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A wind tunnel investigation of the deformation of water drops in the vertical and horizontal electric fields

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[1] Deformation of the uncharged water drops freely suspended in a vertical wind tunnel and subjected to vertical, horizontal, or no external electric field is investigated using movie photography. Electric field elongates the drop along its direction, and the elongation increases with the increase in electric field. Horizontal electric fields are more efficient than vertical ones in deforming the drop. The larger the drop, the larger is the difference between the distortions in the vertical and horizontal field configurations. As compared to the case of no electric field, horizontal electric field, as low as 1 kV cm^{-1}, changes the ratio of minor-to-major axis of the 2.6-mm diameter drop by ~3%. An examination of the frequency distribution of the drop's axis ratio shows that during its oscillations, oblateness decreases more often when subjected to vertical electric field and increases more often when subjected to horizontal electric field. Extreme values of distortion increase and are attained more frequently when drop is oscillating in electric field. It is concluded that the drop size distribution will be wider and thus the rate of drop's growth faster in those regions of cloud where the electric field direction is vertical rather than horizontal.

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1. Introduction

[2] The shape of raindrops plays an important role in estimating the rainfall rate and the drop size distribution detected by weather radars. The shape of an uncharged drop is calculated by assuming the surface tension, hydrostatic, and aerodynamic forces acting on drop's surface to be in equilibrium [*Pruppacher and Beard*, 1970; *Pruppacher and Pitter*, 1971; *Beard and Chuang*, 1987]. For larger drops, these forces induce an oblate spheroidal shape with a smooth curvature at upper pole and flattened base at lower pole. This curvature asymmetry decreases with decrease in drop size, and the drop becomes spheroidal in shape. However, the raindrops located in regions of strong electric field in thunderstorms are influenced by the electrical forces. These electrical forces enhance the elongation of the drop in the direction of the electric field and thus change the preexisting asphericity of large drops resulting in the drop's instability. Theoretical models of *Brazier-Smith* [1971], *Chuang and Beard* [1990], *Coquillat and Chauzy* [1993, 1994], *Georgis et al.* [1997], and *Coquillat et al.* [2003], and laboratory simulation experiments of *Macky* [1931], *Ausman and Brook* [1967], *Abbas and Latham* [1969], *Richards and Dawson* [1971], *Griffiths and Latham* [1972], *Rasmussen et al.* [1985], *Kamra and Ahire* [1989], *Kamra et al.* [1993], and *Georgis et al.* [1997] confirm such elongation and breakup of drops.

[3] *Chuang and Beard* [1990] have extended their previous model for equilibrium shape of raindrops by including electrostatic effects, i.e., influence of vertical electric field and drop charges. Model raindrop shapes in strong electric field show that smaller drops approach a prolate spheroidal shape, whereas large drops develop more conical drop shape closer to those observed in wind tunnel experiments [*Richards and Dawson*, 1971; *Rasmussen et al.*, 1985]. Results show that for an electrically distorted raindrop, the dependence of drop shape on electric field is nonlinear because of the combined effect of electrical stress and aerodynamic force. Also, electric fields higher than predicted by *Taylor* [1964] are required for the onset of instability for large raindrops in downward than in upward electric field. Furthermore, presence of charge on the drop can decrease the field required for instability. *Coquillat and Chauzy* [1993] showed that the vertical stretching due to surface charge separation causes an increase in fall speed because of the equatorial radius reduction and provides a conical shape of large drops with flattened base and stretched upper pole. Drop shapes provided by their model are in good agreement with the work of *Chuang and Beard* [1990] under ambient field conditions, and the predicted critical field for disruption of drop is closer to experimental values of *Richards and Dawson* [1971].

[4] In thundercloud, the ambient electric field is generally considered to be vertical in direction. Therefore in most of the past studies of the effect of electric field on drop distortion, the electric field is taken as vertical. However, many in-cloud measurements show presence of large components of the horizontal electric field [e.g., *Winn et al.*, 1974]. Studies of *Kamra et al.* [1993] show that the values

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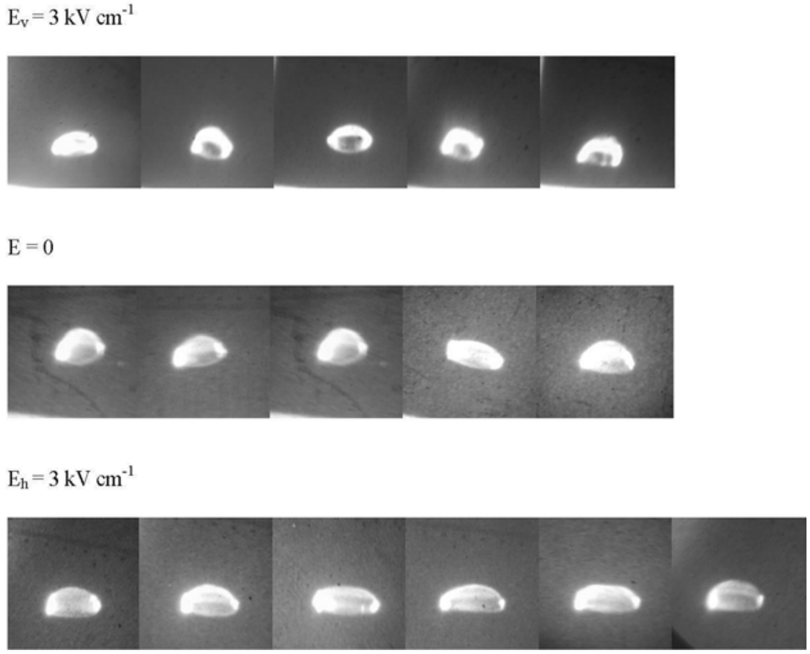

Figure 1. Typical photographs of the water drops of equivalent diameter 4.05 mm, suspended in (a) vertical, (b) no, and (c) horizontal electric field in the vertical wind tunnel. Time difference between the two consecutive frames is ∼20 ms.

of the horizontal electric field required for instability of drops are much lower than those either predicted by Taylor's criterion of instability or observed in earlier experimental studies. *Coquillat et al.* [2003] have numerically modeled the behavior of water drop in both horizontal and vertical electric field and computed the deformation, terminal velocity, and corona emission from water drops. Their calculations show large horizontal stretching with low axis-ratio values of the drops when they are subjected to different horizontal electric fields. Furthermore, their calculations support the experimental results of *Kamra et al.* [1993] that the drop disruption and the corona-onset fields are lower in the horizontal than in the vertical electric field. Their calculations also support the observations of *Kamra and Ahire* [1989] that the presence of electric charge on a drop leads to pronounced reduction of the disruption onset fields in vertical configuration. In horizontal fields, the values of corona and disruption onset field are reduced to the intensities that have been actually measured in thunderclouds. Detailed studies of the drop's distortion in the horizontal electric field are therefore essentially required for accurate assessment of the critical electric fields at which corona sets on or the drop disruption occurs.

[5] The goal of the present study is to compare the influences of the direction of the electric field, vertical and horizontal, on the distortion of the drop which leads to the breakup and initiation of corona from raindrops. We determine the average values of distortion of the drop freely suspended in a vertical wind tunnel and subjected to the vertical, horizontal, or no electric field from large number of drop's photographs such as those shown in Figure 1, taken with a movie camera. We also examine the frequency of the magnitude of drop's distortion with special emphasis on its extreme values during drop's oscillations.

2. Experimental Procedure

[6] Water drops of equivalent diameter $2.6 < d \leq 7.1$ mm are freely suspended at their terminal velocities in a small low turbulence vertical wind tunnel [*Kamra et al.*, 1986, 1991, 1993]. Water drops are freely suspended in a velocity well created in airflow with a cross-wire screen fitted between the diffuser and test section of the tunnel. Figure 2 shows a schematic diagram of the wind tunnel along with those of the cross-wire screen/electrode. To create vertical electric field, a flat circular aluminum plate of 38-cm diameter and 1.2-cm thickness with suitably rounded edges is mounted above the test section. This plate acts as a positive upper electrode as well as the back-pressure plate. The lower electrode is 25 × 25 cm in size and is made of iron wire mesh of size 8 meshes per inch. Lower electrode has a hole of 5-cm diameter at its center. A cross-wire screen made of 40 standard wire gauge (SWG) copper wire is fitted in this hole, and it creates the required velocity well for suspending water drops. The cross-wire screen is replaced with this electrode when taking observations in vertical electric field or without electric field. Lower electrode is fitted between the diffuser and test sections. The upper electrode is connected to a high-voltage power supply of 0–100 kV, and the lower electrode is grounded. Vertical distance between these two electrodes is 16 cm. With these vertical electric field arrangements, no measurable corona is observed from the electrodes even when potentials of up to 80 kV are applied to them.

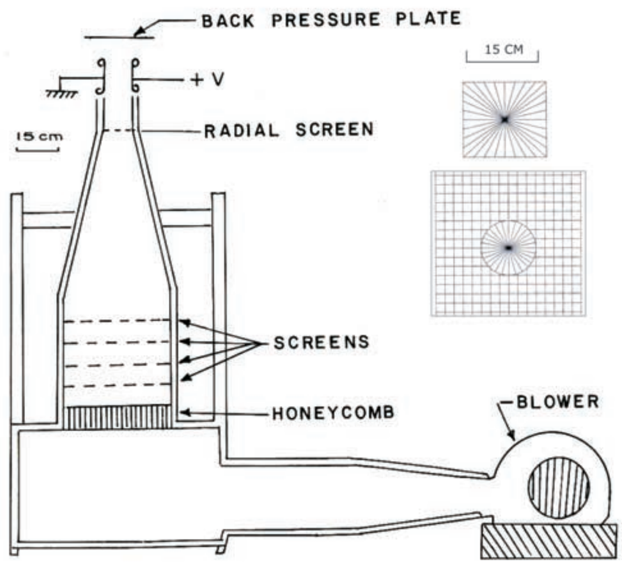

Figure 2. A schematic drawing of a vertical wind tunnel and the cross-wire screen/electrode used to create a velocity well (note different scales for the wind tunnel and screen/electrode drawings).

[7] To generate the horizontal electric field, two flat circular aluminum electrodes of 15-cm diameter and 2.2-cm thickness with edges suitably rounded and smoothened are mounted vertically above the test section. The two electrodes are separated by 12 cm from each other. Raising the potentials of electrodes up to 60 kV is not observed to produce any measurable corona from the electrodes.

[8] The turbulence levels measured in this tunnel with a hot-wire anemometer (Thermal Systems Inc., model 1054A) at different points across the test section and at different heights in the test section are reported earlier by *Kamra et al.* [1991]. These measurements show that the turbulence level with the cross-wire screen and the back-pressure plate in position did not exceed 0.8% in the center of test section where drops are suspended. The fact that suspension time and oscillating/vibrating characteristics of the suspended drops did not show any appreciable change when the cross-wire screen was replaced with cross-wire electrode to apply the vertical electric field indicates that this replacement did not make much difference in the turbulence level in the central portion of the test section where the drops are suspended. Air flows in the central portion of the test section in the two cases, most probably remain similar because of identical geometry of cross-wires in the central portions of the screen and electrode.

[9] Uncharged water drops of known volume are suspended with a grounded pipette above the test section of the tunnel and photographed with a 16-mm movie camera (Bell and Howell, DR-70) at a speed of 48 frames/s. One image of the drop is therefore obtained at every 20 ms during its different phases of oscillation and rotation. The drops are illuminated with 1-kW projection lamp in a dark-field background.

[10] Data on distortion of drops of 2.67-, 3.36-, 4.05-, 5.06-, 6.6-, and 7.1-mm diameter are collected in the absence or presence of both the vertical and horizontal electric fields of 0, 1, 3, and 5 kV cm^{-1}.

3. Data Analysis

[11] Deformation of a drop is computed by measuring the minor axis (b) and major axis (a) of the drop from photographs using a micrometer eyepiece in a microscope. A water drop freely suspended in a wind tunnel undergoes large prolate-oblate oscillations and vibrations around its mean shape. A photographic snap will image the drop in a particular mode of its oscillation. Averaging the data obtained only from a few snaps with a still camera will give only a rough estimate of the distortion. Moreover, in taking photographs at large intervals of time, one is likely to miss the drop's extreme distortion positions. Also, a change in drop's size because of its evaporation may be significant if observations are extended over a long period of time. Therefore to reduce the error, a large number of images ($\sim$100–1214 frames) taken at small intervals with a movie camera have been used to calculate the average axis ratio of a drop. Also, when taken in quick succession, these photographs are likely to cover some states of the extreme distortions of the drop. In both the vertical and horizontal electric field configurations, the residing time of the water drops in high electric field region is long enough to cover its natural oscillations.

4. Results

4.1. Distortion of Drops With or Without Electric Field

[12] The measured axis ratios (b/a) for uncharged drops of different diameters in vertical electric fields of 0, 1, 3, and 5 kV cm^{-1} in this experiment are compared to the wind tunnel experiment data of *Rasmussen et al.* [1985] in vertical electric fields of 0, 2, 4, and 5 kV cm^{-1} in Figure 3. Vertical electric fields of $<$5 kV cm^{-1} do not have any appreciable effect on b/a in case of drops of diameter $<$3.5 mm. The axis ratio b/a decreases with the increase in drop size but increases with the increase in vertical electric field. For example, a drop of 5-mm diameter falling in a vertical electric field of 5 kV cm^{-1} undergoes an increase in its axis ratio of about 10.5% as compared with that when the electric field is equal to zero. As the external electric field increases, the shape of a drop, as *Rasmussen et al.* [1985] puts it, "is the result of a complicated, continuously changing interplay between aerodynamic, surface tension, hydrostatic and electric forces." Experimental observations of *Rasmussen et al.* [1985] and theoretical model results of *Coquillat et al.* [2003] show that with further increase in electric field, the decreasing trend in b/a reverses and large drops become eventually spherical and then prolate. In still higher electric fields, larger water drops break up under the influence of the electric field. *Rasmussen et al.* [1985] extrapolated their experimental results and found the critical electric fields for drop's breakup to be equal to 10.38 and 9.23 kV cm^{-1} for two drops of 3.4- and 5.0-mm diameters, respectively. Also shown in Figure 3 are the axis ratios from the model results of *Chuang and Beard* [1990] and *Coquillat and Chauzy* [1993]. Present results appear to be consistent with those of the theoretical models in the respect that the axis ratio decreases with the increasing

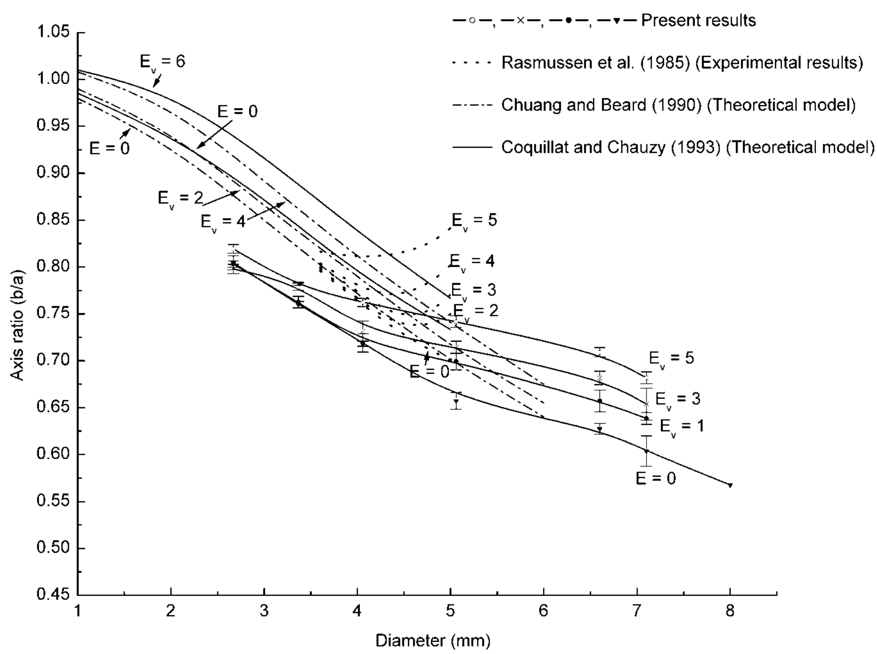

Figure 3. Variation of axis ratio with drop diameters for various external vertical electric field strengths. Also shown are the experimental results of *Rasmussen et al.* [1985] and with model results of (i) *Chuang and Beard* [1990] and (ii) *Coquillat and Chauzy* [1993]. All values of the vertical electric field (E_v) are in kV cm^{-1}.

drop diameter in all ambient electric field conditions. As compared with the theoretical model values, our results show slightly lower values of axis ratio in case of drops of diameter <4.5 mm and slightly higher values of axis ratio in case of drops of diameter >5.5 mm when these drops are subjected to vertical electric fields of up to 5 kV cm^{-1}. Enhanced influence of electrical forces on an oscillating drop in changing its axis ratio is expected because of larger accumulation of charge resulting in larger electric force per unit area on drop's deformed surface as compared to a drop which is prevented from oscillating and is forced to keep an equilibrium shape as in most of the theoretical treatments of the problem [*Pruppacher and Klett*, 1998]. The experimental data of *Rasmussen et al.* [1985] show an opposite trend of the increasing axis ratios when water drops exceed a critical size in the range of 3.4–5.2 mm for the range of electric fields examined in their experiments. Our observations in vertical electric field do show some flattening of the axis ratio versus drop diameter curve in this drop size range but not the increase in axis ratio with diameter as observed by *Rasmussen et al.* [1985] Values in the experiments of *Rasmussen et al.* [1985] and ours, however, will fall within the error bars if it is assumed that our results are slightly biased upwards or *Rasmussen et al.*'s [1985] results are slightly biased downward because of the difference in the airflow characteristics possibly resulting because of different experimental setups in their wind tunnels. There are no data available for comparison of our results for deformation of very large drops of diameter exceeding 6 mm.

[13] Figure 4 shows the change in axis ratio with drop diameter in absence as well as in presence of horizontal/vertical electric field. Vertical bars show standard errors along with the mean axis ratios. The numbers marked above the vertical bars show the number of images of each drop size used to calculate the average axis ratio of the drop. A comparison of the various curves in Figure 4 effectively demonstrates the stretching and elongation of the drop in the direction of electric field. Decrease in axis ratio with the increasing drop size is amply demonstrated for all values of electric field. However, as compared with the case when $E = 0$, vertical electric field decreases the oblateness and tends to make the drop more spherical. On the other hand, horizontal electric fields increase the oblateness of the drop as compared with the case when there is no electric field. Moreover, horizontal electric fields are more effective than the vertical in distorting the drop; the larger the drop, the larger is the difference between the axis ratios produced by the vertical and the horizontal field configurations. For example, an electric field of 3 kV cm^{-1} changes the axis ratio of a 4.05-mm drop by 6.3% if the electric field is horizontal, but only by 1.74% if the electric field is vertical. The observation well illustrates the fact that both aerodynamic and electrostatic distortions act together in a horizontal electric field but counteract in a vertical field. It is important to note, however, that there is sizable difference in the ratio b/a between the field and no-field configurations even in case of drops of diameter < 4 mm when the electric field is horizontal. For example, vertical electric field of 1 kV cm^{-1} or less has no or negligible influence in distorting the drops of diameter < 4 mm. On the other hand, horizontal electric field of the same magnitude changes the axis ratio of 2.6 mm diameter drops by ~3% of the value when $E = 0$. Effect of electric field in changing axis ratio of the drops larger than 4 mm in diameter is much stronger if the field is horizontal rather than vertical.

[14] Behavior of the curves in Figure 4 again significantly changes for very large drops exceeding 6.5 mm in diameter.

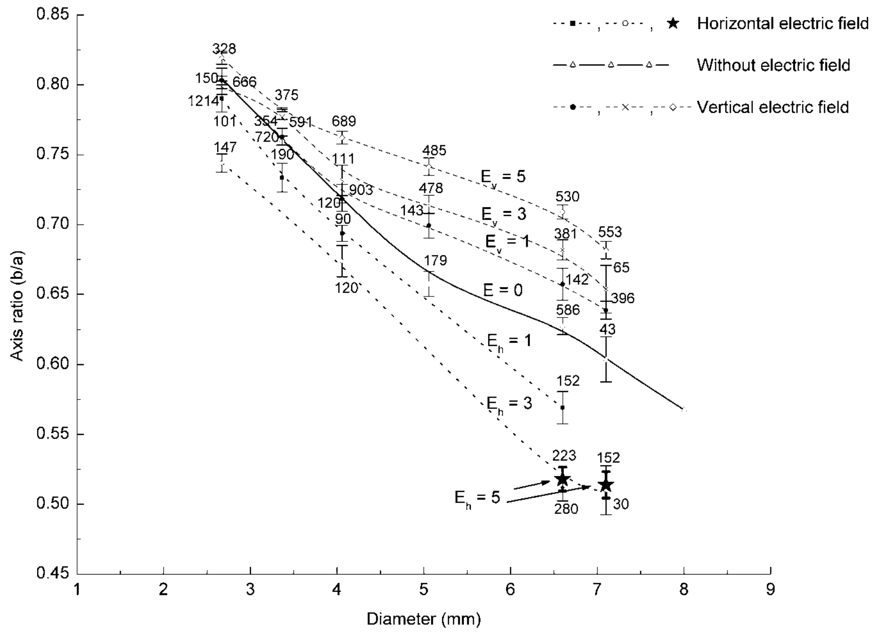

Figure 4. Change in axis ratio (b/a) of the drop with drop diameter in absence and presence of horizontal/vertical electric field strength of 1, 3, and 5 kV cm^{-1}. All values of the vertical and horizontal electric field, E_v and E_h, respectively, are in kV cm^{-1}.

While the curves in case of vertical electric field become steeper for drops of diameter > 6.5 mm, the curve in case of horizontal electric field of 3 kV cm^{-1} for such large drops shows a tendency to flatten and level off when the value of axis ratio becomes ~0.5. Moreover, value of axis ratio does not become lower than this value even when higher values of horizontal electric fields are applied. For example, the lowest value of axis ratio still remains at 0.5 even when horizontal electric field of 5 kV cm^{-1} is applied around such very large drops. It is likely that at this value of average axis ratio, distortion of the drop is sufficient to cause its breakup. In the absence of electric field, drops can attain this value as their size increases. For example, the wind-tunnel measurements of *Pruppacher and Pitter* [1971] also show that the largest stable drop in quiet air is 9.0 mm in diameter whose axis ratio is 0.55. However, the electrostatic forces acting in presence of the horizontal electric field cause even smaller drops to attain these values: the higher the electric field, the smaller is the drop size which can attain this axis ratio. Observations of *Kamra et al.* [1993] show that half-life of drops decreases with the increase in horizontal electric field and that a higher number of drops break up if the value of applied horizontal electric field is increased. For example, the number of 6.3-mm diameter drops that breaks up increases from 20% to 70% or 90% when the horizontal electric field is increased from 300 to 400 or 500 kV m^{-1}, respectively.

[15] *Coquillat et al.* [2003] have recently studied the distortion of uncharged drops falling at their terminal velocities in quiescent air in a horizontal electric field in a theoretical model. In Figure 5, we compare results of our experiment in horizontal electric field with the model results of *Coquillat et al.* [2003]. Somewhat lower values of axis ratio in our experimental results as compared to theoretical values in Figure 5 are most likely due to neglect of the oscillations of the drop in theoretical models. As explained in detail in section 4.1, enhanced influence of electrical forces on an oscillating drop in changing its axis ratio is not considered in theoretical models (see also *Pruppacher and Klett* [1998] for details). The theoretical and experimental curves in Figure 5, however, show two similar features. First, both sets of curves show nonlinear increase in drop distortion with the increase in drop size and horizontal electric field. Second, although theoretical curves are limited to 5.0-mm drops only, both sets of curves indicate a tendency of leveling off when the axis ratio attains a value of about 0.5 under the combined effect of increasing either drop size or electric field.

4.2. Drop Oscillations in Electric Field

[16] The water drops freely suspended in an airstream are known to oscillate in the prolate-oblate mode. Magnitude of oscillations, however, differs from one oscillation to the other. Most of the experimental studies and all theoretical models compute the average axis ratios for distorted drops. The average axis ratio of an oscillating drop differs from its equilibrium value. *Beard* [1984] has shown that prolate-oblate oscillations about an equilibrium raindrop shape produce a shift in the average axis ratio toward higher values. The shift would increase or decrease in the presence of electric field, depending on its direction, because the stresses acting on the drop change as the drop changes its shape. Moreover, it is important to know the extreme values of axis ratio which an oscillating drop undergoes. Knowledge of such maximum distortion is particularly important when the drop is oscillating in presence of an electric field, as such extreme values of drop's distortion may initiate

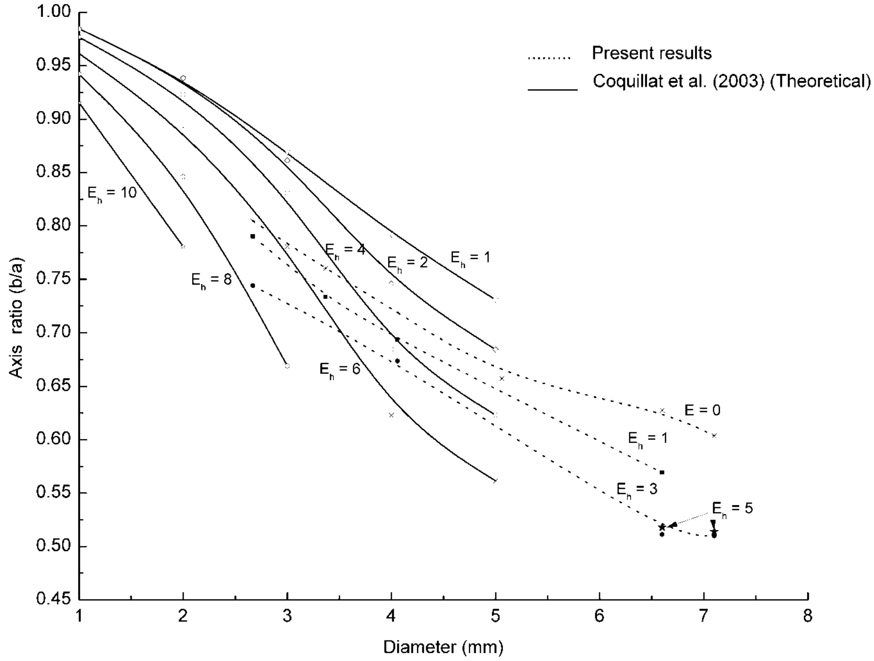

Figure 5. Comparison of axis ratio of present experiment results with the model results of *Coquillat et al.* [2003] for different drop sizes in various horizontal electric fields. All electric field values are in kV cm^{-1}.

instability and cause corona discharge from water drops [*Kamra et al.*, 1993].

[17] In this experiment, we study the frequency distribution of axis ratios which an oscillating drop attains in its deformed state in each oscillation under different electric fields. To compute the frequency of axis ratio of an oscillating drop in an electric field, the axis ratio of every individual drop image in electric field is subtracted from the average value of axis ratio in the no electric field case. This difference is plotted on the x axis in 0.05 interval. The number of times this difference attains a value is plotted on the y axis as percentage of the total number of drop images counted in a particular value of electric field. Figures 6a and 6b show these values for all drops oscillating in the vertical and horizontal electric field, respectively, of 0, 1, 3, and 5 kV cm^{-1}.

[18] In Figure 6a, the center of gravity of histogram shifts toward negative side of the x axis as the electric field increases, indicating that the drop becomes less oblate more often during its oscillations in higher vertical electric field. On the other hand, in Figure 6b, the center of gravity of histogram shifts toward positive side of the x axis as the electric field increases, indicating that the drop becomes more oblate more often during its oscillations in higher horizontal electric field. Moreover, when the drop is subjected to the vertical or horizontal electric field, the maximum value of the oblateness of the drop increases although for a very small number of times, as compared with the case when electric field is absent. This is likely to happen because of the feedback action of distortion and the electric field enhancement at the drop's surface as suggested by *Kamra et al.* [1993]. Although these extreme values of distortion may be attained very rarely, the drop's shape in such oscillations may cause initiation of corona discharge at their surfaces which may eventually result in triggering a lightning discharge. Any effect of the cross-wire screen/electrode on drop's oscillations can be ignored here in view of the fact that for taking drop's photographs in both cases, with and without electric field, the screen and electrode were kept in the same positions.

5. Applicability of the Results to Thunderclouds

[19] Extension of the experimental results obtained on behavior of the water drops suspended in wind tunnels to the raindrop's behavior in clouds has quite often been doubted on grounds of the different windflow patterns and turbulence conditions in the two environments. The present results for the vertical, horizontal, or no electric field conditions have the unique advantage of being obtained in the same experimental setup. Placing the cross-wire screen/electrodes in order to apply the vertical or horizontal electric fields, as discussed earlier in section 2, does not significantly influence the turbulence level at the place of suspension of drops. To our knowledge, this is the first time that the drop's distortion results obtained in all the three electric field conditions with the same experimental setup are being reported. The relative results obtained in different electric field conditions in this experiment can thus be applied to raindrops in clouds with a higher degree of confidence.

[20] In absence of electric field, value of axis ratio of the oblate-shaped drop monotonically decreases as the drop size increases (Figure 4). This decrease in axis ratio continues up to a critical value when the drop becomes unstable and breaks up. Electrical forces in presence of horizontal electric field stretch the drop along its major axis and enhance its oblateness. As a result, smaller drops may attain the critical value for breakup in presence of the horizontal electric

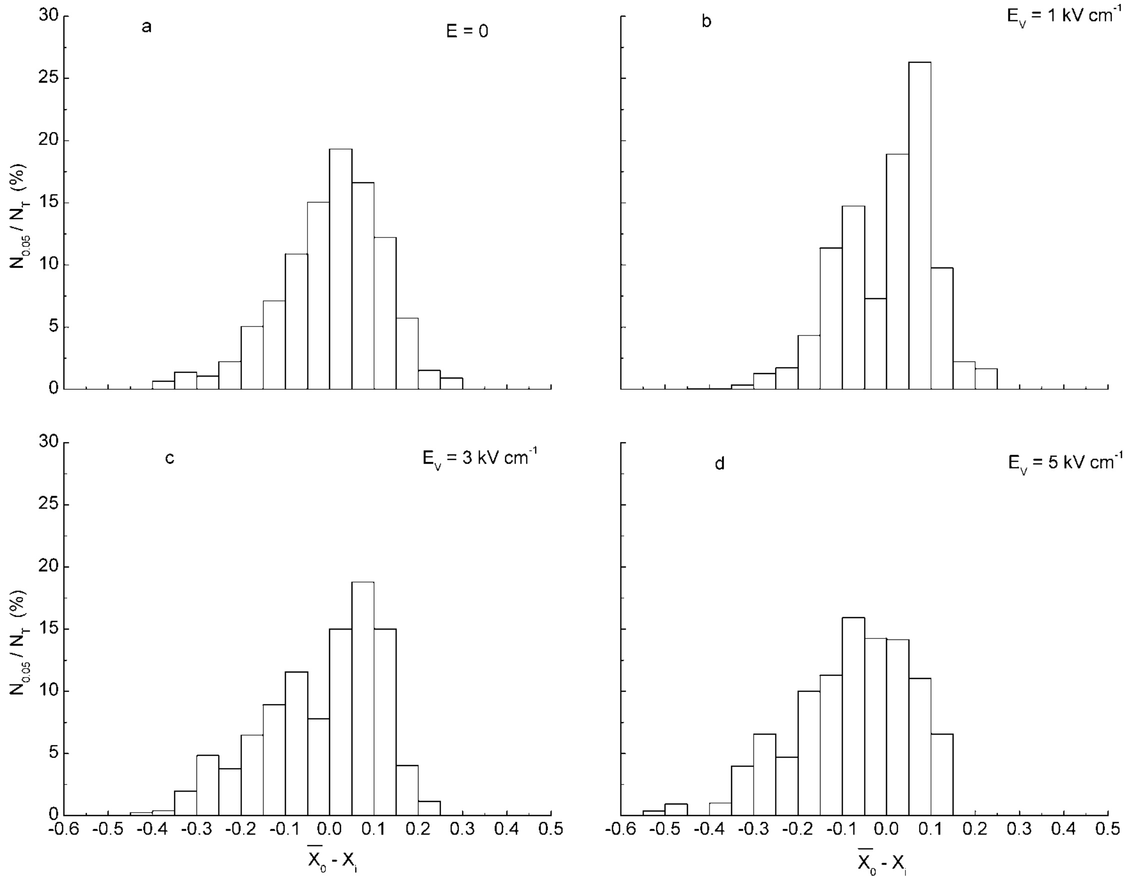

Figure 6. (a) Histograms showing the variation of $\overline{X}_0 - X_i$ with $N_{0.05}/N_{\mathrm{T}}$ in vertical electric field of 0, 1, 3, and 5 kV cm^{-1}. $\overline{X}_0 - X_i$ is the difference between the mean axis-ratio value in no electric field and the axis ratio of individual drop image in electric field. $N_{0.05}/N_{\mathrm{T}}$ is the ratio of number of drops in 0.05 interval ($N_{0.05}$) and total number of drops (N_{T}) of all sizes, in percentage. (b) As in Figure 6a but in horizontal electric field.

fields. For example, oblateness of 7.1-mm drops in Figure 4 attains a value of 0.5 in electric field of 3 kV cm^{-1}. Increase in electric field to 5 kV cm^{-1} does not appreciably change its oblateness, so that this value of oblateness may be close to the critical value for 7.1-mm drop's breakup in electric fields of 3 kV cm^{-1}. On the contrary, the electrical forces in presence of vertical electric fields stretch the drop along its minor axis and tend to make it spherical in shape. So in contrast to the tendency of the drop becoming more unstable with the increasing size in horizontal electric field, the vertical electric fields tend to make it more stable. However, at very high values of vertical electric fields, the drop becomes prolate and unstable in shape. Therefore while all horizontal electric fields tend to make drops more unstable, weak or moderately strong vertical electric fields tend to make them more stable, and very strong electric fields tend to make them unstable. Therefore larger drops which are able to survive in regions of vertical electric field can break up in regions of similar horizontal electric field. It follows therefore that the drop size distribution is expected to be much different and extend to much larger sizes in regions of cloud where the prevailing fields are vertical rather than horizontal. Now as per calculations of *Braham* [1968], the larger size and broad size distributions of drops cause a drop to grow faster in maritime clouds than in continental-type clouds where the maximum size of the drop is comparatively smaller and the drop size distribution is narrow. Computations of *Chin and Neiburger* [1972] also show that drop growth rate is a sensitive function of the drop size distribution. Chin and Neiburger computed that the drop growth rates in a cloud with monodisperse drops are much smaller than in a polydisperse cloud with the same liquid water content and mean volume radius. It happens because of larger relative terminal velocity of the collector drop and the larger number of collisions it undergoes per unit time during its fall in maritime clouds. For similar reasons, it is expected that the drop's growth rate by the collision and coalescence process will be faster in the regions of the cloud having vertical rather than horizontal direction of electric field.

[21] Results of this experiment confirm the elongation of water drops in the direction of electric field. Earlier experiments of *Kamra et al.* [1993] demonstrate that this field-induced elongation can cause the breakup of drops if they exceed 6.6 mm in diameter. Furthermore, the electric field required for breakup of drops is smaller if the field is horizontal than vertical in direction. On the basis of these results, *Kamra et al.* [1993] concluded that the corona triggering from large raindrops, although small in concentration, in horizontal electric field may be responsible for the

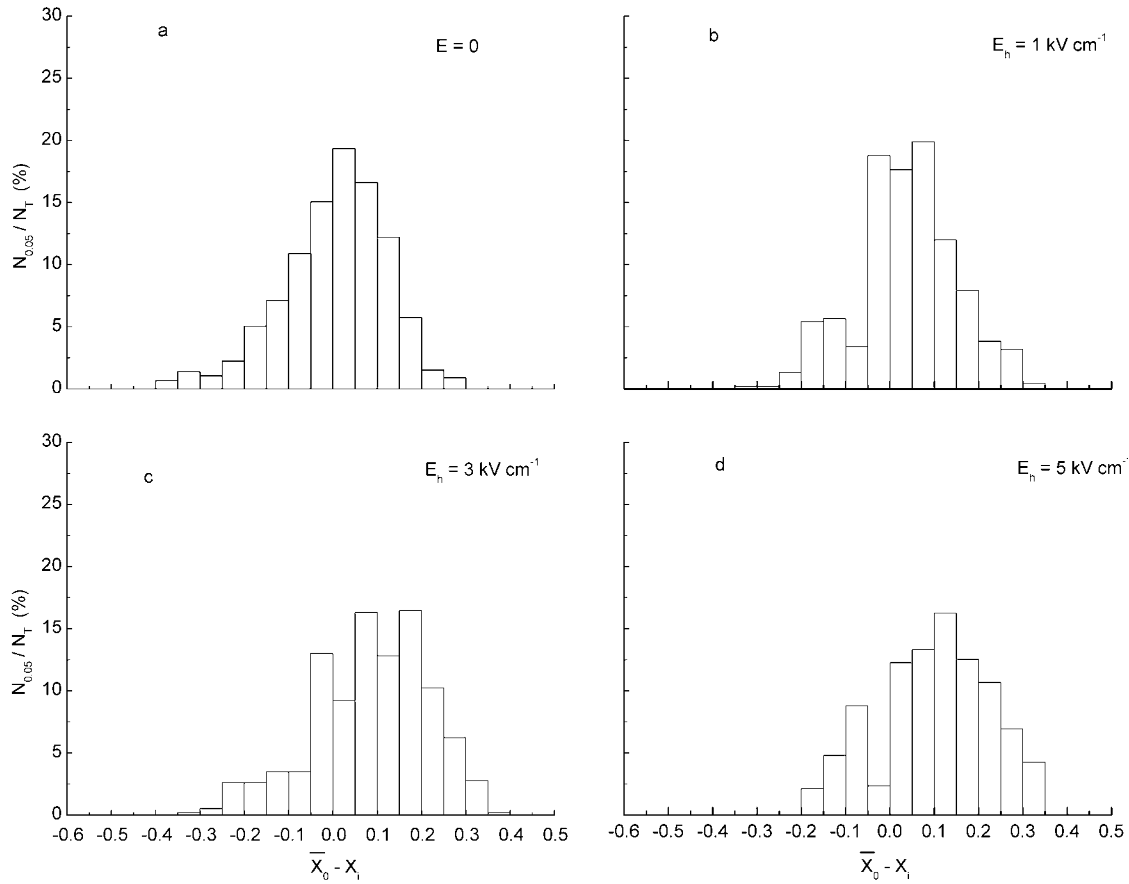

Figure 6. (continued)

lightning discharge initiation. Recent theoretical modeling results of *Coquillat et al.* [2003] sustain these conclusions. The present results not only quantify the higher degree of drop distortion when these are suspended in horizontal rather than in vertical electric field but also support the stronger effect of horizontal than vertical electric field in the drop breaking process.

[22] The present results demonstrate that both the magnitude and direction of electric field affect the stability of water drops. The raindrops falling in a thundercloud pass through different regions where both the magnitude and direction of electric field differ. Above results imply that large drops are more likely to break in those regions of clouds where the prevailing electric field is horizontal rather than vertical. The implication suggests that drop size distribution in a region of cloud may be influenced by the direction of the electric field. Whether this difference in drop size distribution can be used to locate by remote sensing the regions of cloud having different directions of electric field needs to be investigated (*Zrnić et al.*, 1984).

6. Conclusions

[23] Distortion of the shape of a freely suspended drop increases with its size. External vertical and horizontal electric fields elongate the drop along the direction of electric field. Horizontal electric field is more efficient than vertical one, and the difference in distortion of the drop between the vertical and horizontal field configurations increases with the increase in drop size. Consequently, drops will break up more readily if the external electric field is horizontal rather than vertical in direction. Therefore the size distribution of drops is expected to be wider, and therefore the drop growth is likely to be faster in those regions of cloud where vertical rather than horizontal electric fields prevail.

[24] **Acknowledgment.** We are thankful to A. B. Sathe for his help in taking observations.

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