# Effects of Relative Humidity on the Coalescence of Small Precipitation Drops in Free Fall

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ABSTRACT

Observations of the effects of relative humidity on coalescence are limited to studies using supported drops or streams of drops, and the results are contradictory. In this paper, findings are presented on the effect of high and low relative humidity on collisions between freely falling drops. Comparisons between the collision outcomes (coalescence, bounce, and temporary coalescence with and without satellite drops) for high-humidity (RH > 95%) and low-humidity (RH ≈ 30%) experiments were made for small precipitation drops at terminal velocity and with minimal electric charge. Coalescence begins after the air-film between colliding drops is drained sufficiently to allow the drops to make contact. For temporary coalescence, the union of the two drops is not permanent because the rotational energy caused by a non-head-on collision is sufficient to pull the coalesing drops apart. One or more satellite drops form during a temporary coalescence when water filament between the separating drops breaks in more than one location. Experiments with higher drop charge were used to examine further the influence of humidity on coalescence. Our results show that relative humidity does not affect the coalescence efficiency for small precipitation drops. The effect of humidity is limited to collisions where permanent coalescence does not occur, and the collision outcome can be temporary coalescence. In cases where bounce is also a possible outcome, it was found that the probability of bounce is enhanced at the expense of temporary coalescence when relative humidity is decreased. For two of the comparisons between high-humidity and low-humidity results, the fraction of temporary coalescence collision outcomes halved at low humidity. Since the colliding drops are at the wet-bulb temperature, this effect is traced to the colder air gap that drains more slowly and retards coalescence at lower humidities. At high relative humidity the number of satellite drops about doubles with the increased probability of temporary coalescence. Other experiments showed that the increase in satellite drops at higher relative humidities also occurs for cases where collision outcomes are limited to coalescence or temporary coalescence. Since there are more temporary coalescence outcomes at the higher relative humidities in clouds, there are also more satellite drops that can act as embryos for new raindrops. These results apply to rain shafts within and below clouds.

## 1. Introduction

Observations of effects of relative humidity on coalescence are limited and contradictory. Prokhorov (1954) studied 500-$\mu$m radius drops falling at various speeds and impacting on a stationary hemisphere of the same radius. He concluded that low-impact velocities and relative humidities impeded coalescence. Lindblad (1964) found different results as deduced by measuring the time for coalescence of supported water hemispheres at 50% and 97% relative humidity. These latter results showed that high-impact velocities and relative humidities impeded coalescence. Park (1970) used streams of drops fired at each other but found no effect on coalescence for relative humidities between 25% and 60%.

One possible reason that previous studies have contradictory results is different methodologies. In order to evaluate the effects of relative humidity on drop coalescence, we present an analysis of our laboratory results on collisions between small precipitation-size drops falling at terminal velocity in dry and humid air. We also discuss the potential effects of relative humidity on raindrop coalescence in and below clouds. The primary purpose of this paper is to resolve the literature controversy on the effect of relative humidity on coalescence in the atmosphere. Other papers (Ochs et al. 1995; Beard and Ochs 1995) will present a more complete dataset on the coalescence of small precipitation drops and develop formulations for application in numerical models.

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## 2. Experiment

The experimental setup is shown in Fig. 1 and is similar to that used by Czys and Ochs (1988). Deionized, filtered water was supplied to each drop generator from separate regulated pressurized reservoirs. The water passed through a piezoelectric transducer in each generator, exiting through an orifice disk to form a water jet (Fig. 2). Deionized, filtered water is used to eliminate impurities that would clog the orifice disk. The chemical composition of rainwater might be simulated, but little new knowledge would be gained since most solutes in low concentrations have a negligible effect on the surface tension, which is the only way a solute could affect the coalescence of raindrops. Radial vibrations of the piezoelectric transducer were produced using a square wave voltage supplied by digital electronics. The resulting capillary waves on each jet caused them to break into a streams of uniformly sized drops. Since two generators were used with separate pressure regulators, each size drop could be produced close to its terminal velocity. Drop velocities were measured during each experiment to verify that they were within 1% of terminal velocity at the point of collision.

The drop streams were charged by applying a voltage to the charging rings located near jet breakup and were deflected into a gutter by a strong horizontal electric field (Fig. 2). Drops with a much lower, controlled charge were produced by momentarily reducing the charging voltage. These selected drops fell through the deflection field into the fall column (Fig. 1). An IBM-compatible personal computer was used to control various elements of the experiment including drop generation, charging, strobe lighting, and cameras.

The generators were placed in close proximity to one another at the top of the experiment chamber so that the drops would have near vertical fall trajectories. Fine adjustment of the fall trajectories was accomplished by micromanipulators attached to the drop generators (Fig. 1). The timing of drop selection was controlled though the computer interface so that the drops collided in view of two orthogonally placed cameras near the bottom of the fall column. The experiment chamber was made of clear acrylic to allow for visual observations of the drops during their free fall. Mechanical vibrations that interfere with stable drop generation were reduced by using heavy platforms with pneumatic suspension to support the experiment chamber and the water reservoirs. The cameras, lights, electrometer, and hygrometer were on a separate frame to isolate their vibrations from the experiment.

Drop collisions were recorded from orthogonal directions by two 35-mm cameras. Incandescent lamps, positioned about 30° above each camera optical axis, created fall streaks on the film marking the drop trajectories. The streaks were used to measure the separation between the drops in orthogonal planes. A silhouette image of the drops was obtained using stroboscopic lights to provide information on the size, shape, and number of drops after each collision. About

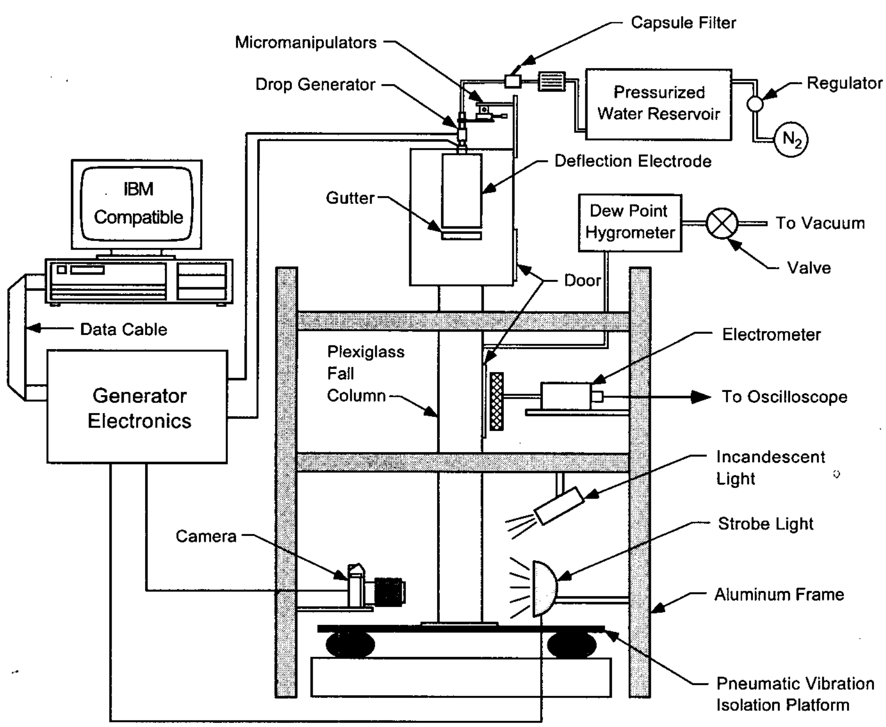


FIG. 1. Schematic of experiment.

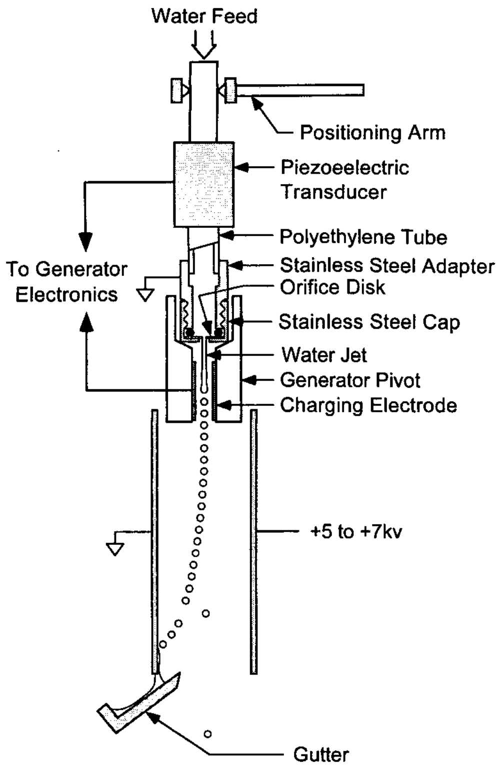


FIG. 2. Schematic of drop generator, charging electrodes, and computer controls. The drop generator is shown in cross section below the polyethylene tube.

100 measurements of drop separation and collision outcome (coalescence, bounce, and temporary coalescence with and without satellite drops) were obtained for each experiment condition to determine the effect of humidity on the coalescence of the colliding drops (e.g., see Ochs et al. 1991). Bounce occurs when the colliding drops separate before the air film between them has sufficient time to drain and allow contact. Coalescence occurs when the air film between colliding drops is drained sufficiently to allow surface contact and the drops permanently unite. For temporary coalescence, the union of the two drops is not permanent because the rotational energy caused by a non-head-on collision is sufficient to subsequently separate the drops. One or more satellite drops form during a temporary coalescence when water filament between the separating drops breaks in more than one location.

Drop charges were measured and adjusted to the desired level using an electrometer, a digital oscilloscope, and a computer. Measurements and readjustments were performed frequently during experimental runs to insure drop charges remained relatively constant. Drop sizes were determined in each experiment by collecting the drop stream for a known period, measuring its weight, and dividing by the generation frequency. This procedure resulted in accurate values for drop radius (<1% error). During each photographic collection period the chamber's temperature and dewpoint were measured to provide accurate relative humidity records. The experiments were conducted at typical laboratory sea level conditions (21 ± 1°C and 1000 ± 30 mb).

## 3. Results

The results presented in this section are compiled from three studies of collisions between minimally charged drops conducted in the Cloud Physics Laboratory of the Illinois State Water Survey (Schaufelberger 1990; Holdridge 1992; Laird 1992). In addition, Laird (1992) explored the combined effects of humidity and drop charge on coalescence. These three studies included more information on the coalescence of small precipitation drops (Ochs et al. 1995), and only the results relevant to the effect of humidity on coalescence are reported here. The drop sizes used in these experiments along with other relevant parameters are shown in Table 1. The experiments in Table 1 are sorted by increasing drop deformation during collision. Deformation is proportional to Weber number and is given by We $= \rho r \Delta V^2/\sigma$, where $\rho$ is the density of water, $r$ is the size of the small drop, $\Delta V$ is the difference in terminal velocities, and $\sigma$ is the surface tension. Since the Weber number is a ratio of the impact kinetic energy to the surface energy, it has been used to scale drop deformation and the tendency for indirect collisions to bounce apart (Ochs and Beard 1984; Beard and Ochs 1984; Ochs et al. 1986). Deformation acts to reduce coalescence by increasing the diameter of the air film gap between colliding drops and retarding the drainage of the air (Foote 1975). If the air film does not drain sufficiently during collision, the drops separate before coalescence is initiated.

TABLE 1. Experiment parameters.

| | Large drop size $R$ ($\mu$m) | Small drop size $r$ ($\mu$m) | Size ratio $r/R$ | Relative fall speed (cm s$^{-1}$) | Weber number We |
|---|---|---|---|---|---|
| Schaufelberger (1990) | 275 | 200 | 0.73 | 64 | 1.13 |
| Laird (1992) | 425 | 300 | 0.71 | 101 | 4.19 |
| Holdridge (1992) | 425 | 200 | 0.47 | 186 | 9.48 |

Table 2 contains the results of each collision in six experiments. In Table 2, the collision outcomes are denoted by letters: C (permanent coalescence), B (bounce), T (temporary coalescence), and TS (temporary coalescence with one or more satellite drops). The number of each collision outcome is given before the letter designation, for example, 5C. The three drop-size pairs (Table 1) were each studied at low and high relative humidities. The electric charge on the drops was maintained at values low enough (<0.05 pC, 1 pC = $10^{-12}$ Coulombs) to have a negligible effect on the coalescence. In the analysis of the data, the horizontal offset, $x = (x_1 + x_2)^{1/2}$, is determined by measuring the separations, $x_1$ and $x_2$, between the streaks on the film from each orthogonally placed camera. In Table 2, the collision outcomes are tabulated in 26 ranges as a function of impact angle, $\theta$, which is the angle between the vertical and the line connecting the centers of the drops at impact and is determined from $\theta = \sin^{-1}[x/(R + r)]$. An impact angle of 0° occurs when the drops undergo a head-on collision, and an impact angle of 90° denotes a grazing collision. The first 25 impact angle increments divide a circle of radius $R + r$ in a plain perpendicular to the fall direction of the drops into equal annular concentric areas. Thus, if all horizontal offsets for the colliding drops are random, then there is an equal probability of collisions occurring in each of the 25 impact angle increments. Collisions occurring with an impact angle of greater than 90° are those with measured offsets slightly exceeding $R + r$. Measurements greater than $R + r$ occur as a result of small errors in determining the drop radii or in measuring the collision offsets.

Several general features of the collision outcomes are evident when examining Table 2. Direct collisions resulted in permanent coalescence, while indirect collisions resulted in bounce or temporary coalescence. Temporary coalescence occurred only for experiments 5 and 6 having the highest Weber number and impact energies. In experiments 1 and 2, there were a few large-offset ($x > R + r$) grazing coalescences (Ochs et al. 1991). Another feature in Table 2 is that collisions at large impact angles are less frequent than more direct collisions. Typically, the drop trajectories were aligned to increase the collision frequency and reduce the effort needed to complete an experiment, since the major focus was at lower impact angles to obtain the coalescence efficiency from the critical offset between coalescence and bounce. Increased collisions at larger impact angle have been obtained in several other experiments by misaligning the drop trajectories.

In Table 2, comparisons of the results of experiment 1 with experiment 2, experiment 3 with experiment 4, and experiment 5 with experiment 6 show that, for each pair of experiments, the region of coalescence for the more direct impacts ends at about the same critical impact angle, $\theta_c$. Slight differences in $\theta_c$ are most likely the result of experimental uncertainties. Thus, we believe that for cases when drop charge can be neglected, there is no significant effect of humidity on $\theta_c$ in the range 30%–100%.

Table 3 shows the results of four additional experiments at two higher charge levels. Experiments 7 and 8 were performed with the absolute value of the relative charge on the colliding drops near 0.4 pC, while experiments 9 and 10 had higher charge levels near 0.7 pC. Experiments 7 and 9 used low humidities near 30% and 21%, while experiment 8 and 10 used >95%. Comparisons of experiment 7 with experiment 8 and experiment 9 with experiment 10 show that humidity does not significantly affect $\theta_c$. However, a comparison of $\theta_c$ for experiments 3 and 4 with experiments 7 and 8 and with experiments 9 and 10 shows an increasing $\theta_c$ with increasing charge. Experiment 7 and 8 resulted in both temporary coalescence and bounce for $\theta > \theta_c$, while experiments 9 and 10 had only temporary coalescence and a few grazing coalescences for $\theta > \theta_c$.

Table 4 presents the relative humidity and the number of each type of collision outcome for experiments 5 through 10. Also shown in Table 4 for each experiment is the ratio of three sets of outcomes: temporary coalescence to all noncoalescence outcome (T + TS)/(B + T + TS), temporary coalescences with satellites to all temporary coalescences (TS)/(T + TS), and temporary coalescences with satellites to all outcomes (TS)/(C + B + T + TS). The confidence level that these ratios are from different populations is shown in Table 5. The second column in Table 5 demonstrates a very high confidence level that the fraction of temporary coalescences in the population of noncoalescences is different for experiments 5 and 6 and different for experiments 7 and 8. This result indicates that high relative humidities encourage temporary coalescences at the expense of bounces in the noncoalescence region. The third column in Table 5 shows little confidence that a temporary coalescence is more or less likely to result in a satellite drop as the relative humidity is changed for experiments 5 and 6 and no confidence for experiments 7 and 8. However, experiments 9 and 10 (the experiments with no bounce for $\theta > \theta_c$) indicate a moderate confidence that increasing humidity increases satellite production. The last confidence level reported in Table 5 shows that high relative humidity collisions produce more satellites in all three comparisons.

## 4. Discussion

We have shown evidence that collisions at higher relative humidity are more likely to result in satellite drops. The data from experiments 5 through 8 in which coalescence, bounce, and temporary coalescence were possible outcomes suggests an increase in satellite drop production with relative humidity. This may be due solely to an increase in temporary coalescence with relative humidity. However, the two experiments (9 and 10) in which coalescence and temporary coalescence

TABLE 2. Collision results from low-charge experiments. The number of each type of collision outcome within each impact angle range is listed with "C" denoting permanent coalescence, "B" denoting bounce, "T" denoting temporary coalescence, and "TS" denoting temporary coalescence with a satellite drop.

| | Collision results | | | | | |
|---|---|---|---|---|---|---|
| | $R$ = 275 $\mu$m, $r$ = 200 $\mu$m | | $R$ = 425 $\mu$m, $r$ = 300 $\mu$m | | $R$ = 425 $\mu$m, $r$ = 200 $\mu$m | |
| Impact angle (deg) | Exp. #1 RH = 30% | Exp. #2 RH > 95% | Exp. #3 RH = 32% | Exp. #4 RH > 95% | Exp. #5 RH = 38% | Exp #6 RH > 95% |
| 0.0–11.5 | 5C | 4C | 6C | 3C | 6C | 6C |
| 11.5–16.4 | 3C | 4C | 4C | 7C | 9C | 6C |
| 16.4–20.3 | 5C | 5C | 8C, 1B | 5C | 5C | 5C |
| 20.3–23.6 | 5C | 8C | 1C | 2C, 6B | 2C | 5C |
| 23.6–26.6 | 3C | 6C | 1C, 2B | 3B | 6C | 4C |
| 26.6–29.3 | 8C | 4C | 1C, 3B | 3B | 5C | 4C |
| 29.3–31.9 | 7C | 8C | 1B | 6B | 4C | 7C |
| 31.9–34.4 | 5C | 8C | 7B | 4B | | 5C |
| 34.4–36.9 | 6C | 5C | 4B | 4B | 4C | |
| 36.9–39.2 | 4C | 6C, 3B | 6B | 9B | 4C | 2C |
| 39.2–41.6 | 2C, 1B | 2C, 1B | 4B | 12B | 3C | 2C |
| 41.6–43.9 | 3B | 5B | 5B | 3B | 10C | 5C |
| 43.9–46.1 | 2B | 1C, 6B | 2B | 3B | 3C | 5C |
| 46.1–48.4 | 3B | 10B | 3B | 7B | 4C, 1T | 3C, 1B |
| 48.4–50.8 | 4B | 3B | 5B | 3B | 1C, 4B | 1C, 2B |
| 50.8–53.1 | 4B | 11B | 1B | 6B | 7B | 2B |
| 53.1–55.6 | 6B | 6B | 4B | 6B | 4B | 7B, 1T |
| 55.6–58.1 | 2B | 5B | 4B | 2B | 1B | 3B, 1T |
| 58.1–60.7 | 4B | | 6B | 3B | 5B, 1T | 2B, 2T, 1TS |
| 60.7–63.4 | 2B | 4B | 3B | 3B | 4B, 1T | 1B, 1T, 1TS |
| 63.4–66.4 | 5B | 1C, 7B | 1B | 2B | 1B, 1TS | 1B |
| 66.4–69.7 | 1B | 2B | | 1B | 1B, 1T, 1TS | 1B, 4TS |
| 69.7–73.6 | 2B | | | | | 1B, 2TS |
| 73.6–78.5 | 3B | 2C, 3B | | | | 1T, 1TS |
| 78.5–90.0 | 1B | | | | 1TS | 2TS |
| >90.0 | 4C | 1C, 1B | | | | |

were the only possible collision outcomes also suggests an increase in satellite production with relative humidity. An explanation for these results is developed in this section. From a meteorological viewpoint, the typical size of the satellites produced (about 80 $\mu$m, Ochs and Czys 1987) is ideal as a new raindrop embryo. Since more satellites occur at higher humidities in clouds, more raindrop embryos are produced where they can grow by accretion and enhance precipitation.

To evaluate the increase in temporary coalescence with relative humidity, we examine the effect of relative humidity on the air film drainage time between the drops. The velocity of the approaching drops in air is found from a simplified Stefan–Reynolds equation (e.g., Charles and Mason 1960) as

$$dx/dt = -8Fx^3/[3\pi\eta a^4], \qquad (1)$$

where the deformation radius ($a$) and force ($F$) pushing the drops together are assumed to be constant (Charles and Mason 1960), $x$ is the air film thickness, and $\eta$ is the viscosity of air. By integration from a fixed initial separation to a much smaller critical separation of one mean free path ($\lambda$), the time for film drainage is

$$\tau = 3\pi\eta a^4(16F)^{-1}\lambda^{-2}. \qquad (2)$$

Using Eq. (2) the variation in air film drainage time with air characteristics can be calculated from

$$\tau/\tau_0 = (\eta/\eta_0)(\lambda/\lambda_0)^{-2}. \qquad (3)$$

From kinetic theory for an ideal gas it can be shown that

$$\lambda/\lambda_0 = (\eta/\eta_0)(p_0/p)(T/T_0)^{1/2} \qquad (4)$$

(e.g., see Beard 1976). Using Eq. (4) to eliminate $\lambda/\lambda_0$ from Eq. (3), the air film drainage time is

$$\tau/\tau_0 = (\eta_0/\eta)(p/p_0)^2(T_0/T). \qquad (5)$$

Thus, at constant pressure, the film drainage time, $\tau$, *increases* as $\eta$ and $T$ *decrease*. For a gas the viscosity is a function only of temperature and for air the viscosity is not measurably affected by relative humidity (Mason and Monchick 1962).

For a change of 50°C or less, the temperature dependence of viscosity is approximated by $\eta_0/\eta = [1 - 0.003(T - T_0)]$ (e.g., see Table 2 in Beard 1977), and the film drainage time evaluated with $T_0$ = 293 K (20°C) and at a constant pressure is

$$\tau/\tau_0 = [1 - 0.003(T - T_0)](T_0/T)$$
$$= [1 - 0.006(T - 20°\text{C})]. \qquad (6)$$

TABLE 3. Collision results from charge experiments. The number of each type of collision outcome within each impact angle range is listed with "C" denoting permanent coalescence, "B" denoting bounce, "T" denoting temporary coalescence, and "TS" denoting temporary coalescence with a satellite drop.

| | Collision results for $R$ = 425 $\mu$m, $r$ = 300 $\mu$m | | | |
|---|---|---|---|---|
| Impact angle (deg) | Exp. #7 $\lvert Q - q\rvert$ = 0.42 pC RH = 30% | Exp. #8 $\lvert Q - q\rvert$ = 0.40 pC RH > 95% | Exp. #9 $\lvert Q = q\rvert$ = 0.68 pC RH = 21% | Exp. #10 $\lvert Q - q\rvert$ = 0.72 pC RH > 95% |
| 0.0–11.5 | 4C | 10C | 12C | 5C |
| 11.5–16.4 | 6C | 4C | 7C | 5C |
| 16.4–20.3 | 9C | 6C | 10C | 7C |
| 20.3–23.6 | 8C | 8C | 5C | 7C |
| 23.6–26.6 | 4C, 1B | 5C | 3C | 5C |
| 26.6–29.3 | 1C, 1B, 2T | 2C, 1B, 2T | 2C | 6C |
| 29.3–31.9 | 1C, 2T | 2C, 5T | 2C | 5C, 1T |
| 31.9–34.4 | 1C, 1B | 1C, 1B | 4C, 5T | 2C, 1T |
| 34.4–36.9 | 3C, 2B, 1T | 2C, 1B, 1T, 1TS | 2C, 4T | 1C, 2T, 1TS |
| 36.9–39.2 | 2B, 3T | 1C, 1B, 3T, 1TS | 2T, 1TS | 3T |
| 39.2–41.6 | 3T | 6T, 4TS | 3T, 1TS | 3T, 6TS |
| 41.6–43.9 | 2B, 2T | 4T, 2TS | 7T | 3T, 2TS |
| 43.9–46.1 | 1B, 1T, 2TS | 1B, 2T | 4T | 3T, 2TS |
| 46.1–48.4 | 4B, 2T, 2TS | 1B, 3T | 2T, 3TS | 2T, 3TS |
| 48.4–50.8 | 4B, 1TS | 3B, 6T, 1TS | 2T, 5TS | 5T |
| 50.8–53.1 | 1TS | 1B, 3T, 3TS | 4T, 1TS | 2T |
| 53.1–55.6 | 3B, 1TS | 2B, 2TS | 2T | 5T, 1TS |
| 55.6–58.1 | 7B | 2B, 1T, 1TS | 4T, 1TS | 1T, 5TS |
| 58.1–60.7 | 6B, 1TS | 2TS | 3T | 2TS |
| 60.7–63.4 | 3B, 2TS | 1TS | 3T | 6T |
| 63.4–66.4 | 4B | | 5T | 5T |
| 66.4–69.7 | 1B | 3T, 2TS | 2T | 4T |
| 69.7–73.6 | 2T | 3T | 1C | |
| 73.6–78.5 | 3T | 3T | | 1C, 6T |
| 78.5–90.0 | 3T | | | 2C, 3T |
| >90.0 | | 1T | | |

Therefore, the drainage time increases with decreasing temperature. The obvious temperature effect is evaporative cooling whereby a falling drop approaches the wet-bulb temperature (e.g., Beard and Pruppacher 1971). Thus, a low relative humidity will reduce the temperature of the drop and, by heat diffusion, the temperature of the air film—thereby increasing the film-drainage time. This relative humidity effect is in agreement with the laboratory observations that low relative humidities have fewer temporary coalescences and more bounces.

To estimate whether the drop is significantly cooled, we consider the relaxation time of about 0.7 s for a drop of $R$ = 400 $\mu$m to cool to the wet-bulb temperature, $T_w$ (Pruppacher and Klett 1978, their Figs. 13–23). This is the time for the temperature of the entire drop (mass-average temperature) to reach 63% of the change to $T_w$ from an air temperature of 20°C. We are concerned here, however, with the surface of the drop, since it is the surface temperature that affects the temperature of the air film between the colliding drops. For a noncirculating drop, the outer shell (beyond $0.95R$) reaches 63% of the change to $T_w$ within 0.01 s, assuming heat conduction in a water sphere. This is the same order as the internal circulation time (Pruppacher and Klett 1978, their Figs. 10–12), so the surface cooling is moderated by replacement of warmer water from the interior. Since 0.01 s is an underestimate of the time

TABLE 4. Collision outcome by type and temporary coalescence ratios.

| Experiment | RH (%) | Collision results C | B | T | TS | Total | $\frac{T + TS}{B + T + TS}$ | $\frac{TS}{T + TS}$ | $\frac{TS}{C + B + T + TS}$ |
|---|---|---|---|---|---|---|---|---|---|
| 5 | 38 | 66 | 27 | 4 | 3 | 100 | 0.21 | 0.43 | 0.03 |
| 6 | >95 | 60 | 21 | 6 | 11 | 98 | 0.45 | 0.65 | 0.11 |
| 7 | 30 | 37 | 42 | 24 | 10 | 113 | 0.45 | 0.29 | 0.09 |
| 8 | >95 | 41 | 14 | 46 | 20 | 121 | 0.83 | 0.30 | 0.17 |
| 9 | 21 | 48 | 0 | 52 | 12 | 112 | 1.00 | 0.19 | 0.11 |
| 10 | >95 | 46 | 0 | 55 | 22 | 123 | 1.00 | 0.29 | 0.18 |

TABLE 5. Confidence level (%) that the temporary coalescence ratios differ for the paired low and high relative humidity experiments.

| Experiments for comparison | $\frac{T + TS}{B + T + TS}$ | $\frac{TS}{T + TS}$ | $\frac{TS}{C + B + T + TS}$ |
|---|---|---|---|
| 5–6 | 97.0 | 67.8 | 97.6 |
| 7–8 | 99.9 | 7.2 | 91.9 |
| 9–10 | — | 82.0 | 88.4 |

constant and the relaxation time of 0.7 s for the mass-average temperature is an overestimate, the actual time constant for $R = 400$ $\mu$m is taken to be of order 0.1 s. Smaller drops will cool faster (about four times faster for $R = 0.2$ mm).

In the experiment, the fall time for a drop of $R = 400$ $\mu$m was $t = 0.31$ s, so that the drop should have cooled appreciably. There is no doubt that the small drops of $r = 300$ and 200 $\mu$m should have cooled significantly since the fall time was longer than the relaxation time for mass-average temperature.

The drop interaction time is much longer than the time constant for heat diffusion in the gap, so the temperature of the air film between the drops should be very close to the surface temperature—or if the two drops have different surface temperatures, between the two surface temperatures. A representative interaction time is $t = 2\sin(45°)(R + r)/\Delta V$, assuming drops passing at relative speed, $\Delta V$, with contact and separation angles of 45° and 135°. For a 425-$\mu$m radius drop colliding with a 300-$\mu$m radius drop, this is about 1 m s$^{-1}$. The time for one-directional heat diffusion from the center of the air gap to a drop is scaled by the distance squared, $(x/2)^2$, divided by the thermal diffusivity of air, $K$. One time constant is about $0.5(x/2)^2/K$ (Bird et al. 1960, their Fig. 11.1-1). If we assume that the gap is $x = 10$ $\mu$m with a diffusivity at 15°C of $K = 2.1 \times 10^{-5}$ m$^2$ s$^{-1}$ (List 1968, Table 113), the time constant is 0.6 $\mu$s. Since bidirectional diffusion is shorter than 0.6 $\mu$s and the interaction time is of order 1 ms, the air gap is essentially at the surface temperature of the drops during the entire dwell time.

Using the wet-bulb temperature (~11°C), the increase in air film drainage time is about 5% at lower humidity in experiments 5 and 6 and experiments 7 and 8. This increase in film drainage time appears to be responsible for the greater tendency of the drops to bounce. Since all of the drops might not have had surface temperatures as cold as the wet-bulb temperature, the increase in bounce observed in the low-humidity experiments might be an *underestimate* of the effect expected if the drops were at their wet-bulb temperature.

This increased air film drainage time might also explain the decrease in satellite production at lower relative humidities for the experiments in which coalescence and temporary coalescence were the only possible collision outcomes. The increased drainage time delays the onset of the coalescence phase of a temporary coalescence event. Therefore, coalescence will not proceed as far by the time the coalesced pair begins to separate. We speculate that a narrower water neck between the drops forms during the shorter coalescence phase and, during separation, decreases its diameter to the breaking point before the water bridge is long enough to break at two points and produce a satellite drop.

## 5. Conclusions

The results of our laboratory investigation show several features of the effect of relative humidity on coalescence. First, the coalescence efficiency for small precipitation drops is unaffected by relative humidities between 30% and 100%. However, relative humidity does alter bounce, temporary coalescence, and satellite production. This effect is caused by the colder air in the draining air film between drops colliding in lower relative humidity air. For combinations of drop size and drop charge where the collision outcomes in the noncoalescence region can result in either temporary coalescence (with or without satellites) or bounce, increasing relative humidity increases the fraction of temporary coalescence outcomes and the number of satellites produced. A small change in film drainage time of about 5% appears to increase the relative number of temporary coalescences by about 100%. Other experiments showed that cases where collisions result in either coalescence or temporary coalescence, increases in relative humidity also produce increased numbers of satellites. Since higher relative humidities are found in clouds, the greater numbers of satellites produced translate to increased numbers of raindrop embryos.

Another interesting feature of this data relates to the trend of coalescence efficiency with Weber number. As was previously discussed, increasing Weber number should result in a greater deformation of the colliding drops, trapping more of the intervening air and impeding coalescence. Thus, higher Weber number collisions should have lower coalescence efficiencies. For the drop size pairs of Table 2 this is clearly not the case. In fact, the middle set of results (experiments 3 and 4) with the intermediate Weber number has the lowest efficiency because the critical impact angle separating the central coalescence region from the outer noncoalescence region is the smallest of the three sets of experiments. Therefore, Weber number alone is insufficient to characterize collisions between small precipitation drops. If we are to extend our data to drop sizes and size ratios not directly studied, a new and more complete scaling of the problem must be found.

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## REFERENCES

Beard, K. V., 1976: Terminal velocity and shape of cloud and precipitation drops aloft. *J. Atmos. Sci.*, **33**, 851–864.

——, 1977: Terminal velocity adjustment for cloud and precipitation drops aloft. *J. Atmos. Sci.*, **34**, 1293–1298.

——, and H. R. Pruppacher, 1971: A wind tunnel investigation of collection kernels for small water drops in air. *Quart. J. Roy. Meteor. Soc.*, **97**, 242–248.

——, and H. T. Ochs, 1984: Collection and coalescence efficiencies for accretion. *J. Geophys. Res.*, **89**, 7165–7169.

——, and ——, 1995: Collisions between small precipitation drops. Part II: Formulas for coalescence, temporary coalescence and satellites. *J. Atmos. Sci.*, in press.

Bird, R. B., W. E. Stewart, and E. N. Lightfoot, 1960: *Transport Phenomena.* Wiley, 780 pp.

Charles, G. E., and S. G. Mason, 1960: The coalescence of liquid drops with flat liquid/liquid interfaces. *J. Colloid Sci.*, **15**, 236–267.

Czys, R. R., and H. T. Ochs, 1988: The influence of charge on the coalescence of water drops in free fall. *J. Atmos. Sci.*, **45**, 3161–3168.

Foote, G. B., 1975: The water drop rebound problem: Dynamics of collision. *J. Atmos. Sci.*, **32**, 390–402.

Holdridge, D. J., 1992: A laboratory investigation of electrostatic charge and relative humidity influences on the coalescence of precipitation size water drops. M.S. thesis, University of Illinois, 89 pp.

Laird, N. F., 1992: A new investigation of relative humidity and electrostatic charge influences on the coalescence of precipitation drops. M.S. thesis, University of Illinois, 98 pp.

Lindblad, N. R., 1964: Effects of relative humidity and electric charge on the coalescence of curved water surfaces. *J. Colloid Sci.*, **19**, 729–743.

List, R., 1968: *Smithsonian Meteorological Tables.* Smithsonian Institution Press, 527 pp.

Mason, E. A., and L. Monchick, 1962: Transport properties of polar gas mixtures. *J. Chem. Phys.*, **36**, 2746–2757.

Ochs, H. T., and K. V. Beard, 1984: Laboratory measurements of collection efficiencies for accretion. *J. Atmos. Sci.*, **41**, 863–867.

——, and R. R. Czys, 1987: Charge effects on the coalescence of water drops in free fall. *Nature*, **327**, 606–608.

——, ——, and K. V. Beard, 1986: Laboratory measurements of coalescence efficiencies for small precipitation drops. *J. Atmos. Sci.*, **43**, 225–232.

——, D. E. Schaufelberger, and J. Feng, 1991: A reassessment of coalescence efficiency observations for small precipitation drops. *J. Atmos. Sci.*, **48**, 946–951.

——, K. V. Beard, N. F. Laird, D. E. Schaufelberger, and D. J. Holdridge, 1995: Collisions between small precipitation drops. Part 1: Laboratory measurements of bounce, coalescence and temporary coalescence. *J. Atmos. Sci.*, **52**, 2258–2275.

Park, R. W., 1970: Behavior of water drops colliding in humid nitrogen. Ph.D. thesis, University of Wisconsin, 577 pp.

Prokhorov, P. S., 1954: The effects of humidity deficit on coagulation processes and the coalescence of liquid drops. *Discuss. Faraday Soc.*, **18**, 41–51.

Pruppacher, H. R., and J. D. Klett, 1978: *Microphysics of Clouds and Precipitation.* Reidel, 714 pp.

Schaufelberger, D. E., 1990: The influence of electrostatic charge and relative humidity on the coalescence of small free falling water drops. M.S. thesis, University of Illinois, 78 pp.