Cloud Droplet Collisions

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ABSTRACT

The necessity for reliably evaluating the collection efficiency between cloud droplets is discussed. Measurements are presented which suggest that present theory needs to be confirmed before it can be finally accepted.

1. Introduction

The importance of obtaining detailed knowledge of cloud droplet collisions was clearly recognized when it was established that rain could originate in a non-freezing cloud. Attempts to create quantitative models of the coalescence rain-forming process have been largely inadequate for a number of reasons, one of which is the poor knowledge of the collision process between individual droplets. The condensation process has been studied by various authors such as Howell (1949) and Squires (1952), and the principal features are beyond doubt. An extremely wide size range of possible condensation nuclei at the initial condensation level gives relatively few droplets. The further release of water as uplift continues tends to reduce the diameter range and a narrow spectrum results. The size to which these droplets grow depends on their concentration and the total quantity of water released in the adiabatic process. Typically we get droplets in different clouds ranging in diameter from, say, 10 μ to 60 μ. However the actual spectra of droplet diameters are broader than this part of the theory suggests and while there are possibly a number of explanations, the relative importance of coalescence can only be decided in the light of accurate collection efficiencies.

A more important aspect is that discussed by Telford (1955) where the role of the few drops experiencing more collisions than the average was shown to be of special interest. This mechanism makes it important to determine whether or not collection efficiencies are exactly zero as predicted by theory.

An exact calculation of the collection efficiencies has not yet been achieved. The most important approximation available is by Hocking (1958) who solved the mathematical problem subject to two restrictions in the initial assumptions. Firstly, he ignored the inertia of the fluid surrounding the drops. This should be negligible for water drops in air. (Possibly another restriction is that any effect of internal circulation was ignored.) The second assumption is that the non-linear terms in the fluid flow equations can be ignored. Past investigations suggest this may be a serious limitation and new measurements presented here support this view. At larger sizes Telford et al. (1955) have demonstrated experimentally that the non-linear effects yield a strong asymmetry between the forces experienced by two nearly equal droplets involved in an impending collision. The rear droplet is not fully supported because of the wake behind the leading droplet and tends to fall in behind it. However, for the drop sizes important in clouds we have little evidence, and the meteorologically important case of nearly equal droplets has not been examined in any detail.

Model experiments involving freely falling spheres in liquids can model only the Reynolds number and not the density ratios. Hence they will fail to simulate the correct trajectories; nevertheless the model observations give some information about the symmetry of the force fields influencing the two droplets. The model trajectories of Sartor (1954) and later Schotland (1957a, b) both confirm that at Reynolds numbers similar to those of cloud droplets the hydrodynamic force fields are asymmetrical. In these experiments the horizontal convergence of the drop trajectories was clearly observed.

It should be explained at this stage that any asymmetry in the flow field about drops results in a horizontal force on the drops which tends to bring the drops together. This effect resulted in a very substantial increase in collection efficiency in the cases quoted and it is this effect which Hocking has excluded from his calculations by his second basic assumption. For the equations he used, the force field is symmetrical; the force is of the same magnitude when the direction of the fluid motion past the drops is reversed.

It is, in principle, possible to measure the forces on each of two spheres moving in a fluid. If this was done for all positions and velocities of each sphere the tabulated results could then be supplied to a computer for integration into droplet trajectories. The measurements
could be made in any appropriate fluid and the resulting answers would be free from the approximations involved when the non-linear terms in the flow field equations are ignored.

In the light of this discussion it would appear desirable to attempt a direct measurement of the forces involved for two equal fixed spheres at Reynolds numbers corresponding to the cloud droplet sizes where Hocking predicts a zero collection efficiency.

2. The experiment

All the difficulties in realizing a measurement such as this must be resolved by accepting a practical compromise. A number of preliminary experiments were undertaken to assess various possibilities. To start with we used as a fluid a saturated hydrocarbon, sold under the name Arochlor, but this failed to yield consistent measurements. This was due partly to difficulties in obtaining a uniform blend free from variations in viscosity, and partly due to the temperature sensitivity of its viscosity. We noted however the necessity to watch viscosity dependence on temperature. Thereafter, even when a more suitable fluid was available, we followed the practice of frequently stirring the fluid, so as to maintain temperature uniformity.

A more important experiment examined the possibility of obtaining the complete collision trajectories. This might be done by supporting the spheres in the fluid and adding mass to the supporting frame on each side of the fluid trough. The total mass could then be centered in the center of the sphere and be of such magnitude so as to simulate a sphere of the same density relative to the oil as water is to air. If this is suspended without any horizontal forces from the supports and a uniform horizontal force applied, the system then models falling droplets. The supporting system could be realized by suspending the spheres and their frame from a further, servo-positioned frame itself suspended from the ceiling. Gravity can be simulated by a constant lead in the position of the upper frame. This approach was unsuccessful as accurate sideways control over the 3 m length of the trough could not be realized with the available equipment. This experiment also brought to light another feature which, because it could not be quantitatively assessed, may have cast some doubt on the validity of any results. This was the distortion of the free liquid surface in the wake of the supporting needles to the spheres.

In evaluating these preliminary trials it was clear that modelling the full dynamics of the problem was not possible. We therefore decided to concentrate on a more fundamental test which would both be practicable and obviate the objections mentioned above. The final experiment was designed with a view to testing only the symmetry of the forces on a moving sphere when an accompanying sphere is moved from in front to behind. The difference between the forces at the same separation is a direct measure of the error incurred by omitting the non-linear terms from the theory. Very small differences can have important effects as the relative motion decides the issue rather than the much larger forward velocities experienced by both. Since we are now testing only the flow symmetry the drag of the supports is unimportant.

A more detailed description now follows and the reasons for each feature should be clear from the preceding remarks. Essentially the experiment compares the inline forces on a sphere for two cases, when another equal sphere is either a fixed distance in front of it or an equal distance behind. These measurements can be made in pairs to avoid any remaining doubts as to changing fluid viscosities, etc.

The fluid selected was a Dow Corning silicone fluid type DC200, blended to a kinematic viscosity of 2900 centistokes. This fluid has the great advantage that the viscosity varies relatively slowly with temperature. Furthermore it is crystal clear and is non-toxic. The

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**Fig. 1.** The force measuring system. An adjustment to the spring tension requires a different speed through the fluid if the pointer is to return to zero. When all necessary adjustments are made the speed is automatically trimmed by the servo loop to maintain the spheres at a constant spacing. The force and hence the velocity is then a function of the setting of the tension adjustment.
viscosity was repeatedly checked with a standard Brookfield viscometer and found to depend only on temperature.

Very uniform motion was needed so that the forces and separation would remain constant over a given run. This was achieved by suspending a frame with magnets and small wheels from a smooth steel plate on the ceiling. (Direct drive by some transport mechanism is impractical because of small irregularities which cannot be eliminated.) From this, the actual framework supporting the sphere was suspended by three 3 m lengths of thin wire. The upper frame was advanced horizontally by a 3 m lead-screw powered by a servo-motor system. A reliable measurement of the velocity of the spheres is then available from the tachometer winding of the servo-motor. The servo feedback loop was closed through a photocell with shutter attached to the force balance pointer and hence the speed automatically adjusted itself to give a constant preset force on the measuring sphere. For each run the force was then adjusted to give the required speed. This arrangement was necessary as the appreciable spring rate of the force measuring system sometimes led to instability of the measuring sphere in certain positions behind the fixed sphere. This relative instability was suppressed with the feedback system. Fig. 1 illustrates the force measuring arrangements, while Fig. 2 gives an overall view.

As can be seen in the figures the disturbance near the sphere is that caused by the single needle supporting it. This is in turn supported by a large rod, which is however, well to the side and "shielded" from the sphere by the stabilizing effect of the viscous drag on the fluid from the nearby trough wall. The forces on the larger rod are not, of course, detected by the measuring system. A camera was also attached to the framework and a photograph was taken perpendicular to the motion during each measurement to provide an accurate measure of the separation of the spheres.

The fixed sphere was identical in diameter and in respect to the submerged parts of its supports, but was attached by a rigid clamp to the framework. This sphere could be changed quickly from the front to the rear position and set at any separation up to about 4 diameters. The surface of the fluid was covered by a floating rigid sheet of perspex, which was attached to one side of the trough so as to leave a narrow path on the other side for the supporting rods to enter the fluid. Hence the spheres were roughly at the center of a square fluid channel contained by rigid walls (see Fig. 2). When the system was properly adjusted, the force appeared to reach a steady state after about 0.15 m travel from rest, and we were therefore able to restrict the length of the trough to about 1.5 m. The readings were taken after the spheres had travelled about half this distance.

3. The forces on the spheres

A number of measurements have been taken for different separations of the spheres and at differing Reynolds numbers. Table 1 shows measurements at three equiva-
lent cloud droplet sizes. There is a reduced force on the rear drop except at the smallest separation for the smaller sizes.

TABLE 1. The last column tabulates the reduction in force when a droplet changes from the front to the rear position. Each value uses the mean of three pairs of measurements. The scatter between the individual measurements is about 25 per cent of the reduction. This comment does not include the four zero values. Here the measured forces gave differences of the same sign but too small to be reliably evaluated. Since the experiment was designed to contrast the difference in forces on the drops in the two positions the forces tabulated for the front drop may not be as accurate as the numbers suggest.

<table>
<thead>
<tr>
<th>Diameter of simulated drops</th>
<th>Spacing in diameters between centers</th>
<th>Forces in arbitrary units</th>
<th>Approximate force on front drop</th>
<th>Reduction of force on rear drop</th>
</tr>
</thead>
<tbody>
<tr>
<td>52 μ</td>
<td>1.25</td>
<td>7.5</td>
<td>0.18</td>
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<td>1.5</td>
<td>7.7</td>
<td>0.12</td>
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<td></td>
<td>2.0</td>
<td>8.2</td>
<td>0.21</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2.5</td>
<td>8.7</td>
<td>0.21</td>
<td></td>
</tr>
<tr>
<td>34 μ</td>
<td>1.25</td>
<td>2.3</td>
<td>0</td>
<td></td>
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<td>1.5</td>
<td>2.5</td>
<td>0</td>
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<tr>
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<td>2.8</td>
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</table>

4. Conclusion

It is difficult to suggest any interpretation of this measurement other than that the force on one sphere near to another does not remain constant in magnitude when the direction of fluid flow reverses (or the positions are reversed, which is the same thing). This observation confirms inferences which can be drawn from other model experiments. Unless some further explanation is forthcoming it would appear that the theory on which Hocking based his collection efficiencies is not wholly adequate. This raises the doubt as to whether two drops, the larger of which is less than 36 μ diameter, can, in fact, never coalesce. This point is of great meteorological significance as in many clouds all drops are smaller than 36 μ. Diem (1948) gives examples of this fact, and Squires' (1958) continental cumuli contain no drops greater than 20 μ diameter. The wide droplet spectra of clouds containing larger droplets are not simply explained by condensation theories and a significant collection efficiency at smaller sizes would greatly ease the problem. Finally, the experimental evidence reported by Battan (1963) favoring the coalescence process in sub-zero clouds emphasizes the importance that should be attached to any possibility that events of relatively low probability can contribute the few larger droplets necessary to initiate the formation of rain.

REFERENCES


