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An experimental investigation of the influence of electric field on the collision–coalescence of water drops

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ABSTRACT

Laboratory experiments were conducted on the collision–coalescence of pairs of water drops of equal size, in two oil media (kerosene and mustard), with and without external vertical electric field (F). The radii of the water drops used were in the range 1.6 to 1.7 mm and the external electric field varied from 0 to 375 V cm^{-1}. Collision frequencies were determined for various combinations of mean lateral (X) and mean vertical (Z) separations of the drop pairs as fixed combinations of X and Z could not be reproduced in any given set of experiments due to the limitations of the mechanical set up of the apparatus.

The collision frequency (E) for any given initial values of X and Z decreased with F up to a certain value of F and thereafter increased. The variations observed in the collision frequency under different external electric fields have been explained quantitatively based on the electrostatic theory of polarization charges. The vertical distance travelled by the pair of drops prior to a collision was less with the external electric field. For collision to occur at a fixed depth (d), the values of Z increased with F when X was zero. For the same initial conditions, collision took place earlier in kerosene than in mustard oil medium.

The collision efficiency (E_x), computed from the measured values of the radius of the collision-cross-sectional area, was less in the presence of external electric field. The drops did not coalesce without the external electric field. The coalescence frequency (E_c) increased with F. The field values for 100% coalescence were lower in mustard oil as compared to those in kerosene. The path length between collision and coalescence events sharply decreased with increase of F. The collection efficiency was zero without external electric field and it increased with F. In the case where the collected drop was slightly smaller than the collector drop the collection efficiency was more compared to that when the drops were of equal size.

1. Introduction

There exists a gap in the knowledge of the role of atmospheric electrical forces on cloud microphysics. Study of the influence of electric forces on the collision–coalescence of water drops will be rewarding for the physical understanding of rainformation in clouds and their modification. Results of laboratory and theoretical investigations on the collision and coalescence of cloud drops have been reported (Sartor, 1954; Beard and Pruppacher, 1968; Dayan and Gallily, 1975; Schlamp et al., 1976; Cohen and Gallily, 1977). Also, the influence of the wake effect on the collision and coalescence of equal size drops has been studied experimentally (Cataneo et al., 1970). The wake effects behind the collector drop can produce values of collision efficiency greater than unity (Wallace and Hobbs, 1977). The collection efficiency of nearly equal size drops has been found to be large (Abbot, 1974) even for drops as small as 25 μm radius.

There is no satisfactory agreement between the theoretically calculated collision–coalescence efficiencies and the experimental values (de Almeida, 1977). Unsatisfactory simulation of the flow field in the air surrounding the moving water drop is considered to be mainly responsible for the higher order magnitude of discrepancy in the theoretically computed collision efficiencies (Lin and Lee, 1975). Theoretical studies indicate that the vertical distance to be travelled in air by a pair of drops of approximately equal size is very long before the collector drop can catch up with the

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Table 1. *Details of simulated cloud and drizzle drops*

Experimental drop radius (mm)	Simulated drop radius at 900 mb and 20 °C	Experimental conditions				Drop terminal velocity cm s^{-1}			Vertical path length of the simulated atmosphere (metres)
		Oil medium	Temp. (°C)	Density (g cm^{-3})	Viscosity (poise)	Oil medium	Simulated atmosphere	Reynolds number	
1.71	0.5575 mm	Kerosene	27	0.788	0.0118	13.0	454.0	297.0	35
1.61	32 μm	Mustard	25	0.910	0.7116	1.1	11.7	0.44	11
1.61	37 μm	Mustard	30	0.910	0.5851	1.3	15.0	0.65	11
1.61	43 μm	Mustard	35	0.910	0.4777	1.6	19.4	0.97	12

Note: Simulated drop radii were computed using the method described by Beard and Pruppacher (1969). The terminal velocity values were determined experimentally.

collected drop. Although this particular condition exists often in nature, conventional laboratory apparatus is limited by its physical dimensions and prevents this phenomenon from being experimentally observed.

The present authors have conducted laboratory experiments to study the influence of electric field on the collision–coalescence of a pair of water drops in two different oil media in order to simulate qualitatively the behaviour of cloud and drizzle drops (Sartor, 1954). The details of simulated drop sizes, their terminal velocities and Reynolds numbers used in the experiments are given in Table 1. The simulation of cloud and drizzle drops in air medium was attempted by matching the characteristics of isolated water drops in oil media.

The simulated conditions of collision–coalescence in the present experiments differ from the natural conditions existing in the atmosphere. The requirements for the dynamical similarity of cloud droplets in air are partially achieved in the laboratory experiments. The differences in the ratios of the densities of water drops to oil and to air are the major sources of error. The results obtained from the present experiments cannot therefore provide independent values of collision efficiency. However, they can reveal many aspects of the influence of the external electric field on the collision and coalescence of water drops since electrostatically the case of cloud droplets in air and that of water drops in oil are similar (Sartor, 1954). Also, the difference in the dielectric constants of water and air is greater than that of water and oil and therefore the polarization will be more effective in the case of the cloud droplets in air. The results of the present study are described below.

2. Experimental set up

The experiments were carried out in a vertical rigid chamber of size 17 × 17 × 100 cm made of perspex sheet. The chamber was well insulated and two parallel copper plates were fitted one at the top and the other at the bottom. The bottom plate was maintained at positive potential with respect to the upper plate which is grounded through the negative terminal of a variable 50 kV d.c. power supply. The apparatus walls were perfect insulators and all the possible care was taken to keep them free from moisture. No electric charges were built up on the apparatus walls. Two scales graduated in centimetres were fitted to the front wall, one in the vertical and the other in the horizontal position, for measuring the lateral (X) and vertical (Z) separations between the pairs of drops. Suitable illumination arrangement for the experimental chamber was provided with intense light sources and reflectors.

A series of experiments were conducted in two different media by filling the chamber with mustard oil or kerosene oil. The oil medium was maintained still and without any air bubbles during the experiments. Experiments in the kerosene oil medium were conducted at 27 °C and in mustard oil medium at 25, 30 and 35 °C. The maximum variation in the oil temperature for a given set of experiments was ±1 °C. Pairs of water drops were released with a suitable drop releasing device consisting of two glass syringes and hypodermic needles. The hypodermic needles were maintained vertically parallel to the front wall of the experimental chamber. The lateral and vertical separations between the drops of each pair could be altered by making suitable adjustments in the drop releasing device. For a given series of experiments various combinations of X and Z and external electric field values ranging from 0 to 375 V cm^{-1} were used. As far as possible, care was taken to release the drops under identical conditions for any given set of experiments. Most of the experiments were performed with a pair of drops of approximately equal size. Limited experiments were also conducted using pairs of drops of unequal size.

The drop sizes were measured frequently during the experiments. The sizes were determined by weighing a known number of drops collected in the oil medium under conditions similar to those in the experiments. The radii of the drops used were in the range 1.6 to 1.7 mm. The maximum variation in the diameter of equal size drops used in any given set of experiments was estimated to be 10%. The terminal velocities of the two drops in a given medium were periodically measured and found to be steady during their fall in the experimental chamber. This observation and the absence of build up of electric charges on the walls indicate that no inhomogeneities in the electric fields were present during the experiments.

For each experiment, a series of photographs of the drop pair starting from the time of release and through their travel in the whole path length in the oil medium of the experimental chamber were taken using a 35-mm Canon camera arrangement. The depth at which the pair of water drops attained terminal velocity in the oil medium was determined by measuring the fall velocity at frequent intervals starting from the time of release of the drops. After the drops attained terminal velocity, the initial X and Z values were evaluated from the sequence of photographs taken during any single experiment. Visual observations of collision and coalescence events were also made during the experiments. From these measurements the trajectories of the pair of drops were obtained. The maximum error in X and Z due to the deviations of the positions of the drops during their fall path was estimated to be about 4%. For any given set of initial experimental conditions the drop trajectories were expected to be reproducible. However, in the present experiments some deviations were noticed which could be attributed to the possible errors in the experimental set up described above.

3. Results and discussion

3.1. *Influence of electric field on drop collision*

Series of experiments were conducted in the two oil media using pairs of equal size drops. During these experiments different combinations of (i) initial lateral separation (X) (ii) initial vertical separation (Z) were used and the values of depth of collision (d) for F values ranging from 0 to 375 V cm^{-1} were noted. The distance travelled by the pair of drops from the point where they attain terminal velocity, to the point of their collision was considered as the depth of collision. During the experiments, for certain limiting values of X and Z, collision of the drops occurred. For higher values of X and Z, however, the drops reached the bottom before collision. In the present study, data relating to the experiments with values of X and Z not exceeding the above limits were considered. The cases where collision did not occur within the above limits of X and Z, were considered only for obtaining collision frequencies (Section 3.7).

3.2. *Lateral separation* (X)

The maximum initial lateral separation (X_{max}) overcome for collision to take place within the vertical fall length of the experimental chamber was determined for different F values and for fixed initial vertical separation (Z). The collision efficiency (E_x) computations were made using the following relation (Wallace and Hobbs, 1977):

$$E_X = \frac{(X_{max})^2}{(R + r)^2} \tag{1}$$

where

X_{max} = radius of the collision-cross-sectional area
R = radius of the collector drop
r = radius of the collected drop

The values of E_X were obtained for different fields for water drops in the two oil media. The collision efficiency (E_X) was less by 30–40% in the presence of external electric field. This could be due to the polarization of the drops in the external electric field and the consequent repulsion between like poles. The charges induced by polarization on two drops with a lateral separation might given rise to repulsion of the drops when the force of repulsion exceeds the force of attraction. An attempt has been made to theoretically evaluate the effect of polarization charges on the collision of drops (Section 3.5). The values of E_X, without external electric field, in mustard and kerosene oil media respectively are 0.64 and 7.0. The values of E_X obtained for water drops in mustard oil are in agreement with the theoretically computed values of collision efficiency for cloud drops (Wallace and Hobbs, 1977; Cataneo et al., 1971; Schlamp et al., 1976). The higher values of E_X for water drops in kerosene, exceeding unity could be attributed to the enhanced wake effect (Wallace and Hobbs, 1977).

3.3 *Vertical separation* (*Z*)

In the case of experiments with mustard oil, the initial vertical separation (*Z*) overcome for different *F* values for collision to take place at a fixed depth of 225 experimental drop diameters was determined with $X = 0$. The value of *Z* was 8.7 drop diameters when *F* was zero. It increased by a factor of 1.11 when the value of *F* was 230 V cm^{-1}.

3.4. *Depth of collision* (*d*)

The values of the depth of collision (*d*) for given *X*, *Z* and *F* combinations were determined. For the experimental conditions of $F = 0$, $X = 0$ and $Z = 7.8$ drop diameters, the value of "*d*" in mustard oil was 210 drop diameters. Similarly, for $F = 0$, $X = 0.1$ and $Z = 7.8$ drop diameters, the value of "*d*" in kerosene oil was 113 drop diameters. The value of *d* decreased with increase in *F*. It decreased by a factor of 0.8 and 0.6 respectively for water drops in mustard and kerosene oil media when *F* increased from 0 to 300 V cm^{-1}. The decrease in *d* with increase in *F* was less marked for higher values of *X*. The results in Sections 3.3 and 3.4 suggest higher probability of collision between the drops in the presence of external electric field. This could be due to the attraction of unlike poles induced by polarization. Within the range of influence of these polarization charges the terminal velocities of the drops might be affected. For larger values of *X* considered the above effect would be small.

3.5. *Forces of attraction/repulsion between a pair of uncharged drops in the electric field*

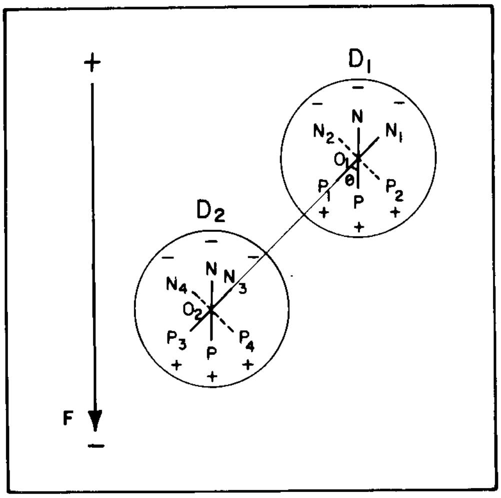

Fig. 1. A pair of uncharged drops D_1 and D_2 in an electric field *F*.

The forces acting between a pair of uncharged water drops under the influence of external electric field can be computed using the method described below. Consider a pair of equal size drops D_1 and D_2 (Fig. 1) with radius *r* and with a small vertical and lateral separation, falling freely in a uniform vertical field of intensity *F*. The line joining the centres of the two drops at any instant is $O_1 O_2$ and its length is *d*. The angle between the external electric field and the line connecting the centres of the drops is θ. The water drops in air or in the oil medium may be considered as spherical conductors in a vacuum. The drops get polarized due to the presence of the external electric field. The upper hemisphere of each drop acquires a negative charge (N) and the lower hemisphere an equal positive charge (P). Each drop may be considered to be equivalent to dipole NP as shown by thick line in the figure. The dipole moment (*M*) of each drop can be expressed as follows (Hutchinson, 1942).

$$M = F r^3 \tag{2}$$

The forces of attraction and repulsion between the two dipoles can be computed following the method described below.

Each dipole moment *M* can be resolved into two components (i) $M \cos \theta$ along $O_1 O_2$ and (ii) $M \sin \theta$ perpendicular to $O_1 O_2$. The resolved components $N_1 P_1$ and $N_2 P_2$ due to D_1 and $N_3 P_3$ and $N_4 P_4$ due to D_2 are also shown in the figure. It is seen from the figure that the pair of dipoles $N_1 P_1$ and $N_3 P_3$ each with the moment $M \cos \theta$ are in the same line along $O_1 O_2$ while the dipoles $N_2 P_2$ and

N_4P_4 each with the moment $M\sin\theta$ are parallel to each other and perpendicular to O_1O_2. The distance between the centres of any pair of dipoles is "d". The force of attraction (f_a) exerted by N_3P_3 on N_1P_1 is directed from O_1 to O_2 and is given by

$$f_a = \frac{6M^2\cos^2\theta}{d^4} \tag{3}$$

The force of repulsion (f_r) exerted by N_4P_4 on N_2P_2 is directed from O_2 to O_1 and is given by

$$f_r = \frac{3M^2\sin^2\theta}{d^4} \tag{4}$$

Hence the net force of repulsion (f_R) between the dipoles of D_1 and D_1 is given by

$$\begin{aligned} f_R &= f_r - f_a \\ &= \frac{3M^2}{d^4}(\sin^2\theta - 2\cos^2\theta) \\ &= \frac{3M^2}{d^4}(1 - 3\cos^2\theta) \end{aligned} \tag{5}$$

In the above cases the dipole of D_1 affects the potential of D_2 and vice versa. Hence it is necessary to have image dipoles of suitable strength corresponding to each of the dipoles of D_1 and D_2. It may be shown that the strengths of the images of the dipoles N_1P_1, N_2P_2, N_3P_3 and N_4P_4 are respectively $-(M\cos\theta)\,r^3/d^3$, $-(M\sin\theta)\,r^3/d^3$, $-(M\cos\theta)\,r^3/d^3$ and $-(M\sin\theta)\,r^3/d^3$.

The images of N_1P_1 and N_2P_2 are situated at distances r^2/d from O_2 along O_2O_1 while the images of N_3P_3 and N_4P_4 are situated at distances r^2/d from O_1 along O_1O_2. In the present case the forces due to further images of doublets are neglected. The total force of attraction (F_a) due to each of the dipoles N_3P_3 and N_1P_1 and their respective images is given by

$$F_{a_1} = 2\times 6M\cos\theta\times M\cos\theta\times\frac{r^3}{d^3}\times\frac{1}{(d-r^2/d)^4} \tag{6}$$

Similarly, the total force of attraction due to each of the dipoles N_4P_4 and N_2P_2, and their respective images is given by

$$F_{a_2} = 2\times 3M\sin\theta\times M\sin\theta\times\frac{r^3}{d^3}\times\frac{1}{(d-r^2/d)^4} \tag{7}$$

Hence the total force of attraction due to each of the four dipoles N_1P_1, N_2P_2, N_3P_3 and N_4P_4 and their respective images is obtained by combining eqs. (6) and (7) and can be written as follows:

$$\begin{aligned} F_A &= 2\left[\frac{6M^2\cos^2\theta}{(d-r^2/d)^4}\times\frac{r^3}{d^3}+\frac{3M^2\sin^2\theta}{(d-r^2/d)^4}\times\frac{r^3}{d^3}\right] \\ &= \frac{6M^2r^3(1+\cos^2\theta)}{d^3(d-r^2/d)^4} \end{aligned} \tag{8}$$

The resultant force of repulsion between the two drops D_1 and D_2 is obtained by subtracting eq. (8) from eq. (5) and can be written as follows:

$$\begin{aligned} F_R &= f_R - F_A \\ &= \frac{3M^2}{d^4}(1-3\cos^2\theta) - \frac{6M^2r^3}{d^3(d-r^2/d)^4}\times(1+\cos^2\theta) \\ &\approx \frac{3M^2}{d^4}\left[1-3\cos^2\theta-\frac{2r^3}{d^3}(1+\cos^2\theta)\times\left(1+\frac{4r^2}{d^2}\right)\right] \\ &= \frac{3M^2}{d^4}\left[1-\cos^2\theta\left\{3+\frac{2r^3}{d^3}\left(1+\frac{4r^2}{d^2}\right)\right\}-\frac{2r^3}{d^3}\left(1+\frac{4r^2}{d^2}\right)\right] \end{aligned} \tag{9}$$

Let X_l and Z_l represent the lateral and vertical separations between two drops D_1 and D_2 measured along the horizontal and vertical directions respectively at any instant. The values of X_l and Z_l are expressed in units of experimental drop diameters. Let $X_l = 2r\times C_1$ and $Z_l = 2r\times C_2$ where C_1 and C_2 are constants. Hence

$$\begin{aligned} d &= \sqrt{X_l^2+Z_l^2} \\ &\doteqdot 2r\sqrt{C_1^2+C_2^2} \end{aligned} \tag{10}$$

Using the above relation eq. (8) may be expressed in terms of the lateral and vertical separations and in terms of C_1 and C_2 as follows:

$$F_R = \frac{3M^2}{16r^4(C_1^2 + C_2^2)^2}\,[1 - (\cos^2\theta)(3 + A) - A] \tag{11}$$

where

$$A = \frac{1}{4(C_1^2 + C_2^2)^{3/2}} + \frac{1}{4(C_1^2 + C_2^2)^{5/2}}$$

The highest value of A will be 0.49 when $C_1 = 1.0$ and $C_2 = 0.1$. For the above case the force of repulsion between the two drops D_1 and D_2 becomes zero when θ is approximately equal to 68° or 112° (eq. 11). In other words, when the value of θ lies between 68° and 112° the drops of the pair experience mutual repulsion due to the polarization charges. Thus for any given value of A the limiting angles (θ_1 and θ_2) between which the drops of the pair experience a force of repulsion can be computed from the following equations:

$$\cos^2\theta = \frac{1 - A}{3 + A} \tag{12}$$

or

$$\left.\begin{aligned} \theta_1 &= \cos^{-1}\left(\sqrt{\frac{1-A}{3+A}}\right) \\ \theta_2 &= \cos^{-1}\left(-\sqrt{\frac{1-A}{3+A}}\right) \end{aligned}\right\} \tag{13}$$

From eq. (11) it may be seen that the force of attraction between the drops of the pair will be maximum when $\theta = 0°$ and similarly the force of repulsion will be maximum when $\theta = 90°$. For any given values of X and Z, other conditions remaining the same, there will be a force of attraction between the drops of the pair for values of $\theta_1 > \theta > \theta_2$. Under the above conditions, due to the force of attraction, the upper drop D_1 will be accelerated towards the lower drop D_2 and results in a decrease of X and Z values. During the course of descent of the upper drop D_1, if the condition $\theta_1 > \theta > \theta_2$ is maintained, there will be a force of attraction between the drops of the pair and the drops will collide, other conditions being favourable.

The larger the external electric field (F) the smaller the values of X as compared to Z, the sooner X will approach zero (i.e. $\theta = 0°$) and the collision of the drops of the pair would facilitate due to the attractive forces of the polarization charges. For certain combinations of X and Z and external field values the forces of attraction between the drops due to polarization may be weak and in such cases the acceleration of the upper drop D_1 towards D_2 will be less in magnitude. Under such conditions, before D_1 approaches D_2 and when θ exceeds θ_1, mutual repulsion of the drops of the pair results and the drops do not collide. Similarly, for given X and Z values, by increasing the external field it would be possible to maintain the condition $\theta < \theta_1$ throughout the fall-path of the upper drop D_1 so that collision takes place.

The above two conditions could be present in the present laboratory experiments conducted as seen in Fig. 3 where for certain X and Z values there was a decrease in collision frequency up to a certain value of the external field F beyond which the collision frequency again showed an increase. Thus the results of Fig. 3 are consistent with the theory presented above.

3.6. *Limits of lateral (X) and vertical (Z) separations for divergence of drops*

During the experiments the drops used to diverge horizontally without colliding for certain limiting values of X when Z is small. In the case of equal size drops, the limiting values of various combinations of X and Z for drop divergence were determined for different F values. The limiting values of the combination of X and Z increased with increase of F up to 200 V cm^{-1} and decreased thereafter. The decrease noticed at higher values of F may be due to the polarization of the drops and repulsion of like poles when they are separated by a small lateral distance.

3.7. *Collision*

The percentage number of collisions (collision frequency, E), observed in the total number of experiments for different combinations of X, Z and F was determined. The results are shown in Figs. 2 and 3. The collision frequency was more for higher values of F. The collision frequency decreased with increase in X and Z.

For the same set of initial experimental conditions the collision frequency is expected to be either zero or unity. Figs. 2 and 3 show that the percentage collision frequency obtained in the

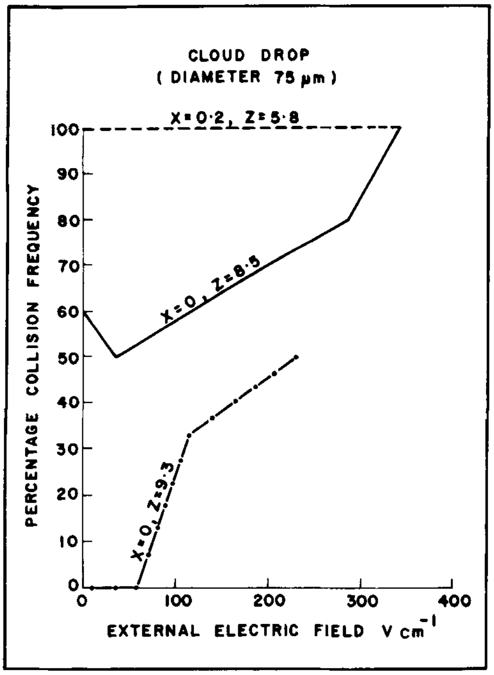

Fig. 2. Collision frequencies of equal size water drops in mustard oil with different X and Z values (experimental drop diameters) for different external electric fields.

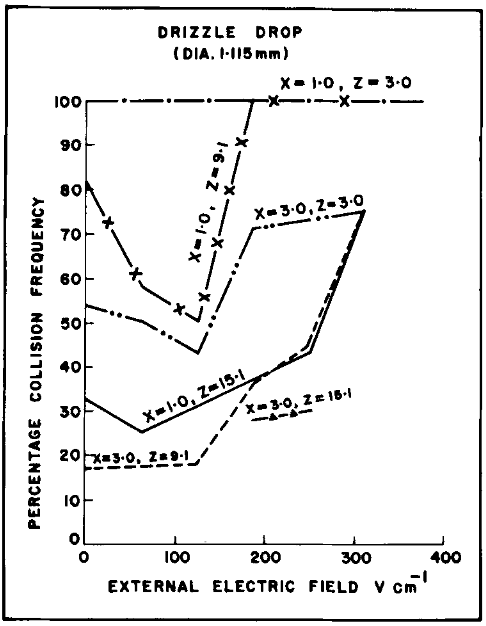

Fig. 3. Same as Fig. 2 for drops in kerosene oil.

present experiments was in the range 0–100%. The reasons for this deviation from the expected values are explained below.

The collision frequency of the drops was obtained from various combinations of mean X and mean Z instead of fixed values of X and Z. The variations in X and Z were $\pm 50\%$. The values of X and Z in a given series of experiments could not be maintained constant due to the mechanical limitations of the apparatus. The collision frequency of the drops was found to be a function of X and Z. This observation is in agreement with others (Shafrir et al., 1968). For any given collision frequency the values of X and Z were larger for the drops in kerosene as compared to those in mustard oil. This observation is consistent with the higher collision efficiency obtained from the experiment with kerosene oil (Section 3.2). The collision frequency, in general, decreased with increase in the external electric field and thereafter increased. The decrease noticed in the collision frequency is consistent with the collision efficiency values obtained in Section 3.2. For drops in mustard oil and kerosene oil media the respective limiting values of F up to which E decreased were about 90 and 125 V cm^{-1}.

The initial decrease of E with increase in F may be, as pointed out earlier, due to the effect of polarization. At higher values of F, the force of attraction may exceed the force of repulsion with favourable relative configuration of the distribution of positive and negative charges on the pairs of drops and lead to higher values of E.

The following important results were observed in the case of drops in mustard oil for certain combinations of X and Z. These were (i) when $X = 0.2$, $Z = 5.8$ drop diameters, the collision frequency (E) was 100% and was independent of F (Fig. 2); (ii) when $X = 0.7$ and $Z = 5.9$ drop diameters, the value of E decreased to zero for $F \geqslant 175$ V cm^{-1} (Fig. 3). In the case of drops in kerosene oil similar results as in (i) was observed. When $X = 1.0$ and $Z = 3.0$ the collision frequency was 100% and was independent of F (Fig. 3).

3.8. *Path length between collision and coalescence*

The pair of drops, after collision travelled together a small distance in the experimental chamber before coalescence. The path length between the collision and coalescence events was determined for different F values. The results are

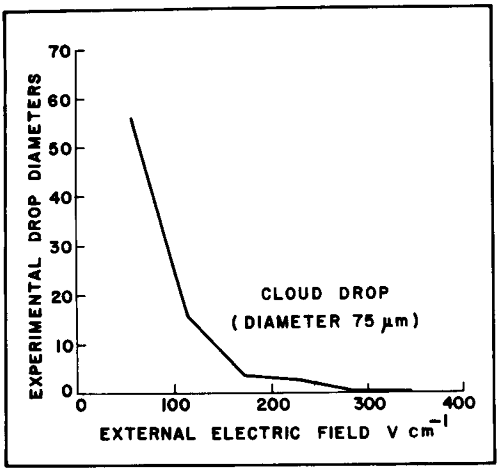

Fig. 4. Distance travelled by the pair of drops in mustard oil, from the point of collision to the point of coalescence.

shown in Fig. 4. The path length sharply decreased with increase of F. For values of $F \geqslant 300$ V cm^{-1} all collisions resulted in immediate coalescence. These observations are in agreement with those reported by other investigators (Lindblad and Semonin, 1963).

3.9. *Coalescence and collection*

There was no coalescence of the drops either in mustard oil or in kerosene oil in the absence of external electric fields. The percentage number of coalescence events (coalescence frequency) was determined from the total collision events observed in the experiments. Value of collection efficiency (product of the coalescence frequency and the collision frequency) was also computed. The mean collision frequency, coalescence frequency and collection efficiency are shown in Figs. 5 to 8 for different combinations of X and Z. One of the cases considered related to experiments with water drops of unequal size in mustard oil (Fig. 7).

3.10 *Drops of equal size in mustard oil*

Two experiments one with $X = 0$ (Fig. 5) and the other with $X = 0.0$–0.8 (Fig. 6) were performed. The coalescence and collection efficiencies were less in the latter case for all values of F (Fig. 6).

3.11. *Drops of unequal size in mustard oil*

When the collector drop was slightly smaller than the collected drop there was no collision–

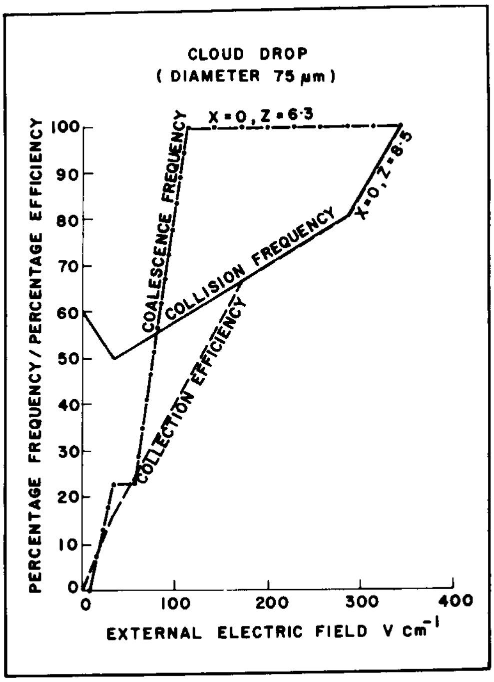

Fig. 5. Collision frequency, coalescency frequency and collision efficiency of equal size drops in mustard oil.

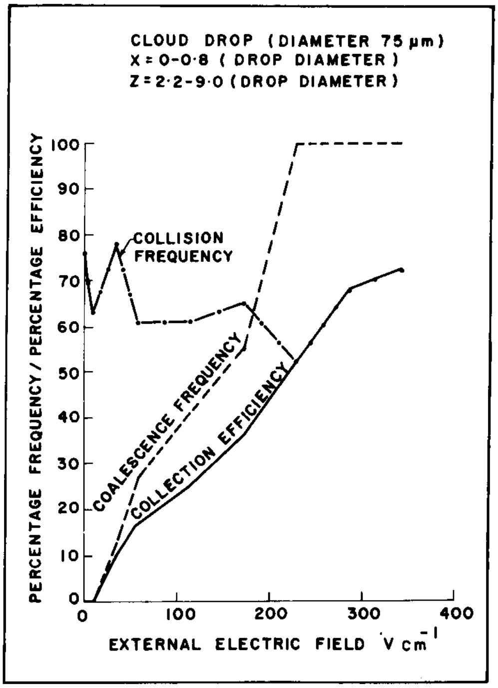

Fig. 6. Same as Fig. 5.

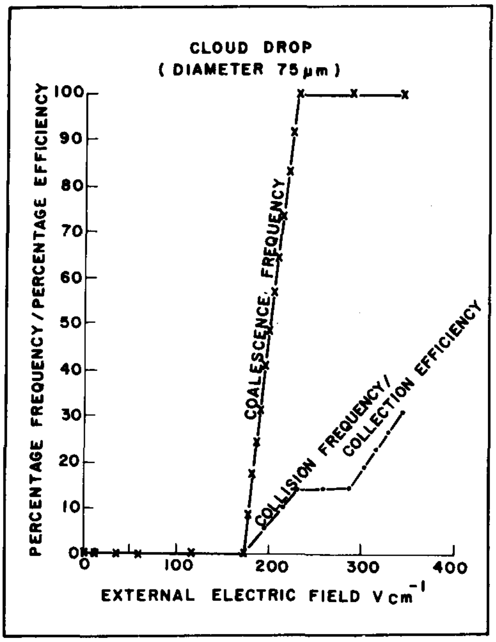

Fig. 7. Same as Fig. 5. for unequal size drops.

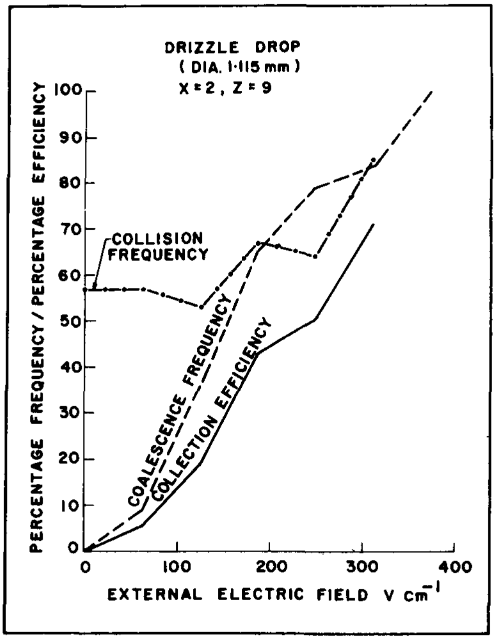

Fig. 8. Same as Fig. 5 for drops of equal size in kerosene oil.

Table 2. *Percentage collision–coalescence frequencies and the percentage collection efficiency of water drops in mustard oil*

	$r/R = 1.0$		$r/R < 1.0$	
	$X = 0.1$ $Z = 2.7$ $F = 0.0$	$X = 0.1$ $Z = 2.4$ $F = 11.5$	$X = 0.1$ $Z = 3.1$ $F = 0.0$	$X = 0.1$ $Z = 2.5$ $F = 11.5$
Collision frequency	0.0	41	0.0	57
Coalescence frequency	0.0	60	0.0	74
Collection efficiency	0.0	25	0.0	42

Values of X and Z in experimental drop diameters and F and V cm^{-1}.

coalescence for F values up to 175 V cm^{-1} (Fig. 7). The collision frequency attained 31% at $F = 345$ V cm^{-1}. The coalescence frequency was, therefore, zero up to 175 V cm^{-1} and attained 31% for $F = 345$ V cm^{-1}. When the collector drop was slightly bigger than the collected drop, the collision–coalescence frequencies were found to be higher than in the case of the drop pair of equal size (Table 2). The collision–coalescence frequencies increased with F.

3.12. *Drops of equal size in kerosene oil*

The coalescence frequency of water drops increased from 0 to 100% when F increased from 0 to 375 V cm^{-1} (Fig. 8). The collection efficiency was 71% at $F = 312$ V cm^{-1}.

3.13. *Significance of the results in warm rain-formation*

Aircraft measurements inside clouds (Selvam et al., 1976; Ramachandra Murty et al., 1976) showed vertical electric field values up to 3 V cm^{-1} and cloud drop charges up to 10^{-16} C. Also, cloud droplets of diameter less than 15 µm are present in concentrations up to 50 cm^{-3} in warm monsoon clouds (Kapoor et al., 1976). A recent study (Mary Selvam et al., 1977) has also pointed out that cloud drops in warm monsoon clouds acquire charges by the mechanism proposed by Takahashi (1974).

The above observations indicate that the electric field values in natural conditions of the summer monsoon clouds are two orders of magnitude smaller than the experimentally determined values required for enhancement of the collision–coalescence process. However, the charges carried by the cloud droplets in warm monsoon clouds are sufficiently large to significantly enhance the collection efficiencies of droplets with radii less than 10 μm (Latham, 1969).

4. Conclusions

Laboratory investigation on the collision–coalescence of millimetre-sized water drops in mustard and kerosene oil suggested the following.

(i) the collision efficiencies (E_X) of a pair of equal size drops, as obtained from the measured values of the radius of the collision-cross-sectional area, were respectively 0.64 and 7.0 for drops in mustard and kerosene oil media without external electric field (F). E_X decreased with increase of F, which could be due to the polarization of the drops and repulsion of like poles, when the drops are adjacent to each other.

(ii) Vertical path length for collision of drops was less in the presence of external electric field. For the same initial conditions, collision took place earlier for drops in kerosene than for drops in mustard oil medium.

(iii) Drop divergence (lateral) took place for certain limiting values of initial vertical (Z) and lateral (X) separations. The limiting values increased up to a certain value of F and thereafter decreased.

(iv) The collision frequency (E) for certain initial separations was 100% and was independent of the external electric field. For higher values of the initial separations, E decreased up to a certain value of F and thereafter increased.

(v) There was no coalescence of drops in the absence of external electric field. Coalescence frequency (E_C) increased with F. The field values for 100% coalescence were lower for drops in mustard oil as compared to those in kerosene oil.

(vi) When the collector drop was slightly smaller than the collected drop the collection efficiency was small compared to that of equal size drops.

(vii) The collection efficiency was zero in the absence of external electric field and it increased with increase in F.

The collision and coalescence of water drops in mustard and kerosene oil media were undertaken to simulate the cloud droplet (75 μm diameter) and drizzle drop (1.115 mm diameter) respectively as already mentioned in Section 1. The results of the present experiments are to be used with the recognition that simulation of relative motions of droplets in oil media differ from those in air media and as such cannot provide independent reliable values of the collision–coalescence efficiencies of cloud droplets under natural conditions existing in the atmosphere.

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ЭКСПЕРИМЕНТАЛЬНОЕ ИССЛЕДОВАНИЕ ВЛИЯНИЯ ЭЛЕКТРИЧЕСКОГО ПОЛЯ НА СЛИЯНИЕ ВОДЯНЫХ КАПЕЛЬ ПРИ СОУДАРЕНИЯХ

Были проведены лабораторные эксперименты по слиянию при соударениях пар водяных капель одинакового размера. Эксперименты проводились в двух средах-керосине и горчичном масле при наличии вертикального электрического поля F и без него. Радиусы водяных капель были в пределах от 1,6 до 1,7 мм, а внешнее электрическое поле менялось от 0 до 375 В см$^{-1}$. Частоты соударений определялись для различных комбинаций поперечных (X) и средних вертикальных (Z) разнесений капель в парах, поскольку фиксированные комбинации X и Z не могли быть воспроизведены в экспериментах из-за механических ограничений аппарата.

Частота соударений E для любых заданных начальных величин X и Z уменьшается с F до определенного значения F, после чего она увеличивается. Вертикальное расстояние, проходимое парой капель до их соударения было меньше при наличии внешнего электрического поля. При соударениях на фиксированной глубине d величина Z растет с ростом F, когда $X = 0$. При одних и тех же начальных условиях соударения происходят раньше в керосине, чем в горчичном масле.

Эффективность соударений E_X, вычисленная из измеренных значений радиуса поперечника соударений, была меньше в присутствии внешнего электрического поля, что было приписано поляризации капель и последующему отталкиванию между одинаковыми полюсами во время благоприятных конфигураций капель. Капли не сливались без внешнего электрического поля. Частота слияний E_C увеличивалась с F. Величина поля для 100%-ного слияния была меньше в горчичном масле, чем в керосине. Длина пути между соударением и слиянием резко уменьшалась с ростом F. Эффективность забора равнялась нулю без внешнего электрического поля и росла с ростом F. В случае, когда забираемая капля была несколько меньше, чем забирающая капля, эффективность забора была больше, чем в случае капель одинакового размера.