A Wind Tunnel and Theoretical Study on the Melting Behavior of Atmospheric Ice Particles: III. Experiment and Theory for Spherical Ice Particles of Radius > 500 μm

R. M. RASMUSSEN,1 V. LEVIZZANI2 AND H. R. PRUPPACHER

Department of Atmospheric Sciences, University of California, Los Angeles, CA 90024

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ABSTRACT

An experimental and theoretical study has been performed on the melting of spherical ice particles between 3 and 20 mm in diameter. For the experimental study the UCLA Cloud Tunnel was employed in determining the melting rate, the mode of melting, the shedding rate, and the hydrodynamic behavior of the melting ice particles. Our experimental results demonstrate that the melting mode of ice particles can be grouped into distinct categories depending on the Reynolds number. For these categories, comparison was made to various theoretical expressions reported in literature and to our own formulations. These comparisons show that experiment and the appropriate theory agree within experimental error.

1. Introduction

In recent years increased attention has been given to the physical processes involved in the melting of solid hydrometeors. These melting processes are particularly important to the formulation of convective cloud models because the latent heat of melting contributes significantly to the production of downdrafts in clouds, and the shedding of meltwater redistributes the loading of the liquid water in the cloud. Melting hydrometeors also affect radar interpretations since the backscattered radiation depends critically on an accurate knowledge of the shape and the water-to-ice ratio of the hydrometeor (Herman and Battan, 1961; Battan and Herman, 1962).

To the present time, relatively few studies on the melting of hydrometeors have been reported in literature. These studies have been reviewed by us in a previous article (Rasmussen and Pruppacher, 1982). It was concluded in this review that the previous studies were lacking in their quantitative ability to describe the melting and shedding rates of ice particles, and also in their ability to quantitatively describe the shape and hydrodynamic behavior of a melting ice particle. Their deficiency can be attributed mainly to the fact that in most of these studies the ice particles were not kept at their terminal velocities during melting. On the other hand, the study in which terminal velocity was maintained (Mossop and Kidder, 1962) determined only the change in shape of the melting ice sphere.

2. Experimental procedure

The experimental study described herein was carried out in the UCLA Cloud Tunnel. The experimental set-up was similar to that used for our melting experiments reported previously (Rasmussen and Pruppacher, 1982). In deviation from our previous experiment, the temperature and relative humidity of the airstream at the site of observation was kept constant at about 20°C and 40% relative humidity. The level of turbulence was determined to be less than 0.5% for all the air speeds used. Although the tunnel allows melting ice particles of less than one millimeter diameter to freely float at their terminal velocity, as reported in our previous study (Rasmussen and Pruppacher, 1982), the present study required that larger ice particles during melting be restricted in their movement somewhat so they would not collide with the tunnel walls. This was achieved by suspending the ice particle from a 0.13 mm diameter nylon fiber, frozen halfway into the ice sphere, allowing the particle to move horizontally only a few particle radii, suppressing any tumbling motion, but allowing some restricted spinning. Although attached to a thin fiber, the particle's terminal velocity was maintained at all times during melting by continually adjusting the tunnel velocity.

The melting rates and total melting times of ice particles larger than 1 mm in diameter were determined as follows: 1) the original ice particle, formed in a teflon mold, was weighed by a Metler balance in a

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1 Present affiliation: National Center for Atmospheric Research, Boulder, CO 80307.
2 Present affiliation: Istituto FISBAT-CNR, Reparto Nubi e Precipitazioni, Bologna, Italy.

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subzero environment; 2) the particle was then introduced into the tunnel airstream and melted at terminal velocity\(^3\) (indicated by a slackness in the fiber) for a specified period and 3) the particle was then removed from the airstream, the meltwater removed by a sponge, and the remaining ice portion weighed and measured. This procedure was followed repeatedly for a given initial ice particle size for various time intervals of melting.

Shedding rates were determined by photographing the particle just prior to removal from the tunnel. These photographs allowed us to compute graphically the total volume of the melting particle. By subtracting from this volume the volume of the ice core determined separately by weighing, the volume of the meltwater, and thus its mass, was obtained. This mass added to the mass of the ice core gave the total mass of the melting ice particle. By comparing this total mass with the mass of the ice particle before melting, we could determine the mass of any meltwater shed.

All our observations were documented by color motion picture, which illustrated qualitatively the melting and shedding processes and also allowed us to determine the size of the drops shed. The film also gave valuable information on the internal circulation in the meltwater. The ice particles investigated in this study had diameters between 3 and 20 mm before melting.

3. Melting modes

The results of our investigation are summarized schematically in Fig. 1. This figure shows that one must distinguish between seven melting modes. The initial diameter of the melting particle in this figure is 2 cm. Ice particles of initial diameter smaller than this size assume the melting mode appropriate to their size, after which the sequence given in Fig. 1 is followed. In the following we shall give a brief description of these modes.

As melting commences (Mode-1) a ring (annulus) of water forms near the equator of the ice particle. This ring is a combined result of the tangential stress on the lower surface of the particle, which advects the meltwater upwards, and of the flow separation near the equator of the particle, which allows the meltwater to accumulate there due to gravity. Once formed, the ring is supported by both the normal and tangential stresses. After about 20% of the mass of the particle has melted, the ring starts to shed drops on the order of 1.5 mm diameter. Shedding occurs due to the velocity shear at that location and due to the turbulent boundary layer that exists at these high Reynolds numbers (Mode-2). Melting is observed to occur mainly on the lower half of the particle, causing the formation of an ice core that is oblate in shape, in agreement with the observations of Macklin (1963) and Mossop and Kidder (1962) on larger ice spheres.

When the ice particle sheds meltwater, its mass—and therefore its terminal velocity—is reduced. This terminal velocity change is shown in Fig. 2 for a 2 cm ice sphere. Note that a significant decrease in terminal velocity occurs even before shedding as a result of the formation of the meltwater ring. The reduction in terminal velocity, in turn, reduces the stress on the meltwater, thereby allowing gravity to lower the meltwater ring farther upstream (Mode-3). The melt-water ring also becomes wider as it moves upstream, and as a result the drops sheared off are now larger (\(~3\) mm diameter), and shedding occurs more intermittently as the meltwater ring requires more time to build up to its former unstable size.

At Reynolds numbers \(~1.4 \times 10^4\), the entire melting ice particle starts to move back and forth, exhibiting slight ascending motions as it moves away from the center of the tunnel. This results in a sinuosoidal trajectory for the particle in free fall. A similar type of motion has been predicted by List et al. (1973) for spheroids of similar Reynolds number and axis ratio. They measured the drag and lift coefficients on sta-

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\(^3\) The drag force on a 6 cm long fiber of 0.13 mm diameter held perpendicular to a flow with free stream velocity equal to the terminal velocity of a 20 mm diameter ice sphere at sea level can be calculated to be 5% of the ice sphere weight (Pruppacher and Klett, 1980). This drag force would result in a change in terminal velocity of approximately 2.5%. Considering that the fiber holding the ice sphere is usually nearly parallel to the flow, the change in terminal velocity of the ice sphere is expected to be less than 1%. This small change in terminal velocity is well within experimental error.
tionary spheroids and modeled the resulting motion by solving the equations of motion numerically. One of the steady modes of fall they predicted was a constant amplitude back and forth oscillation with ascending motion as it moved away from its equilibrium position, similar to that observed in the present experiments.

Another possible fall mode predicted by List et al. (1973) was that of continuous tumbling, resulting from amplification of the above mode. Since in the present experiment tumbling was prohibited, our shedding results must be applied to the constant amplitude oscillation mode of fall discussed above. The melting results, however, are expected to be valid for tumbling motions as well, since Macklin’s (1964) results showed that rotation and oscillation have only a small effect on the heat transfer to an ice spheroid.

As shedding continues the size of the particle decreases further and the ring of water continues to thicken and move upstream (Mode-4). At Reynolds number near $\sim 1.0 \times 10^4$, the oscillation and sinusoidal displacement of the particle discussed above are strongly damped, although still noticeable. At Reynolds number $\sim 8.5 \times 10^3$, nearly all oscillations of the particle have stopped. At this stage the ice core is nearly completely embedded in the meltwater, and the shape of the melting particle progressively assumes the form of a raindrop. The meltwater ring observed in this size range tends to have a strong insulating effect on the ice inside, resulting in the ice core becoming pill-shaped as it melts (rounded upper and lower surfaces, with nearly vertical lateral walls).

Any perturbations of the meltwater are continuously damped out by the ice core, allowing the maximum width of the melting particle to reach 1.3–1.4 cm. This is somewhat larger than the 1.0 cm width predicted by Klett (see Pruppacher and Klett, 1980) for the critical width before break-up of a raindrop of equilibrium shape. Larger stable base widths of raindrops were also found by Blanchard (1950) when he had an air bubble inside a drop. Air bubbles as well as an ice core appear to damp out perturbations in the raindrop, allowing the stable size to be larger.

As the ice core melts to an even smaller size, the damping effect on any meltwater perturbations decreases, allowing further drop shedding. These sheds proceed via the bag-breakup mechanism and produce drops on the order of 4.5 mm diameter. The breakup initiates as a wave on the lower water surface. These shed drops often encounter the weak flow region directly behind the melting ice sphere, and fall back to re-collide with the ice sphere. Collision induces a large perturbation in the meltwater, and frequently results in a violent “explosion” of 300 to 400 $\mu$m diameter drops emerging from the melting particle.

Once the stable raindrop size is reached (Mode-5), $N_{Re} \approx 6 \times 10^2$, or $d = 9$ mm, no further shedding occurs. This is in agreement with Blanchard’s (1955) experiments which showed that no shedding occurs if the particle is smaller than 10 mm in diameter. However, the present results are in disagreement with Chong and Chen’s (1974) theoretical model for water shells on ice cores. In their model, they predict that an ice core of 0.1 cm radius will shed water once a water shell thickness of 0.19 cm is reached. The resulting ice particle radius would be 0.29 cm, which is significantly smaller than the 0.45 cm radius observed for no shedding in this study. Once this 0.45 cm radius stable size is reached, the ice core melts in this raindrop configuration with no further shedding.

The ice core melts oblate as long as the diameter of the raindrop-shaped meltwater is larger than 5 mm diameter. This is due to the lack of internal circulation observed in the meltwater of these particles. This lack of circulation may be caused by the very flat upstream side of the raindrop-shaped meltwater, which results in a relatively small area on the particle’s sides, over which the air’s shear stress can be effective in inducing internal flow.

However, particles smaller than 5 mm diameter were observed to have a significant internal circulation (Mode-6). This circulation was made visible by charcoal particles in the meltwater. These tracer particles were filmed and found to reach speeds of up to 14 cm s$^{-1}$. This circulation also caused the shape of the ice core to be distinctly conical. Observations from films showed that the streamline patterns were somewhat turbulent, possibly caused by oscillations set up in the drop by the rear eddy shedding. We classify this motion as semiturbulent because at times it can appear as the laminar internal flow inside water drops less than 500 $\mu$m radius, and then suddenly it becomes chaotic; and just as suddenly it may return to the laminar type motion again.
The melting Mode-7 of spherical particles less than 1 mm diameter was discussed by us previously (Rasmussen and Pruppacher, 1982).

Figure 1 shows that the outer appearance of the melting ice particle continuously changes. This behavior is presented quantitatively in Figs. 3 to 7 in terms of the axis ratio of the melting ice sphere as a function of the nondimensional mass melted for various initial ice particle diameters. These figures show that the axis ratio of the melting ice particle rapidly decreases with increasing mass melted. For the three cases for which no shedding occurs (0.92, 0.77 and 0.64 cm), the axis ratio decreases rapidly to the limiting value of 0.5 when 80% of the particle has melted. As already discussed, the reduction in axis ratio is due to the ring of water thickening and spreading during melting. Due to the oscillations of the meltwater at the nearly melted stage, the data points at this point show a slight spread. Note that the initial decrease in axis ratio is very large, so that for a 0.92 cm particle, the axis ratio has decreased to 0.85 after only 10% of the particle has melted. This trend was also observed for the two larger sizes for which shedding occurred. However, instead of the axis ratio decreasing uniformly, as for the smaller sized particles, the decrease in axis ratio with mass melted dramatically slows down once shedding has begun. Following this slowdown, the curve usually exhibits large jumps. This behavior is due to shedding which reduces the mass of the meltwater and allows the particles to attain new equilibrium axis ratios under reduced aerodynamic forces.

4. Shedding

Figure 1 shows that ice particles larger than 9 mm in diameter shed their meltwater during melting. This behavior was quantitatively studied during our experiments and the result of these studies summarized in Fig. 8. This figure gives the cumulative nondimensional mass shed as a function of the nondimensional ice core mass. The bold diagonal line in this figure represents the case for which it is assumed that all the meltwater is being shed. The actual shedding curves were determined by a linear regression of the experimental data. The error bars represent the 95% confidence limits. Note that the experimentally observed shedding follows curves which lie below the limiting bold diagonal line, implying that only part of the meltwater of the ice particle is shed. Note also that the smaller the initial ice sphere diameter, the smaller the fractional mass that is shed.

Note also that the difference between the all mass shed curve and a particular shedding curve is nearly constant during melting for the 1.08 and 1.25 cm diameter ice spheres. This means that the amount of meltwater remaining on the ice core’s surface is on the average nearly constant during melting. For a 1.08 cm diameter sphere this amount is ~0.23 g, equivalent to a ~7.6 mm diameter water drop, while for a 1.25 cm diameter sphere the amount is ~0.26 g, equivalent to an ~8.0 mm diameter water drop. This is also the size of the completely melted particle for these two sizes. For a 1.84 cm diameter particle, the amount of liquid on the ice core’s surface is initially large (~0.54 g), then decreases down to a value of ~0.30 g at the end of melting. This final size is equivalent to an ~8.3 mm diameter water drop, and is one-tenth of the original mass of the ice sphere.

Figure 8 also shows that the onset of shedding occurs at a lower nondimensional ice core mass the smaller the initial size of the ice sphere. Note, for instance, that for an initial ice sphere of 1.08 cm diameter that
sheding does not begin until \( \sim 40\% \) of the sphere’s mass has melted.

5. Theory

A theoretical model for the melting rate of an ice particle melting in Mode-7 was presented and discussed by us in our previous article (Rasmussen et al., 1984).

For melting Mode-6 our observations show that the meltwater is well mixed due to the semiturbulent internal circulation. To a first approximation, one may assume that any temperature gradient across the meltwater is therefore immediately eliminated, which means that one may set \( T_a = T_0 \), where \( T_a \) is the temperature at the outer surface of the well mixed layer, and \( T_0 = 273.15 \) K is the temperature at the surface of the conically shaped, eccentrically located ice core. Due to the condition \( T_a = T_0 \), the geometric position and shape of the ice core no longer enters into the heat transfer equation. Simple heat transfer considerations (Pruppacher and Klett, 1980), lead then to the equation:

\[
4\pi \rho_i a_i^2 L_m \frac{da_i}{dt} = -4\pi a_i D_{v,i}(\rho_{v,\infty} - \rho_{v,0}) f_v - 4\pi a_i D_{v,i} D_{v,a}(\rho_{v,\infty} - \rho_{v,0}) f_v,
\]

where \( \rho_i \) is the density of ice, \( a_i \) the equivalent radius of the ice core, \( L_m \) and \( L_e \) are the latent heat of melting and evaporation, \( t \) is the time, \( a_d \) the equivalent radius of the melting ice sphere, \( D_{v,a} \) the diffusivity of water vapor in air, \( \rho_{v,\infty} = \phi_v \rho_{v,\text{sat}}(T_\infty) \), and \( \rho_{v,0} = \rho_{v,\text{sat}}(T_0) \) are the water vapor densities far away and at the drop surface, respectively, \( \phi_v \) is the relative humidity of the air, \( k_a \) is the thermal conductivity of air, \( T_\infty \) the temperature in the environment far from the drop’s surface, and \( f_v \) and \( f_v \) are the mean ventilation coefficients for heat and water vapor. The \( L_m \), \( D_{v,a} \), \( \rho_i \) and \( k_a \) were obtained from empirical relations given in Pruppacher and Klett (1980). Values for \( f_v \) and \( f_v \) were taken from Pruppacher and Rasmussen (1979). The quantity \( \rho_{v,\infty} \) was calculated from the dewpoint of the air in our wind tunnel.

A comparison of melting times (the time to reach a specified ice core radius) derived from Eq. (1) with our experimental results is given in Table 1. The good agreement between the two results verifies the applicability of the above given theory for the melting of spherical ice particles between 1 and 5 mm diameter.

In melting Mode-5, our observations show that no internal circulation occurs in the meltwater. As discussed earlier, this is probably due to the relatively flat upstream portion of the meltwater and the relatively small area over which the air shear stress can be effective in inducing internal flow. The present problem reduces therefore to a description of the heat transfer through a stagnant fluid into an eccentrically located ice core. The appropriate heat transfer equation given below in bispherical coordinates has been derived and its method

<table>
<thead>
<tr>
<th>Initial diameter of ice sphere (cm)</th>
<th>Final ice core radius (cm)</th>
<th>Time to melt until final ice core radius (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Experiment</td>
<td>Well-mixed theory</td>
<td></td>
</tr>
<tr>
<td>0.37</td>
<td>0.158</td>
<td>32</td>
</tr>
<tr>
<td>0.365</td>
<td>0.132</td>
<td>52</td>
</tr>
<tr>
<td>0.35</td>
<td>0.135</td>
<td>42</td>
</tr>
<tr>
<td>0.33</td>
<td>0.127</td>
<td>17</td>
</tr>
</tbody>
</table>
of solution given in our companion article (Rasmussen et al., 1984).

\[
4\pi \rho a_i^2 L_m \frac{da_i}{dt} = 8\pi c k_w[T_d(a_i) - T_0] \\
\times \sum_{n=0}^{\infty} \frac{1}{e^{(2n+1)\eta_0} - e^{(2n+1)\eta_0}} \\
= -4\pi a_i k_w(T_\infty - T_d(a_i)) f_h \\
- 4\pi a_i L_m D_v(\rho_v - \rho_v, a_i) f_v,
\] (2)

where \( k_w \) is the thermal conductivity of water, \( \eta_0 \) and \( \eta_0 \) the bispHERical coordinates of the outer meltwater surface, and of the ice core, respectively, \( c \) is a dimensional bispHERical parameter determined from the eccentricity of the ice core. The eccentricity of the ice core was determined from our films, and it was found that the meltwater gap at its narrowest point at the downstream end of the particle was nearly constant during melting and equal to about 30 µm (the meltwater thickness was very small near the downstream portion of the melting particle). The parameter \( a_i \) is again the equivalent radius of a sphere of the same volume as the melting ice particle, and \( f_h \) and \( f_v \) the mean ventilation coefficients for heat and vapor determined by Pruppacher and Rasmussen (1979) for evaporating water drops based on the equivalent radius of the evaporating drops. The above summation contains the difference of two exponentials in its denominator, and thus converges rapidly in only seven terms. Note that the summation starts from \( n = 0 \).

A comparison of the equivalent ice core radius determined from Eq. (2) with our experimental results is made in Table 2. Again, good agreement is found between experiment and theory, justifying the applicability of the above theory for the melting of ice particles between 5 and 9 mm diameter.

Melting Modes 4, 3 and 2 during which shedding occurs can be theoretically be derived by Macklin (1963) based on the melting of ice spheroids of semi-major axis greater than 1.9 cm. Since shedding significantly reduces the amount of meltwater on the particle's surface, Macklin assumed that all the meltwater is shed. This allows the surface temperature of the melting particle to be set equal to \( T_0 = 273.15 \) K. This simplification led Macklin to the following equation:

\[
\frac{dm}{dt} = -\frac{\chi AN_{Re}^{1/2}}{2a_i L_m} \left[ N_{Re}^{1/2} k_w(T_\infty - T_0) \right. \\
\left. + N_{Sc}^{1/2} L_m D_v(\rho_v, \rho_v, a_i) \right],
\] (3)

where \( N_{Sc} = \nu / D_v, a_i \), where \( \nu \) is the kinematic viscosity of air, \( N_{Sc} \) the Schmidt number, \( N_{Re} = \nu / k_a \), where \( k_a \) is the thermal diffusivity of air, \( N_{Re} \) the Prandtl number, \( N_{Re} = 2a_i U_\infty / \nu \), where \( N_{Re} \) is the Reynolds number, and \( a_i \) the semi-major axis of the melting particle, \( U_\infty \) the terminal velocity of the particle, \( A \) is the surface area of the ice spheroid, and \( \chi \) a heat transfer coefficient experimentally determined by Macklin as a function of the axis ratio of the spheroid. For a spherical particle, Macklin determined \( \chi = 0.76 \). For the experimentally observed change in ice core axis ratio, the value of \( \chi \) determined by Macklin increased by only 8%. Since this change is fairly small, and also within the experimental error of Macklin's experiment, we chose \( \chi = 0.76 \) in Eq. (3) for the entire melting period.

A comparison of the mass fraction melted determined from Eq. (3) with our experimental results is given in Table 3. For this comparison the experimentally derived terminal velocities of the melting particles was used in Eq. (3). Again, good agreement is found between experiment and theory, justifying the applicability of the above theory for the melting of ice particles larger than 9 mm diameter.

6. Application

In the following, application of these results will be made to the melting of hail, graupel, and frozen drops.

a. Hail

The melting rate results of this study show that smaller particles melt more mass in unit time than larger particles if given the same initial amount of mass of each. In an actual hailstorm, the hail size distribution can be approximated as exponentially decreasing towards larger sizes. A typical size distribution (Pruppacher and Klett, 1980) has 0.2 hailstones per cubic meter for a 1 cm diameter stone, and 0.02 hailstones per cubic meter for a 2 cm stone. Thus the number of hailstones at 1 cm diameter is 10 times the number at 2 cm diameter. However, the mass of a 1 cm stone is \( \sim 1/8 \) that of a 2 cm stone. This means that the actual mass of ice in each size interval is nearly the same. Since the smaller sized hailstones melt more mass per unit volume during the same time interval, the smaller stones will be more effective in cooling the environment. Also, since smaller hailstones also spend more time in the air melting than larger hailstones, the cloud creating the most negative buoyancy due to melting will be the cloud with many small hailstones.

<table>
<thead>
<tr>
<th>Initial diameter of ice sphere (cm)</th>
<th>Time melted (s)</th>
<th>Final ice core radius (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Experiment</td>
</tr>
<tr>
<td>0.92</td>
<td>122</td>
<td>0.26</td>
</tr>
<tr>
<td>0.77</td>
<td>120</td>
<td>0.20</td>
</tr>
<tr>
<td>0.60</td>
<td>120</td>
<td>0.17</td>
</tr>
<tr>
<td>0.57</td>
<td>120</td>
<td>0.17</td>
</tr>
</tbody>
</table>
Table 3. Mass fraction melted from present experiment compared to theory for $d \geq 9$ mm.

<table>
<thead>
<tr>
<th>Initial diameter of ice sphere (cm)</th>
<th>Time melted (s)</th>
<th>Experiment</th>
<th>Macklin’s (1963) theory for all melt water sheds</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.08</td>
<td>180</td>
<td>0.74</td>
<td>0.73</td>
</tr>
<tr>
<td>1.25</td>
<td>180</td>
<td>0.72</td>
<td>0.69</td>
</tr>
<tr>
<td>1.84</td>
<td>180</td>
<td>0.44</td>
<td>0.45</td>
</tr>
</tbody>
</table>

Another important microphysical effect observed during our study is the reduction in terminal velocity that larger ice spheres undergo during melting. This is due to the water torus formed by the meltwater which increases the cross-sectional area of the particle, and the shedding of the meltwater which reduces the particle’s mass. A reduction in terminal velocity means that the particle spends a longer time in the cloud. Spending a longer time in the cloud, however, does not mean that more of an individual hailstone mass is melted per unit time, since the ventilated heat transfer to the particle is also reduced when the terminal velocity is reduced. On the other hand, a reduced terminal velocity *does* mean that the particle will arrive at the ground with less energy than the original hailstone, and therefore cause less damage. Since melting also converts a destructive solid particle into a less damaging liquid particle, partial melting and its associated reduction of a particle’s terminal velocity seems to be a very efficient means of reducing the destructiveness of hail.

Some important conclusions can also be drawn from our observations on meltwater shedding. We found that for spherical particles less than 2 cm in diameter, shedding of meltwater did not occur until at least 20% of the mass of the particle was melted. This implies that it would not be correct to assume that all meltwater is shed from a melting particle, as many cloud modelers have done. The shedding process also significantly affects the distribution of liquid water in a cloud, since meltwater shed inside a cloud is added to the cloud water. The meltwater shed on the way from the cloud to the ground also affects the size distribution of rainwater. The shed drop size distribution depends on the hail size distribution since each particular hail size sheds drops of a different size and at a particular frequency. Consequently, the raindrop size distribution may become significantly altered due to the addition of these shed drops.

b. Graupel particles

Graupel particles differ from hailstones mainly in their density. Hailstones have a density close to 0.90 g cm$^{-3}$, while graupel particles typically have densities less than 0.7 g cm$^{-3}$ (Pruppacher and Klett, 1980).

Also, graupel particles typically have a conical or irregular shape. In the cloud, graupel particles are usually less than 5 mm equivalent diameter. Thus, they will not shed water, and will probably develop an internal circulation towards the latter part of melting. Since the graupel particle has a very irregular surface, the heat transfer is expected to be significantly increased, as was found for the case of small frozen drops which had surface roughness and irregularities. An extension of the present work to include the melting behavior of graupel particles is currently underway.

c. Frozen drops

The melting of frozen drops less than 1 mm diameter has been investigated in detail in Part II of this study (see article immediately preceding). It was found that the melting particle increased its terminal velocity $\sim 6\%$ upon melting. Internal circulation and eccentric location of the melting ice core decreased the melting time $\sim 10\%$ compared to concentric melting and pure diffusive heat transfer. Surface and shape irregularities of these frozen drops as well as sailing motions, served to decrease the melting time $\sim 20\%$–40$\%$ over concentric pure diffusive heat transfer. The above effects combined lead to a $\sim 30\%$–50$\%$ decrease in the melting times of these frozen drops compared to concentric pure diffusive heat transfer. The main effect of this observation on the air in a cloud is to cool the air surrounding falling and melting ice particles faster than previously predicted. This, in turn, results in a more localized and stronger development of negative buoyancy, which may eventually lead to a stronger downdraft. Quantitative verification of this suggestion must await the incorporation of our results into a numerical cloud model.

7. Conclusion

The above study and preceding article attempt a comprehensive treatment of the melting and shedding rates of spherical ices particles between 0.2 mm and 20 mm in diameter falling at terminal velocity in air. The main results of this study are:

1) Melting rates for spherical ice particles less than 1 mm diameter agree well with theory for eccentric melting with laminar convection inside the meltwater if the ice sphere is smooth. For irregular and rough ice particles (usually found in the atmosphere), the external ventilation has to be increased by a factor of 2.4 to account for the effect of surface irregularities and sailing motions on the heat transfer. For these particles no meltwater is shed.

2) Between 1 and 5 mm diameter, melting rates agree with theory that assumes that the meltwater is

* Diameter of a sphere with same volume as the graupel particle.
well mixed \(T_a = T_0\). This is due to the rapid semi-
turbulent internal circulation observed in the meltwater
of these particles. Again, no meltwater is shed in this
size range.

3) For ice particles between 5 and 9 mm diameter,
melting rates agree with theory for eccentric melting
without convection. This is due to the lack of internal
circulation found for these particle sizes. Meltwater is
also not shed in this size range.

4) For ice particles larger than 9 mm diameter,
melting rates are well represented by Macklin’s (1963)
equation with \(\chi = 0.76\). This is due to the onset of
shedding near 9 mm diameter.

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