Drop rebound in clouds and precipitation

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Abstract

The collection efficiency has been measured for 17 size pairs of relatively uncharged drops in over 500 experimental runs using two techniques. The results indicate that collection efficiencies fall in a narrow range of 0.60 to 0.70 even though the collector drop was varied between 63 and 326 μm and the size ratio from 0.05 to 0.33. In addition the measured values of collection efficiencies (E) were below the computed values of collision efficiencies (E) for rigid spheres. Therefore it has been concluded that rebound was occurring for these sizes since inferred coalescence ($\varepsilon = E/E$) efficiencies are about 0.6 to 0.8. At a very small size ratio ($r/R = p = 0.05$, $R = 326$ μm) the coalescence efficiency inferred from our experiment is in good agreement with the experimental findings for a supported collector drop. At somewhat larger size ratios ($0.11 \leq p \leq 0.33$) our inferred values of ε are well above results of supported drop experiments, but show a slight correspondence in collected drop size dependency to two models of drop rebound. At a large size ratio ($p = 0.73$, $R = 275$) our inferred coalescence efficiency is significantly different than all previous results.

Experimental study on cloud drops

An experiment has been developed[1] to investigate the possibility of rebound for colliding cloud drops as postulated by Levin et al.[2] The collection efficiency is being determined from the amount of tracer captured by a stream of widely separated drops falling at terminal velocity through a monodisperse cloud of chemically tagged droplets.

Design and procedure

The current experimental setup is shown in Figure 1. The cloud is produced by a vibrating orifice device (TSI Model 3050). With careful adjustment of the transducer frequency, the liquid jet is disrupted into a stream of uniform size drops which is free of smaller satellites and also larger multiplets. Recombination of the drops is greatly reduced by dispersion in an axial jet of turbulent air and by subsequent dilution. Both air streams are saturated slightly above room temperature to prevent evaporation. The tracer solution of lithium sulfate (0.1% Li^+) is fed to the cloud droplet generator from the solution reservoir under pressure. The amount of tracer is apparently much less than has been used in previous collection studies[3,4] and has a negligible effect in the physical properties of the cloud water (e.g., surface tension). The reference pressure is adjustable and remains essentially constant by virtue of a large, nitrogen reservoir. An electrically neutral cloud is achieved with an ion discharge device (TSI 3054). The cloud is continuously generated during the experiment and flows at 11 lpm through a cloud chamber 1.3 m long and 10.6 cm in diameter.

Sampling ports are located in the chamber to permit the insertion of slides coated with a dye and gelatin mixture for an evaluation of the droplet sizes. The stain produced by the droplets was calibrated by using the direct output of the droplet generator, and was found to be consistent with the results of a similar method used by Liddell and Wootten[5]. For a typical experiment the droplets in the cloud chamber were found to be composed of over 98% singlets. A typical standard deviation for the singlet distribution was 1.5%. The droplet concentration was measured from photographs taken with a strobe and 35 mm camera. The illumination was arranged in a vertical plane of well defined thickness by two cylindrical lenses and two slits. Typical concentrations vary between 1 and 75 cm^{-3} depending on the size of droplet being used with the smaller droplets yielding a higher concentration.

An orifice device was also used to produce the collector drops[6]. Drops with a wide vertical spacing (several centimeters) were separated from the main stream with an electronically controlled charging ring and high voltage deflection plates. The drops were allowed to reach terminal velocity before entering the top of the cloud chamber. The vertical spacing was determined from the terminal velocity and the production rate. The charge on the collector drops was determined with a laboratory built electrometer. The charge on individual drops was measured with an oscilloscope to a sensitivity of about 10^{-16} Coulombs per drop.

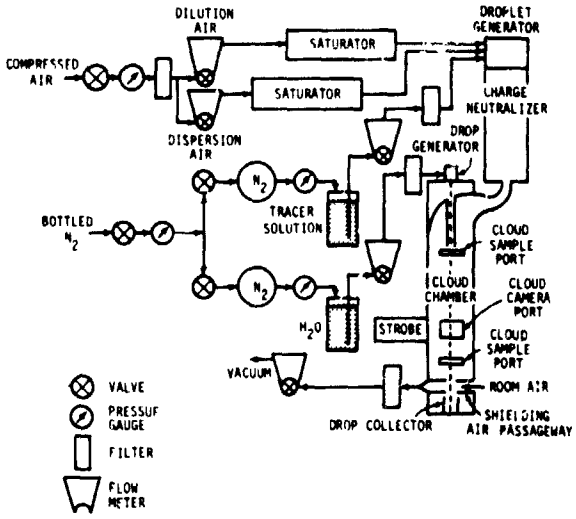

Figure 1. Diagram of experimental setup used to measure the collection efficiencies of cloud drops.

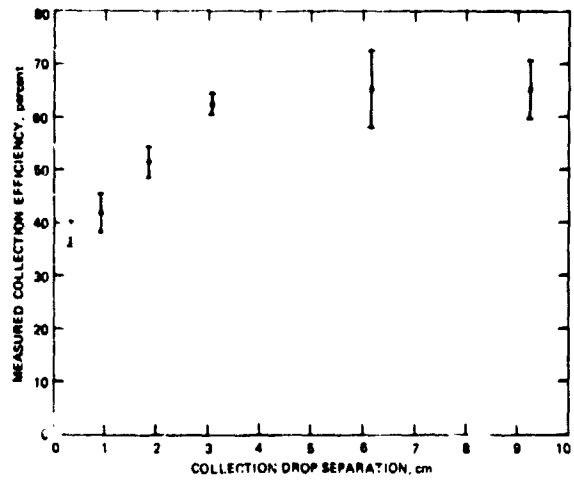

Figure 2. Collection efficiency as a function of R-drop separation for R = 95 μm and r = 19 μm.

During an experimental run the drops were collected beneath the cloud chamber in a polypropylene jar for a known period and covered for later analysis. After chemical analysis the collection efficiency was determined from experimental parameters using the following equation:

$$E = M/[\pi R^2(1+p)^2\ \Delta V\ n\ m\ X\ t\ N] \qquad (1)$$

where M is the amount of lithium measured for an experimental run and the term in brackets is the amount of lithium expected from capture of all cloud droplets in the geometric path of the collector drops (i.e., unity collection efficiency). The term $\pi R^2(1+p)^2$ is the geometric cross section for the drop-droplet interaction. Multiplication of this cross section by the relative terminal velocity (ΔV) and the number concentration of droplets (n) results in the number of cloud droplets encountered geometrically per unit time by a single collector drop. Further multiplication by the mass of one cloud droplet (m) and mass fraction of lithium in one cloud droplet (X) results in the amount of lithium encountered geometrically per unit time by a single collector drop. Finally, the lithium encountered by all collector drops is found from multiplication by the interaction time for one collector drop (t) and the total number of collector drops for one experimental run (N).

The number of collector drops (N) was calculated from the drop generation rate and the experimental time. The amount of lithium for each run (M) was determined by atomic absorption analysis. The size of the collector drop (R) and cloud droplets (r) was used to obtain the size ratio (p), and the relative terminal velocity (ΔV) using the equations in Beard[7]. The cloud droplet concentration (n) was determined photographically by the method discussed above. The initial droplet size was used to determine droplet mass (m), whereas the initial lithium was fixed by the concentration of the tracer in the cloud water solution (X = 0.001). The interaction time (t) was determined from the fall speed of the collector drop, the downward air velocity in the cloud chamber and the cloud chamber height. Accurate knowledge of the air velocity was unnecessary because its magnitude was ≤4% of collector drop velocity.

Error analysis

The most obvious potential source of error in an experiment of this type is chemical contamination. Beyond checking for inconsistent or unrepeatable data several precautions and tests were made to assess and eliminate this problem. New polypropylene jars with plastic lids were always used for sample acquisition. During the course of an experiment several unopened jars were included for chemical analysis. Also experimental runs were made without any collector drops falling through the system to test for cloud droplet contamination in the jars. The jars in these runs were handled identically to the jars with collector drops. Chemists, trained in microanalysis, performed the atomic absorption measurements necessary to determine the amount of Li^+ in each sample. Our tests have shown that total errors from chemical contamination and analysis are less than 3%.

Since electric charge on both the collector and collected drops can alter both the collision and coalescence efficiencies, we have been careful to minimize charge effects. The cloud droplets were passed through a charge neutralizer (TSI) designed to achieve a Boltzmann charge distribution at much higher flows than used in our experiment. We have computed that the mean magnitude of charge on a cloud droplet is $< 2 \times 10^{-18}$ C. Our method of charge minimization for the collector drop leads to a charge magnitude $< 3 \times 10^{-16}$ C. Considering the extremely small charge on the cloud droplets only induced charge effects are of possible significance in our experiment. The stronger influence of oppositely charged drops of a magnitude of $\geq 10^{-14}$ C is necessary to significantly affect coalescence[8].

The final and possibly most subtle source of experimental error is a depletion effect. Since one collector drop follows the next through the center of the cloud column, there is the potential for depletion of the cloud droplet concentration by the stream of collector drops. In the data analysis this effect would be reflected as an anomalously low collection efficiency. Figure 2 shows the depletion effect for 19 μm cloud droplets and 95 μm collector drops. All data were taken at a sufficient collector drop separation to eliminate the depletion shown in Figure 2.

Results

The measured collection efficiencies are shown in Figure 3 as a function of cloud droplet size. Also shown for comparison are experimental and theoretical findings at comparable collector drop sizes. Our 1980 measurements (closed triangles) were extended to a wider range of droplet sizes in 1981 (closed circles). Although charge control was improved in 1981 there is no apparent systematic difference between '80 and '81 data. Each data point has an uncertainty of about ±10%. In every instance our measured collection efficiency lies below the theoretical collision efficiencies, whereas other work at smaller droplet sizes is more comparable to the computed efficiencies. There is a tendency evident in our results of a convergence with theoretical efficiencies at smaller droplet sizes. No apparent trend in the experimental data with collector drop size can be deduced, perhaps because of experimental scatter. The theoretical efficiencies, however, also are rather insensitive to collector drop size in the investigated range.

Coalescence efficiencies calculated from our experimental data on collection efficiencies and theoretical collision efficiencies are shown in Figure 4. In addition to our experimental error of about ±10% there is an uncertainty in ε from the use of computed collision efficiencies. For instance, our values of ε would increase by about 15% with the use of de Almeida's[9] collision efficiencies.

Some correspondence is found between our results and coalescence theories. For example, our data lie somewhat above the geometric coalescence factor ($\varepsilon = (1+p)^{-2}$) of Whelpdale and List[10]. On the other hand, our data falls somewhat below one of the several models of Arbel and Levin[11] (their Table 4). Their other results do not correspond as well. Our results all lie above the empirical formula of Levin and Machnes[12] based on an extrapolation of their findings for larger collector drops.

The experiments were conducted at two levels of charge. In 1980 the charge was maintained to $10^{-15} \leq |Q_R - Q_r| \leq 10^{-14}$ Coulombs whereas in 1981 the charge was lowered to about 3×10^{-16} Coulombs for all data. No systematic differences were found in the data obtained at these two charge levels. Thus, charges of these magnitudes, which are found in weakly or moderately electrified clouds, apparently are too weak to significantly enhance coalescence. It therefore follows that the experiment should be extended to higher levels of charge to determine the magnitude needed to suppress the rebounding of falling drops. In addition, the amount of charge transferred by rebound in the range $10^{-18} \leq |Q_R - Q_r| \leq 10^{-13}$ Coulombs should also be measured to help determine the viability of the induction mechanism for cloud electrification.

Conclusions

Collection efficiencies were measured for 15 pairs of drop sizes in the range of $63 \leq R \leq 98$ μm and $11 < r < 26$ μm. The resulting efficiencies were all in the 60-70% range, most lying significantly below the computed hydrodynamic collision efficiencies. The physical basis of a nearly constant collection efficiency in this range may be due to a critical contact angle for rebound [11] or geometric coalescence factor[10] with hydrodynamic effects, if any, masked by experimental scatter.

The inferred coalescence efficiencies of 63-83% were only somewhat consistent with the coalescence models of Whelpdale and List[10] and of Arbel and Levin[11]. Both our empirical results and the models show a decrease in ε with increasing droplet size. In contrast to the models, however, no systematic change in efficiency was found as a function of collector

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drop size. Even the qualitative agreement in r-drop dependency could be fortuitous since our measurements at other size ratios (reported in the following sections) show no correspondence with the models.

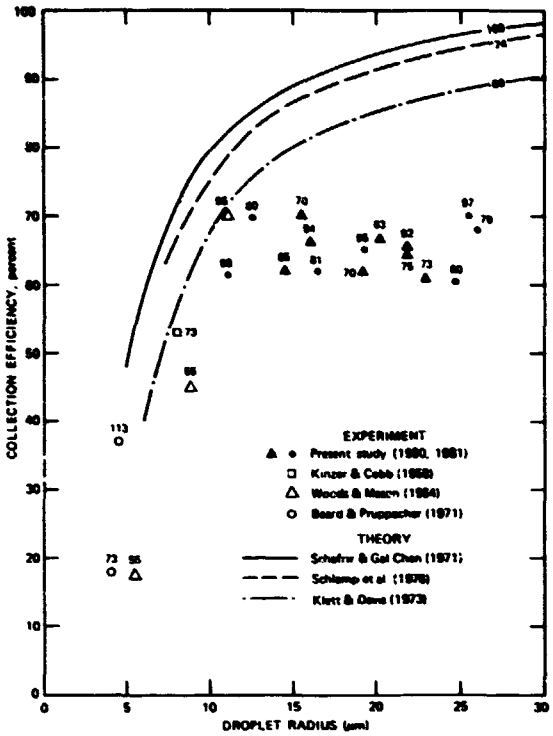

Figure 3. Collection efficiency as a function of r-drop radius.

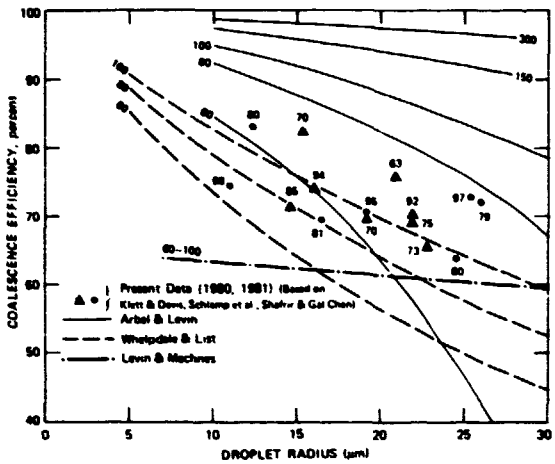

Figure 4. Coalescence efficiency as a function of r-drop radius.

Experimental study on accretion

A slight modification was made to the apparatus described in the previous section to permit the generation of collector drops of precipitation size for a study of the collection of much smaller cloud drops. The large capacity water feed system and the generator controls (described in the next section) were connected to the cloud drop experiment. Other aspects of the experimental arrangement remained unchanged.

The water feed rate and the generation frequency were selected so that 326 μm collector drops reached within 1% of terminal velocity before entry into the cloud chamber. A drop charge of $< 2 \times 10^{-15}$ Coulombs was maintained with the technique described in the previous section. A collection efficiency of 0.59 ± 10% was measured for accretion with 17 μm cloud droplets ($p = 0.05$) from 12 experimental runs at 2 different vertical separations (32 and 64 cm). A coalescence efficiency of $\varepsilon = 0.63$ has been inferred from a collision efficiency of $E = 0.94$ based on computations for small size ratios[13]. Our result is nearly the same as Levin and Machnes[11] ($\varepsilon = 0.61$) even though their empirical formula is a fit to a pure coalescence study (i.e., the "collector" drop was supported). We may have reached a small enough size ratio where the collision and coalescence mechanisms are relatively uncoupled. This important finding suggests that for accretion the collection efficiency may be calculated from computed collision efficiencies where $E \sim 1$ and empirical coalescence studies where $\varepsilon \sim 0.6$, that is $E \sim 0.6$. A few more measurements are desirable to verify this hypothesis for the accretion process at other sizes and size ratios.

Experimental study on precipitation drops

A study of the collection efficiency of small precipitation drops has been initiated[14]. The experiment is designed so that the drops interact initially at *terminal velocity* and the closure velocity and impact angle are determined by the natural system. This approach circumvents the difficulty of trying to combine the results of coalescence studies[12,15,16] with collision theory.

Design and procedure

An apparatus has been designed and constructed to measure the collection efficiency of small precipitation drops with size ratios $0.6 \leq p \leq 1$. In the following paragraphs, this system will be described. The present system can readily be used to measure collection efficiencies for drops $R < 400$ μm with $p > 0.6$.

Drops are produced by perturbing a liquid jet using a method first demonstrated by Rayleigh[17]. Adam et al.[6] described a technique for producing unequal sized drop pairs from a single jet. A sinusoidal voltage is applied to a piezeoelectric transducer which induces capillary waves on the jet resulting in uniform drop production. The excitation frequency is periodically switched between two values to produce drops of one size followed by drops of another size. The drops can be charged and deflected between high voltage electrodes. When pulses of controlled width and voltage are superimposed on the charging voltage then selected drops from either group of drops can be generated with a negligible charge. As the main stream is deflected between the high voltage electrodes the uncharged drops fall as repetitive drop pairs.

Several design changes, some of which are indicated in Figure 5, have been made to improve the system of Adam et al.[6] First TTL digital logic has been adopted for the majority of the electronic controls. By using a 10 MHz crystal controlled oscillator, good frequency control and long term stability is achieved. Digital counters are used to divide the clock frequency by integer numbers selected by thumbwheel switches indicated by A and B in Figure 5. Thus, square waves of varying frequencies can be generated, and then amplified to drive the transducer.

The integers N_A and N_B are also selected by thumbwheel switches. These integers control the number of cycles of frequency A* and B* (corresponding to the integers A and B) between changes in frequency. Thus, after N_A cycles of frequency A*, N_B cycles of frequency B* are generated and the sequence is repeated. A rotary switch (not shown) is used to select either frequency A* and B* or alternative packets of A* and B*.

The flip-flop circuit used to switch the two data selectors also triggers the four indicated time delays. These delays control the timing of the pulses that are used to generate the uncharged drops and trigger the strobe and camera. Electronic controls not shown in Figure 5 allow the camera to be triggered before the strobe so that the strobe flash occurs at the instant when the shutter has fully opened.

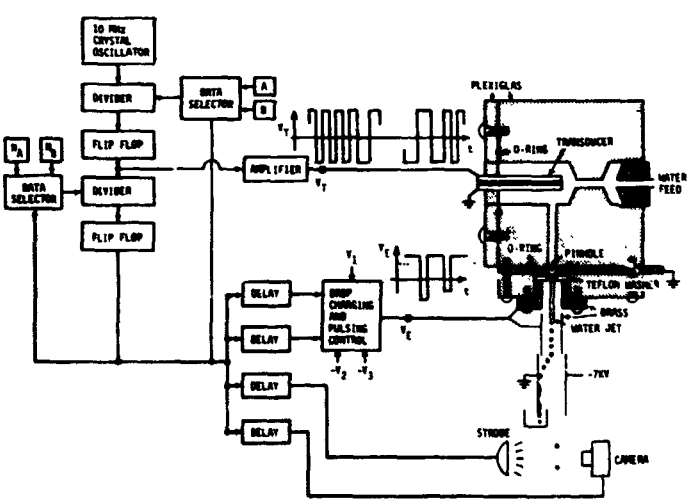

Figure 5. Diagram of drop generator and control circuits for experiment to measure collection efficiencies of small precipitation drops.

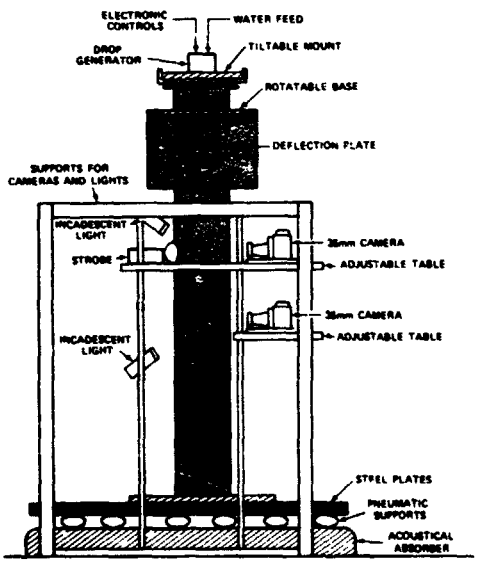

Figure 6. Experimental apparatus for the precipitation drop experiment.

This drop generating system has several advantages over the system described in Adam et al.[6] The use of a square wave to drive the transducer appears to have improved the system performance. Troublesome satellite drops are almost never formed in the stable frequency range. This may result from sharper edges on the perturbation imposed on the liquid jet. The size ratio obtained can be extended using a lower harmonic during jet breakup. However, the use of higher multiplets is restricted to < 100 μm radius because larger drops tend to break apart when pulsed out. Thus, the singlet range of $0.6 \leq p \leq 1$ might be extendable down to $p \sim 0.5$ when the small drops are ≤ 60 μm radius.

The drop generator is mounted on a platform that can be adjusted to about 15° from level so that the water jet can readily be directed vertically downward (Figure 6). The platform is located on top of a small plexiglas enclosure that can be rotated to align drop pairs parallel to the film plane. The experiment occurs in a 100 cm tall plexiglas chamber with a square cross section of 100 cm^2. The drops fall through this chamber and collide in a saturated environment at room temperature after they have each attained their terminal velocities. Data on drop trajectories is obtained photographically.

At the onset of an experiment the repetition rate can be set high enough such that the drops appear stationary under stroboscopic light. Individual small and large drops can be pulsed out of the stream and adjusted to fall vertically between high voltage electrodes. At this point the drop stream may appear as shown in Figure 7, however, in practice a much larger initial separation is chosen so that both drops will achieve terminal velocity before they approach each other. Since both the large and small drops are generated from the same stream it is impossible to produce both sizes at their terminal velocities.

The drop pairs must be separated in time so that each event is unaffected by the preceding one. Greater time separation is achieved by simply adding more trailing large drops to the drop cycle. Since the delay for the pulses is always measured from the point at which the first small drop is produced, these delays are unaffected by the addition of trailing large drops and the drop pairs can be made arbitrarily far apart. As more large drops are added the pulses must be slightly readjusted since aerodynamic factors have changed. This is done by viewing the position of streaks produced by the drops as they pass the incandescent light. As a practical matter drop events are usually separated by about 0.5 s. After the events have been adequately separated minor readjustments are made to enhance the probability of an interaction

Two polyethylene lined 55 gallon drums partially filled with distilled water are used as a water feed system for the drop generator. Pressure is supplied from bottled nitrogen. Because of the large water surface the flow remains essentially constant for several hours. The water reservoirs and experimental chamber are each on an isolation platform to reduce interference from building vibrations. These platforms consist of massive steel plates suspended pneumatically above an acoustic absorber.

Streak and strobe photographs are obtained near the top of the 100 cm column. The streaks are created by an incandescent lamp located 30° above the camera axis and on the opposite side of the chamber. The collection efficiency is determined from the maximum horizontal separation measured for coalescence. An observed coalescence that results from drops falling in a plane more than about 15 degrees out of parallel with the film plane will result in a measurement that is at least 3% too low. Therefore, the platform which supports the drop generator is turned to align the plane of the falling drops parallel to the camera film plane so that the streak photograph represents the best possible measure of the horizontal separation. A position for a second camera at right angles to the first camera has been constructed for an unambiguous measure of the horizontal separation.

A free running strobe light placed about 45° to one side of the optical axis creates successive exposures on the film. Using the frequency of the strobe flashes, the fall speed of each drop can be computed. Triggered strobe observations are also used to verify the vertical drop separation at the point where the streaks are recorded. Another camera is triggered at the point where the drops come together to record the results (miss, coalescence, rebound, or possibly breakup) in the form of streak photographs.

Results

The apparatus just described has been used to measure the collection and coalescence efficiencies for a 275-200 μm drop pair. Two cameras are used to obtain the necessary data. The upper camera recorded streak data for a measure of the initial horizontal offset of the drops that is used to determine the maximum separation for collection (i.e., the collection efficiency). In addition multiple strobe exposures were used to verify fall speeds. Figure 8a depicts a sample of the data taken with the upper camera. The lower camera was used to record streak images of the interaction to determine whether a collection event had occurred. Figure 8b shows the characteristic signature of a coalescence event whereas Figure 8c shows a rebound event with an indication of the oscillation due to deformation at impact. No

evidence of partial coalescence has been noticed. Data from the lower camera was also used to estimate the rebound probability from the fractional number of rebound events out of the total of rebound and coalescence events. To obtain the coalescence efficiency (or probability) the rebound probability is subtracted from unity.

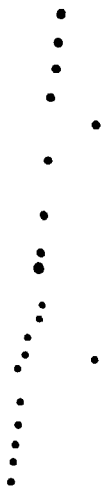

Figure 7. Stream of charged drops and one uncharged pair falling between high voltage plates.

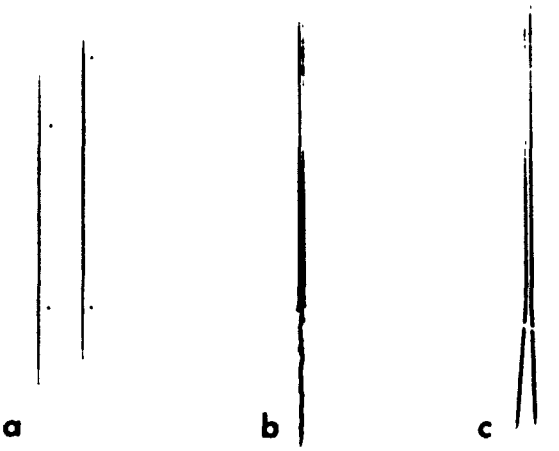

Figure 8. Camera data showing: (a) horizontal separation, upper camera; (b) coalescence event, lower camera; and (c) rebound event, lower camera.

The drop sizes were determined by weighing a timed sample of uniform droplets from the stream. By knowing the frequency at which the drops were produced, their mass could be determined. This method leads to less than a 1% error in determining the drop radius. However, it was not possible to set up the experiment in precisely the same manner from day to day resulting in a 5% variation in the radius of each drop. Both drops were falling approximately 3% faster than their terminal velocities when approached within 100 radii of each other, and their relative velocity was about 4% high.

To date, we have obtained and analyzed data from several hundred photographed events. Out of 56 collision events (either coalescence or rebound) we have determined the coalescence efficiency to be 0.72 ± 0.05 and the collection efficiency to be 0.71 ± 0.05. This result is consistent with an expected collision efficiency close to unity.

Park[16] has obtained the only data on unsupported drops in the size range used in this experiment. His data was obtained by firing streams of drops at each other and not by using drops at terminal velocity. Our data point lies outside the rebound region based on his data. The coalescence efficiency of Levin and Machnes[12] for this size pair with one drop supported is only 0.36. They acknowledged that this experimental approach was only an approximation to the collection problem since it artificially divides a "continuous" process into collision and coalescence. The degree of approximation in such an experiment can only be determined by comparison with data on collection as obtained in our initial experiment. The comparison shows, at least for small precipitation drops of similar size, that such approximate coalescence studies may result in a large uncertainty.

Acknowledgments

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