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Wind-Tunnel Studies of the Shape of Charged and Uncharged Water Drops in the Absence or Presence of an Electric Field

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ABSTRACT

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Experimental results on the shape of charged and uncharged water drops suspended above the test section of a vertical wind tunnel and subjected to a vertical or horizontal electric field, are reported. The equivalent spherical radii, a_0, of uncharged water drops ranged from 1.75 to 3.30 mm, and that of the charged water drops from 1.50 to 3.20 mm. Our results show that the external vertical or horizontal electric fields up to 5 kV cm^{-1} and 3.5 kV cm^{-1}, respectively, do not significantly affect the shape of uncharged drops. Also the shape of charged drops carrying charges of up to half of Rayleigh's limit and falling in the absence of an electric field, does not show any significant changes. However, when charged drops of $a_0 = 2.0$ and 2.5 mm carrying electric charges of $2.5 \cdot 10^{-10}$ C and $5.0 \cdot 10^{-10}$ C, respectively (about one fifth and one seventh of Rayleigh's limit for the respective sizes), fall in the presence of a vertical electric field, a significant increase in distortion ratio is observed as the electric field is increased from zero to 4 kV cm^{-1}. The significance of the results in the evolution of precipitation in electrical environments of thunderstorms is discussed.

RESUME

On présente des résultats expérimentaux sur la forme de gouttes d'eau chargées et non chargées suspendues dans une soufflerie verticale, et soumises à un champ électrique vertical ou horizontal. Les rayons équivalents, a_0, des gouttes d'eau non chargées vont de 1,75 à 3,30 mm, et celles des gouttes chargées de 1,50 à 3,20 mm. Les résultats montrent que des champs électriques verticaux ou horizontaux aussi élevés que respectivement 5 kV cm^{-1} et 3,5 kV cm^{-1} n'ont pas d'influence appréciable sur la forme des gouttes non chargées. De même, la forme de gouttes portant des charges jusqu'à la moitié de la limite de Rayleigh, et tombant en l'absence de champ électrique, ne présente pas de changement notable. Cependant, si des gouttes de rayons $a_0 = 2{,}0$ et 2,5 mm portant des charges de respectivement $2{,}5 \cdot 10^{-10}$ C et $5{,}0 \cdot 10^{-10}$ C (environ 1/5 et 1/7 de la limite de Rayleigh pour les dimensions respectives), tombent en présence d'un champ vertical, on observe une augmentation significative du taux de déformation lorsque le champ élèctrique passe de 0 à

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4 kV cm^{-1}. On discute du sens de ces résultats sur l'évolution des précipitations dans l'environnement électrique des orages.

INTRODUCTION

Hydrometeors back-scatter the incident electromagnetic energy emitted by radars. Propagation and back-scattering of these electromagnetic waves as detected by weather radars are strongly influenced by raindrop shape (e.g. see review articles by Oguché, 1981 and Rogers, 1984). This fact has been used to derive information on raindrop shape and rainfall from radar observations. For example, differential reflectivity measurements of Seliga and Bringi (1976) and Seliga et al. (1981) show much improvement in determining the size distribution of raindrops and rainfall rates by radar. These measurements have also the possibility of defining the hydrometeor type (Humphries and Barge, 1979; Hall et al., 1980). Such studies are based on the knowledge of a relation between raindrop shape (distortion ratio) and size. Thus an accurate computation of rainfall rate requires an accurate relationship between drop shape and size. So far, rainfall rate computations have been made on the basis of drop shapes theoretically predicted by Pruppacher and Pitter (1971) and verified by the wind tunnel experiments of Pruppacher and Beard (1970) and others. Theoretical estimates of the drop deformation have since been improved in recent works such as that of Beard (1984) and Beard and Chuang (1987). In calculating these drop shapes, it is assumed that surface tension force, internal hydrostatic force and aerodynamic force acting on the drop are in equilibrium, and are the only acting forces. Effects of electrostatic forces on drop shape are, thus, generally neglected in such computations. However, some investigators have studied the distortion ratio of the drop as a function of the external electric field and its charge and equivalent spherical radius. Their results are summarized below.

Assuming the drop to be static and originally of spherical shape, O'Konski and Thatcher (1953), Taylor (1964), Abbas and Latham (1969) and Brazier-Smith (1971), have theoretically studied the change in drop shape under different electric fields. These studies show that the drop deforms from oblate to a prolate spheroid as the external vertical electric field is increased. Results of these studies, particularly their prediction of the maximum deformation of the drop before its break-up, are in fairly good agreement. Richards and Dawson (1973), using numerical methods, calculated the aerodynamic pressure profiles around the drops from photographs of the drops falling at a terminal velocity in an electric field. Green (1975), although not incorporating any electrical effects, took account of the internal pressure and aerodynamic forces for determining the drop shape, neglecting the hydrodynamic flow in and around the drop. Using Green's model, however, Zrnic et al. (1984) calculated the

eccentricity of the drop in terms of the external electric field and the charge of the drop. The results of Zrnic et al. are of particular importance to our experiments to be described here. According to their theoretical results, electric fields required for distortion of the drops are much larger than those typically observed in clouds. However, when these drops carry electrical charges of the order of magnitude sometimes observed in drops in intensely electrified regions of thunderstorms then the oblateness of the drop is enhanced. Results of wind tunnel studies of Richards and Dawson (1971), however, do not agree with the prediction of Zrnic et al. (1984).

In most of the experimental studies (Wilson and Taylor, 1925; Nolan, 1926; Macky, 1931; Ausman and Brook, 1967; Mathews, 1967; Griffiths and Latham, 1972) on the influence of electrical forces on drop shape, the emphasis was on determining the critical condition for break-up of the drop. Consequently, not much information was given for quantitative determination of the change in drop shape with changes in external electric field and size and charge of the drop. Moreover, drops in these experiments were not falling at their terminal velocity and entered adruptly into an electric field region created between two electrodes. Under these conditions drops may not get enough time to adjust their shapes under different forces acting on them.

Recently, Rasmussen et al. (1985) investigated the effect of a vertical electric field on the shape of uncharged water drops falling at their terminal velocities. Their results show that for distortion of uncharged drops of equivalent radii equal to 1.7 mm and less, the electric field needs to be about 5 kV cm^{-1}. For larger drops, they report some distortion even at weaker electric fields. They extrapolate their results to show that critical electric fields required for break-up of drops, may not be independent of their size, as previously thought, but may be smaller for small drops and larger for large drops. In their experiments, however, they did not study charged drops or drops falling in horizontal electric fields. In the present study, we have investigated this problem in a small vertical wind tunnel and tried to choose the values of different parameters such that the results could be applied to thunderstorms. Magnitudes of electric fields, drop charges, drop sizes, etc. taken here are comparable to those that exist in active thunderstorms. Both charged and uncharged water drops in the absence of or exposed to vertical or horizontal electric fields have been used. Possible application of these results to thunderstorms are also discussed. It is hoped that such studies will be of use to radar meteorologists for computations of drop size distributions and rainfall rate and also in locating the regions of intense electrification in thunderstorms.

EXPERIMENTAL SET-UP

The present experiments were carried out in a low-turbulence, small vertical wind tunnel (Kamra et al., 1986). Fig. 1 shows a schematic diagram of the set-

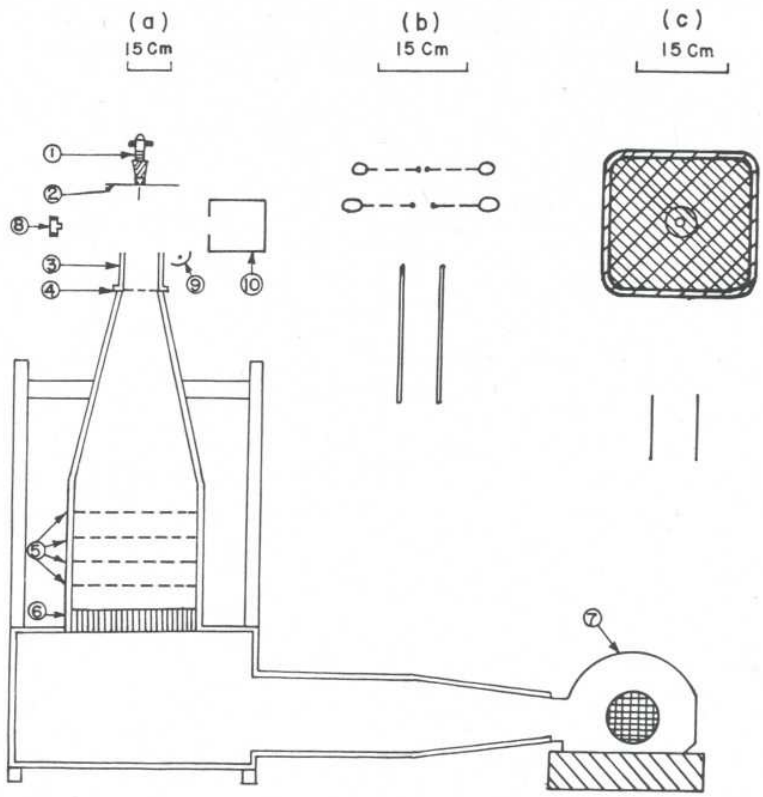


Fig. 1. Schematic diagram of a vertical wind tunnel with horizontal and vertical views of the test-section and electrodes required to produce vertical and horizontal electric fields: 1 = hypodermic syringe; 2 = back pressure plate; 3 = section of uniform cross-section; 4 = radial screen; 5 = screens; 6 = honeycomb; 7 = blower; 8 = camera; 9 = light source; 10 = black box. (b) Horizontal view of the high voltage electrodes. (c) Vertical view of the high voltage electrodes.

up with vertical and horizontal views of the electrodes. The drop was suspended in between the two electrodes. Air velocities up to 12 m s^{-1} could be achieved in the test section (cross-section 12×12 cm^2) of the wind tunnel. A cross-wired screen generated a velocity-well where a drop could be suspended for many minutes. All experiments reported here were performed in an open atmosphere of about 950 mb atmospheric surface pressure. Observations extended over several days at different times in a year when the temperature varied in the range of 25°–35°C and relative humidity in the range of 15–40%. The results can be divided into two parts. In the first part we deal with the uncharged water drops and in the second with the charged water drops. The equivalent radii, a_0, of the uncharged water drops ranged from 1.75 to 3.30 mm and those of charged water drops from 1.50 to 3.20 mm. In order to simulate the effects of electric fields in thunderclouds, we applied external electric fields (vertical or horizontal) on the drop suspended above the test section of the wind tunnel.

Vertical electric field arrangement

Two specially constructed screens were used as electrodes. These electrodes were mounted horizontally above the test section of the tunnel with a vertical separation of 6.5 cm. The lower electrode was 25×25 cm^2 in size and was made of an iron wire mesh of 8 meshes per inch, and the upper electrode was 22×22 cm^2 in size and made of a copper wire mesh of 21 meshes per inch. The ends of each wire mesh were soldered between two thick copper strips, also soldered together, and their corners were smoothened to increase the corona threshold. The upper electrode had a 2-cm diameter hole at its centre for bringing the water drops into the region of the electric field. The lower electrode had a hole of 5 cm diameter at its center in order to reduce the turbulence in the region of the electric field. These holes in the electrodes caused some non-uniformity in the vertical electric field between the electrodes. However, this non-uniformity is minimum and the electric field can be assumed to be nearly vertical near mid-way of the electrodes and along the axis of air flow where the drop is suspended (Smythe, 1939). The upper electrode was kept at the ground potential while the lower electrode was connected to a d.c. power supply of ± 50 kV. In all our experiments, the lower electrode was raised to positive potentials and no attempt was made to make measurements in a reversed polarity of the electric field. Uncharged water drops were introduced in the test section of the tunnel by means of a hypodermic syringe or glass capillary. In order to suspend the water drops mid-way between the two electrodes, the velocity-well was located there by placing a back pressure plate 12 cm above the upper electrode. The back pressure plate had a cross-section of 20×20 cm^2 and was connected to the ground. The syringe was fixed into the back pressure plate.

Water drops of required size were first released by the calibrated syringe. The suspended drops were then subjected to the desired value of electric field strength by applying the necessary potential to the lower electrode. With the present set-up, vertical electric fields up to 5 kV cm^{-1} could be applied with no significant corona occurring from the electrodes. Air velocity was somewhat reduced when an electrode was placed horizontally over the cross-section of the tunnel. In spite of some turbulence produced by the presence of the electrodes, drops could be suspended for many minutes.

Horizontal electric field arrangement

Two identical rectangular brass electrodes, $11 \times 21 \times 0.32$ cm in size, with rounded corners had been constructed for this purpose. These electrodes were placed vertically with a horizontal separation of 8 cm. External horizontal fields were generated by applying a positive d.c. high voltage to one of the electrodes while keeping the other electrode at ground potential. The back pressure plate is kept at a distance of 8.5 cm above the top of the electrodes and was grounded.

With this setup, horizontal electric fields up to 3.5 kV cm^{-1} could be applied with no significant corona occurring from the electrodes.

OBSERVATIONAL TECHNIQUE

The equivalent spherical size of the drop was measured by mechanically collecting it in a small glass container having a close fitting top and was weighed in a microbalance with a sensitivity of 0.1 mg. The drops were illuminated with a 150-W projector and photographed with a 35-mm camera (F2, 1/500 s). The camera was placed perpendicular to the beam of light and against a dark background. A solution of sodium chloride and silver nitrate (1 part in 10^5 parts of triply distilled water) was used for the water drops (Blanchard, 1948). This provides a colloidal solution of silver chloride. When used in such low concentrations these substances are not likely to produce appreciable changes in electrical properties or surface tension of water.

The drop shape was determined from the measurements of the distortion ratio (or deformation parameter), b/a, which is the ratio of the semi-minor to the semi-major axis of the drop. In these experiments, the major and minor axes of the drop were measured from photographs. If the exposure time of a photograph is less than the oscillation or vibrational frequency of the drop, the photographic impression of the drop will depend upon the phase of the oscillation or vibration of the drop during the exposure time. This will lead to some error in the measurements of b/a. However, to minimize this error, we have taken 12 photographs for each case of a drop and each point in our observations is an average of 12 observations.

Our experiments described in the first part were performed with uncharged water drops of sizes $a_0 = 1.75$, 2.65 and 3.30 mm and $a_0 = 1.8$, 2.4 and 3.3 mm for the vertical and horizontal electric field studies, respectively. In the second part of our experiments, we studied the shape of electrically charged water drops. These drops were charged by inserting a wire in the triply distilled water in the syringe and raising it to the desired positive d.c. voltage. The deformation of the charged drops was first investigated in the absence of electrodes. The back pressure plate was kept 21 cm above the test section. Three different sizes of water drops were used, with $a_0 = 1.50$, 2.55 and 3.20 mm and with charges to approximately one tenth and one half of the Rayleigh limit. For comparison also uncharged drops of similar sizes were studied.

In the next case, vertical electric fields were applied. Charged drops were first introduced in the test section of the tunnel in the absence of an electric field. The positive d.c. potential of the lower electrode was then increased so as to get a vertical electric field with the desired value. As we increased the electric field, the terminal velocity of the charged water drops continuously decreased due to electrostatic force acting on the drop. This was, however, compensated by simultaneously decreasing the wind speed in the tunnel while

increasing the electric field. Two drop sizes are used of $a_0 = 2.0$ and 2.5 mm, carrying electrical charges of $2.5 \cdot 10^{-10}$ C and $5.0 \cdot 10^{-10}$ C, respectively, which are about one fifth and one seventh of Rayleigh's limit for the respective sizes of drops. The vertical electric field is varied from 0 to 4 kV cm^{-1}.

Studies on charged drops falling at terminal velocities in horizontal electric fields are not possible with the present experimental setup because the horizontal electric field causes the charged drop to come out of the velocity-well and the air stream. Horizontal electric fields of about 1 kV cm^{-1} or less are sufficient to displace the drops of sizes and charges studied here.

The calibration of the electric charges of drops was done by collecting them outside the test section in a copper cylinder shielded with another grounded aluminium cylinder. The copper cylinder was placed on a teflon sheet and connected to a Keithley electrometer. The values of the drop sizes, drop charges and voltages applied to the syringe or the capillary were noted. Similar values were used when introducing drops of the required size and charge in the region of the electric field.

RESULTS AND DISCUSSIONS

Results of our experiments with uncharged water drops are shown in Figs. 2 to 4. Vertical dotted lines in these and all the following figures show the error bars. The large circles, crosses and triangles show the mean values and the smaller ones show the respective extreme values. Each data point represents

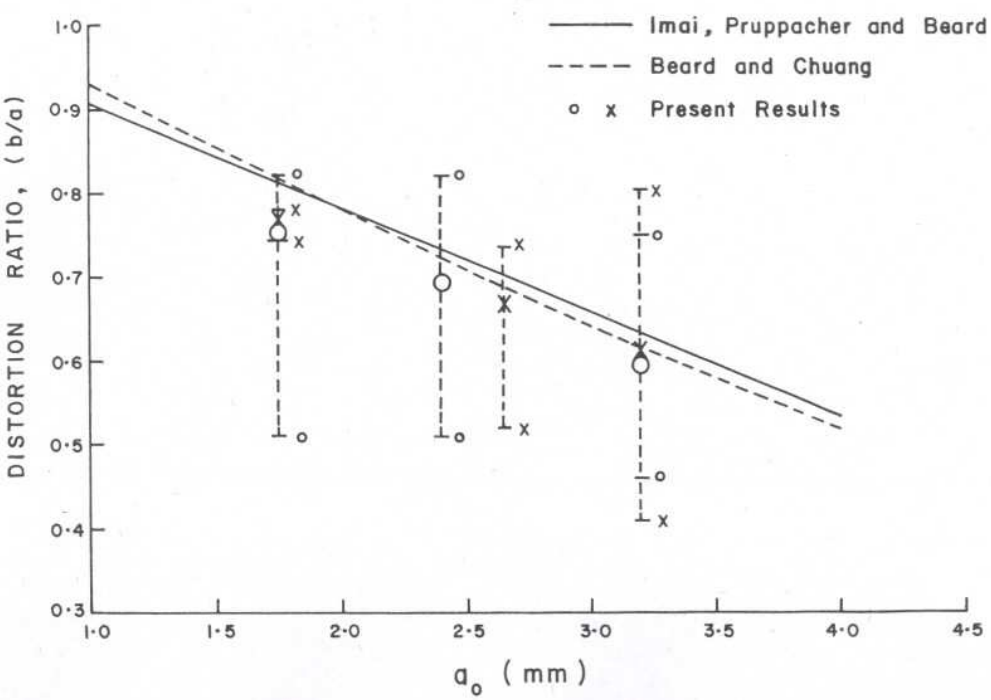


Fig. 2. Variation of distortion ratio with equivalent drop radius with electrodes arranged in vertical (×) or horizontal (○) field configurations.

an average value of 12 photographic measurements of the distortion ratio, b/a.

Fig. 2 shows the variation of distortion ratio with equivalent radius, a_0, of the drop. These observations were made for $E_0=0$ but with electrodes arranged

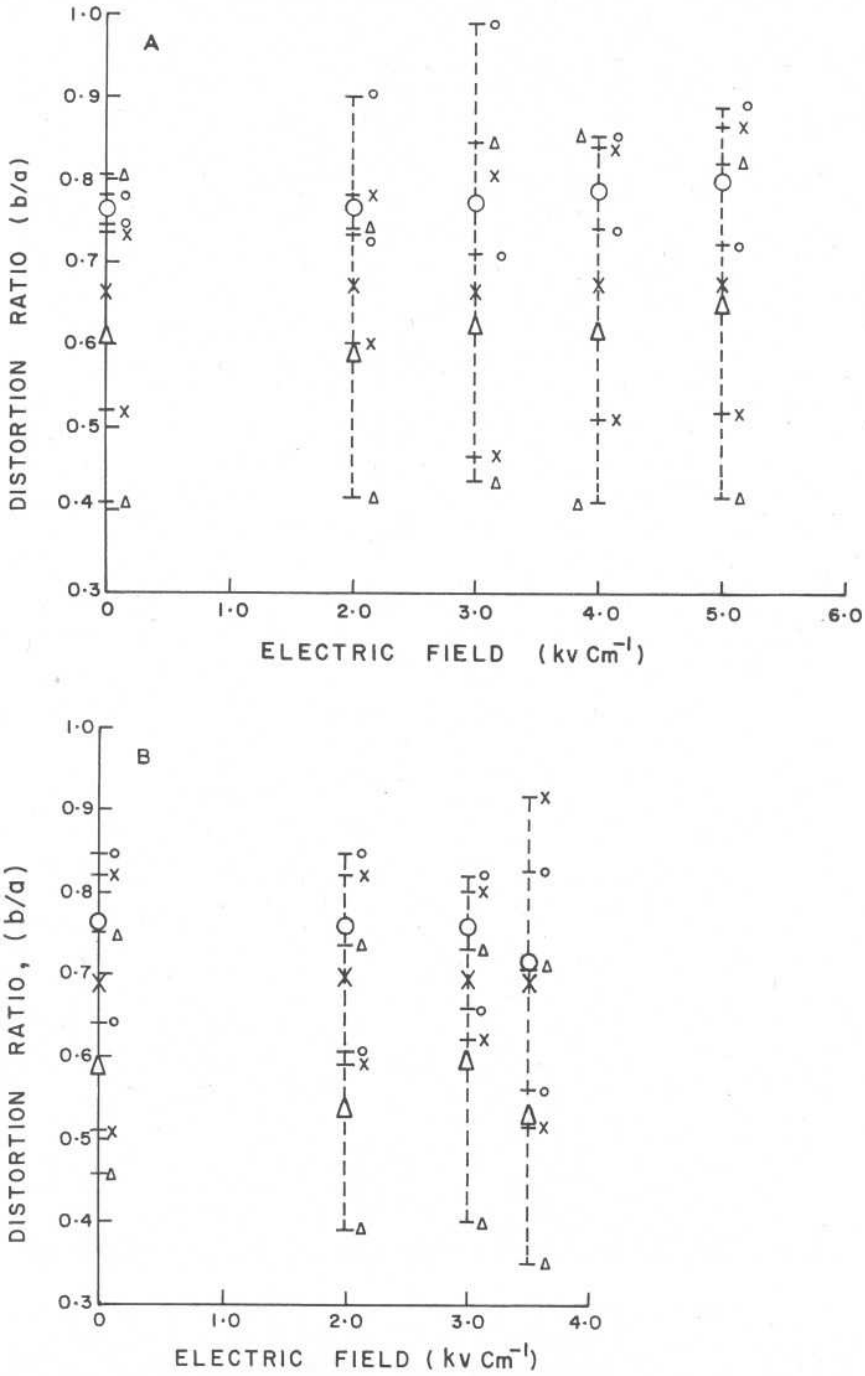


Fig. 3. A. Variation of distortion ratio with vertical electric field strength. ○: $a_0=1.75$ mm; ×: $a_0=2.65$ mm; Δ: $a_0=3.30$ mm.
B. Variation of distortion ratio with horizontal electric field strength. ○: $a_0=1.8$ mm; ×: $a_0=2.4$ mm; Δ: $a_0=3.3$ mm.

in vertical (crosses) or horizontal (circles) field configurations. The solid line is drawn on the basis of empirical expressions derived by Imai (1950) and Pruppacher and Beard (1970). Such a linear relationship between b/a and a_0 is also predicted by the semi-empirical calculations of Savic (1953). The dotted curve is drawn on the basis of recent theoretical calculations of Beard and Chuang (1987). Our experimental results are in fair agreement with theoretical predictions of Imai (1950) and Savic (1953) as well as the experimental results of Pruppacher and Beard (1970). Also our results for larger drops are in better agreement with the theoreticallly derived results of Beard and Chuang (1987). The small excess deformation in our results may be caused by the presence of the electrodes. Presence of these electrodes will introduce some additional turbulence in the airflow. Amplitude oscillations due to transient distortions excited in the drop by this turbulence and by some pulsations in the airflow may cause this excess deformation of the drop.

Variation of drop distortion ratio with variation in electric field strength for various drop sizes is shown in Fig. 3. Fig. 3A shows the variation of b/a in the vertical electric field for three drop sizes: $a_0 = 1.75$, 2.65 and 3.30 mm. Fig. 3B shows the variation of b/a in the horizontal electric field for three drop sizes: $a_0 = 1.8$, 2.4 and 3.3 mm. It can be seen that, even for the largest drop sizes studied here, the distortion ratio is not significantly affected by application of a vertical electric field up to 5 kV cm^{-1}, or a horizontal electric field up to 3.5 kV cm^{-1}. Thus it can be concluded that the electrical fields of these magnitudes do not significantly affect the stability of uncharged water drops of these sizes falling at their terminal velocity. These results are in good agreement with the experimental results of Ausman and Brook (1967) who report that no distortion appears until horizontal electric fields exceed values of about 7.5 kV cm^{-1} for uncharged drops with a radius of 2.1 mm; for smaller drops higher field values are required. The horizontal electric field will tend to elongate the drop only along one of its major axes and will thus destroy the axial symmetry. Viewed with the camera, one can only see two of the axial dimensions. A quantitative answer to the question whether the drop appears as an oblate spheroid, as most of our photographs indicate, or as a prolate spheroid, as observed by Ausman and Brook (1967), therefore requires the observation from a third axial dimension. However, it will be appropriate to mention here that the drops in the experiments of Ausman and Brook (1967) fell at a speed smaller than their terminal velocities. Our results are in agreement with those of Macky (1931) who also did not observe any noticeable distortion even for the largest drops until a field of 5 kV cm^{-1} is reached.

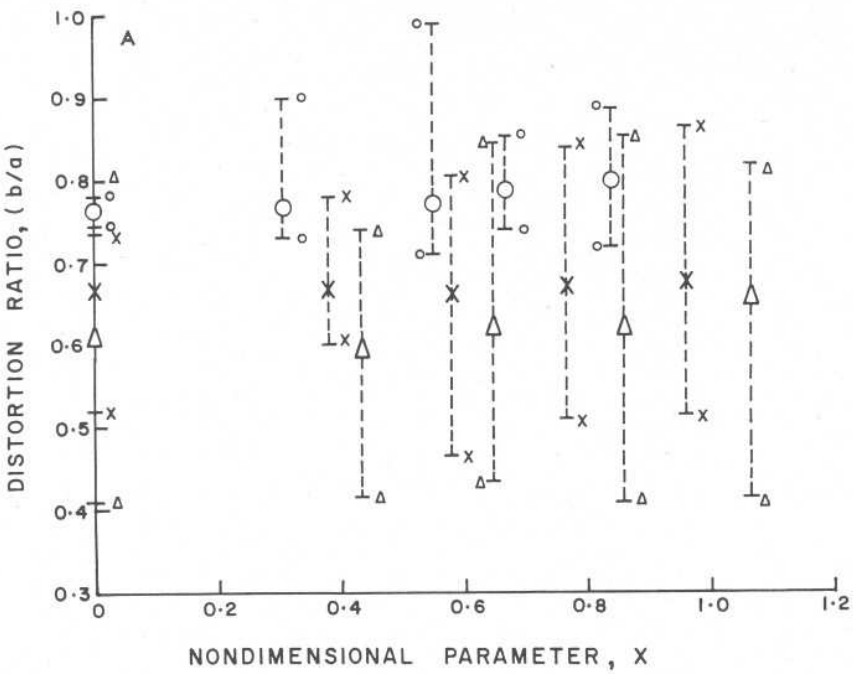
Our experimental results are confined to values of vertical electric field strength of less than 5 kV cm^{-1}. We could not investigate the problem with stronger electric fields because of the occurrence of corona discharge at our electrode system when it was raised to higher potentials. Rasmussen et al. (1985) investigated distortion of drops up to much higher electric field

strengths. Contrary past observations and to those of ours too, they report some distortion of uncharged drops at electric field strengths less than 5 kV cm^{-1} for drop sizes larger than 1.7 mm. For distortion of uncharged drops with $a_0 = 1.7$ mm and smaller, Rasmussen et al. also observed that the electric field strength must to be 5 kV cm^{-1} or more.

Although the value of b/a in our experiments does not show any significant change with variation of electric field, a general tendency of b/a increasing with the vertical electric field and decreasing with the horizontal electric field is obvious from Fig. 3. These results are not unexpected as the vertical or horizontal electric fields will tend to elongate the drop along its minor or along its major axis, respectively.

Results of studies of the instability and disruption of water drops in electric fields are often presented in terms of a nondimensional parameter, $X = E_0(a_0/\gamma)^{\frac{1}{2}}$, where γ is the surface tension of the water, first introduced by Zeleny (1915, 1917). Taylor (1964) also considered that in the critical condition for the mechanical stability of drops the surface electrostatic stresses must be balanced by the surface tension stresses acting on its surface, and the parameter involved in this critical condition must be based on this balance. Thus in the critical condition for a sphere, from $E_{0c}^2/8\pi = 2\gamma/a_0$ one gets that $E_{0c}(a_0/\gamma)^{\frac{1}{2}} = \text{constant}$, where E_{0c} is the critical electric field at the onset of the drop instability. Taylor (1964) predicted that the value of this constant, X_c ($X_c = E_{0c}(a_0/\gamma)^{\frac{1}{2}}$ for a critical unstable condition) is 1.625. Subsequently, Ausman and Brook (1967), Brazier-Smith (1971) and Griffiths and Latham (1972) found $X_c = 1.56$, 1.603 and 1.81, respectively. Although our experimental results do not extend to the high electric fields required for drop instability, we have plotted our results in terms of X for comparison with other past results. Fig. 4 shows the variation of b/a with the nondimensional parameter, X, for various drop sizes; Fig. 4A for drops with $a_0 = 1.75$, 2.65 and 3.30 mm exposed to vertical electric fields, and Fig. 4B for drops with $a_0 = 1.8$, 2.4 and 3.3 mm exposed to horizontal electric fields. The distortion ratio b/a clearly shows a general tendency to increase with X for drops exposed to a vertical electric field, and to decrease with X for drops exposed to a horizontal electric field.

Our results show similar trends as those of Rasmussen et al. (1985). However, our results do not show any measurable difference in the relative variation in the distortion ratio b/a, with increasing E_0, between smaller and larger drops as in the experimental results of Rasmussen et al. Results of Rasmussen et al. (1985) show that X_c does not have these unique features and is not independent of a_0 when electric forces are acting on the drop in addition to aerodynamic and hydrostatic forces. Their results show more deformation for larger drops than for smaller drops with increasing vertical electric field strength E_0. Consequently, X_c is larger for larger drops and smaller for smaller drops. Our results do not show such differences within the limited range of parameters examined by us.



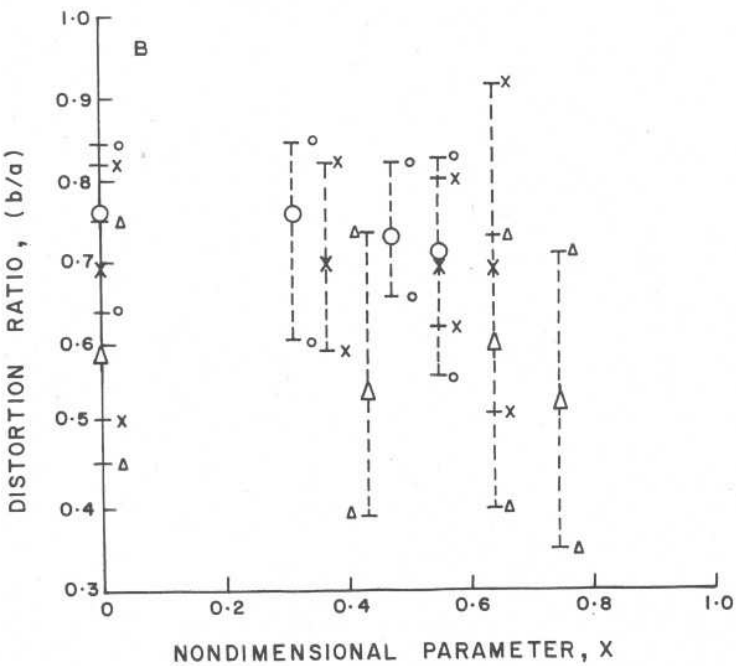


Fig. 4. A. Variation of distortion ratio with nondimensional parameter X for vertical electric fields. ○: $a_0=1.75$ mm; ×: $a_0=2.65$ mm; Δ: $a_0=3.3$ mm.
B. Variation of distortion ratio with nondimensional parameter, X, for horizontal electric fields. ○: $a_0=1.8$ mm; ×: $a_0=2.4$ mm; Δ: $a_0=3.3$ mm.

Fig. 5 shows the variation of distortion ratio with variation of equivalent drop radius, a_0, for two charged drops. Magnitudes of charges are about one tenth or one half of the Rayleigh limit, q_R, for instability of the drop. Measurements of distortion ratio for uncharged drops of the same sizes are also made

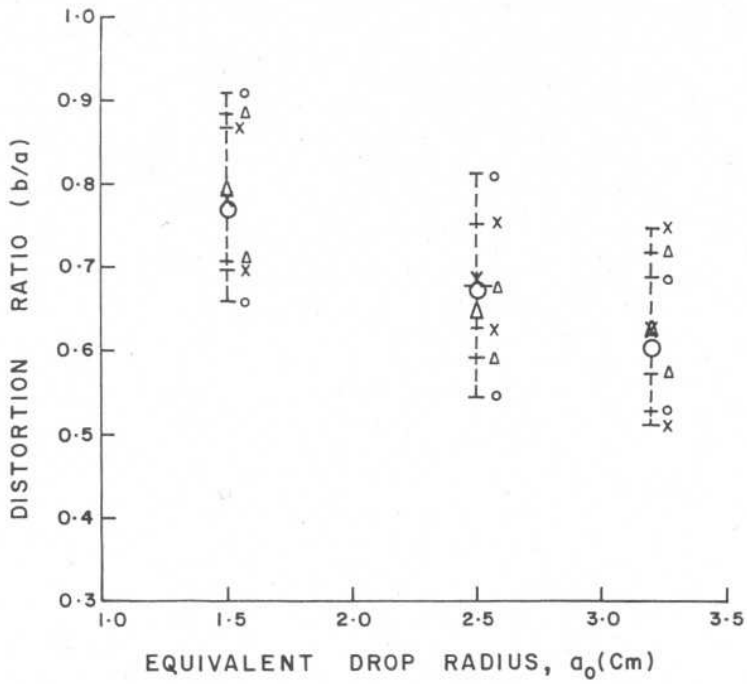


Fig. 5. Variation of distortion ratio with equivalent drop radius for different charges on drop. ○: $q=0$; ×: $q \approx$ one tenth of Rayleigh's limit; Δ: $q \approx$ one half of Rayleigh's limit of charge.

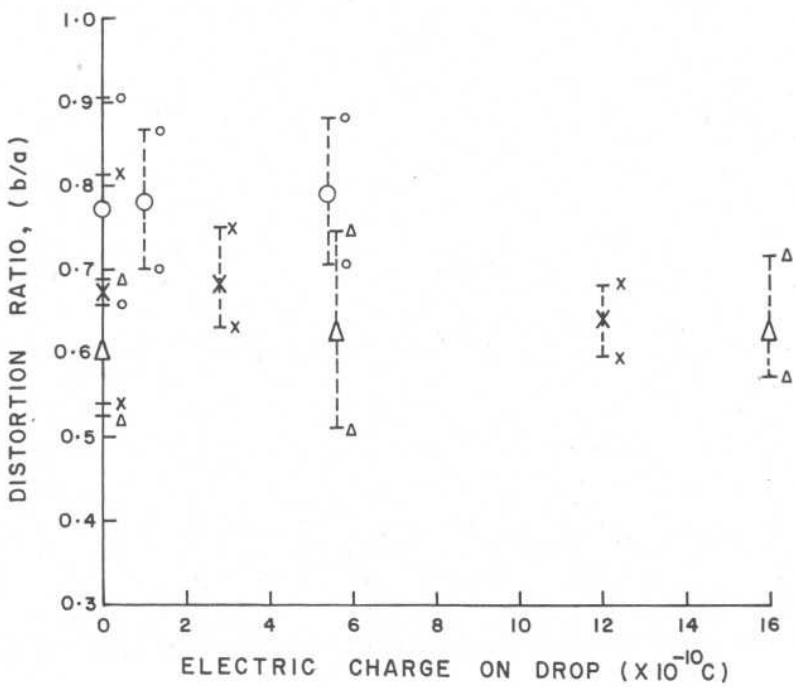


Fig. 6. Variation of distortion ratio with electric charge on drop for various drop sizes. ○: $a_0=1.50$ mm; ×: $a_0=2.55$ mm; Δ: $a_0=3.20$ mm.

for comparison. Only small variations in b/a with drop charges occur when $q \approx \frac{1}{2} q_R$. It follows therefore that for such drop sizes and charges, the surface tension and aerodynamic and hydrostatic forces dominate in determining the

shape of the drop, and cause b/a to decrease with increase in a_0. Similar inference can also be made from Fig. 6 which shows the variation of drop deformation ratio for different electrical charges on drops.

Fig. 7 shows the variation of the distortion ratio of charged drops with varying vertical electric field strengths. Drops of two sizes, $a_0=2.0$ and 2.5 mm, carrying electrical charges of $2.5\cdot10^{-10}$ and $5.0\cdot10^{-10}$ C, respectively, are studied here. These charges are about one fifth and one seventh of the Rayleigh limit for the corresponding drop sizes. Vertical electric field strengths are varied from 0 to 4 kV cm^{-1}. It may be emphasized that the distortion ratio increases as the field strength is increased. These variations in drop deformation, though small, are significant. Thus electric field strengths of about 4 kV cm^{-1} are sufficient to produce the changes in the shape of these charged drops. Due to this change, the shape tends to change from oblate spheroidal to spherical.

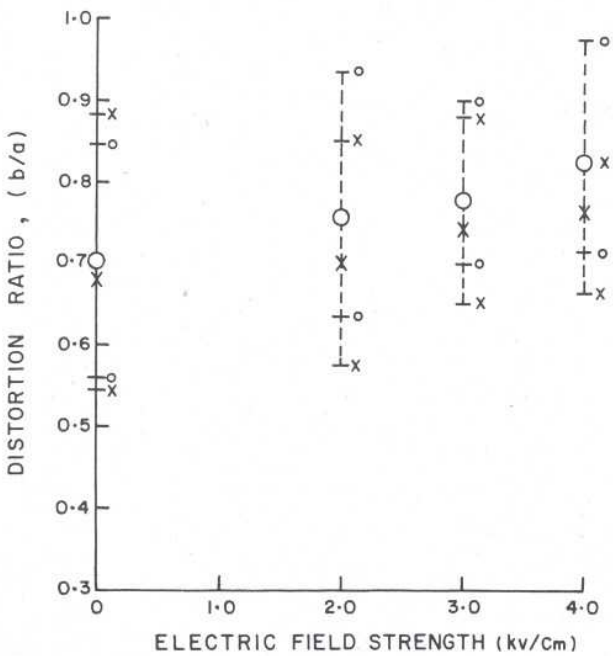


Fig. 7. Variation of distortion ratio with vertical electric field strength for two different sizes of charged drops. ○: $a_0=2$ mm and $q=2.5\cdot10^{-10}$; ×: $a_0=2.5$ mm and $q=5\cdot10^{-10}$ C.

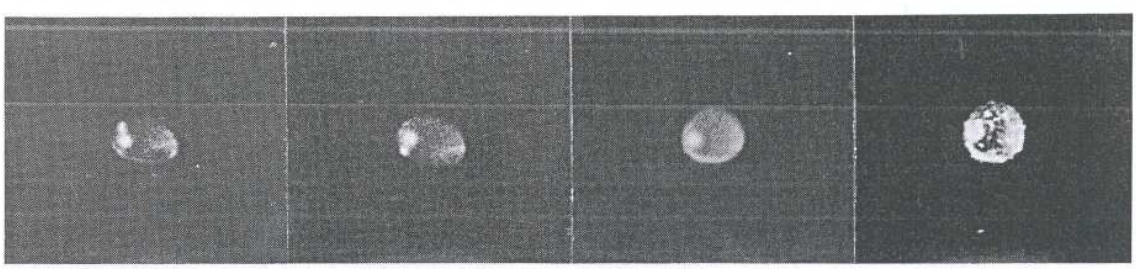


Fig. 8. Photographs of charged water drops ($a_0=2$ mm and $q=2.5\cdot10^{-10}$ C) suspended in the airstream of a vertical wind tunnel and exposed to various external electric fields. From left to right: $E_0=0, 2, 3, 4$ kV cm^{-1}, respectively.

TABLE I

Mean values of distortion ratio and their standard deviation for all observations plotted in Figs. 2–7

Radius of water drop, a_0 (mm)	Electric charge on drop (C)	Electric field (kV cm^{-1})		Mean value of distortion ratio (b/a)	Standard deviation
		Vertical	Horizontal		
Data from Figs. 2, 3A, 4A:					
1.75	–	0	–	0.77	0.01
		2	–	0.77	0.04
		3	–	0.77	0.07
		4	–	0.79	0.03
		5	–	0.80	0.05
2.65	–	0	–	0.66	0.06
		2	–	0.67	0.07
		3	–	0.66	0.12
		4	–	0.67	0.10
		5	–	0.67	0.13
3.3	–	0	–	0.61	0.14
		2	–	0.59	0.10
		3	–	0.62	0.12
		4	–	0.61	0.14
		5	–	0.65	0.15
Data from Figs. 2, 3B, 4B:					
1.8	–	–	0	0.76	0.08
		–	2	0.76	0.07
		–	3	0.75	0.04
		–	3.5	0.71	0.09
2.4	–	–	0	0.69	0.09
		–	2	0.70	0.08
		–	3	0.69	0.05
		–	3.5	0.69	0.09
3.3	–	–	0	0.59	0.11
		–	2	0.54	0.11
		–	3	0.60	0.11
		–	3.5	0.52	0.11
Data from Figs. 5, 6:					
1.5	–	–	–	0.77	0.08
	$1.0 \cdot 10^{-10}$	–	–	0.78	0.05
	$5.4 \cdot 10^{-10}$	–	–	0.79	0.04
2.55	–	–	–	0.67	0.08
	$2.8 \cdot 10^{-10}$	–	–	0.68	0.04
	$1.2 \cdot 10^{-9}$	–	–	0.65	0.03
3.2	–	–	–	0.60	0.05
	$5.6 \cdot 10^{-10}$	–	–	0.62	0.07
	$1.6 \cdot 10^{-9}$	–	–	0.62	0.04
Data from Fig. 7:					
2.0	$2.5 \cdot 10^{-10}$	0	–	0.70	0.09
		2	–	0.76	0.10
		3	–	0.78	0.06
		4	–	0.83	0.06
2.5	$5.0 \cdot 10^{-10}$	0	–	0.68	0.13
		2	–	0.70	0.08
		3	–	0.74	0.07
		4	–	0.77	0.04

Fig. 8 shows the photographs of a 2-mm-radius drop carrying a charge of $2.5 \cdot 10^{-10}$ C as the vertical external electric field strength is increased from 0 to 4 kV cm^{-1}. It can be noticed that the shape of drop changes from oblate to nearly spherical as the electric field strength is increased.

Once the drop begins to deform, the changes in distortion ratio with increasing field strengths become very rapid. The reason may be that when the electric field strength exceeds about 4 kV cm^{-1}, the corresponding changes in the terminal velocities of the charged drops are so large it becomes difficult to keep them suspended within the region of the electric field. Although the vertical air velocity in the wind tunnel was not continuously monitored, changes required to be made in the blower's voltage to keep the drop in position, indicated that these changes in air velocity were roughly up to about 1 m s^{-1}. A change in polarity of the electric field required an opposite change in blower's voltage. Changes in terminal velocity of such charged drops in such electric fields have been observed to be in the same range in experiments of Gay et al. (1974) and in theoretical calculations of Beard (1980). The importance of such changes in velocity of drops in thunderstorms was earlier proposed by Kamra (1970, 1975) and Kamra and Vonnegut (1971).

In Table I we give the mean values and standard deviation for all the points plotted in Figs. 2 to 7. The comparatively larger values of standard deviation for drops of $a_0 = 3.3$ mm are apparently caused by the larger fluctuations and vibrations of such large drops.

APPLICABILITY OF THE RESULTS TO THUNDERSTORMS

Water drops, when exposed to external electric fields, elongate in the direction of the electric field. Thus a water drop of an oblate spheroidal shape in the absence of electric field will become spherical and then prolate spheroidal when the strength of the external vertical electric field is increased. Electric fields required for such changes in the shape of uncharged drops have been observed in previous experiments to be very high. Our results also confirm that in thunderstorms, vertical or horizontal electric fields of up to 5 kV cm^{-1} or 3.5 kV cm^{-1}, respectively, may not significantly affect the shape of freely falling uncharged drops of $a_0 = 1.75$ to 3.30 mm. Thus, the hydrostatic and aerodynamic pressures acting on the water drops may determine their shapes and the electrical stress of the magnitude used in our experiments may not have any significant effect on their shapes. The shapes of uncharged drops in low electric fields may, therefore, be not significantly different from theoretical predictions such as that of Beard (1984) and Beard and Chuang (1987).

When the drop is charged then the forces due to the charge are spherically symmetric if the drop is small and it can be assumed that the drop has a spherical shape. For such small drops, the forces due to charge will not enter into the balance between other forces. However, for large drops which are already

distorted into an oblate or prolate shape, surface charge density is not uniform, being higher where the surface curvature is stronger. Thus on average the pull will be strongest in the regions of the drop with higher surface curvature. This will enhance the oblateness or prolateness of the drop. Thus, as Zrnic et al. (1984) have concluded theoretically, "charge on the drop is not capable of initiating distortion in a spherical drop but it only enhances a preexisting a-sphericity". The drops in our experiments did not carry high enough charges required for such changes in drop shape.

In the electrical environment of a thunderstorm drops are charged as well as exposed to external electric field. The range of values used in our experiment for drop sizes, electric charges on drops and electric field strengths, have been observed in active thunderstorms (Griffiths and Latham, 1972; Winn and Moore, 1971). Thus, charged water drops in a thunderstorm which are of an oblate shape in the absence of an electric field will elongate vertically and become more spherical or prolate in the presence of a vertical electric field. This change in eccentricity of drops might be detected as a change of differential radar reflectivity. Observations of some enhancement of differential radar reflectivity have been reported by some investigators (e.g. Zrnic et al., 1984). Such changes in differential radar reflectivity may be caused by highly charged drops located in strong electric fields, and these radar measurements may be used to locate the regions of intense electrification in thunderstorms.

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