# Experimental Evaluation of Collection and Coalescence Efficiencies of Cloud Drops

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## ABSTRACT

Collection efficiencies of drops of radius $A$ less than 120 $\mu$m falling through clouds of drop radius $a$ for which the size ratio $p=a/A$ was between 0.18 and 0.25 were found experimentally to be considerably lower than the corresponding theoretically computed collision efficiency. Assuming the difference to be due to failure of some of the colliding drops to coalesce, the coalescence efficiency was computed and found to decrease with increasing $p$, in qualitative agreement with the results of Whelpdale and List obtained for much larger collector drops.

The initiation of precipitation by the warm rain (collision and coalescence) process depends on the collection efficiency of larger cloud drops falling relative to the smaller ones. Computations of collision efficiencies have been carried out, but these involve approximations that lead to uncertainty about their validity. In addition, the question whether all drops which "collide" under natural cloud conditions will coalesce has never been determined. Thus, experimental determination of the collection efficiency of drops in the range of sizes and under conditions simulating natural clouds is needed.

The present note describes an extensive series of experiments that were carried out to meet this need. In it the rate of growth of cloud drops by collection of smaller droplets was measured. In each experiment a collector drop was held in a fixed position by adjusting the velocity of upward-moving cloudy air in the UCLA cloud tunnel, a wind tunnel with a vertical observation section and extremely low turbulence. From the record of the air speed in the tunnel, which had been calibrated previously in terms of the terminal velocity of the suspended drop, the rate of growth of the collector drop was evaluated.

The cloud was formed by condensation of supersaturated vapor introduced from a steam generator onto droplets introduced by an ultrasonic nebulizer. The air entering the tunnel was filtered before reaching the steam entrance, so that no other effective condensation nuclei were present. Condensation on the nebulizer droplets resulted in a very narrow spectrum of droplet sizes. The sizes of the cloud droplets were determined by an optical method (Neiburger *et al.*, 1972). The liquid content of the cloud was measured by drawing a cloud sample isokinetically through a heated tube into a Cambridge dew-point hygrometer. The drops were evaporated in the heated tube, and the difference between the vapor density of the air into which the drops had evaporated, as determined by the dew-point hygrometer, and the vapor density in equilibrium with the drops at the temperature of the tunnel provided a measure of the liquid content of the cloud, which ranged from 0.8 to 1.5 gm m$^{-3}$. Wet- and dry-bulb thermocouple thermometers were used to measure the humidity in the tunnel. [See Neiburger *et al.* (1973) for further details.]

For collector drops of radius $A$ less than 40 $\mu$m suspended in an upward-moving cloud with average radius $a$ about 10 $\mu$m ($p\equiv a/A\approx 0.25$), no growth was observed, even when the large drop was suspended for 20 min. Larger drops ($A>40$ $\mu$m) in clouds with $p$ ratios less than 0.23 were observed to grow, but at a slower rate than that predicted on the basis of computed collision efficiencies. During each individual experiment the collector drop growth was limited to 10 $\mu$m, to avoid the possibility that the cloud droplet size distribution might change with change in air speed. The collection efficiency $E$ of the drop was computed from the continuous growth equation

$$\frac{dA}{dt}=\frac{E(1+p)^2(V-v)l}{4\rho_w},\tag{1}$$

where $V$ and $v$ are the terminal velocities of the collector drop and the cloud droplet, respectively, $l$ the liquid content of the cloud (mass of liquid water per unit volume), and $\rho_w$ the density of the drop.

In Table 1 the experimental values of $E$ averaged for various values of $A$ and $p$ are compared with the values of the collision efficiency $E_s$ computed from

TABLE 1. Comparison of observed collection efficiencies $E$ with theoretical collision efficiencies $E_s$ computed by Shafrir and Neiburger (S-N), averaged for various radii $A$ of collector drops and ratios of drop radii.

| | Drop radii ratios | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | 0.18 | | 0.20 | | 0.22 | | 0.24 | |
| $A$ ($\mu$m) | $E$ (Obs.) | $E_s$ (S-N) | $E$ (Obs.) | $E_s$ (S-N) | $E$ (Obs.) | $E_s$ (S-N) | $E$ (Obs.) | $E_s$ (S-N) |
| 45–54 | 0.26 | 0.49 | | 0.53 | 0.12 | 0.56 | | 0.60 |
| 55–64 | | 0.61 | 0.23 | 0.66 | | 0.68 | | 0.71 |
| 65–74 | | 0.68 | | 0.71 | 0.07 | 0.74 | 0.07 | 0.77 |
| 75–84 | | 0.74 | | 0.77 | | 0.80 | | 0.82 |
| 85–94 | | 0.79 | 0.23 | 0.82 | 0.10 | 0.84 | 0.11 | 0.86 |
| 95–104 | | 0.83 | | 0.85 | 0.11 | 0.87 | | 0.88 |
| 105–114 | 0.23 | 0.86 | | 0.88 | 0.13 | 0.90 | | 0.91 |
| Average | 0.25 | | 0.23 | | 0.11 | | 0.09 | 0.91 |

theory by Shafrir and Neiburger (1963, 1964). It is seen that the experimental collection efficiency $E$ is much less than the theoretical collision efficiency $E_s$, and that whereas $E_s$ increases with $p$ for each value of $A$, $E$ decreases. Other computations of $E_s$ for these values of $A$ and $p$ give still higher values (Shafrir and Gal-Chen, 1971; Klett and Davis, 1973), and thus would indicate larger discrepancies. It is possible that the computed collision efficiencies are wrong, but this explanation of the difference seems unlikely in view of the general consistency of the values computed by different procedures and the agreement of the Shafrir-Neiburger values with some earlier experimental results (Neiburger, 1972). Instead, we suggest that the differences occur because only a small fraction of the drops which "collided" coalesced under the conditions of our experiment, which approximate the processes in natural clouds more closely than those of previous experiments.

The total collection efficiency $E$ may be represented as the product of the collision efficiency $E_s$ and the coalescence efficiency $E_L$. $E_s$ is determined solely by hydrodynamic considerations, and is defined as the fraction of the small droplets in the path of the large drop that would be brought within some small distance $\epsilon$ of the large drop by action of the hydrodynamic forces. As pointed out by Hocking and Jonas (1970), the hydrodynamic forces cannot bring the drops into actual contact, at least for the small drops for which the Stokes approximation is valid; on the other hand, when the distance between drops becomes of the order of the molecular mean free path, continuum hydrodynamics no longer applies. Once the separation between drops approximates the mean free path of the molecules additional factors, such as the surface tension of the drops, the electric charge on them, the ambient electric field, the electric double layer at the water-air interface, and the van der Waals forces, become important. The actual process of coalescence is controlled by capillary waves on the drop surfaces. If all drops that come closer than $\epsilon$, taken to be $10^{-3}$ $A$ or $10^{-4}$ $A$, would coalesce, the collection efficiency determined by the experiments would agree with the computed collision efficiency (assuming the latter to be evaluated correctly). The difference may be due to $E_L$ being considerably less than 1.

Until recently, relatively little work has been carried out to determine $E_L$. Whelpdale and List (1971) evaluated it experimentally for collector drops considerably larger than those in our experiments. For very small $p$ ratios they found $E_L$ to be approximately 1, but for larger values of $p$ it was considerably smaller. They found its variation with drop sizes could be represented by the equation

$$E_L=\frac{A^2}{(A+a)^2}=\frac{1}{(1+p)^2}. \tag{2}$$

TABLE 2. Coalescence efficiencies $E_L$ computed from observed collection efficiencies $E$ using collision efficiencies computed by Shafrir and Neiburger (S-N) for various radii $A$ of collector drop and for various ratios of drop radii.

| | Drop radii ratios | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | 0.18 | | 0.20 | | 0.22 | | 0.24 | |
| $A$ ($\mu$m) | $E$ (Obs.) | $E_L$ (S-N) | $E$ (Obs.) | $E_L$ (S-N) | $E$ (Obs.) | $E_L$ (S-N) | $E$ (Obs.) | $E_L$ (S-N) |
| 45–54 | 0.26 | 0.53 | | | 0.12 | 0.215 | | |
| 55–64 | | | 0.23 | 0.35 | | | | |
| 65–75 | | | | | 0.07 | 0.095 | 0.07 | 0.09 |
| 85–94 | | | 0.23 | 0.28 | 0.10 | 0.12 | 0.11 | 0.13 |
| 95–104 | | | | | 0.11 | 0.125 | | |
| 105–114 | 0.23 | 0.27 | | | 0.13 | 0.145 | | |
| Average | 0.25 | 0.40 | 0.23 | 0.32 | 0.11 | 0.12 | 0.09 | 0.11 |

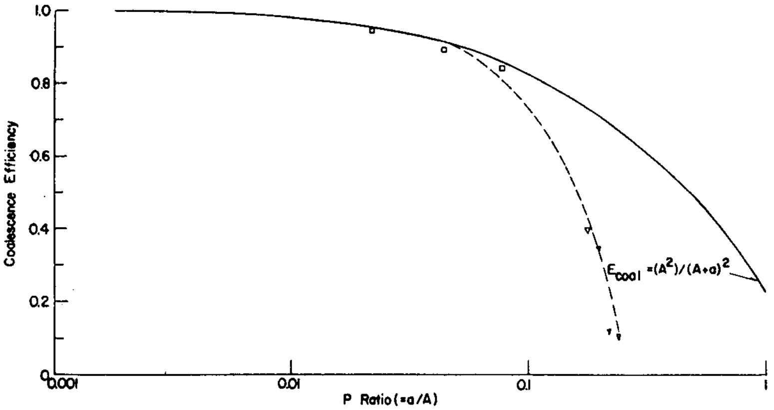

FIG. 1. Average coalescence efficiencies as a function of the radius ratio $a/A$. The solid curve [Eq. (2)] and the open squares (experimental values) are from Whelpdale and List (1971); the open triangles are based on the completed collision efficiencies of Shafrir and Neiburger (1963, 1964) and the present collection efficiency measurements.

If it is assumed that the computed collision efficiencies are correct (e.g., those given by Shafrir and Neiburger), one can calculate $E_L$ from our experimental measurements of $E$. Table 2 presents the results of this computation. As in Whelpdale and List's experiments, $E_L$ decreases with increasing $p$ for each $A$. In Fig. 1 the average values of $E_L$ are plotted in comparison with the curve representing Eq. (2). Our values are seen to fall below the curve suggested by Whelpdale and List. If we assume that the variation has the form

$$E_L=(1+p)^{-n}, \tag{3}$$

the value of $n$ that fits our data best is 8.2, but with this exponent the equation gives considerably lower values than observed for the range of $p$ in Whelpdale and List's experiments.

The fact that our data do not fit their curve may be in part due to the difference between our experimental set-ups. The values of $A$ and $a$ in our experiments were considerably smaller than theirs. Their collector drops were supported by a needle, which prevented internal circulations that may modify slightly the coalescence efficiency (Foote, 1971). But there is also no reason for assuming that (2) applies to larger values of $p$ than the ones from which it was derived, or that the equation representing $E_L$ has the form of (3). It would be possible to formulate an equation which fits both their data and ours, but we consider it premature to do so.

The difference between the present experimental results, which appear to be characterized by small coalescence efficiencies, and earlier experiments, in which the collection efficiencies agree with the computed collision efficiencies, can be readily explained. In those instances in which the $p$ ratio was not so small that $E_L$, as given by Eq. (2), is expected to be near unity, the experiments were conducted in a manner that may have given rise to moderately large electric charges on the collector drops.

These results suggest that other factors than a dispersion of drop sizes in clouds are necessary for the initiation of precipitation by collision and coalescence. Electric forces due to charges on the drops or to an external field can definitely promote coalescence. Whelpdale and List found for the large drop sizes of their experiments that the charges required were very large. However, for the smaller drops normal to clouds before the inception of precipitation, the magnitude of charge needed may be considerably smaller. Experiments to study the effect of charges and electric fields on the coalescence efficiency are presently underway.

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