On the Heat Transfer to Ice Spheres and the Freezing of Spongy Hail

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ABSTRACT

The rate of heat transfer during melting of solid ice spheres and freezing of spongy ice spheres has been measured over a range of experimental conditions. The results agree quite well with other published heat transfer data, and show that heat transfer to a melting hailstone, whose surface is covered by a film of water, is described by the same expression as that for a freezing hailstone with a dry surface. Using the measured heat transfer rates in a numerical model of the freezing of spongy hailstones in an updraft, it is shown that there is probably time for smaller spongy hailstones to freeze before reaching the ground, but that freezing of spongy hailstones 3 cm in diameter or larger is improbable. This finding, in conjunction with field measurements of liquid water contents of natural hailstones, casts doubt upon hailstorm models which imply growth of large spongy hailstones in an "accumulation zone" of high supercooled liquid water content aloft.

1. Introduction

Considerable uncertainty still exists concerning the mechanism by which nature grows hailstones. This uncertainty reflects rather large gaps in our knowledge of the environment in which hailstones grow (temperature, available liquid water, vertical wind field, abundance of hailstone embryos, etc.) and, to a lesser extent, of the mechanism by which water is accreted and frozen on a hailstone. These two problem areas are inextricably linked since the controlling factor in hailstone growth, the rate of removal of the heat of fusion of the accreted ice, is a function both of the environmental parameters and of the mechanism of accretion.

The fundamental problem, which has not yet been satisfactorily resolved, is the difficulty encountered in explaining the apparent rapidity with which natural hailstones grow. Hitschfeld and Douglas (1963) and Sulakvelidze (1967) have reported that the time interval between first appearance of a radar echo from a given cloud and the observation of hail reaching the ground from this cloud can be as short as 15 min. On the basis of such observations, Hitschfeld and Douglas, Sulakvelidze, and others have suggested that hailstones grow in a region of the cloud where very large concentrations of supercooled water (10–40 gm m^{-3}) exist, thus enabling a very high rate of accretion. Under these conditions, however, the hailstone is unable to dissipate the heat of fusion of all the accreted water to the surrounding air. In early theoretical investigations of the rate of hailstone growth (Schumann, 1938; Ludlam, 1958) it was assumed that the excess liquid water was shed by the hailstone. Hail tunnel experiments by List (1959) have since shown that this assumption may be erroneous. He found, when the rate of accretion exceeded a critical value dependent on the heat transfer rate, that the excess liquid water was trapped in a matrix of dendritic ice crystals which formed upon impact of supercooled droplets at the frozen surface, giving rise to a "spongy" ice deposit. Such spongy hailstones can apparently exist without disintegrating even when less than half the accreted water is actually frozen.

The possibility of spongy hail growth raises a further question, however. Either the hailstones must arrive at the ground in the spongy state, or else the hailstorm must provide some mechanism for subsequent freezing of the trapped liquid water. Data on the occurrence of spongy hail at the ground are sparse. Summers (1968) reports that, over a three-year period, 47% of all hail reports from an extensive volunteer observer network noted some soft hail. Soft hail occurred most frequently in the spring and late summer (May, June and September) but was less frequent in midsummer (July and August). It is unfortunately not possible to estimate the "sponginess," i.e., the liquid water content, of the hail in these reports. Gitlin *et al.* (1968) have measured the liquid water content of freshly fallen hailstones, using a calorimetric technique, from midsummer hailstorms in South Dakota and northeastern Colorado and from hailstorms in Kenya, Africa. Although the number of cases studied is certainly too small to allow unambiguous conclusions, the data show that about 90% of all the hailstones collected, including all the large hailstones investigated, contained less than 4% liquid water. On the basis of the calorimetric measurements, it therefore appears either that spongy hailstones containing large amounts of liquid water are not too common in nature, or that spongy hailstones spend sufficient time in a dryer, cold environment, after growth is completed, to freeze the trapped water. The purpose of the present work has been to measure the rate of freezing of spongy hailstones, and to apply the results to a typical hailstorm model to see whether sufficient time is in fact available to freeze spongy hailstones in nature.

Previous measurements of the rate of heat transfer to ice spheres by Macklin (1963) were made by melting solid ice spheres in a warm air stream. Under these conditions, the surface of the sphere is covered with a layer of water. In the freezing experiments carried out here, on the other hand, the surface of the sphere was of course dry. To see whether the different boundary conditions affect the heat transfer process, melting experiments were also performed. We report the comparison between our heat transfer measurements under both conditions and the measurements of Macklin.

2. Experimental procedure

The general approach followed was to suspend ice spheres containing a known liquid water content in a vertical air jet whose temperature was accurately concontrolled. After a specified time, the sphere was removed and, in freezing experiments, the liquid water content determined calorimetrically. In the melting experiments, the amount melted was determined from the weight loss.

a. Apparatus

All experiments were carried out in a standard horizontal domestic deep-freeze unit. The freezer was equipped with additional refrigeration capability and a temperature control system, so that the temperature in the airstream could be maintained constant within ±1C for any temperature between −18 and +18C. The airstream was supplied by a small centrifugal blower mounted inside the freezer. The blower exhausted into a vertical conical tube 11 cm high whose diameter increased from 3 cm at the bottom to 6 cm at the top. The sensing unit for the temperature control system was mounted in the airstream below the point at which the ice spheres were suspended.

Ice spheres 2.8 cm in diameter were suspended by the airstream near the center of the conical tube, where the airstream velocity equalled their terminal fall velocity. Pitot tube measurements of the airstream velocity in this region gave values in the range 21–22 m sec^{-1}. The terminal velocity calculated for a typical ice sphere, assuming a drag coefficient of 0.5, was about 23.6 m sec^{-1}. The calculated velocity was used in the analysis of the heat transfer measurements. The measured air velocities were nearly constant over the central portion of the conical tube, but were somewhat lower and more variable near the edges. There was some asymmetry in the velocity profiles, which induced considerable rotation of the ice spheres. Also, the spheres did not remain stationary but oscillated about the equilibrium point. Since these effects were present in all experiments, however, it was felt that the relative values of the heat transfer measurements from run to run would not be greatly affected, although a constant deviation from measurements in a completely homogeneous airstream might be present.

The apparatus and techniques for the calorimetric measurement of liquid water content of hailstones has been discussed by Gitlin *et al.* (1966).

b. Preparation of spongy ice spheres

Spongy ice spheres were made by immersing spherical snowballs in ice water. Sifted dry snow was compacted in a spherical mold 2.8 cm in diameter to form snowballs whose density was about 0.5±0.2 gm cm^{-3} which were then stored at −17C until needed. Prior to an experiment, the spheres were placed in a 0C cold box and allowed to warm nearly to the freezing point. For each run, a snowball was weighed, immersed in an ice-water bath for 1 min, and weighed again; the liquid water content was determined from the difference between the dry and wet weighings. Ice spheres for the melting experiments were obtained by refreezing such spongy ice spheres, and warming them to within 1C of the freezing point just before each run.

The spongy ice spheres made in this fashion obviously exhibited considerable variation in their properties from sample to sample. However, the average values for the density and liquid water content were, respectively, about 0.844 gm cm^{-3} and 0.40.

(An interesting side observation is that when spongy ice spheres containing more than 40% liquid water were frozen in an airstream colder than −10C and then sectioned, well-defined concentric layers of air bubbles were observed in the interior. Apparently, the air dissolved in the water is rejected upon freezing and is swept ahead of the inward-moving freezing interface. When the internal pressure generated by expansion during freezing is suddenly released, as by cracking of the ice shell, air bubbles nucleate at the interface and are trapped by its advance. The process then repeats itself until sufficient pressure again builds up. As many as 5 or 6 concentric layers of bubbles have been observed. This observation, which has also been reported by List (1963), suggests that the layered structure of natural hailstones does not necessarily imply large variations in their growth environment, as has generally been assumed.)

c. Freezing measurements

For the freezing measurements, spongy ice spheres were placed in the airstream immediately after preparation and weighing, as described above. After a predetermined time (ranging from 1–4 min) they were removed, weighed again, and rapidly placed in the calorimeter, where the heat required to melt the remaining ice was measured. A considerable number of runs were carried out at each of the following airstream temperatures: −9, −12, −15 and −18C.

The final weighing of the partially frozen ice spheres showed that they lost a small amount of weight (average about 0.25 gm) while suspended in the airstream. This weight loss appeared to be nearly independent of the airstream temperature or the duration of the experiment. Since visual observation revealed that the spheres shed some liquid water immediately after being placed in the airstream, presumably due to centrifugal force as the sphere began rotating, the liquid water content of the stone was corrected on the assumption that all of the weight loss could be accounted for by this initial shedding of liquid water.

d. Melting measurements

Melting experiments were carried out by placing solidly frozen ice spheres in the airstream for a known period of time (again ranging from 1–4 min), the amount melted being determined from weighings immediately before and after each run. Measurements were made at airstream temperatures of 9, 12, 15 and 18C.

3. Analysis of data

In the experimental conditions employed here, heat transfer between ice spheres and the airstream can take place by conduction and convection processes, and by transfer of latent heat of evaporation or condensation. Macklin (1963) has shown that h, the rate of heat transfer per unit area to a melting ice spheroid, is given to fair accuracy by

$$h=x(\mathrm{Pr}^{\frac{1}{3}}k\Delta T+\mathrm{Sc}^{\frac{1}{3}}L_v D\Delta\sigma)\mathrm{Re}^{\frac{1}{2}}/2r, \qquad (1)$$

where Pr, Sc and Re are, respectively, the Prandtl, Schmidt and Reynolds numbers; k is the thermal conductivity of air, L_v the latent heat of vaporization of water, D the diffusion coefficient of water vapor in air, r the hailstone radius, ΔT the temperature difference between the airstream and the hailstone surface, $\Delta\sigma$ the difference between the water vapor density of the airstream and the equilibrium water vapor density at the surface of the hailstone, and x is an adjustable parameter dependent upon the shape of the spheroid. For ice spheres, Macklin found good agreement between theory and experiment with x about 0.75. In our work, good agreement was obtained in both freezing and melting experiments when x was unity. This relatively small disparity probably represents the increased heat transfer attributable to the non-ideal nature of the airstream in our experiments.

Since the Prandtl and Schmidt numbers are equal to 0.71 and 0.60, respectively, for air over a wide range of temperatures and pressures, the terms $\mathrm{Pr}^{\frac{1}{3}}$ and $\mathrm{Sc}^{\frac{1}{3}}$ differ only by a few per cent. To simplify further calculations, these terms have been equated to 0.85 and x to unity. Thus (1) becomes

$$h\cong 0.85(k\Delta T+L_v D\Delta\sigma)\mathrm{Re}^{\frac{1}{2}}/2r. \qquad (2)$$

a. Analysis of melting experiments

Analysis of heat transfer rates during melting conditions is relatively straightforward. Ice spheres lose mass by melting (and shedding of liquid water) at a rate governed by the heat transfer rate h, and, in relatively dry air, by diffusion of water vapor away from the surface. The rate of change of mass m with time is then given by

$$\frac{dm}{dt}=-\frac{4\pi r^2 h}{L_f}+1.7\pi r D\Delta\sigma\,\mathrm{Re}^{\frac{1}{2}}$$
$$=-\frac{1.7\pi r\mathrm{Re}^{\frac{1}{2}}}{L_f}[k\Delta T+(L_v-L_f)D\Delta\sigma], \qquad (3)$$

where L_f is the heat of fusion per gram of ice. The right-hand side of (3) varies only as $m^{\frac{1}{3}}$, so that for small changes in m the rate of weight loss is almost linear with time.

The equilibrium water vapor density at the freezing point is large enough (4.85×10^{-6} gm cm^{-3}) that the transfer of latent heat of evaporation makes a substantial contribution to the total heat transfer rate. In fact, if the air is dry, cooling due to evaporation outweighs the warming effect of heat conduction in (1) at all temperatures $\lesssim$9C; at lower air temperatures, no melting would occur. Measurements of the relative humidity of the airstream under the conditions of our melting experiments showed substantial fluctuations from time to time, but with a general trend to higher water vapor densities at higher temperatures. The average water vapor density at each experimental temperature was used in analysis of the heat transfer data; these values ranged from about 0.8–1.6×10^{-6} gm cm^{-3}.

b. Analysis of freezing experiments

Analysis of the heat transfer data from freezing experiments was considerably more complex. As the spongy ice sphere freezes, its surface temperature decreases and a freezing interface propagates radially inward. One must thus solve the heat conduction equation (Carslaw and Jaeger, 1959)

$$\frac{\partial T}{\partial t}=\frac{k_i}{c\rho_i}\left[\frac{\partial^2 T}{\partial r^2}+\frac{2}{r}\frac{\partial T}{\partial r}\right], \qquad (4)$$

with time-varying boundary conditions. At the surface of the sphere, the rate at which heat is conducted from within the hailstone must equal the rate at which it is delivered to the airstream, giving

$$k\left(\frac{dT}{dr}\right)_{r=r_s}=h \qquad (5)$$

as one boundary condition. At the freezing interface

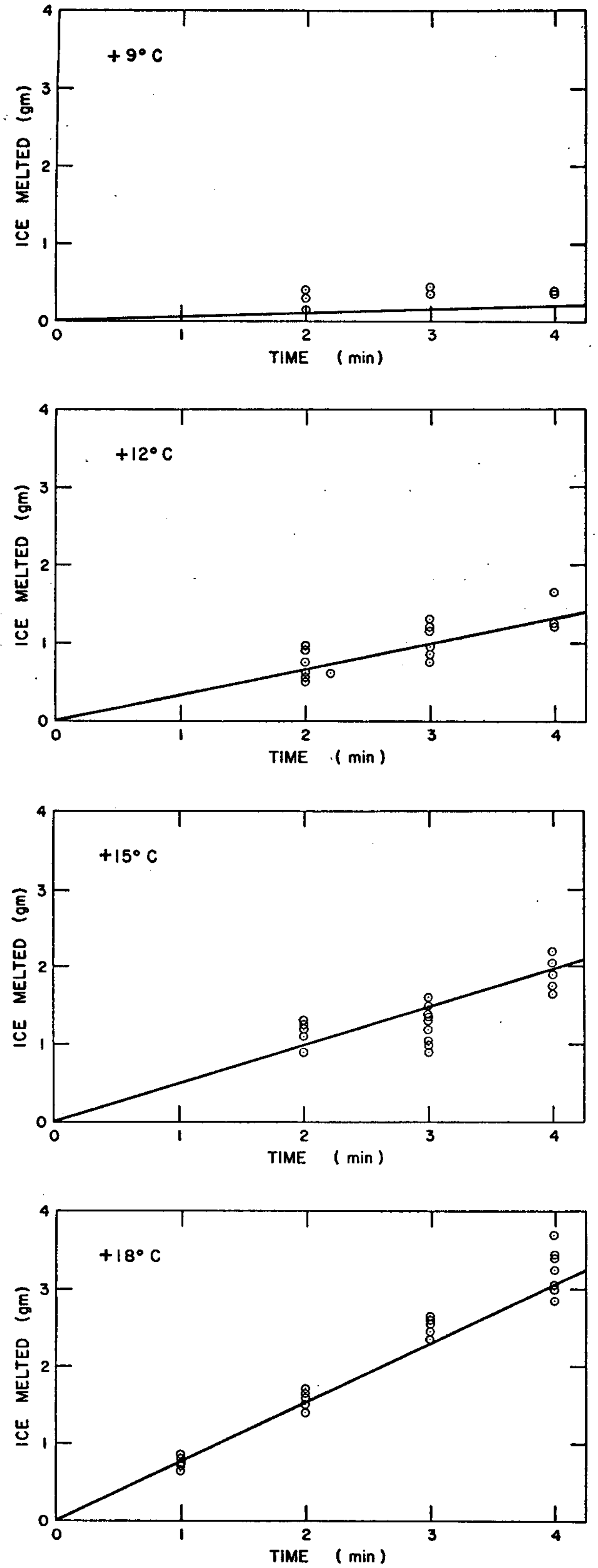

FIG. 1. Rate of melting of solid ice spheres, showing comparison of experimental results (points) with theoretical curve from Eq. (3), at the indicated temperatures.

the temperature is 0C, and the rate of liberation of the heat of fusion of the water frozen must be equal to the rate at which heat is conducted outward. The inner boundary conditions thus become

$$T_f=0, \quad \frac{dr_f}{dt}=\frac{k_i}{\rho_i Z L_f}\left(\frac{dT}{dr}\right)_{r=r_f}. \tag{6}$$

In these equations, k_i is the thermal conductivity of ice whose density is ρ_i, c the specific heat per gram of ice, and Z the fractional liquid water content of the ice sphere. Subscript s denotes conditions at the surface of the sphere, and f those at the freezing interface.

Eq. (4), subject to the boundary conditions (5) and (6), was solved numerically on a digital computer for initial conditions characteristic of the experimental work, using a finite-difference scheme described by Richtmyer and Morton (1967). Density, liquid water content, and airstream temperature were varied over the range of experimental values. Experimental determinations of the relative humidity showed that it was quite low during the freezing experiments. For the numerical computations, the air was thus assumed to be dry. At the colder experimental temperatures, this assumption can cause little error; at the warmer temperatures, it could lead to a slight overestimation of the rate of freezing. The thermal conductivity of the ice in the ice spheres was taken to be 0.0035 cal cm^{-1} (°C)$^{-1}$ sec^{-1}. This value is in reasonable agreement with thermal conductivities reported for snow of various densities in the International Critical Tables. The exact value employed was chosen for purely computational reasons; computations in which k_i was varied over the physically reasonable range showed that the results were quite insensitive to this parameter.

The calorimetric measurements are subject to one systematic source of error, which was accounted for in the computer program. Since the outer shell of the freezing ice sphere grows colder as freezing progresses, the heat needed to melt this region includes the heat required to warm it to the freezing point in addition to the latent heat of fusion. Thus, the calorimetric measurements overestimate the amount of ice formed by an amount which increases as freezing progresses. Since the computer program generates the radial temperature profile in the sphere as a function of time, it was relatively easy to integrate numerically to find the total heat required to melt the sphere. All data reported in the following section, as well as the computed curves of amount frozen vs time, thus show the apparent quantity of ice frozen, determined by dividing the total heat required for melting by the latent heat of fusion. Some freezing experiments were run in which thermocouples were embedded in the ice spheres to monitor the temperature as a function of time at interior points; in general, these temperature curves agreed quite well with computed interior temperature curves, thus

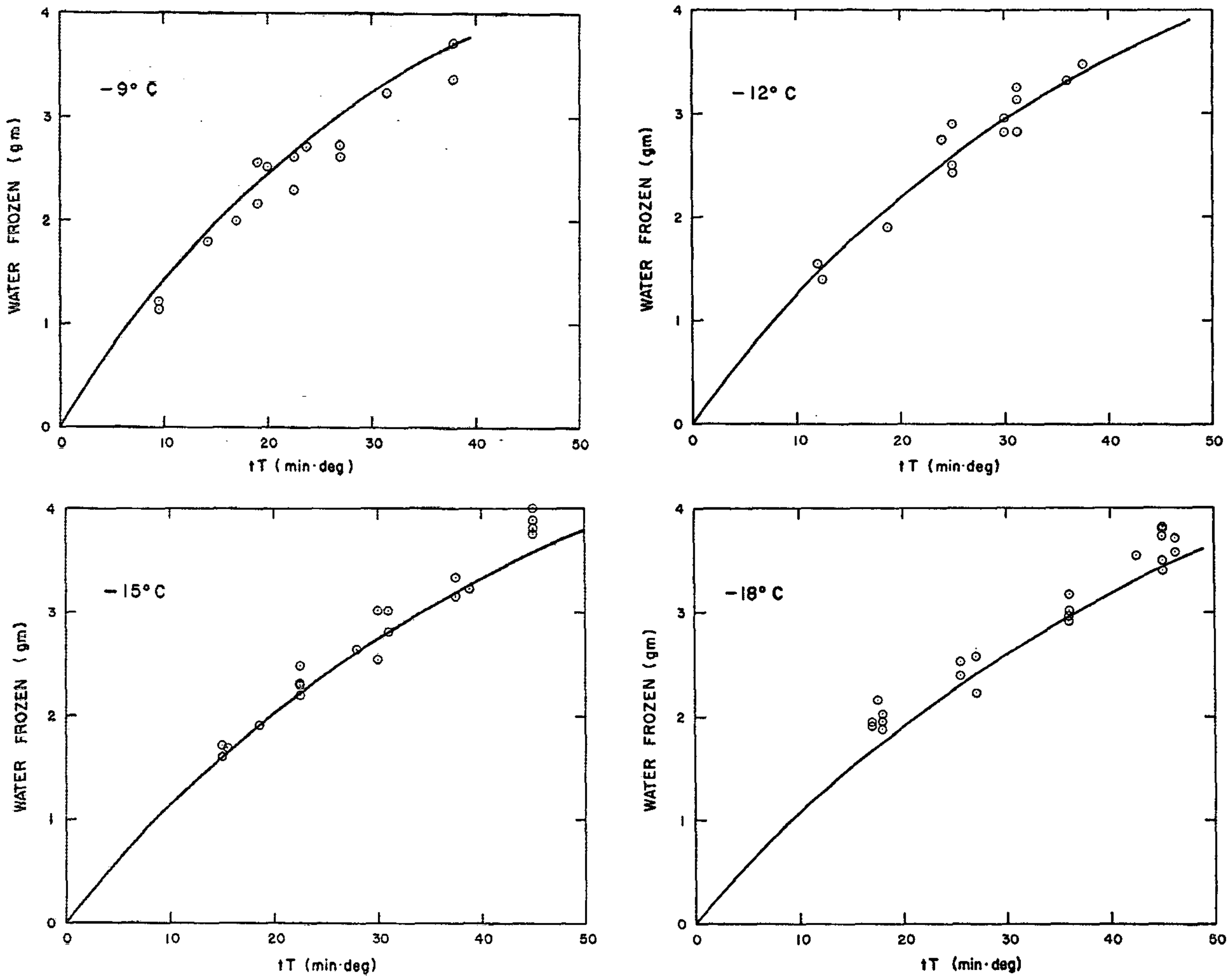

FIG. 2. Rate of freezing of spongy ice spheres, showing comparison of experimental results (points) with theoretical curves from Eqs. (4)–(6), at the indicated temperatures.

increasing our confidence in the numerical model's ability to simulate the experimental work.

4. Results

a. Melting experiments

The results of the melting experiments, plotted as weight loss vs time, for 2.8-cm diameter ice spheres at airstream temperatures of 9, 12, 15 and 18C are shown in Fig. 1. The weight loss curves calculated from (3) are also plotted, showing the rather good agreement between theory and experiment. The experimental data confirm the importance of the evaporative cooling term in (2); at an airstream temperature of 9C, the weight loss is almost negligible, since evaporation removes heat at a rate roughly equal to the rate of conduction to the surface of the sphere. Practically all the weight loss at 9C is attributable to evaporation rather than melting. As airstream temperature and humidity increase, however, the conduction term becomes dominant and the rate of weight loss increases rapidly.

b. Freezing experiments

The results of the freezing experiments are shown in Fig. 2 at airstream temperatures of −9, −12, −15 and −18C. Since the airstream temperature control system permitted long-term temperature fluctuations of the order of ±1C (although the temperature in any given run was constant within ±0.3C), it was difficult to carry out all experiments at precisely the desired temperature. The numerical freezing calculations had shown that in the absence of evaporative cooling effects, the time required to freeze a given quantity of water in a spongy ice sphere was almost exactly inversely proportional to the airstream temperature. Therefore, the data are plotted in Fig. 2 as the apparent quantity of water frozen vs the product of airstream temperature and time, to provide a first order correction for the effect of these temperature fluctuations.

The calculated freezing rates are also plotted as smooth curves in Fig. 2, using the same expression for the heat transfer rate at the surface of the sphere as for

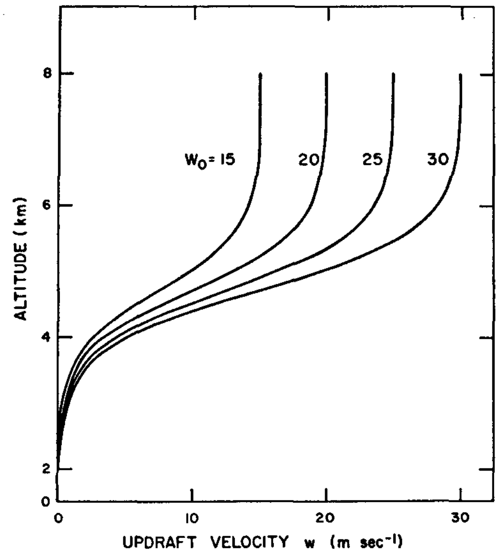

FIG. 3. Updraft velocity vs altitude from Eq. (7), for different values of w_0, used to estimate rate of freezing of spongy hailstones.

the analysis of the melting experiments. Again, the agreement between theory and experiment is quite good. There is a slight tendency for the theoretical curves to overestimate the rate of freezing at warmer temperatures and to underestimate at colder temperatures. This may be due to the assumption, made in the numerical calculations, that the air in the freezer was completely dry as mentioned in the previous section. In any case, the effect is small, of the same order as the scatter in the experimental data.

c. Comparison with the results of other investigators

A good summary of the rates of heat transfer to spherical bodies in general, and to melting or accreting ice spheres in particular, is given by Macklin (1963). As mentioned above, the rate of heat transfer given by (1) agrees satisfactorily with the available data when the shape parameter x is of the order of 0.75. We find good agreement between theory and experiment with x about unity, in both the freezing and melting experiments. This apparent increase of about 30% in heat transfer rate is very probably due to the non-uniform nature of the air flow in our relatively crude "wind tunnel." Of greater interest is the fact that the equation for the heat transfer rate did not require adjustment of parameters to account for the different boundary conditions present during our melting and freezing experiments. The presence of a liquid film on the surface in the melting experiments apparently has negligible effect on the transfer of heat from the ice sphere to the air stream.

5. Freezing of spongy hail in a model updraft

The computer program for the freezing of spongy ice spheres was used to study the rate at which spongy hailstones might freeze while falling in the atmosphere. There is yet no wholly satisfactory model of the growth and fallout regions of a hailstorm. We have thus employed a greatly simplified description of the environment through which a hailstone might fall, and have chosen conditions that are undoubtedly more favorable for hailstone freezing than any that might actually occur in nature, so that the results provide an upper limit to the amount of freezing that can occur.

The hailstones are assumed to fall in an updraft which varies with altitude in the manner suggested by Hitschfeld and Douglas (1963). The vertical wind velocity is given by

$$w=\tfrac{1}{2}w_0\{1+\tanh[1.1(y-4.7)]\}, \quad (7)$$

where w is the vertical wind velocity, w_0 the maximum vertical velocity, and y the height above sea level in kilometers. This expression gives an updraft which increases monotonically with increasing altitude, asymptotically approaching w_0 at great heights. Since in any realistic hailstorm model the vertical wind velocity must eventually diminish with altitude, the model here will tend in the limit to overestimate the amount of freezing, by overestimating the residence time of the hailstones in colder regions high in the cloud.

Secondly, the hailstones are assumed to fall in a region of zero cloud liquid water content, so that no further growth, with consequent release of latent heat,

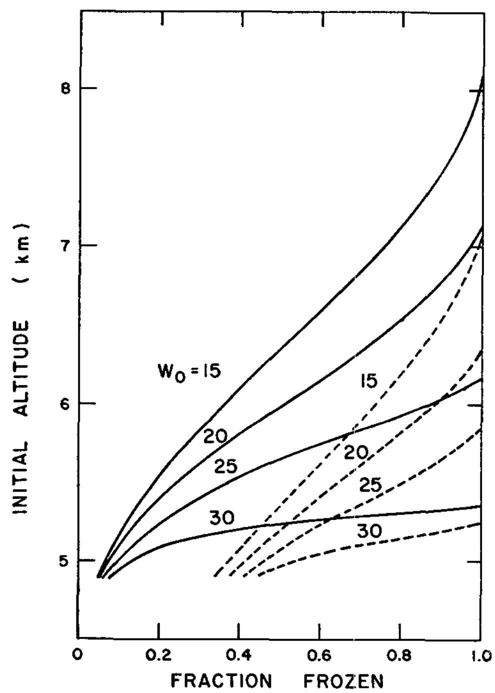

FIG. 4. Freezing of 2-cm diameter spongy hailstones containing 40% liquid water, for indicated values of w_0. Curves show the fraction of initial liquid water content frozen as function of the altitude from which hailstone falls, for hailstones falling in dry air (dashed curves) and air at 90% relative humidity (solid curves).

takes place. Calculations were carried out for hailstones falling through air at 90% relative humidity and, as an extreme and totally unrealistic case, zero humidity. The freezing level was taken to be 4.4 km, and the temperature lapse rate $-6.2C\ km^{-1}$.

Fig. 3 shows the updraft profiles as a function of altitude for values of w_0 of 15, 20, 25 and 30 m sec^{-1}. For hailstones 2 cm in diameter containing 40% by weight liquid water, Fig. 4 shows the fraction of the initial liquid water content which is frozen as a function of the height from which the hailstone starts its fall, in both dry and humid environments. It can be seen that in all such cases, sufficient time is available for total freezing of the hailstones when they start their fall from reasonable heights in the cloud. As hailstone size increases, however, the height from which the hailstones must fall increases very rapidly. The increased mass of liquid water which must be frozen, coupled with the increase in fall velocity of the larger hailstones, makes it unlikely that spongy hailstones >3 cm in diameter can freeze completely when falling from any reasonable altitude. Fig. 5 shows the extent of freezing taking place in a 3-cm diameter hailstone with 40% liquid water content, as a function of the updraft velocity and the initial altitude above ground, in air with both zero and 90% relative humidity. The liquid water content of the 3-cm hailstones when they reach the ground is shown in Fig. 6, again plotted as a function of the initial altitude and updraft velocity. Ground level was taken to be 1 km above sea level, and the melting taking place during the time spent at above-freezing temperatures was included in the calculation. It is shown in the figure that hailstones starting their descent from the 6-km level or lower lose, by melting, all the ice frozen at colder temperatures, and that hailstones descending through all but the strongest updrafts must fall from very high altitudes if they are to arrive at the ground in a completely frozen state.

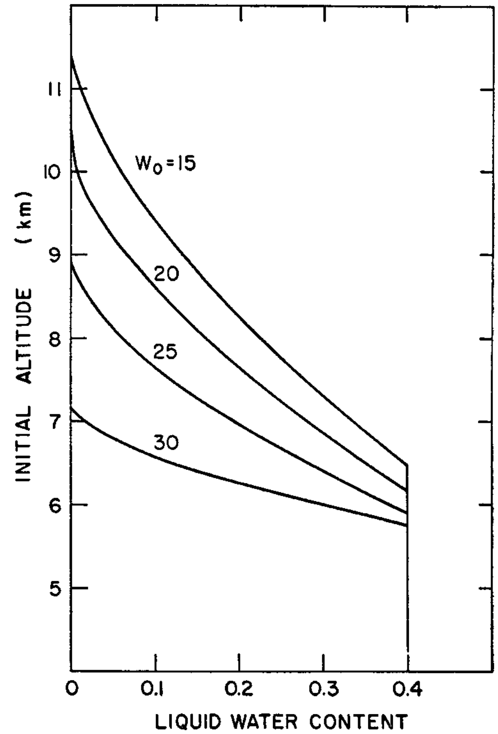

FIG. 6. Liquid water content of 3-cm diameter spongy hailstones at ground level (1 km MSL), as a function of initial altitude and updraft velocity, for hailstones with initial liquid water content of 40% falling through air at 90% relative humidity.

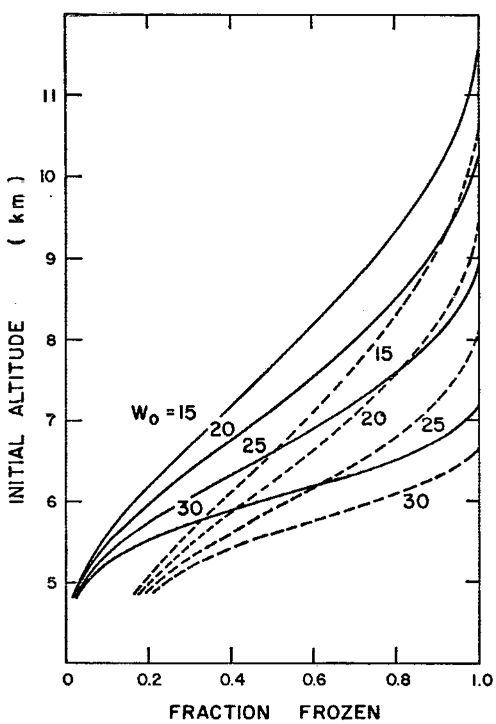

FIG. 5. Same as Fig. 4 except for 3-cm diameter spongy hailstones.

6. Discussion

There are several factors in the simplified freezing model treated in the preceding section which could be changed to simulate more realistically the conditions which most probably occur in nature, and whose effects can be discussed at least qualitatively. In the first place, the assumption of a strong updraft devoid of liquid water is, under hailstorm conditions, improbable. Thus, even the freezing rates calculated assuming relatively humid air will be too high. The calculations assuming dry air (zero humidity) are even more unrealistic. It has been often suggested that spongy hailstones might be ejected from the upper regions of a hailstorm into the relatively dry air completely outside the cloud. Under these circumstances, however, this air would undoubtedly have a near-zero or even negative vertical velocity, which would greatly reduce the residence time of the hailstone aloft and reduce the amount of freezing which could take place. In opposition to these effects, there is the probability that surface irregularities could increase the heat transfer rate above that measured using spherical bodies, as suggested by Browning (1966). Schuepp and List (R. List, private communication) have shown that this increase might amount to as much as a factor of 2. In the calculations reported here, the heat transfer rates measured in our freezing experiments, which were about 30% higher than those reported for smooth spheres in a relatively less turbulent air stream, were employed, so that this effect is at least partially included in the results. We feel, therefore, that the computations overestimate, by an unknown but perhaps considerable degree, the amount of freezing which actually could take place in a hailstorm.

In any case, one can state with complete generality that the formation of a completely frozen hailstone via spongy growth with subsequent freezing will take longer than growth of a similar hailstone at the optimum rate for formation of solid ice (the "just wet" growth condition). Since the controlling factor is the rate of removal of heat of fusion, the formation of ice will be most rapid when the temperature difference between the hailstone surface and the surrounding air is a maximum; namely, when the hailstone surface is at the freezing point. Removal of heat of fusion from the interior of a spongy hailstone, since the freezing interface advances radially inward, results in a temperature gradient in the outer frozen shell, a lowered surface temperature, and a lower rate of heat transport to the environment. Therefore, the spongy growth mechanism cannot be invoked to "explain" the apparently rapid rate at which large natural hailstones grow, if the hail stones are to be completely frozen when they reach the ground.

It thus appears that one of two conclusions must be drawn: either hailstorm models calling for growth of large hailstones in a region of high supercooled liquid water content, which implies growth of very spongy hailstones, are unrealistic, or else it must be possible for non-spongy hailstones to grow in such regions, in contradiction to laboratory results on the growth of ice bodies in a simulated supercooled cloud.

7. Conclusions

In summary, the conclusions to be drawn from this work are:

1) It is immaterial, to the question of the rate of heat transfer at a hailstone surface, whether that surface is wet or dry.

2) Heat transfer rates measured here agree, with reasonable accuracy, with other published measurements of heat transfer rates to ice spheres.

3) Using these heat transfer rates, it is found that it is unlikely that sufficient time is available for large spongy hailstones (greater than 3 cm in diameter) to freeze completely in a reasonable dynamic model of a hailstorm.

4) Hailstorm models which imply growth of spongy hailstones in an accumulation zone of high liquid water content are incompatible with field observations of the liquid water content of hailstones at the ground.

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