that the droplet size and suspension time in the airstream before impact were more than adequate to obtain an equilibrium, not only of temperature but also of dissolved air in water.

The *air bubble pattern* showed homogeneous distributions for the B series and most stones of the C series (Fig. 3); a fan-like arrangement was observed for some

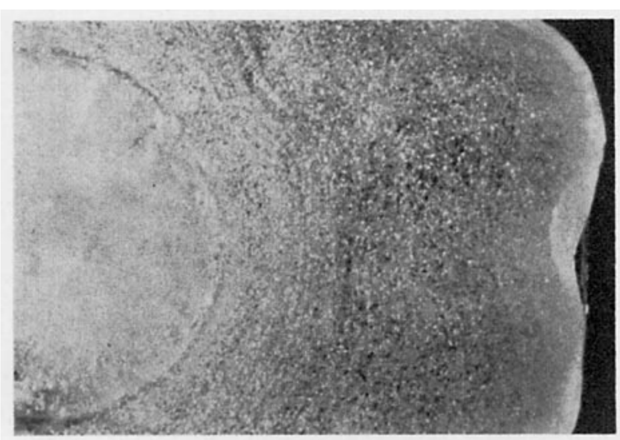

FIG. 3. Partial view of thick section of stone S2−17B, grown at a liquid water content of 4 gm m^{-3} and an air temperature of −17C. The diameter of the core particle is 2 cm.

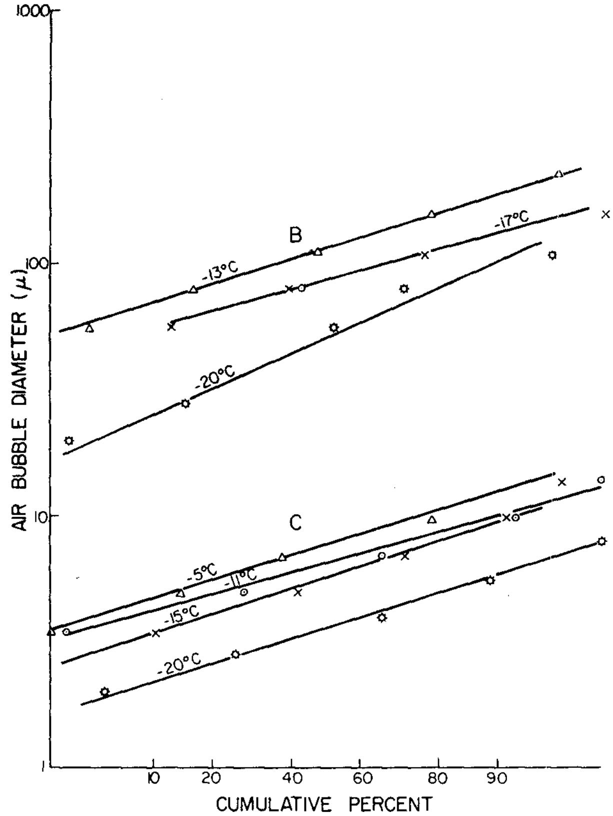

FIG. 4. Logarithm of planar bubble diameter D as function of the cumulative probability of bubbles with diameters $\leqslant D$, for different air temperatures. The liquid-water content is 4 gm m^{-3} for the B series, and 2 gm m^{-3} for the C series.

stones of the C series. The reason for this arrangement of bubbles in more or less regularly spaced sheets with equal orientation relative to the local radius is not understood. It could be caused by the presence of lobes which may lead to variations in the local values for heat and mass transfer as well as accretion rates, described by Aufdermaur and Joss (1967), Macklin and Payne (1967), Schuepp (1971), and Levi and Aufdermaur (1970). Local variations in bubble density and distribution were averaged for display in diagrams.

The *air bubble distributions* were found to be log-normal, as expressed by Fig. 4. The standard geometrical deviation σ_y (given by the slope of the lines) of the logarithm of the bubble diameters as measured in a plane does not change much from deposit to deposit. It may be added that the bubble concentration did not vary appreciably along radial directions. (In cases of fan-like structures the bubble size distribution and average concentration were the same as for subsequent homogeneous shells.) Fig. 4 shows that the distribution curves are grouped according to the liquid water content, with another regular subdivision caused by air temperature. Increasing the liquid water content or the air temperature both produced larger air bubbles. This is emphasized in Fig. 5 with plots of mean planar bubble diameters versus air temperature. Whether or not the functional dependence on air temperature is truly linear in this type of display cannot be judged on the basis of experimental data available at present.

If air temperature in Fig. 5 is replaced by radial rate of growth of the ice particles, Fig. 6 is obtained. Again a similar clear-cut separation of the data for the two liquid water contents is observed. For each series the logarithm of the mean bubble diameter is a linear function of the radial growth rate of the ice particles. This result is in agreement with Carte (1961), who investigated thin ice sheets.

A word of caution has to be added here about the effect of the freezing of the spongy ice particles before investigation. It may well be that the bubble diameter depends somewhat on the freezing velocity. But since most ellipsoidal hailstones do not show large cracks, if any, slow freezing is indicated (or no spongy ice) where the plastic properties give time to the ice to adjust to the pressures occurring inside when freezing starts from the outside (see also Knight and Knight, 1970). This is different from the quenching which also was studied by the same authors.

All the figures on bubble size distributions contain diameters D_p measured in a plane. If a conversion to volumetric means $\bar{D}_v$ is desirable, one can follow the procedure of List *et al.* (1972) which shows that, because the distributions are log-normal,

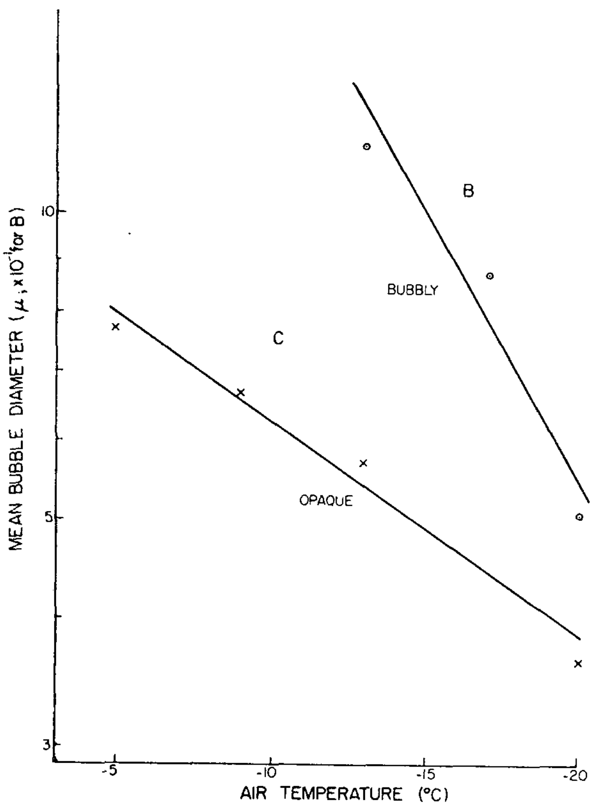

FIG. 5. Mean planar bubble size as function of air temperature, for B and C series. Note that the mean bubble diameter for the B series is scaled down by a factor 10.

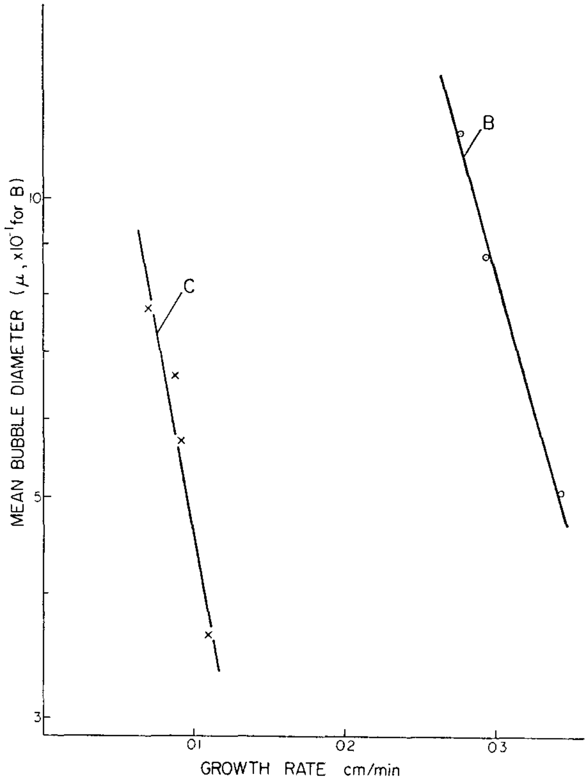

FIG. 6. Mean planar bubble diameter as function of the growth rate, for B and C series. Note that the mean bubble diameter for the B series is scaled down by a factor 10.

$$\bar{D}_v = \frac{\pi}{2}\bar{D}_p \exp(-\sigma^2_{\ln D_p}),$$

where $\sigma_{\ln D_p}$ is the geometric variance of the logarithms of the planar diameters. Because this latter factor is constant for all stones within quite narrow limits, the above equation can be reduced to

$$\bar{D}_v = 0.92\bar{D}_p.$$

This expresses that the mean volumetric diameter does not differ much from the mean planar diameter. The multiplicative factor for a sample of real hailstones was found to be 0.98 (List *et al.*, 1972).

The planar ***bubble number densities*** for the specimens are shown versus mean planar bubble diameters in Fig. 7. In this double logarithmic representation all points, represented by solid dots, lie on one straight line, with the exception of the value of 8720 cm^{-2} for the C series stone grown at −20C. For comparison the findings of List *et al.* (1972) on natural hailstones are also shown, together with the dividing lines for transparent and opaque ice designated in that study. The difference in the characteristics of the opaque shells may be explained by considerable differencies in icing conditions.

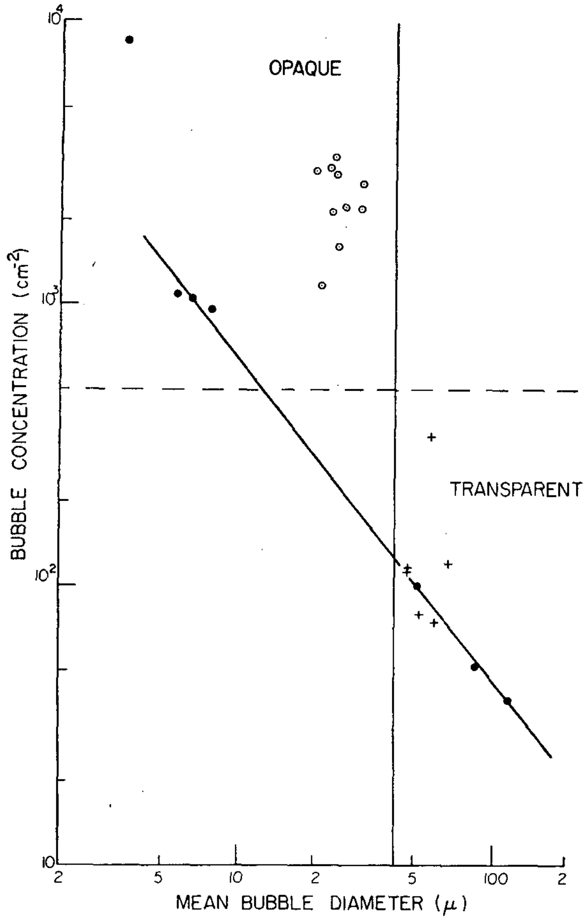

FIG. 7. Number concentration (solid dots) as function of mean planar bubble diameter, with indication of appearance. Lower liquid water content is leading to opaque deposits with high bubble concentrations, while higher liquid water content is leading to transparent deposits with low bubble number densities. Separations and data from real hailstones (crosses and open circles) are from List *et al.* (1972).

The main conclusion to be drawn from Fig. 7 is that opaque shells contain more numerous but smaller air bubbles, while transparent shells contain fewer but larger bubbles. The air enclosed in spherical bubbles leads to ice densities not lower than 0.913 gm cm^{-3}, and only up to 3% of the originally dissolved air remains in that form in the ice. These figures may change somewhat if large irregular air enclosures would be considered; but because they occur irregularly they are not accounted for in bubble concentration and mean bubble diameter.

The decrease in liquid water content from 4 to 2 gm m^{-3} changed the shell appearance from transparent to opaque while the bubble concentration increased by a factor $\geqslant 10$. Changes in air temperature from −5 to −20C did not affect the appearance of the deposits studied. (For comparison of bubble concentration with air temperature use data given in Fig. 5.)

One thing becomes quite clear. Ice which definitely grew spongy (series C, $\bar{D}_p < 10$ μm, at −5, −11, −13 and possibly −15C) is unquestionably opaque. Besides the fact that opacity is not a proper physical term (see Brownscomb and Hallett, 1967) and should not be used, we have now proof that associations of transparent with frozen spongy ice and that of opaque with "dry growth" ice are not tenable.

An interesting glimpse into the *surface temperatures* of the deposits was obtained with the IRM. The results reported here are restricted to the main growth areas on the equator of the artificial hailstone; no temperature variations are given as they occur as one gets nearer to the poles. The most striking temperature-time curve was obtained for the C series stone grown at −20C (Fig. 8). For all the others the temperature did not show anything special because with possibly one or two exceptions, they all grew spongy as indicated by a constant 0C response by the IRM (and cracking during freezing) after the initial icing period. The situation for the hailstone under consideration is as follows: While the air temperature varied between −19 and −21C, the stone temperature was at equilibrium at about −23C due to evaporation. As soon as the water was switched on, the surface temperature T_D jumped to −10C, followed by a reduced increase until T_D was as high as −2C around the 3-min mark. From then on T_D dropped steadily to about −10C at 10 min. Then the experiment was terminated by switching the water injection off. A more rapid cooling of the surface followed. This hailstone had partly a fan-like structure which can easily be related to the temperature changes. For the first 3 min of injection the sensible heat of the core particle delayed achievement of an equilibrium temperature. During the first half of this period the core heat sink helped to produce an opaque shell with high bubble concentrations tapering off to clear ice. After attaining a temporary equilibrium, T_D started to drop. This situation was accompanied by the fan-like structure. Why the bubble distribution suddenly becomes homogeneous near the 7-min mark and stays that way until termination of the experiment is unknown and demonstrates that very fine distinctions may be read into hailstone structures. It may be added that surface observations showed that the opaque regions grew "dry" while the fan structure with its clear ice and the bubble sheets was accompanied by partly wet surfaces (the lobes normally wet, the regions in between dry); clear areas were connected to lobes, opaque bubble sheets to areas in between. There was no indication of a fan-like arrangement of single crystals, neither in shape, direction nor size.

On the basis of heat exchange considerations one would expect that the larger a particle gets the lesser the heat transfer per unit area and the larger T_D would become. However, temperature is not just a function of direct heat exchange. What may be more important sometimes is the lowering of the collection efficiency with increasing size (Macklin and Bailey, 1968). This effect leads to a faster cooling and drying of the surface.

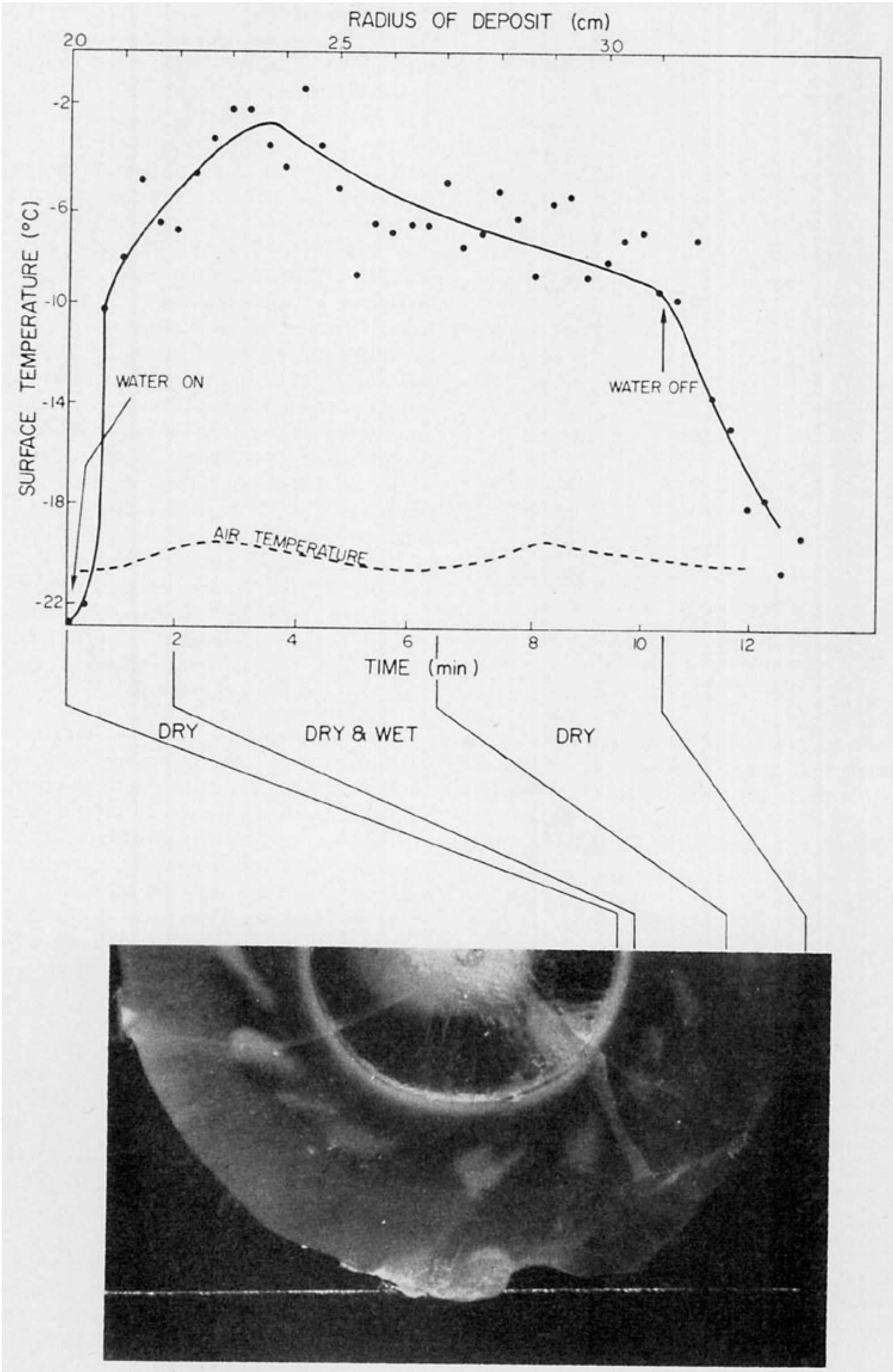

FIG. 8. Surface temperature and air bubble pattern of a hailstone grown at an air temperature of −20C and a liquid water content of 2 gm m^{-3}. Upper part: surface temperature as measured by the IRM during the experiment as a function of time, with indication of the approximate radius of the deposit; lower part: air bubble patterns corresponding to different growth times and growth stages (dry, dry and wet, dry).

This study was aimed at air bubbles. Nevertheless, some crystallographic data were obtained in form of mean surface *areas of single crystals*. Fig. 9 shows a dependence of average (planar) crystal area on tem-

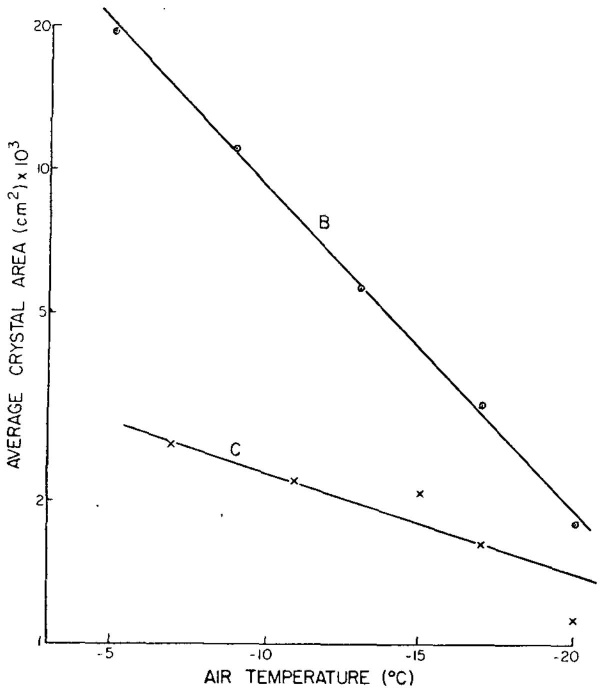

FIG. 9. Mean area of ice single crystals as a function of air temperature, for liquid water contents of 4 and 2 gm m^{-3} as represented by the B and C series, respectively.

perature, which is greatly affected by the liquid water content (compare B and C series). Since de-ionized water with a resistivity of 0.5 MΩ cm was used throughout the experiments and the structure depends upon impurities, this figure should only serve to demonstrate trends; it does not have the same significance as the bubble distributions and concentrations.

4. Summary and concluding remarks

The study of ice accretions on 2-cm ice particles, rotating at 1 Hz around a horizontal axis in a vertical wind tunnel at an airspeed of 18 m sec^{-1} and at liquid water contents of either 4 or 2 gm m^{-3}, leads to the following conclusions:

1) As in natural hailstones, planar air bubble size distributions in shells are log-normal, with a constant standard geometric deviation.

2) The main factor affecting the mean bubble size is the liquid water content. A secondary effect is produced by temperature variations. Changes in test particle radius alone are, in general, not important (except for patterns), but changes in terminal speeds may produce other effects.

3) The main factor affecting the air bubble number density is the liquid water content. A secondary effect is produced by temperature changes. Decreasing the liquid water content and/or the temperature leads to increased concentrations of smaller bubbles and smaller crystal areas.

4) Frozen spongy ice can either be transparent or opaque. Therefore, appearance cannot be used as a criterion to distinguish between "wet" and "dry" growth of ice deposits.

5) Structural properties like fan-like arrangements help to pin down or rule out certain aerodynamic motions. Since the authors have never seen any hailstone with such a bubble arrangement, it is concluded that the commonly used rotation rates of about 1 Hz (Macklin, 1961, 1962; Levi and Aufdermaur, 1970) are unrealistic. They could be either too low or too high, depending on the situation. But this will be substantiated in other papers. Kidder and Carte (1964) may have treated more realistic conditions with rotation rates of 24 rpm, but they were unable to draw any quantitative conclusions. In case liquid water content and air temperature are the major variables describing the growth of given hailstones, then it may be possible to deduce these two quantities from air bubble concentration and mean bubble diameter for each shell; hence, an interpretation of icing conditions on the basis of hailstone structure may be possible. This implies, however, that hailstone aerodynamics is adequately considered (possible rotational motions and their effects). If the relationships do not allow that separation of variables, at least good estimates about the liquid water content are feasible.

The measurements with the Infrared Radiometric Microscope have provided a new and easy procedure for the measurement of surface temperature once proper calibrations were performed. This is particularly important for non-spongy growth where deposit temperatures are extremely hard to measure otherwise. Unfortunately, the range of conditions to be covered with the Toronto facility are not sufficient, because wind speeds $\leqslant 18$ m sec^{-1} and temperatures $\leqslant -20$C are not adequate to produce reasonably fast-growing, low-density ice. There is also no provision to study the effect of reduced air pressure.

In summary, these pilot experiments have demonstrated that the study of air bubble size distributions and concentrations may lead to a good interpretation of hailstone histories. It is obvious that the new ideas and findings expressed in this paper can and should be incorporated into the planning and execution of new and more comprehensive experiment series.

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