Binary Collisions of water drops in presence of horizontal electric fields: A wind tunnel study

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Abstract:

Coalescence/breakup characteristics of binary collisions of small water drops (d_S=0.4-1.8 mm diameter) with large drops (d_L=3-3.5 mm diameter) occurring in the absence/presence of horizontal electric field (E_H) = 0, 100, and 300 kVm^{-1} have been investigated in a small vertical wind tunnel using a high-speed digital camera. The coalescence efficiency (E_C) of 0.299 observed for average diameters (d_L=3.2 mm, d_S=1.2 mm) in E_H = 0 decreased to 0.244/0.211 when E_H is increased to 100/300 kVm^{-1}. The increase in the electric field reduces the probability of coalescence when Weber number (We) <1. However, when We 1, an increase in We restricts the probability of coalescence. Our data, when plotted in the regime diagram in the We*- p plane, delineates the collision outcomes in all-electric field values but does show the overlapping of some data points in the adjacent categories. After a binary collision, the relaxation time required for the occurrence of coalescence is higher than that for the breakup. Further, the relaxation time increases from the filament to sheet to disk mode of breakup in all-electric field values. Fragment size distributions after the filament and sheet types of breakups differ and are differently affected by the applied electric field. Higher collision kinetic energy (CKE) has a tendency to increase the number of fragments of the sizes between d_L and d_S. It is concluded therefore that, the effect of the electric field needs to be included in the estimation of drop growth and precipitation in clouds.

1. Introduction

Manifestation of several dynamical, microphysical and electrical processes and their mutual interactions in the cloud result in rainfall, the most desired component of global water cycles. In warm clouds, raindrops are formed by a "Chain reaction'' involving several microphysical processes such as nucleation, condensation, collision, coalescence, and the breakup of drops [Langmuir, 1948]. Drop breakup is an important process that limits the maximum size of the raindrops. Two mechanisms are usually considered to be responsible for the drop breakup process that control the drop size inside the clouds: i) collision-induced breakup following binary collisions of raindrops in which drops temporarily coalesce and then break up into several fragments, and ii) spontaneous breakup where a single large raindrop becomes hydro-dynamically unstable and breaks up spontaneously into smaller fragments in absence of collision. Generally, large raindrops are formed either as a result of the melting of large ice pellets or snowflakes originating from mixed-phase regions [Hobbs and Rangno, 2004]. Both the breakup processes contribute to the evolution of raindrop size distribution (DSD) and may have different significance to drop spectrum evolution in different clouds. However, owing to difficulties in the formation of large raindrops in the clouds, several experiments and theoretical studies emphasize the collision-induced breakup process as the overwhelming cause of drop breakup and are considered to be as influential to the resulting DSD in warm rain processes [Pruppacher and Klett, 1997].

Despite the importance of collision-induced breakup, only a limited number of experimental or numerical studies exist to provide data for an appropriate understanding of the process. In literature, the drop breakup following the collision of two drops has been studied in a variety of experimental arrangements. For example, the collisional breakup has been observed in a vertical wind tunnel [Blanchard, 1949, 1950; Cotton and Gokhale, 1967, Montgomery, 1971; Emersic and Connolly, 2011 - hereafter EC11; Szakáll et al., 2014 - hereafter SZ14, Szakáll and Urbich, 2018], in long fall shafts (McTaggart-Cowan and List, 1975 - hereafter ML75; Low and List, 1982a, 1982b - hereafter LL82a and LL82b; Barros et al., 2008 - hereafter BA08) and by directing droplet jets at each other (Brazier-Smith et al., 1972; Testik and Barros, 2007; Testik, 2009, 2011). These investigations revealed that the process of collision of two raindrops may result in three outcomes: i) Bounce apart before surface contact is made; ii) coalescence i.e. the permanent union of two drops to form a larger drop, or iii) temporary coalescence followed by break up of drop and produce several small droplets which feedback again the collision process. In warm clouds, the latter two processes are of importance as they directly influence the growth and temporal evolution of the size distribution of raindrops.

The process of coalescence is responsible for the growth of cloud drops to form precipitation-sized drops and the probability of occurrence of coalescence is generally represented by the coalescence efficiency (E_C), which is defined as the ratio of the number of collisions resulting in coalescences to the total number of collisions. Cotton and Gokhale (1967) in their wind tunnel observations of the interaction of large water drops ranging in size from 3.5 to 9.0 mm in diameter have shown that the coalescence of drops depends on the relative impact velocity and the impact angle of a pair of drops. The average E_C was estimated to be of the order of 50% in their experiment. Brazier-Smith et al. (1972) conducted experiments on the collision of relatively small raindrops with a radius ranging from 150 to 750 mm to study the critical conditions under which drops remain permanently coalesced or separate with the breakup. They developed a parameterization equation for coalescence efficiency. Later, from the unique and pioneering experimental observations of ML75 and LL82a, the collision-induced drop breakup process has been studied for a data set based on 10 different drop-pairs combinations ranging in diameter from 0.395 to 4.6 mm across the raindrop spectra. They considered collisions that result in either coalescence or breaking up for further analysis. Results show that significant growth through coalescence was observed only when the small drops were $<$ 0.6 mm in diameter. They classified the visual observations of different types of breakups with photographic records into three different categories: neck/filament, sheet, and disk type of breakup, and analyzed fragment size distribution after the breakup. They showed that the specific mode of breakup depends on the value of collision kinetic energy (CKE), the impact location, and the angle between the colliding drops. Further, from this data-set, LL82b developed parameterizations of the collisional breakup for numerical models of rainfall microphysics McFarquhar (2004a) later reformulated parameterizations that took into account mass conservation, provided a more physical basis for extending the results of the original 10 colliding pairs to arbitrary drop pairs, and had a complete uncertainty analysis. These parameterizations formed the standard to which all subsequent research made comparisons. BA08 performed similar laboratory experiments at NASA's WFF facility in which 6 drop pairs of moderate size drops were vertically accelerated and collided with each other. They showed that their fragment size distributions (FSD) were slightly different from those determined by LL82a; however, they confirmed that a certain limit for coalescence appears as given by LL82a. But, they did not propose parameterization based on their observations.

A comprehensive laboratory investigation of the binary raindrop collision outcomes in air and its interpretation based on dimensionless parameters and physical considerations has been established by Testik (2009) and Testik et al. (2011). A theoretical regime diagram was proposed by Testik (2009) that defines the physical conditions responsible for the occurrence of the collision outcome regimes i.e., bounce, coalescence, and break up regions in the We - p (Weber number -drop diameter ratio) plane. In this diagram, two curves corresponding to DE_1=1 and DE_2=1 divide the We - p plane into 3 regions delineating the collision outcomes where DE represents the dimensionless energy based on the ratio of the CKE and surface energy (SE) of the two colliding drops. This regime diagram was further modified by Testik et al. (2011) with the dataset collected in drop collision experiments at NASA's WFF facility. The regime diagram was extended to provide breakup patterns of collision outcomes by including the critical angle of impact.

To study the collision-induced breakup, Emersic and Connolly (2011) -hereafter EC11 -levitated a larger water drop in the vertical air stream of an open-ended wind tunnel, and a smaller drop was injected from above – i.e., from the downstream end, and collided with the stagnant large drop. The drop-drop interactions were carried out with drop pairs of sizes ranging from 3 to 8mm in size. They observed more bag types of breakup events along with the filament and sheet types of breakups. The resulting drop-size distributions after a collision-induced breakup were computed using the parameterizations given by LL82b and McFarquhar (2004a) for the larger drop-pair sizes and verified the extrapolations from the parameterizations.

Using laboratory-based measurements, various semi-empirical parameterizations for E_C as a function of dimensionless parameters We and p have been proposed. Beheng et al. (2006) performed Direct Numerical Simulations (DNS) of binary collisions for the drop pairs. In addition to the drop pairs as considered by LL82a, eight added drop pairs were taken into account to compute the E and FSD. Later, Scholottke et al., 2010 (hereafter - SCH10), and Straub et al., 2010 (hereafter SA10), extended the earlier raindrop collision outcome database ofLL82a, and Beheng (2006), through DNS of collisions of 32 drop pairs with large drop diameter (d_L) = 0.6 - 4.6 mm and small drop diameter (d_S) = 0.35 – 1.8 mm, to cover the entire size parameter range relevant to breakup. They computed the E_C and FSD with the emphasis on eccentricity as an additional parameter controlling the collision outcome, especially the specific breakup modes and consequently the respective FSD.

In the electrical environment of thunderclouds, strong electrical forces acting on the charged drops modify the velocity and shape of raindrops by deforming them in the direction of the electric field [Richards and Dawson, 1971; Griffiths and Latham, 1972; Gay et al., 1974; Rasmussen et al., 1985; Kamra and Ahire, 1989; Chuang and Beard, 1990; Coquillat and Chauzy, 1993, 1994; Georgis et al., 1997; Coquillat et al., 2003; Bhalwankar and Kamra, 2007; Bhalwankar et al., 2015]. In thunderclouds, the large-scale electric field is generally considered to be vertical in direction. However, many in-cloud measurements reveal that the electric field inside the active thunderclouds are frequently inclined from the vertical direction. Moreover, in most of cloud-to-ground lightning flashes, especially in storms with large stratified regions the horizontal structure of intra-cloud discharges is often predominant [MacGorman et al., 1981; Krehbiel et al., 2000].The local charge generation mechanisms and/or the advection of charge from the convective cores may be the cause of high electric fields observed in stratiform clouds[Rutledge &MacGorman,1988;Stolzenburg et al.,1994;Krehbiel et al.,2000].Additionally, Winn et al., (1974), in their balloon measurements, measured the maximum electric field of 430 kVm^{-1} to be horizontal in direction. Several experiments [Nolan, 1926; Macky, 1931; Ausman and Brook, 1967; Kamra and Ahire, 1989; Kamra et al., 1993; Georgis et al., 1997] were performed to study the influence of a horizontal electric field on the behaviour of raindrops. They show that the disruption field at sea level pressure is lowered in such a field configuration for uncharged drops since both aerodynamical and electrical forces act in the same direction when disturbing the drop stability. Further, the results of the wind tunnel experiments of Kamra et al. (1991) and Bhalwankar and Kamra (2007) show that if the drops are highly charged or situated in the external horizontal electric field, the electrical forces enhance the distortion of the drop, make them more unstable and thus breaks up more readily. On the other hand, in the vertical electric field drops tend to become more stable and larger drops can survive. Thus, the DSD is expected to be wider, and therefore the drop growth is likely to be faster in those regions of the cloud where vertical rather than horizontal electric fields prevail.

In their field experiments, Mudiar et al. (2017) observed a significant difference in DSDs for drops of diameter above 2 mm for strongly and weakly electrified events in clouds. It has also been shown that the cloud electric field can modify the rain rate at the Earth's surface by enhancing the growth of raindrops. A recent study by Mudiar et al. (2021) also confirms the microphysical link, earlier proposed by Moore et al. (1962, 1964), between lightning and enhanced precipitation intensity after the occurrence of the lightning flash. It is concluded from these observations that the lightning-induced atmospheric ions and prevailing electrical forces may potentially modulate the DSD as well as enhance the rain intensity by influencing the collision-coalescence process and the growth rate of raindrops after lightning. Thus, all the above laboratory and field investigations suggest that it is important to study the influence of electrical forces on binary drop collisions and their fragment size distribution.

In the earlier studies, the interaction between electrically charged drops in the external electric field in Strokes flow has been determined by Lindblad and Semonin (1963),Davis (1965), and Plumlee and Semonin (1965) using the electrostatic force model. Their calculations of collision and coalescence efficiencies are strongly dependent on the size of the droplets, the charge residing on the drop, and the external electric fields. Schlamp et al. (1976, 1979) numerically calculated the effect of electric charges (0 to 4 x 10^{-14} C) and vertical external electric fields (0 to 3.48 kVm^{-1}) on collision efficiency of cloud drops for different collector drops of radius in the range 11 to 75 µm. Their results demonstrate that the presence of electric fields and charges enhances the collision efficiency and it was found to be more pronounced for smaller collector drops. The above-mentioned numerical studies have been performed for very small cloud droplets of less than 100 µm radius. Further, Ochs and Czys (1987) and Czys and Ochs (1988) showed that the collisions of drops of 0.68 mm and 0.38 mm, charged with the same polarity resulted in permanent coalescence for all impact angles if their relative charge exceeded 2×10^{-12} C, while in the absence of charge, coalescence occurred only at a critical impact angle of 43°. The Coulomb interaction enhances the drainage of the air film trapped between the colliding drops, which help the drops to coalesce permanently. The parameterization of electrical processes in numerical models will help in improving the estimation of rainfall measurements from thunderclouds. Unfortunately, neither experimental nor theoretical data are available for raindrop size which would allow the quantitative comparison of our results for controlled conditions of external electric field or charge on binary raindrop collision.

In this article we study the effect of an electric field on the outcomes of the binary drop collisions occurring in the vertical flow of a small vertical wind tunnel in the absence/presence of the horizontal electric field (E_H). A high-speed digital camera capable of capturing the evolution of the binary collision process and its outcomes has been used to study the drop-drop interactions. The study is focused primarily on the analysis of the collision outcomes, coalescence and breakup efficiencies of the drops, and modes of the drop's breakup, paying special attention to the eccentricity of the initial drops and the influence of the electrical forces on the above processes. Results of this experiment may thus provide a novel data-set to understand the effect of electric field on the binary collisions of drop-pairs in this size range, in particular, and the effect of cloud electrification on its DSD, in general.

2. Experimental Set-up and Methodology

2.1 Vertical Wind Tunnel and Horizontal Electric Field Arrangement

An experiment on the collision-induced breakup of water drops was conducted in a small low- turbulence, open-ended vertical wind tunnel (Figure 1). It consisted of - a blower that sucks the air; a divergent section to streamline the incoming air, a straight section fitted with a honeycomb and screens, a diffuser section, a test section, and a back-pressure plate (described in detail by Bhalwankar et al., 2015). Water drops were freely suspended at their terminal velocities ina velocity well created in airflow with a cross-wire screen fitted between the diffuser and test section of the tunnel. Vertical air velocity of up to ~12 ms^{-1} could be achieved in the observation section of the wind tunnel. The measurements of the turbulence level in the air stream in the wind tunnel carried out with a pre-calibrated VelociCalc-Multifunction ventilation meter (TSI model 9565-P) show that the intensity of turbulence is 0.65%in the center of the observation section where the drops were suspended. Thus, the drops of different diameters could be floated at their terminal velocities in the observation section above the test section, for several minutes.

To generate the horizontal electric field, two flat circular electrodes specially designed with edges suitably rounded and smoothened were mounted vertically above the test section. Separating the two electrodes by 12 cm distance from each other, a high voltage of up to 60 kV was applied to the positive electrode to generate the required horizontal electric field without the occurrence of any measurable corona discharge from the electrodes (details are given in Bhalwankar and Kamra, 2007). Such electric fields, though on the higher side of the large-scale fields observed in thunderclouds, may exist in small regions of the intensely electrified thunderstorms.

The experimental setup to generate large and small drops had the following components. The large drop generator (LDG) was mounted at a height slightly higher than that of the back-pressure plate. It consisted of a 500 ml grounded bottle filled with distilled water (a reservoir) from which the water continuously flowed through a capillary tube. To control the flow of water a roller clamp was attached to the capillary tube. The end of the capillary was connected to the plastic tip of a Finnpipette and a small portion of the tip was inserted into the test section through a small hole in the central portion of the back-pressure plate. In this way, water drops of d_L =3.0 to 3.5 mm kept dripping at an approximately constant rate against the vertical air. The corresponding terminal velocities of the large drops were determined by measuring the airspeed with a VelociCalc at the place where the drop was suspended and the average airspeed for the drop-size range was 7.26 ms^{-1}.This airspeed was set and maintained throughout our experiment. After the suspension of the large drop, the capillary tube with tip was removed and the hole was closed to avoid turbulence in the observation section.

To generate small drops, we followed a set-up of a small drop generator (SDG) similar to the one used by SZ14. It consisted of a 5 ml plastic syringe connected to a 30 cm long needle with a 300 m inner diameter. This needle was inserted in the airstream of the wind tunnel through a minute hole in the test section at 2 cm above the cross-wire screen. To reduce the effect of turbulence caused by the needle in the test section, the needle was placed exactly parallel to one of the wires of the crossed-wire screen. Several small drops were generated and introduced into the vertical air stream by pushing the knob of the syringe. The diameters of the colliding small drops were between diameters d_s = 0.4 - 1.8 mm in the experiments.

2.2 Methodology

One uncharged water drop of d_L = 3.0-3.5 mm was released from the capillary tip and suspended between the electrodes in the absence of the electric field. Then the electric field was quickly raised to the desired value. The suspended drop was photographed after 2–3s of its detachment from the pipette using a high-speed camera at 1000 fps. This decay time provides to stabilize the drop in the airflow by compensating for the effect of residual oscillations caused by the generation of drop while detaching from the pipette (Lamb, 1945; Beard, et al., 1991; Bhalwankar et al., 2015). Simultaneously, the small drops were injected into the flow upstream of the larger drop to collide with the large drop already floating in the observation section. The images were recorded till the large drop collided with a small drop and then either coalesce or break up into small fragments. As reported by SZ14, we do observe a slight upward acceleration of the large drop due to collision in our experiment; however, it was negligible since this change was captured within the small field of view of the camera after the collision.

A high-speed video camera (Mega Speed MS55K, Canadian Photonic Labs, Inc.) captured the sequence of the drop collision process with a time interval of 1ms and provided information on the change in its shape at the moment of collision and the time evolution of drop collision outcomes. The pixel size of the camera chip is 12 µm and a lens with a magnification of 1:2 was attached to the camera so that a spatial pixel resolution of 24 µm was obtained during the measurements. The drops were illuminated with a 300 W DC cold light lamp creating a bright-field background. A milk-glass plate placed in between the light source and the drop maintains a diffused uniform illumination. This set-up provided a suitable high contrast for further image analysis of each captured collision event. The estimated accuracy of drop diameter determination was 2 pixels or, equivalently, 50 m. Every single event was captured from the time of the large drop's suspension till its collision outcome. In our analysis, only those binary drop collisions were selected which resulted in coalescence, and then either remained as a coalesced drop or broke up into smaller fragments. Each captured drop collision sequence was analyzed visually for classifying the breakup and coalescence. The breakup events were further categorized into different breakup modes.

2.3 Microphysical Parameters

The basic significant microphysical parameters that govern the collision outcome are thesize and velocity of the colliding drops and the angle of impact between them. These parameters were computed from the frame-by-frame examination of the photographic images captured with a time interval of 1ms for individual collision events. The volume equivalent diameters of large and small drops in the absence/presence of an electric field were determined from the average of shadow images of the recorded drop before the collision, using image-processing software - Image-J. The standard method of the calibration and scaling of images from pixels to millimeter-scale was used by taking an image of a ruler placed at the test section of the wind tunnel where the actual collision occurs. The small drops were carried upward with the air stream. So, the images of small drops appeared as streaks before the collision. Since the shape of the small size drops up to 1 mm in diameter are considered to be spherical and the distortion of drops in the range 1 $<d_S$ 1.8 mm is marginal/negligible [b/a ~ 0.95; Pruppacher and Klett, 2010] the widths of the streaks were considered to be equal to the diameters for the small drop range considered in the experiment. Following the method described by SZ14, the impact velocities were calculated from the length of the streak of moving drops by the change in position of each drop in sequential images with known time intervals just before the collision occurred. The measured average impact velocity of the drop pairs considered in our experiment was2.4 ms^{-1}which is around 34% lower than the relative velocity of the drop pair considered in our experiment in the real atmosphere. This was because the small drops were carried up with the air stream with a velocity of the large drops but the distance from their insertion point to the point when the collision occurred was not sufficient to accelerate them to their terminal velocity [SZ14].From these computed diameter and velocity values, the energy parameters and the dimensionless parameters were calculated. Other microphysical parameters like surface tension, relative humidity, ambient pressure, and temperature were kept constant throughout our experiment. Another important parameter that controls the outcome of collision is the eccentricity ( ) of the colliding drop (SCH10). The eccentricity ( ) is defined as the ratio between the horizontal distances of the colliding drops' centers to the arithmetic mean of drop diameters of colliding drops (d_L+d_S). In the present experiment, the eccentricity of the colliding drops was estimated from the visual observations of photographic images just before the collision occurred and confirmed with the results of the numerical simulations by SCH10, shown in the form of snapshots.

The positive potential applied to one of the electrodes created some electric field at the tip of the needle generating a vertical electric field between the lower portion of the positive electrode and the needle tip; as a result, the small drops produced by the needle carried some negative charge. This was apparent when these drops started deviating from their vertical path towards the positive electrode when they entered the horizontal electric field area between the two vertical electrodes. However, no such deviation was observed, when the applied electric field was $<$ 300 kVm^{-1}. A comparison of the vertical gravitational and viscous forces with the horizontal electrical forces reveals that small drops of about ~1 mm diameter carried a charge of «10^{-12} C . It was supported by Figure 2 also where the impact velocity is plotted against the d_S for electric fields of $<$

300 kVm^{-1}. The fact that the drop's impact velocities did not differ much when the electric field was changed from 0 to 100or 300 kVm^{-1} supports the fact that the small drops were weakly charged. Therefore, we confined our observations of binary drop collision to the E_H 300 kVm^{-1} in the present experiment.

3. Results and Discussion

3.1 Sizes of Colliding Drops and Magnitudes of Electric Fields

Primarily the drop collision outcomes were classified into the coalescence and breakup events from the sequences of photographic images. In the present experiments, a total of 315 drop collisions including coalescence (79) and breakup (236) events are considered for the analysis in E_H = 0, 100, 300 kVm^{-1}. The range of diameter of large drops varied from d_L= 3.0 - 3.5 mm with average value $d_L = 3.2 \pm 0.15$ and that of small drops from d_S= 0.4 -1.8 mm with average value $d_S = 1.2 \pm 0.25$ mm. Thus, the dimensionless parameter, $p = (d_S/d_L)$ covered is 0.14 to 0.61. The drop pair sizes selected in our experiment simulated the frequent collisions in clouds and are comparable with the drop sizes considered in earlier experimental or/and numerical studies (LL82a; SCH10).

In a cloud, the collision rate that a large drop interacts with a smaller drop depends on their number concentration and hence on the rain rate. Szakáll and Urbich, (2018), estimated the normalized rate of collision for drop pairs in the case of stratiform precipitation. The collision rates of the averaged drop pair (d_L and d_S) investigated in our wind tunnel experiment and earlier studies are plotted with different symbols in Figure3.The cluster of points indicates the region of high collision rate of different precipitation-sized drop pairs as shown in the contour plot by Szakáll and Urbich, (2018) in the case of stratiform precipitation of 5mmhr^{-1} rain rate, utilizing gamma DSD. The average value of the diameters of the selected drop pairs in our experiment falls in the region of a high collision rate, so it might have an important contribution to the collisional breakup mechanism. Further, electric fields are frequently reported to be inclined from the vertical direction in storms with large stratified regions [e.g., Kamra, 1977; Moore and Winn, 1974; Stolzenburg et al., 1994]. Thus, the results of our experiment are more appropriate to be applied in stratiform rain for a rain rate of 5 mm hr^{-1}.

3.2 Coalescence Efficiencies

Analysis of photographic observations in our experiment has been carried out in terms of coalescence/breakup efficiency. A total of 97 events of drop-drop collisions were captured for d_L= 3.0 - 3.5 mm and p varying from 0.14to 0.6,in $E_H = 0$. Observations reveal that 29 collision events ended with coalescence and 68 with breakup. This gives Ec = 0.299, which is well within the range of the E_C reported between 0.21 and 0.65 by LL82a for d_L = 1.8-4.4 mm and p< 0.56in absence of the electric field (Table 1). However, Szakáll and Urbich, (2018), in their wind tunnel experiment obtained high coalescence efficiency, $E_C = 0.624 \pm 0.014$ on collision between drop pairs of 2.5 and 0.5mm average diameter and p in the range 0.13 - 0.32. A somewhat higher value of E_C observed by them is most likely because of the smaller diameter of the colliding small drops (d_S< 0.8), used in their experiment.

We extended our observations to study the effect of horizontal electric fields on collision outcomes. From a total of 123 and 95 events of the drop-drop collisions, we get E_C= 0.244 and 0.211 in E_H = 100 and 300 kVm^{-1} respectively (Table 1). Thus, the coalescence efficiency decreased to 0.244/0.211 when E_H is increased to 100/300 kVm^{-1}. Consequently, the breakup efficiency increased to 70/76/79 % when the electric field is increased from 0 to 100 to 300 kVm^{-1}.The increase in breakup efficiency observed in the horizontal electric field may be attributed to the enhanced stretching of coalesced large drops in the horizontal direction due to the induced electric charges on the drop surface [Bhalwankar et al., 2015]. Since large drops are suspended in the horizontal electric field for a sufficiently long time in our experiment, both hydrodynamic and electrical forces may feedback each other during their oscillations and contribute to the enhancement of the distortion of the larger drops. Thus, the temporarily coalesced drop in one of its oscillations may have sufficient electric force acting outward in the horizontal direction to overcome the surface tension force trying to keep the coalesced drop intact and cause its breakup.

From the energy point of view, the competing energies involved in drop collision outcome are, i) collision kinetic energy that has a destabilizing effect, and ii) the surface energies of the colliding drops (SE_L and SE_S) that have a stabilizing effect. These quantities are governed by the diameters and velocities of the participating drops and the ratio of the CKE to SE determines whether the collision will result in permanent coalescence or breakup. During the early stages of coalescence, the coalescing drop-drop system is often highly unstable. If the collision does not have sufficient kinetic energy to overcome the surface energy of coalesced drop, then coalescence occurs. Figure 4 presents sequential images of the coalescence process of two colliding drops of d_L= 3.2 mm and d_S = 0.75 mm. Images show that the small drop collides with the large drop at the eccentricity of 0.02, they coalesce and form a single larger drop that starts oscillating to dissipate the collision-induced energy by restoring the surface tension forces through viscous damping. The time evolution of the complete coalescence process in this event was 27ms.

In the process of coalescence, there is a net loss of surface area because the coalesced drop has a smaller surface area in spherical approximation than the total surface area of colliding drops. Coalescence of drops occurs when both CKE and change in SE of colliding and coalesced drop (ΔS), are adequately dissipated through oscillations and deformations of the coalesced drop.LL82a argued that the ability of the coalesced drop to dissipate the total energy of coalescence (E_T) would determine the E_C of the colliding drop. They formulated an empirical relation involving E_T and E_C to fit their experimental drop pairs and calculated the E_C (equation 4.5 in LL82). They showed that the critical value of E_T for coalescence to occur after the binary collision was less than 5.0 µJ. Using the same formula of LL82 for our averaged data in absence of an electric field, E_T = ~ 2.2 µJ, and E_C = 0.38. Thus, the condition (E_T < 5 µJ) of LL82a for the occurrence of coalescence was confirmed in the present investigation.

The collision outcome of the colliding drops also depends upon the eccentricity ( ) of the large drop at which the collision occurs (SCH10).The values of in the present experiment have varied from 0.02 for the central and 0.95 for grazing collision. Our photographic observations indicate that the probability of the breakup after binary drop collision is higher for larger eccentricity values and a general increase in the occurrence of coalescence has been observed with a decrease in d_S and for small or near-center (= 0.02 - 0.4) eccentricities in all-electric field magnitudes. However, the accurate determination of the eccentricities has a limitation due to the one-dimensional photography in our experiment.

3.3 Effect of CKE on E_C in Different Horizontal Electric Fields

We have grouped our data into four categories in Table 2, ranging from low CKE to high CKE viz. 0<CKE<1; 1 CKE<1.9; 1.9 CKE<2.9; and 2.9 CKE 5.1 (CKE in µJ).This grouping automatically organized the corresponding colliding drop diameters in each group of CKE. This allowed a more detailed examination of the collision outcome of the total range of drop diameters in different electric fields. One benefit of this grouping was that in all the four CKE categories the average value of d_L was almost constant i.e, ~ 3.2mm, while the average values of d_S increased from 0.8 to 1.4 mm for different values of the horizontal electric field. Thus, there were four almost similar drop pairs for each fixed value of E_H. Table 2 also shows the calculated value of E_C by three different methods: 1) by definition i.e., the ratio of the number of coalescences to the number of total collisions, 2) the empirical equation of LL82, and 3) the equation E_C = exp(-1.15We) derived for parameterization by SA10, for the present data of the averaged drop pairs from four CKE groups in absence of electric field. Results in Table 2 show that in the absence or presence of the electric field, the values of CKE, E_T, and We increase and E_C decreases with the increase in $d_{s.}$ Such a result was found by LL82a in the absence of an electric field. The results of our experiment extend its validity also under the electric fields applied in our experiment. Thus, the drop growth occurs mainly through the smaller drop size whether the collision occurs in the absence or presence of the electric field. However, the decrease in E_C with the increase in the small drop diameter decreases or even vanishes for We > 3 in all-electric field values.

Figure 5 shows the coalescence efficiencies (E_C) plotted as a function of the Weber number (We).The solid line represents the empirical curve derived by SA10for the limit of coalescence efficiency for a particular We. The figure illustrates that, 1) E_C decreases with an increase in We, irrespective of the method of calculation, in all CKE groups in absence of an electric field. 2) When CKE is low (We<1), our experimental values show a systematic decrease in the coalescence efficiencies from 0.66 to 0.23 with an increase in E_H from 0 to 300 kVm^{-1}. However, E_C is almost in the same range (0.11 - 0.16) for the higher CKE range

(We   1). This illustrates that the effect of electric field on coalescence efficiency is stronger when CKE is small. 3) In agreement with the results ofSA10, the probability of breakup increases (i.e., E_C approaching zero) as the We increase. 4) For the lower CKE group, an increase in the electric field will reduce the probability of coalescence, however, for the higher CKE group, an increase in We will restrict the probability of coalescence.

The wind tunnel data of Szakáll and Urbich (2018) also show a higher E_C (0.64) for the lower Weber number (0.39). Figure 5 shows that the E_C values calculated from the empirical formula from LL82 for the present data for four different CKE groups in $E_H = 0$ fit well within the limits set by SA10.

3.4Drop Breakup

i) Modes of Drop Breakup and Eccentricity

The collisions that resulted in a breakup in our experiment were further categorized according to their geometric shapes after immediate impact and the pattern of fragments produced after the breakup. Three types/modes of breakup viz., neck or filament, sheet, and disk were identified from photographic evidence in our experiment. Figures 6a, 6b, and 6c show the evolution of the binary drop collision and the breakup patterns in the sequential images. The probability of breakup is higher for larger colliding drops and larger eccentricity. The dependency of drop breakup mode with the eccentricity can be seen in Figures 6a, 6b, and 6c. Qualitative descriptions of each breakup type are given below:

i) A filament breakup occurs when a bridge (neck) of water connecting the two drops forms at the extreme ends or near grazing collisions (0.6 >   0.95).The original sizes of colliding drops are mostly retained and the interconnecting bridge disintegrates into smaller fragments (Figure6a). ii) A sheet breakup results when a smaller drop collides with the larger one at an intermediate eccentricity value (0.4   0.6), and the bulk of the larger parent drop is spread to form a sheet of water after impact (Figure 6b). The smaller parent drop usually disappears in this sheet and the coalesced system becomes strongly distorted. The disintegration of this sheet produces several small and satellite droplets. iii) Disk breakup occurs when the small drop collides with the larger drop near the center or heads-on collisions (0.05 <   < 0.4), and from the temporary coalesced drop the disk spreads out until rupture, generating a large number of satellite drops (Figure 6c). Besides, it has been observed that as   shifts from lower to higher values i.e., from disk to sheet to filament type of breakup, the number of fragments after breakup decreases.

Table 1 summarizes the breakup efficiency for a specific breakup mode calculated by taking a ratio of the number of collisions leading to the breakup of the temporary coalesced drop in that particular mode i.e., E_{bf}, E_{bs}, E_{bd} where the subscripts indicate those of filament, sheet, and disk breakup respectively. Data indicate that the most prominent breakup mode observed is filament type of breakup then sheet or disk in all-electric field values. Moreover, the number of observations in the filament mode of breakup increases with an increase in the electric field from 0 to 300 kVm^{-1}.

The relaxation time for coalescence ($_c$) and breakup ($_b$) of two approaching drops have been calculated from the photographic observations after a binary drop collision. $_c$ is the period between the time ($_c$=0) when the small drop collides with the larger one to its permanent coalescence till the amplitude of oscillation decays to a steady-state shape. Similarly, $_b$ is the period between the time ($_b$= 0) when the small drop collides with the larger one to its temporary coalescence followed by its first break up. Table 3 shows the average relaxation time (ms) and CKE (µJ) for i. coalescence ($_c$), and ii. Specific breakup mode: $_f$ = Filament, $_s$ = Sheet, $_d$ = Disk in E_H= 0, 100, 300 kVm^{-1}. Results show that the relaxation time required for coalescence is higher than for its breakup. Moreover, for different modes of breakups, the relaxation time increases from the filament to sheet to disk in all-electric field values. From the energy point of view, the lowest CKE is required for coalescence more needed for filament type of breakup, and most for sheet-type whether the collision takes place in the absence or presence of the electric field. Even though the observed changes in relaxation time and CKE are small, they systematically increase with the mode of breakup. However, since these changes have been observed in a very small diameter range of incident colliding drops examined in our experiment, so it adds confidence to our results.

3.5 Coalescence and Breakup Regimes

Testik (2009) and Testik et al., (2011) pointed out that one single parameter cannot define properly the collision outcome, so they used the Weber number for characterizing the collision. From the combination of the basic governing parameters like the drop diameters, velocities, surface tension, and impact angle of colliding drops, the dimensionless parameters like Weber number (We or We* where We = CKE/S_c and We*= $(d_S/2)(\Delta V)^2/$); Both Weber numbers are related to each other by We*=$12[1+((p)^3)^{5/3}/$ p]We]and diameter ratio ($p=d_S/d_L$) were calculated to characterize the outcome of the collision (Testik, 2009; Szakáll and Urbich, 2018). Further, Testik (2009) explained that the ratio of the CKE to SE_L or SE_S of the colliding drops becomes an important criterion in determining-1) the collision outcome and 2) the dimensionless energies based on the ratio of CKE and SE ($DE_1=CKE/SE_L$ and $DE_2=CKE/SE_S$). From these physical considerations, Testik (2009) developed a theoretical regime diagram that delineates the different regimes of collision outcomes in the We*- p plane. Two curves corresponding to DE_1=1 and DE_2=1 divide the We*-p plane into 3 regions delineating - the conditions for coalescence and neck type of breakup to occur in region I and only breakup to occur in absence of coalescence and bounce to occur in region II.

A total of 97, 123, and 95 drop-drop collision events observed in our wind tunnel experiments in presence of E_H= 0, 100, and 300 kVm^{-1} respectively were categorized in coalescences and breakup outcomes. The breakup types were subsequently differentiated in filaments, sheets, or disk types from photographic observations. The values of We* and p in the absence and presence of electric fields were computed using the size and velocity of the colliding drops calculated by the methodology given in section 2. The experimental range of dimensionless parameters covered is We* = 7.0–75.8 and p= 0.14 to 0.6**.**The theoretical curves for dimensionless energies in the We* -p plane introduced by Testik (2009) have been reproduced in Figure 7(a, b, c). The calculated We* and p values from the drop collision experiments are plotted in this regime diagram in the We*- p plane for E_H= 0, 100, and 300 kVm^{-1} in Figure 7(a, b, c).In all three figures, different symbols represent our experimental observations and solid lines represent regime separation curves ($DE_1 = 1$ and $DE_2 = 1$).As shown by Testik et al. (2011), we do observe an overlap of the coalescence and filament type of breakup in regime I, and filament and sheet type of breakups overlap disk breakups in regime II. However, few exceptional data points of coalescences were observed in regime II and that of sheet type in regime I. Likewise, the disk type of breakup observed only in the upper part of regime II distinguishing the two overlapping regimes by Testik et al. (2011) was not noticed in our observations in Figure7(a, b, c).This may be because of the drop sizes and their eccentricities for these particular drop pairs that may contribute to changing the regime of the collision outcome. Eccentricity plays a crucial role in the occurrence of collision outcome and a specific breakup mode (SCH10). In agreement with Szakáll and Urbich (2018), our data also show that, although the parameters like the size of the colliding drops or their CKE are similar, the outcome of the collisions can end with filament breakup if eccentricity is high and with coalescence, if the eccentricity is low i.e., central collision (SCH10).

3.6 Fragment Size Distributions

The laboratory experiments and numerical study [LL82a,b; McFarquhar (2004); SCH10, and SA10] provide systematic parameterizations of the FSD after the collision induced breakup of the dropsand discussed the type of distribution function that is best able to describe natural rain. Moreover, the breakup phenomenon can be better understood if the resulting FSD analysis is carried out for the individual breakup type after collisional breakup. In the present study, the number of total fragments was measured from the photographs. The sizes of the fragments were computed using image-processing software - Image-J and categorized into bins with bin-width 0.5 mm. Among the three modes of breakup identified from the photographic evidences, the FSDs were obtained only for filament and sheet type of breakup. Due to the less number of observations obtained in the disk type of breakups, this data has not being considered for the statistical analysis of FSD.

Fragment size distributions after a binary drop collision depend on several factors such as drop sizes, drop velocities, drop CKEs, mode of a breakup, and angle of collision. Our data was not vast enough to satisfactorily group it into various categories which will be statistically rich enough to examine the dependence of FSD on all these factors. Nevertheless, we have tried to examine the tendencies of the FSDs with two major factors. Firstly, the whole data is divided into six different groups separately for the filament and sheet types of breakups under E_H = 0, 100, and 300 kVm^{-1} (Figure 8a). In the filament type of the breakup in absence of E_H, the FSD shows two peaks, one near d_L and the other near d_S alongwith some other fragments. When an electric field has been applied, the height of the peak for d_S slightly decreases and for d_L slightly increases. In sheet type of breakup in the absence of electric field, the FSD differs as compared to the filament type of breakup in three respects: i) both the d_S and d_L peaks are suppressed; (ii)the d_S peak slightly shifts to bigger sizes, (iii) the fragment numbers in other than d_S and d_L size-ranges increases. When the electric field is applied, the above changes in the FSDs are seen more prominently. Secondly, the whole data is divided into four groups of increasing values of CKE under E_H= 0, 100, and 300 kVm^{-1}(Figure 8b). There is a general tendency of the increase in the number of fragments of the sizes between d_S and d_L in different groups of increasing CKE in the presence of the electric field.

4. Conclusions

Main results of our experiment can be summarized as below:

The values of coalescence efficiencies of the 3.2 mm and 1.2 mm averaged diameter drops colliding with each other in the absence of electric field in our experiment compare well with the different parameterizations based on the empirical formula by LL82a and direct numerical simulations by SA10 considering different drop sizes involved in these studies (Table 1) However, as compared to the no electric field case where E_C is 30%, it decreased to ~ 24/21% when the collisions occurred for the similar drop pair in the presence of E_H = 100 /300 kVm^{-1}. Consequently, the horizontal electric field increases the probability of breakup of the temporarily coalesced drops as proposed by Bhalwankar et al. (2015).

As pointed out by Testik et al. (2011), one single parameter cannot properly define collision outcome. A plot of E_C vs. We (Fig. 4) shows that when We < 1, an increase in the electric field will reduce the probability of coalescence. However, when We   1, an increase in We will restrict the probability of coalescence.

Our data, when grouped in four categories of low to high CKE (Table 2) illustrate that, for a given large drop size, E_C decreases with an increase in the diameter of small colliding drops in E_H 300 kVm^{-1}. Further, for given sizes of small and large water drops, E_C also decreases with E_H but only for CKE of up to 1.9 µJ. Therefore, the drop growth occurs mainly through the drops of smaller sizes having small CKE.

For all the coalescence events in the present investigation, E_T lies in the range of 0.76 - 4.28 µJ which falls well below the limit of 5 µJ derived by LL82a as an upper limit of total energy necessary for coalescence to occur.

From our photographic observations, three modes of the breakup, viz. i) filament, ii) sheet, and iii) disk were observed. A general increase in the occurrence of coalescence has been observed with a reduction in drop sizes and for drops colliding at near-center eccentricities. Further, a greater probability of coalescences was observed when the values of CKE and We are low (Table 2). Moreover, a lower value of CKE is required for filament type than for sheet and disk types of breakups.

Plotting of our data points in the regime diagram in the We*- p plane delineates the collision outcomes i.e., coalescence and different breakup types in $E_H = 0$, 100, and 300 kVm^{-1}. Similar to the observations of Testik et al., (2011), we do observe the overlapping of some data points in the adjacent categories of the collision outcomes.

The relaxation time required for the coalescence to occur after a binary collision is higher than that for the breakup. Moreover, the relaxation time required for the breakup to occur increases from the filament to sheet to disk mode in all-electric field values.

The sizes of the selected drop pairs in our experiment fall in the region of a high collision rate and simulate the frequent collisions in stratified clouds with a precipitation intensity of ~5 mm/hour. Results of our experiment show that the electric field exerts a strong effect on the coalescence/breakup processes of the binary drop collisions. Therefore, collision outcomes are grossly influenced if the collisions occur under an electric field and this will affect the drop size distribution and thus the growth of drops. So, the results obtained in the past on the collision/breakup efficiencies in the absence of electric fields cannot be directly applied to calculate the drop size distribution in clouds.

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