Direct measurements of coalescence efficiency and frequency of small water droplets in an electric field

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ABSTRACT

Small water droplets with diameter $d \leqslant 8$ μm are allowed to fall in a settling chamber in the presence of a quasi-uniform electric field varying from zero to 600 V/cm. The trajectories of these droplets are photographically recorded through an incident-light microscope with dark field illumination. Results from 2 000 photographs, each one containing about 25 droplet pairs, show that the coalescence efficiency is almost unity. The coalescence frequency is almost zero in the absence of an electric field and increases rapidly at fields stronger than 400 V/cm. The coalescence frequency increases about linearly with electric fields from 100 to 400 V/cm. A survey of coalescences of droplets with parallel trajectories gives some order of magnitude for the collision efficiency, which indicates that the influence of the electric field is very pronounced for small droplets.

Introduction

The growth of water droplets in a cloud takes place not only by condensation of water vapour on these droplets but also as a result of the fusing or coalescence of droplets. In the modern concept of droplet growth by coalescence, it is necessary to separate the collision from the coalescence in two steps of the capture or collection phenomena, because of the possibility that colliding droplets might "bounce-off" instead of coalescing. In order for one droplet to come in contact with a large droplet, its centre must pass within a critical area. The radius of this cross-sectional area is the largest initial horizontal separation x of the falling droplet centres for which the droplets just make contact, and is taken as a measure of their collision cross section. The collision efficiency ε is defined as the square of the ratio of this separation x to the radius R of the large droplet, i.e. $\varepsilon = (x/R)^2$. The coalescence efficiency K is the percentage of fraction of colliding droplets which merge to form a larger drop. The product of ε (collision efficiency) and K (coalescence efficiency) is called collection efficiency.

Collision efficiency

Hocking (1959) was the first author to obtain the collision efficiency of droplets pair by computing the grazing trajectories of droplets while subjected to gravitational and aerodynamical forces. The results show that ε varies from 0 to 1.5 for droplets radii between 19 μm and 30 μm. An extension of Hocking's solution for droplets smaller than 19 μm was obtained by Davis & Sartor (1969), their results show that the collision efficiency of 8 μm droplets and 5 μm droplets is about 5×10^{-2}, thus small but not zero.

Computations of electric field influence on droplet collision efficiency have been made by several workers, especially by Krasnogorskaja (1965), Plumlee & Semonin (1965), and Sartor (1967). Krasnogorskaja (1965) predicts that two uncharged droplets of radius 15 μm and 25 μm having a collision efficiency of about 0.8 in the absence of a field, will attain values of 1.6, 5.2 and 8.4 in a vertical electric field strength of 2, 6, 10 KV/cm respectively. If the radii of the uncharged interacting droplets are reduced to 8 μm and 10 μm, the collision efficiencies are found to increase more rapidly, from zero in the absence of a field to unity at a field strength of about 500 V/cm and approximately 4 at 1 000 V/cm. Sartor's theoretical results (1967) show that collision efficiency of a droplet pair of 8 μm in radius is about 8×10^{-2} at zero field and increases to 100 at field strength of 11 e.s.u. (3.3 KV/cm). Plumlee & Semonin

(1965) found that the collision efficiency of a 50 μm radius drop with a 10 μm droplet increases by a factor of about 1.3 when the horizontal field is changed from 0 to 3 600 V/cm, while in the same range of field strength the collision efficiency increases by a factor of 34.5 for the 30 and 5 μm droplet pair.

The calculations of these various workers demonstrated that collision efficiencies of droplets are increased with increased external electric field and, in general, the influence of the electric field is more pronounced for smaller droplets, particularly for droplets of radius smaller than 20 μm. In spite of this possibly important role of the electric field these excellent theoretical studies, to our knowledge, have not been verified by detailed laboratory measurements of droplet collision efficiency in the presence of an electric field.

Coalescence of water droplets

When two drops collide with each other, several things must happen before they can coalesce. The air between the two drops must be expelled so that their surfaces can come into contact, the surface-structure must be destroyed over the area of contact in order that the drops can actually join, and then they form a single larger drop. These two steps represent the principal obstacles to the coalescence. However, the first obstacle may be negligible for the small droplets because of their small size.

Laboratory measurements of coalescence efficiencies are performed mostly for large drops and the results generally do not agree. The experiments of Gunn & Hitschfeld (1951) and those of Telford et al. (1955) show that the coalescence efficiency must approach unity over a considerable range of droplet sizes (diameter > 100 μm). Goyer et al. (1960) found that the coalescence efficiency between 700 μm diameter droplets is less than 30% in the absence of a field. With a field strength of 40 V/cm, the coalescence efficiency becomes about 100%, while the coalescence efficiency is reduced to zero at 923 V/cm. More recently Montgomery (1971) has shown that coalescence efficiency is about 0.5 for drops of $0.5 < d < 2$ mm diameter colliding in an electric field of 70 V/cm.

For small droplets, Telford & Thordike (1961) have observed that coalescence efficiency of uncharged droplets 30 and 35 μm in diameter was zero in a field of 150 V/cm and only about 0.2 in fields between 1 KV/cm and 3 KV/cm. Woods & Mason (1964) in an experimental determination of collection efficiencies for small water droplets in air come up with a different opinion. These authors mentioned in their discussion that: "the fairly good agreement between the experimentally determined collection efficiencies and the computed collision efficiencies, at least for values of $r/R > 0.1$, suggests that the coalescence efficiency for drops of $R < 60$ μm is practically unity". Finally, Krasnogorskaja computation (1965) indicates that strong electric fields may cause the coalescence of very small droplets whose sizes belong to the region where the collision efficiency due to gravitational and hydrodynamic forces is zero.

In the present experiment, we have photographed the collisions of uncharged small droplets ($d \leqslant 8$ μm) in a vertical uniform electric field varying from 0 to 600 V/cm, with the purpose of verifying wether the electric field influences the collision, or the coalescence efficiencies, or both of them.

Experimental procedure

Small water droplets, produced by an ultrasonic nebulizer, are introduced in a cloud chamber of about 0.5 m^3, communicating with a settling chamber where two smooth edge electrodes are horizontally suspended by Plexiglas rods. The electrode separation is 8 cm. A low power incandescent lamp (15 watts) was used to illuminate a 45° angle inclined ring mirror which combines with a condenser to perform a dark field (Fig. 1). The light beam is reflected from the focus point 0 through a low power microscope to a 35 mm camera. The total magnification of the system "camera-microscope" is 22.3. A second condenser-objective system is located in the opposite side of the focus point 0 to compensate for the electric field distortion caused by the first system. With this symmetrical geometry, the lines of force in the central plane, i.e. the focal plane of the microscope, are straight lines and hence a quasi-uniform field is obtained in the photo-

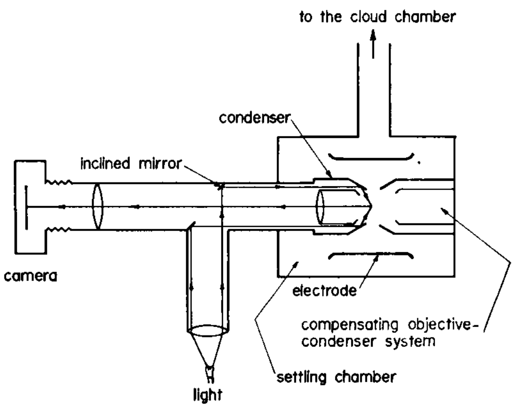

Fig. 1. Schematic diagram of experimental set-up.

graphed region. (Note that the water droplets produced by the ultrasonic nebulizer may not all be neutral. Our system of electrodes is not only used to produce a vertical electric field but serves also to filtrate the charged droplets. Indeed, before they are allowed to fall in the focal plane of the microscope, the droplets must pass through the electric fields of the electrodes and hence the charged droplets will be displaced out of the photographed region. To be sure of this neutrality of droplets we have employed the method used by Phillips & Kinzer (1957) in their investigation of charged cumuliform cloud droplets to check the presence of charged particles.) At the start of an experiment, the cloud chamber is carefully humidified, fog droplets are introduced and allowed to fall under the influence of gravity to the settling chamber. After having disconnected the aerosol generator from the cloud chamber, with the purpose of keeping turbulence at a minimum, 2 minutes elapsed before the application of the electric potential between the electrodes, droplet trajectories were then photographically recorded. In order to keep a uniform droplet concentration, only six pictures were taken in a total time of about 30 sec. The droplets were then reintroduced before another run. This precaution is particularly important at high field (⩾ 300 V/cm), because the short precipitation time of small droplets (Phan-Cong & Jordan, 1969). For each value of the electric field, 300 negatives of Kodak 2485 film were taken (Kodak 2484 and Tri-X are very good too), and only the negatives having approximately the same sharpness and droplets concentration were considered acceptable. These were enlarged 10 times for collision observation. The negatives were reexamined a second time through a stereomicroscope with transmitted light, and the width of the sharp trajectories were measured which yields the droplet diameter. Our negatives contain about 50 droplets each, during the recording time (30 sec) this value remained appreciably unchanged. The working (photographed) volume is about 2.36 ×

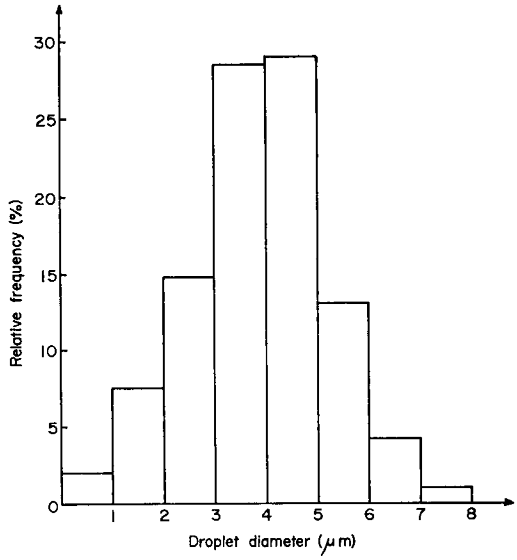

Fig. 2. Frequency distribution of 574 droplets ($E = 0$).

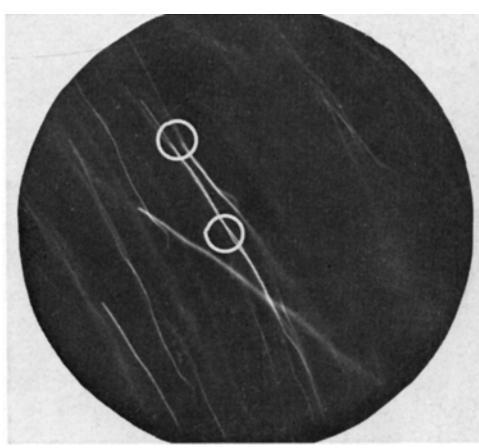

Fig. 3. Elastic collision at 400 V/cm: the droplets bounce apart after collision.

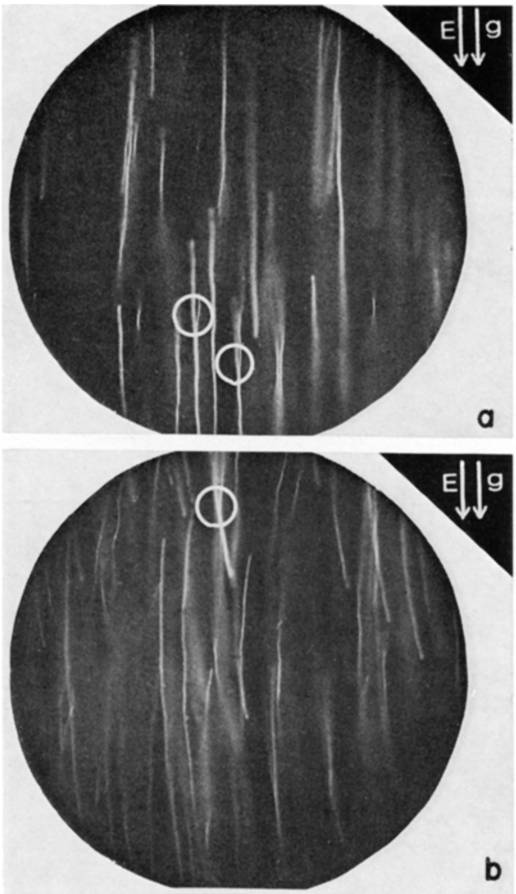

Fig. 4. Coalescence: (*a*) parallel trajectory droplets: $E = 200$ V/cm; $d_1 = 6$ μm, $d_2 = 2$ μm (left); $d_1 = 5$ μm, $d_2 = 2$ μm (right); (*b*) non-parallel trajectory droplets: $E = 400$ V/cm; $d_1 = 4$ μm, $d_2 = 4$ μm.

10^{-2} mm^3, thus the droplet concentration is 2.12×10^6/cm^3. Fig. 2 shows the droplet diameter spectrum.

Results and discussions

1. *The coalescence efficiency*

Examination of droplet trajectories exhibits two different cases:

Elastic collision (Fig. 3). The two droplets seem to have come in contact and then separated by a "bounce"; they seem to have two successive bounce-offs. In this photograph, the droplet cloud is not tranquil; the path of the particles is not vertical.

Coalescence. Fig. 4*a* shows coalescences of parallel trajectory droplets whilst fusing of non-parallel trajectories are shown in Fig. 4*b*. We observe that coalescence between a small and a large drop does not change the direction of the latter; this situation, however, is quite different (Fig. 4*b*) for droplets of nearly equal size.

For a total of 125 collisions, only two of them are elastic collisions and hence the coalescence efficiency for these small droplets in the presence of the electric field is almost unity (123/125).

2. *Influence of the electric field upon the frequency of droplet coalescence*

Fig. 5 shows the number of coalescence counted for 2 500 droplet pairs on 100 acceptable negatives.

The most probable curve has been drawn through the experimental data. The number of coalescences increases faster at high fields; observations made in the range of 600 to 1 000 V/cm indicate a very large number of coalescences taking place so rapidly upon application of field that they could only be observed visually.

Coalescence frequency, defined as the number of coalescences per unit volume, per second, can be calculated directly from the number of coalescences taking place over one-third of a second (the exposure time) in the working volume, 2.36×10^{-2} mm^3. The coalescence frequencies—thus proportional to the number of coalescences plotted in Fig. 5—at different fields are reported in Table 1 with a mean concentration of 2.12×10^6 droplets per cm^3.

Furthermore, after the definition of the

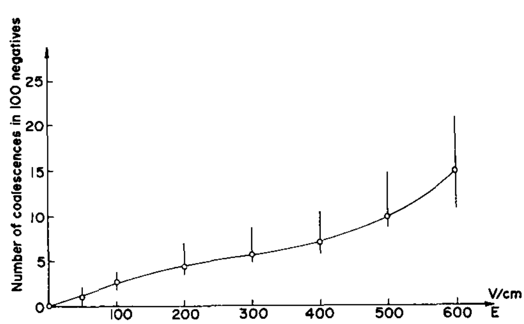

Fig. 5. Number of coalescences counted on 100 negatives (2 500 droplet pairs) versus vertical electric field.

Table 1.

E(V/cm)	0	100	200	300	400	500	600
Coalescence frequency (cm^{-3} sec^{-1})	0	3 800	5 100	7 600	8 900	12 700	19 200

collision efficiency ε (see Introduction), the number of collisions between two droplet populations of radius and concentration r_1, n_1 and r_2, n_2 respectively ($r_1 > r_2$), during the time dt is

$$dw = \varepsilon\, \pi r_1^2 (v_1 - v_2)\, n_1\, n_2\, dt$$

where $v_1 - v_2$ is relative speed of droplets. And the coalescence rate or coalescence frequency

$$\frac{dw_c}{dt} = \frac{dw}{dt} K = \varepsilon K \pi r_1^2 (v_1 - v_2) n_1 n_2$$

is thus proportional to the collection efficiency (εK), or simply to the collision efficiency $\varepsilon(K = 1)$.

3. *The collision efficiency*

Observation of droplet parallel trajectories prior to the collision permits the computation of the collision efficiency. By the collision efficiency definition, the limit trajectories of the droplets colliding with a larger droplet must be found, i.e. the largest distance between the colliding droplet trajectories and the trajectory of the large droplet. This distance must be measured far away from the contact point. In order to obtain this largest distance a considerable number of photographs containing collisions with parallel droplet trajectories must be used. Table 2 shows the order of magnitude of the collision efficiency of some droplet pairs. The exact collision efficiency may be higher than the values indicated in this table because of the scarcity of the parallel trajectory collisions obtained.

From the values indicated in Table 3 we observe that:

For a given droplet pair, tth collision efficiency increases with the electric field.

At the same field strength: (*a*) the collision efficiency is maximum for quasi equal size droplets, (*b*) the collision efficiency of a smaller pair of droplets is higher than that of a larger pair.

Our results (Table 2), obtained with droplets of a smaller size in a weaker field when compared with the values used by Sartor and Krasnogorskaja, give an order of magnitude of the collision efficiency comparable to these two authors' results.

Table 2.

Field (V/cm)	Droplet 1 (diameter, μm)	Droplet 2 (diameter, μm)	Order of magnitude of the collision efficiency [$\varepsilon = (x/R)^2$]
100	7.5	7.5	9
200	7.5	7.5	16
200	5	5	18
200	3.5	3.5	16
300	3.5	5	18
400	3.5	3.5	25
400	5	7.5	25

Table 3.

Author	$d_1(\mu m)$	$d_2(\mu m)$	E(V/cm)	Collision efficiency
Plumlee & Semonin (1964)	10	60	400	0.08
	24	60	400	0.45
Krasnogorskaja (1965)	30	50	600	0.931
	16	20	500	1
	16	20	1 200	4.599
Sartor (1967)	16	16	0	0.08
	12	16	3 300	17
	16	16	3 300	100

Conclusions

1. The coalescence efficiency is almost unity for small droplets ($d \leq 8$ μm) at field strengths from 0 to 600 V/cm.

2. The coalescence frequency is almost zero in the absence of an electric field, and increases about linearly with electric field. At fields higher than 400 V/cm, the coalescence frequency increases with field at an increasing rate.

3. For small droplets between 3.5 and 7.5 μm in diameter, the order of magnitude of the collision efficiency is in agreement with the theoretical computations of Sartor and Krasnogorskaja.

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ПРЯМЫЕ ИЗМЕРЕНИЯ ЭФФЕКТИВНОСТИ И ЧАСТОТЫ СЛИЯНИЯ МАЛЕНЬКИХ КАПЕЛЬ ВОДЫ В ЭЛЕКТРИЧЕСКОМ ПОЛЕ

Прослеживалось падение маленьких капель воды с диаметром меньше 8 *мкм* в специальной камере в присутствии квазиоднородного электрического поля, менявшегося от нуля до 600 *в/см*. Траектории капель регистрировались фотографически с помощью темнопольного микроскопа. Результаты 2 000 фотографий, каждая из которых содержит около 25 пар капелек, показывают, что эффективность слияния почти равна единице. Частота слияния близка к нулю в отсутствие электрического поля и быстро растет при полях, сильнее 400 *в/см*. Частота слияния растет примерно линейно с ростом поля в интервале от 100 до 400 *в/см*. Изучение слияния капель с параллельными траекториями дает возможность определить порядок величины эффективности столкновений, что указывает на существенное влияние электрического поля на поведение маленьких капель.