Charge separation due to water drop and cloud droplet interactions in an electric field

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SUMMARY

Measurements were made of the electric charge acquired by drops of mean radius of about 750μm, in the presence of a vertical electric field \( E \), the value of which could be varied from 4-5 to 27kV/m. It was found that the average charge acquired by the water drop as a consequence of the inductive process increased from 0-1fC to about 0-25fC as the electric field strength increased from 5kV/m to about 15kV/m, but thereafter decreased with increasing values of electric field.

This work suggests that the collisions between polarized rain-drops and cloud droplets in natural clouds could give rise, very effectively, to the production of electric fields of about 30kV/m; but that significantly larger fields could not be produced since all collisions in the higher fields would result in permanent coalescence.

1. INTRODUCTION

Most theories of cloud electrification have assumed that precipitation plays an important role in the generation and separation of the electric charge and there has been a tendency to associate that generation with the presence of the ice phase. Nevertheless, other theories of cloud electrification not involving the ice phase must be invoked to explain the electrification of clouds whose summits are always warmer than 0°C. One possible explanation for this is the inductive mechanism, operating through the collision of cloud droplets with raindrops.

The efficacy of this mechanism in explaining the growth of electric fields is uncertain since separation probabilities between larger raindrops and cloud droplets are quite low in the absence of a field (Whelpdale and List 1971) and are known to decrease with increasing values of electric field (Rayleigh 1879; Allan and Mason 1961; Jayaratne and Mason 1964; and others) and so the process may be self-limiting. Indeed, it may even be a dissipative process if separation of the smaller droplet occurs from the uppermost half of the larger drop as in the case of the collision of water-drop pairs (Jennings and Latham 1972).

So it was decided to conduct experiments to obtain values of separation probabilities between water drops of raindrop size interacting with cloud droplets in the presence of polarizing electric fields and so determine to what extent this particular form of the inductive process can result in effective growth of the initial field.

2. EXPERIMENTAL APPARATUS AND TECHNIQUES

The experimental arrangement is shown schematically in Fig. 1. An uniformly sized stream of water drops was produced by modulating the rate of flow of water through a hypodermic needle which was connected to a small, in-line, water pump driven by a variable frequency oscillator. This technique was first described by Atkinson and Miller (1965). The drops were directed vertically downwards through a cloud of water droplets bounded by a pair of parallel horizontal electrodes, separated by a distance of about 0.3m.
across which an electric potential could be applied by means of a continuously variable 0–30kV power supply. Observation of the drop-stream stability was facilitated by means of a stroboscope working in synchronization with the oscillator. Typical velocity values were about 75% of terminal velocity of the drops at the centre of the experimental chamber.

In these experiments, a cloud of small water droplets was produced by using two air-driven spinning disk droplet generators (May 1966). The cloud generators were housed in an airtight box whose walls were wetted to provide a saturated environment for the droplets. In a typical experimental run, the cloud was drawn through the interaction channel by means of a suction pump, drawing air which had passed through a honeycomb section. The air-flow velocity was usually maintained at about 0.3m s⁻¹ to ensure that each successive large drop encountered a new volume of cloud. Each generator was capable of atomizing up to around 3g of water per minute.

The size distribution of droplets in the cloud was determined by allowing the droplets to fall on to magnesium oxide coated slides (May 1950). An alternative method employed the use of PVA (polyvinyl alcohol) coated slides. The values of mean droplet size measured by the two techniques for the same cloud sample, showed agreement to within about ±8%. Liquid feed rates of the order of 1g per minute produced a narrow spectrum of cloud droplets which was approximately monodisperse. A typical frequency distribution of droplet sizes yielded a mean size of 16-0μm with a standard error of about 0.2μm.

Separate experiments were necessary to determine the liquid water content of the cloud and were based on a method described by Gunn and Hitchens (1951). It is depicted in Fig. 2. A sample of cloud near the drop-droplet interaction zone was sealed off by a pair
of shutters when released simultaneously. The captured sample was then heated by means of electrically heated tape wound around the chamber, until the liquid droplets were evaporated. The original liquid water content of the cloud is equal to the difference between the saturation vapour densities at the experimentally determined dew-point and the temperature at which the main experiments were conducted. Calibration experiments, in which a known amount of water was introduced into the trapping chamber, showed that this technique provided values of water content which were correct to within 15%. This cloud content meter formed an integral part of the cloud channel and thus errors associated with the removal of cloud samples from the parent cloud were eliminated.

The electrical charge on the cloud droplets was measured by drawing the cloud through a Faraday type collecting vessel whose central electrode was filled with metal filings to capture the impinging droplets. A sensitive vibrating-reed electrometer connected to the Faraday vessel gave a measure of the volume change density of the cloud, which is proportional to the cloud droplet concentration. Typical values were of the order of 250pC/m³ of cloud for measured cloud concentrations of 4g/m³. An ultraviolet chart recorder was used to provide a continuous record of the charge density of the cloud throughout each experimental run.

3. EXPERIMENTAL PROCEDURE

Because of drop stability considerations and the necessary long fall distance (of the order of one metre) of the water drops, limitations on drop-size were imposed and the drop-size range was confined to between 725 and 740µm in radius. Adequate screening of the water drops from the applied electric field, and the application of an ionizing alpha Americium source, reduced the average charge carried by a drop to less than 0.1fC. The average amount of electric charge per drop could be measured accurately by directing the drop stream into a shielded Faraday cylinder connected to a vibrating reed electrometer and the current flowing to the electrometer was continuously monitored on an ultraviolet chart recorder. It was imperative to maintain a very stable drop stream throughout the experiment as any slight fluctuations from stability gave rise to spurious drop charge measurements.

As the cloud, generated by a pair of spinning disk devices, was introduced into the experimental channel it encountered the water drop stream and was then drawn through the Faraday collecting vessel in order to measure the cloud droplet charge. It was always noted that the cloud water content, as indicated indirectly by the charge density measurements, decayed gradually after the onset of production and approached a constant value after about 5 to 10 minutes had elapsed from the initial introduction of the cloud. This decay in the rate of cloud-droplet formation is primarily a consequence of the build-up of unwanted satellite droplets which have failed to escape from the spray-head of the generators. However, the detection and measurement of electric charge transferred in drop-droplet interactions was confined to the period of time which coincided with the plateau region of cloud production. Separate direct measurements were made of the cloud water concentration, using the cloud content meter as described in section 3, at the operating liquid feed rates of the main experiments. In addition, the simultaneous measurement of the net charge carried by the cloud droplets provided a useful method of calibrating the cloud water concentration as selected values of volume charge density. It was established that two cloud generators using liquid feed rates of 2g/min typically yielded cloud concentrations of about 4g m⁻³, although individual values of cloud water content, as inferred from the known charge density values at the period of the main experiment during which charge-transfer measurements were taken, varied between 2·8 and 5·2g m⁻². This represented, on average, a loss of about (50 ± 10)% of cloud water to the walls and floor of the cloud generator.
housing with additional losses due to the accumulation of satellite droplets in the annular rim of the spinning top atomizers.

Preliminary tests were conducted to minimize the effect of the applied electric field by carefully shielding the drop-producing apparatus and the cloud-droplet generators. The experimental procedure entailed a continuous monitoring on an oscillograph of the electric charge acquired by the larger drops, together with the charge density of the cloud droplets. First, measurements were made in the absence of an electric field. The acquisition of a small electric charge (of the order of 60aC per drop) due to the capture (by the drop stream) of cloud droplets as they traversed the interaction zone of the drops, was recorded. This accreted charge was consistent with the simultaneous measurement of the net charge carried by the cloud in conjunction with separate measurements of cloud water concentrations.

Two preliminary but important tests were conducted after the polarizing electric field was switched on. Complete screening of the drops, at the higher values of electric field in particular, was not possible and a small induced charge on the drops of the order of the residual drop charge in the absence of the field (about 0.1fC) was noted and taken into account in subsequent charge transfer calculations. No effect of applied electric field upon the net charge transported by the cloud droplets was observed by the sensitive vibrating-reed electrometer. When the necessary experimental procedures were carried out, measurements were made of the amount of electric charge transferred to the drops as they traverse the cloud of droplets at selected values of electric field strength. This important stage of the experiment was normally in progress for at least two minutes so as to provide reliable average values of charge-transfer. Measurements of the pertinent parameters were continued after the electric field was switched off, so as to exclude any spurious data from the measurements and to provide a re-check on the background readings of the critical parameters. The duration of the experiment was usually between 15 and 25 minutes.

4. Experimental results

Because of the expected low numbers of charge transfer events associated with the drop-droplet collisions in the presence of an electric field, a continuous stream of water drops at the rate of between 250 to 300s⁻¹ was used in order to increase the sensitivity of the charge detection apparatus. Since a large difference in velocity existed between the larger drops and the cloud droplets, the assumption was made throughout this work that the droplets were effectively stationary with reference to the falling drop. No completely trustworthy results were observable for electric field strengths below a value of 4.5kV/m since measurements at this level of sensitivity approached the noise level and became liable to spurious effects. Although maximum electrical screening was employed, the occurrence of intermittent electrical discharges at high values of electric field in the presence of cloud, necessitated an upper limit of about 27-0kV/m for the electric field strength in this series of experiments. It was observed that, in all of the twenty-two experimental runs undertaken in the best controlled conditions, negative charge was transferred to the larger drops in the prevailing downwardly directed electric field. One experimental run was performed with the electric field oriented in the opposite direction and it was found that, in this situation, positive charge was transferred to the large drops. This confirms the prediction that electric charge was transferred inductively. Experimental values of charge acquired by the drops (proportional to the product of separation probability and \cos \theta) as a function of polarizing electric field are shown in Fig. 3. It is seen that the average charge transferred per drop increases with the magnitude of the existing field up to a value of approximately 15kV/m and then gradually falls off towards negligible values with increasing electric field.

The number of interactions, \( N_{\text{int}} \), in the volume swept out by a drop of radius \( R \) as it
CHARGE SEPARATION

Figure 3. Average measured values of electric charge transferred per drop, $Q_n$, as a function of applied electric field, $E$.

falls a distance $L$ and interacts with a cloud of droplets of mean radius $r$, concentration $c$ and density $\rho$ can be expressed as

$$N_i = 3(R + r)^2 Lc/4r^2 \rho$$

(1)
on the assumption that the collision efficiency for these drop-droplet categories can be taken as unity. Charge will be transferred between a cloud droplet and a drop only if a collision between the two results in subsequent separation. If $f$ is defined as the probability that a collision between a drop and a droplet will result in separation then the number of charge-transfer interactions, $N_c$, can be written as

$$N_c = fN_i$$

(2)

Latham and Mason (1962) showed that for uncharged spheres of radii $R$ and $r$ ($R > r$) the amount of charge transferred, $q$, is given by the following equation

$$q = \gamma Er^2 \cos \theta$$

(3)
where $\theta$ is the angle between the electric field and the line of centres of the spheres at the moment of separation, and $\gamma$ is a calculable function of $r/R$ which is approximately equal to $\pi^2/2$ for $R \gg r$. The application of Eq. (3) to a pair of spherical water drops of dielectric constant 81 has been shown by Davis (1969) to be justifiable. Jennings and Latham (1972) found good agreement between the theoretical values derived from Eq. (3) and the measured values of charge transfer resulting from the collision and separation of water drops ranging in radius from 200 to 600$\mu$m, falling in an electric field. Accordingly, Eq. (3) was taken to represent the amount of charge transfer per interaction resulting in separation in these experiments, and the charge $Q_n$, transferred to a drop in falling through a cloud of droplets, can be expressed by the relation

<table>
<thead>
<tr>
<th>$f \cos \theta \times 10^4$</th>
<th>$E$(kV/m)</th>
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</thead>
<tbody>
<tr>
<td>$11.5 \pm 3.4$</td>
<td>4.9</td>
</tr>
<tr>
<td>$8.6 \pm 1.7$</td>
<td>6.8</td>
</tr>
<tr>
<td>$9.9 \pm 1.2$</td>
<td>10.0</td>
</tr>
<tr>
<td>$11.4 \pm 1.2$</td>
<td>14.7</td>
</tr>
<tr>
<td>$8.2 \pm 0.8$</td>
<td>20.0</td>
</tr>
<tr>
<td>$3.8 \pm 0.8$</td>
<td>22.2</td>
</tr>
<tr>
<td>$3.1 \pm 0.4$</td>
<td>24.6</td>
</tr>
<tr>
<td>$1.8 \pm 0.3$</td>
<td>27.0</td>
</tr>
</tbody>
</table>
\[ Q_R = fN_q \]
\[ = 3(R + r)^2 \cos \theta \frac{E}{4\pi \rho} \tag{4} \]

Consequently, measurement of \( Q_R \) can yield information on the value of the product of the separation probability and \( \cos \theta \) as a function of the polarizing field \( E \). Values of the product \( f \cos \theta \) are shown in Table 1 as a function of field strength \( E \). The separation probability, \( f \), can be accurately determined only if the angle \( \theta \) is known for each drop-droplet collision.

5. DISCUSSION

The experimental results indicate that the larger drop, of precipitation dimension, acquires electric charge, by means of the induction process, which increases from about 0.1fC to 0.25fC as the polarizing field is increased from 5kV/m to approximately 15kV/m. However, this process, by which charge is transferred between the drop and droplet, becomes increasingly less effective with increasing values of electric field. It can be inferred from the experimental results that essentially all collisions between drops and droplets will result in coalescence in fields greater than about 30kV/m.

The results suggest that electric charge can be separated in electric fields which are relatively low. For example, the field values employed were about an order of magnitude lower than those of Aufdermaur and Johnson (1972) in their (ice pellet—supercooled droplets) interaction experiments. The measured rate of charging of about 0.1fC per drop compares favourably with that observed by Aufdermaur and Johnson, although the experimental results seem to imply that appreciable charge separation for water drop-droplet interactions will probably no longer occur at higher values of ambient field, such as they measured.

One can rule out the possibility that the charge transfer mechanism was caused by a spark discharge between the drop and droplet surfaces in the ambient electric field since the maximum values of field-strength utilized in these experiments were at least one order of magnitude too weak. It is suggested that the charge transfer mechanism is dependent upon a small fraction of the droplets partially coalescing with the larger drops upon collision. This phenomenon of partial coalescence followed by separation of the drop-droplet pair was observed by Brazier-Smith, Jennings and Latham (1972) over a wide range of operating conditions for water drops in the radius range 150 to 750\( \mu \)m. Further evidence of this particular collision type process between droplets of radius 35\( \mu \)m interacting at near grazing incidence with water drops of radius 500\( \mu \)m and greater has been reported by Whelpdale and List (1971), with separation mainly occurring on the underside of the larger drops.

Based on the calculations of earlier workers (for example Mason 1972) it is clear that collisions between drops and droplets can result in effective growth of the initial electric field until a value of about 30kV/m is achieved, at which point all collisions will result in coalescence and field growth will cease. However, it is known that all-water clouds possess much lower maximum fields, in general, than those occurring in thunderstorms, and it seems quite possible that this particular form of the inductive process could be primarily responsible for warm cloud electrification.

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