EFFECTS OF ELECTRIC FIELDS ON WATER-DROPLET COALESCENCE [1]

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(Manuscript received 11 February 1960)

ABSTRACT

Growth of incipient precipitation particles by collision and coalescence with cloud droplets is one of the primary mechanisms of natural rain. Comparison of previous research shows wide divergence between various theoretical and laboratory values of collision efficiency and coalescence efficiency. In an effort to obtain additional laboratory measurements of droplet coalescence, high-speed photographs were taken of colliding droplets at the breakup point in a Rayleigh jet. With 700-micron diam droplets, less than 30 per cent of the collisions result in coalescence under no field condition. At fields of about 40 v per cm, the coalescence was about 100 per cent under all conditions of field.

1. Introduction

Coalescence of water droplets is a matter of prime importance in meteorology. This importance arises from the fact that natural precipitation involves the collision and coalescence of cloud droplets with incipient precipitation particles [1]. Unfortunately, the efficiencies of these processes are poorly understood.

Collision efficiency denotes that fraction of the droplets in the fall path of the larger drop which actually collide with it. Several scientists have attempted to compute or measure this quantity. Apparently, the earliest study of importance in this area is the classical work of Langmuir and Blodgett [2], who considered the one-body problem of potential flow with the result that the theoretical values of the efficiency depended largely upon the relative sizes and falling speeds of the interacting particles and upon the density and viscosity of the surrounding medium. Das [3] also considered the potential-flow problem but took into account the sizes of both the collecting and collected drops. Subsequently, Langmuir [4] considered the viscous-flow regime and computed collision efficiencies for this important region. The two-body problem (*i.e.*, one which allows for the mutual interaction of the escape motions around the two drops), has been considered by Pearcey and Hill [5] and Hocking [6]. The results of these studies differ considerably in the range of drop sizes important in meteorology (fig. 1). The work of Pearcey and Hill is particularly interesting in that it predicts collision efficiencies in excess of unity between droplets of similar size because of the effect of the turbulent wake behind the drop. The role of the wake in permitting "missed" droplets to collide with the back side of the larger drop was first observed by Telford *et al* [7], whose experiments suggested collection efficiencies considerably in excess of unity. Model studies involving steel balls falling through sugar solutions, Schotland [8], and Schotland and Kaplan [9], also gave collision efficiencies in excess of unity for droplets of similar size.

Levin [10] has considered the possibility that small droplets, below the critical size computed for collision by Langmuir and Blodgett, and Hocking, might be caused to collide with larger drops because of the effects of unequal electrical charges. Levin's computations suggest that charge effects might materially

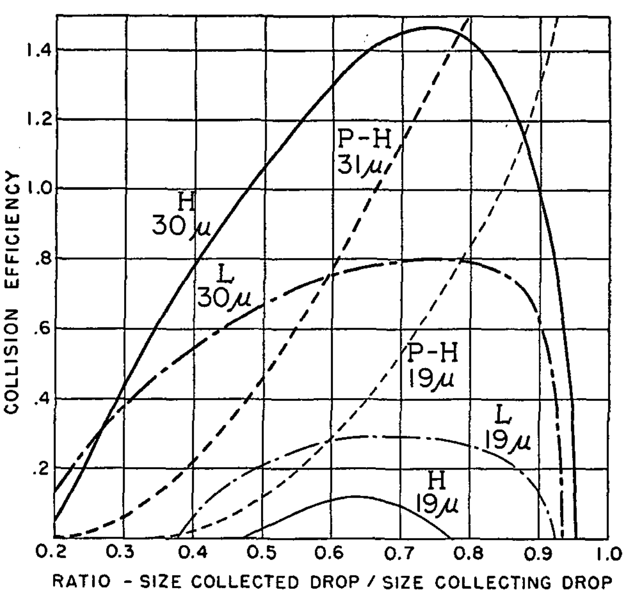

FIG. 1. Comparison of theoretical droplet collision efficiencies as computed by Hocking, H; Pearcey and Hill, P-H; and Langmuir, L. Numerals inside graph refer to size of collector drop.

[1] The research reported in this document was sponsored in part by the Geophysics Research Directorate, Air Force Cambridge Research Center, Air Research and Development Command, under Contract No. AF 19(604)-618 and in part by the National Science Foundation under Contract No. NSF-G4644.

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increase the collision efficiency if the collected droplet is of very small size (order of 1- to 2-micron diam). However, the charges assumed by Levin appear unrealistically high.

Obviously, with this lack of agreement between various workers in the field, computations involving collisions between droplets are subject to a fair degree of uncertainty. However, even greater uncertainty is involved in the coalescence problem.

Compared with the studies of collision, the problem of coalescence has been much less studied in meteorological circles. Coalescence efficiency is defined as the fraction of collisions which result in coalescence. For lack of information to the contrary, many early workers ignored the possibility that colliding droplets might "bounce-off" instead of coalescing. This is tantamount to equating collision efficiency and collection efficiency. Unfortunately, nature isn't quite so simple. It is now well established that the likelihood of coalescence depends strongly upon the conditions under which the collision takes place and the conditions of the droplet surfaces at the time of collision. Fortunately, in the problem of rain formation, we are concerned with relatively pure water and relatively clean surfaces. (In this problem, we are not concerned with clouds which have formed in highly polluted or artificially contaminated atmospheres.) Meteorologists, therefore, have been primarily interested in determining the coalescence probability for collisions between pure-water droplets of various sizes and the effects that external conditions, such as electric field and space charge, might have upon this probability.

One of the interesting early discoveries in this field was made by Rayleigh [11] who observed the behavior of droplets obtained from two jets of water in the presence of a weak electric field. Rayleigh suggested a jet breakup mechanism involving the presence of smaller satellite droplets in a stream of almost uniformly sized drops. The spreading of the jet after breakup was accounted for as a result of collisions between the droplets not resulting in coalescence. In the presence of the electric field, the jet breakup was greatly reduced, and he attributed this to an increased coalescence efficiency.

Sartor [12] undertook an investigation of the relationship between the coalescence of simulated drops and the electric-field conditions under which they fall. Because of the difficulty of observing water droplets falling in air, Sartor employed drops of water falling through mineral oil. This study was important in that it was responsible for initiating a whole host of studies by other scientists; however, the values obtained probably are not too applicable to the problem of coalescence of water droplets in air. The principle difficulties with these experiments lie in the impossibility of simultaneously modeling the electrical forces and the viscous-inertial forces and in the fact that the water-oil interface must surely act differently than a water-air interface.

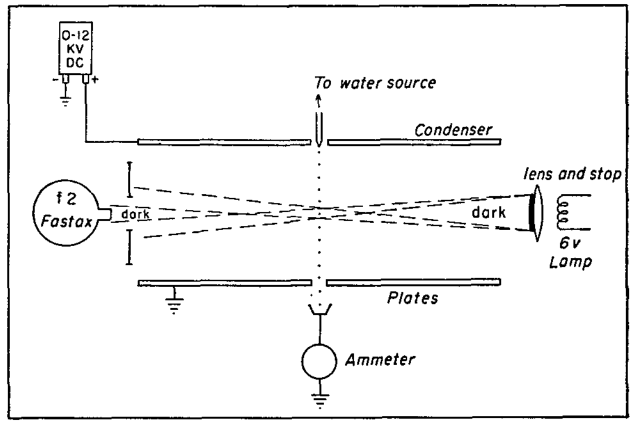

FIG. 2. Apparatus used for coalescence studies.

Relatively few detailed laboratory studies of collection efficiencies, for droplets of sizes of meteorological interest, have been carried out. Gunn and Hitschfeld [13] measured the increase in mass of 3200-micron-diam drops which were permitted to fall through three clouds of differing droplet sizes (ranging from about 10 to 200 microns in diam). The results seemed to verify the Langmuir collision efficiencies (assuming the coalescence efficiency to be unity). By using a somewhat more elaborate instrumental setup, Kinzer and Cobb [14] measured the time required for a drop of 150 microns in diam to grow to 1500 microns while floating in a cloud-filled vertical wind tunnel. From these measurements, they calculated the collection efficiency as a function of the size of the growing drop. Their results gave unexpectedly low growth rates for collector drops smaller than 300 microns and larger than 1000 microns in diam. At intermediate sizes, the collector grew considerably faster than expected (assuming Langmuir collision efficiencies and a coalescence efficiency of unity).

During the winter of 1953–54, a series of experiments was performed in the Cloud Physics Laboratory, University of Chicago, in an effort to determine the effect of electric fields on droplet coalescence. Unfortunately this study was never carried to a conclusion. During the summer of 1954, it was necessary to terminate this study because of a cut-back in support from our sponsor. Subsequently two of the authors left the University, and the other two have become deeply involved in other problems.

Because of the considerable increase of interest in coalescence problems in the past five years, and in view of the shortage of published experimental work in this area, it was decided that the results of the Chicago experiments, in spite of their admitted inadequacy, should be reported.

2. Experimental technique

The experimental setup used in these measurements was designed to determine the coalescence efficiency of colliding water droplets issuing from an inverted Rayleigh jet. A jet of water was allowed to break up between horizontal plates of a parallel-plate condenser, 13 cm apart and 47 cm in diam (fig. 2). The holes through which the droplets fell were well centered and kept small to reduce distortions of the electric field. The jet was created by forcing water through a suitably dimensioned glass capillary which was inserted through the top plate with its tip protruding about 1 cm below the lower surface of the top plate. The jet breakup occurred near the top plate, its exact position being determined by the velocity of efflux from the jet.

A variable potential of 0–12,000 vdc could be applied to the condenser plates. Events occurring at the point of jet breakup were photographed with a high-speed camera, at frame speeds ranging from 4000 to 7000 per sec. In the first series of experiments, light field illumination was used, together with nigrosine-dyed water droplets on a bright background. Dark field illumination of pure water was subsequently used in order to extend the range to smaller droplet sizes.

The diameter of droplets used in this experiment ranged from 50 to 750 microns; however, most of the data were obtained with only two sizes—approximately 700 microns and 95 microns. Larger droplets can be obtained from a Rayleigh jet, but they are of little interest in meteorological work. It was observed that the jet-breakup invariable consisted of primary droplets interspersed with one, two, or three satellite drops of somewhat smaller size, as predicted by Rayleigh. The size differences between the primary and satellite drops increased with increasing jet diameter. In the case of the 95-micron droplets, the primary and satellite droplets were about the same size as contrasted with a size ratio of 5/1 to 10/1, for millimeter-sized primaries. As a result of a sudden decrease in surface energy and increase in kinetic energy accompanying the breakup, the satellite droplets move faster than the primary (larger) ones with the result that they frequently collide with the droplets ahead. It was such collisions, occurring about 1 to 2 cm below the capillary tip, which were studied.

These collisions are not strictly comparable to the collisions between drops of different sizes within clouds. The relative velocities involved in the experiment exceeded differences in terminal speeds by a considerable margin, a factor which might have tended to inhibit coalescence. In addition, the ambient relative humidity was approximately 50 per cent instead of nearly 100 per cent as in a cloud. These experiments were carried out at a temperature of about 20C.

The lower limit of droplet size in this study was imposed by the resolution of the camera and the pressure required to force water through a capillary of small aperture. Perfectly-clear pictures of 95-micron-diam droplets were obtained on a dark field. Droplets of 50 microns in diam were obtained from a jet using a 30-micron capillary, but it was not possible to photograph them properly. The great pressures needed to force water through the small apertures indicated that the lower limit of the sizes readily obtainable by this method had been reached.

The sizes of the largest droplets were measured directly from the films. However, in the measurements of the effect of electric fields on coalescence, it was necessary to locate the camera beyond the edges of the condenser with the result that it was not possible to size the smaller droplets directly from the film. In these cases, previously established relationships between jet size and droplet size were used.

The electric charges on the droplets were measured as the charge per unit time leaking to ground from a platinum droplet collector. Knowing the droplet size and the mass of water collected, one could compute the *average* charge per droplet. No attempt was made to measure charges on individual droplets (which, of course, represents a serious defect in these data).

The analysis of the films was carried out as follows. The films were projected slowly, and the number of coalescences and the total number of collisions were counted. Noncoalescences resulted in bounce-offs which were easily observed. Over one hundred collisions between droplets could easily be counted in this manner from each 100 ft of film.

3. Results

The coalescence efficiencies of 100-micron satellite droplets colliding with 600- to 790-micron-diam primary drops are shown in table 1.

TABLE 1. Coalescence efficiencies as a function of field strength. Collisions between drops 600 to 790 microns in diam and droplets ca 100 microns in diam.

Field strength volts/cm	Coalescence efficiency	Standard deviation
0.0	29.4	3.1
3.1	33.5	2.4
15.4	88.7	3.6
38.4	95.3	1.6
923.0	0.0	

These results show an increase in coalescence efficiency from approximately 30 per cent in the case of zero electric fields to approximately 100 per cent for fields of about 40 v per cm. At still higher field values, the efficiency again dropped to zero. It is important to note that the maximum coalescence efficiency values occur at field values only about 20 times the fair-weather field and substantially less than observed under thunderstorm clouds.

A similar study was carried out with a jet producing ca 95-micron-diam droplets. These experiments showed collisions with 100 per cent coalescence at fields ranging from 0 to 25 v per cm. At fields above 25 v per cm, the coalescence efficiency quickly dropped to zero, and the droplets recurved to the upper plate.

Measurements of droplet charges were made as a function of droplet sizes and electrical fields under widely differing operating conditions. It was found that negatively charged droplets were produced from an unshielded, grounded water supply, even in the absence of electric fields.[4] Shielding the actual breakup point of the jet and applying negative potential to the top condenser plate reduced the magnitude of these charges, but it did not reverse the sign. However, when the jet breakup point was placed above the upper condenser plate, shielded from stray fields and biased with a positive potential, the jet produced uncharged droplets regardless of the potentials applied to the condenser plates.

Quantitative droplet charges which apply to the coalescence data of table 1 are given in table 2.

Table 2. Measured values of droplet charges obtained with upper plate positive.

Electric field volts/cm	Charges per drop 600 to 650-micron-diam drops	95-micron-diam droplets
0.0	6.3×10^{-6} esu	7.3×10^{-6} esu
3.1	1.0×10^{-3}	4.3×10^{-5}
15.4	5.1×10^{-3}	2.1×10^{-3}
38.4	1.3×10^{-2}	5.3×10^{-3}

4. Discussion

It appears that the observed coalescence-electric field relationship might result from either of two factors: (a) the effect of droplet polarization in the electric field, with the result that approaching droplets present surfaces of opposite charge, or (b) an effect of droplet charge, operating independently of the electric field. Although an effort was made to disentangle these effects, this research has not been completed at the time the work was terminated.

In considering these two possibilities, one is prone to prefer (a) because it appears to fit the observations best. It would appear that the field effect augments coalescence in spite of the repulsion effect which would result from having droplets of like sign. Only when the field reached values in excess of several hundred volts per centimeter were the repulsive forces large enough to prevent coalescence in the case of 100-micron droplets colliding with 650-micron drops.

On the other hand, it was observed that the 95-micron droplets coalesced with very high efficiency even in the absence of electric fields. As far as it is realized, the only essential difference between the two sets of experiments was the higher average charge density on the smaller droplets. If this accounts for the coalescence of the small drops, how can one rule out the possibility that it might be important in the case of the large ones? Further research is needed to settle these questions and to determine the applicability of these findings to cloud-physics problems.

[4] This frequently observed phenomenon is usually attributed to an ordered rupturing of the surface double layer, although Harper [15] has recently taken issue with this explanation, proposing instead a mechanism involving the relative mobility of the H^+ and OH^- ions within the water.

REFERENCES

1. Braham, R. R., Jr., 1956: The physics of precipitation in cumulus clouds. *Geofis. pura e Appl.*, **35**, 126–138.
2. Langmuir, I., and K. B. Blodgett, 1946: *A mathematical investigation of water droplet trajectories.* Army Air Forces Tech. Rep. 5418, Washington D. C.
3. Das, P. K., 1950: The growth of cloud droplets by coalescence. *Indian J. Meteor. and Geophys.*, **1**, 137.
4. Langmuir, I., 1948: The production of rain by a chain reaction in cumulus clouds at temperatures above freezing. *J. Meteor.*, **5**, 175–192.
5. Pearcey, T., and G. W. Hill, 1957: A theoretical estimate of the collection efficiencies of small droplets. *Quart. J. r. meteor. Soc.*, **83**, 77–92.
6. Hocking, L. M., 1959: The collision efficiency of small drops. *Quart. J. r. meteor. Soc.*, **85**, 44–50.
7. Telford, J. W., N. S. Thorndike, and E. G. Bowan, 1955: The coalescence between small water drops. *Quart. J. r. meteor. Soc.*, **81**, 241–250.
8. Schotland, R. M., 1957: *Droplet collision efficiency.* Final Rep., Contract AF 19(604)–993, Dept. Meteor. and Oceanog., New York Univ.
9. Schotland, R. M., and E. J. Kaplin, 1956: *The collision efficiency of cloud droplets.* Sci. Rep. 1, Dept. Meteor. and Oceanog., New York Univ.
10. Levin, L. M., 1954: The coalescence of charged cloud drops. *Doklady Akad. Nauk U.S.S.R.*, **95**, 467–470.
11. Rayleigh, Lord (J. W. Strutt) 1878: *Theory of sound.* London, Macmillan & Co. (reprinted Dover 1945), 302 pp.
12. Sartor, D., 1954: A laboratory investigation of collision efficiencies, coalescence and electrical charging of simulated cloud droplets. *J. Meteor.*, **11**, 91–103.
13. Gunn, K., and W. Hitschfeld, 1951: A laboratory investigation of the coalescence between large and small water-drops. *J. Meteor.*, **8**, 7–16.
14. Kinzer, G. D., and W. E. Cobb, 1956: Laboratory measurements of growth and of the collection efficiency of raindrops. *J. Meteor.*, **13**, 295–301.
15. Harper, W. R., 1957: The generation of static charge. *Philosoph. Mag.*, **6**, 365–317.