A Laboratory Investigation of the Effect of Particle Collisions on the Generation of Electric Fields in Thunderstorms

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ABSTRACT

A laboratory experiment has been performed to study the relative effect of aerodynamic and electrical forces on small electrically conducting particles of radii 100–200 μ colliding with a particle of 2 mm radius suspended in an upward moving vertical air stream of a wind tunnel and placed in a vertical polarizing electric field. It has been observed, in a low electric field, that the smaller particles collide and move up with the air stream. However, as the electric field is increased, the smaller particles start coming down, after the collision, against the air stream. The electric field required for this change of direction for different particle sizes is higher for the larger angles of collision. When these results are applied to thunderstorms with high electric fields, it is shown that the electrical forces on the charged cloud particles must be taken into account in any consideration of the gravitational separation of charges. Our experimental results indicate that in high electric fields these electric forces can limit and even oppose the further separation of charges.

1. Introduction

One of the yet unsolved mysteries of thunderstorm electricity is how the electric charge is generated and separated in thunderstorms so as to create electric fields high enough to initiate a lightning discharge. In most of the mechanisms advanced thus far, it is proposed that large precipitation particles acquire negative charge, and the smaller cloud particles, positive charge. These large and smaller particles are then assumed to separate in space due to their different terminal velocities under gravity. Thus, an electric dipole with positive charge up and negative down is created whose electrical strength increases with time until the first lightning discharge occurs. Such a mechanism was originally proposed by Elster and Geitel (1885) and has been further developed in recent years (Sartor, 1954, 1967; Müller-Hillebrand, 1954; Latham and Mason, 1962; Mason, 1968.) According to this idea, cloud particles and falling precipitation particles exchange charge in vertical negative electric fields, causing the small cloud particles to acquire positive charge, and the falling precipitation particles, negative charge. After this initial charge separation, the negative precipitation particles and the positive cloud particles are then assumed to separate from each other because of their different terminal velocities under the influence of gravity.

One of the assumptions made in this inductive charging mechanism (as in all other charge generating mechanisms involving falling precipitation) is that the electrical forces acting on cloud and precipitation particles have little or no effect on their mutual separation under gravity. In negative electric fields of thunderstorms, the positively charged cloud particles will tend to move down, and negatively charged precipitation particles will tend to move up. If the electrical forces acting on cloud and precipitation particles are high enough, their further separation under gravitational forces will be impossible. It has been pointed out by Gunn (1954) and Schonland (1964) that in some cases the electrical forces may be high enough to support many of the raindrops against the force of gravity. Further, Gunn (1957) has mentioned that in high electric fields the electrical forces acting on cloud droplets can oppose and limit further accumulation of charges. Kamra (1970) has shown theoretically that in high electric fields of thunderclouds the electrical forces acting on precipitation and smaller particles should play a deciding role in determining the rate of field build-up and the maximum electric field that can be generated by colliding ice crystals and hail pellets in polarizing electric fields. In spite of these considerations, there is little, if any, experimental evidence that the cloud particles can move, under the electrical forces, against the air stream. In this paper we will report on laboratory experiments showing that when small particles collide with a large particle, their subsequent direction of motion is considerably influenced by the electric field. The possible significance of these effects on thunderstorm electrification is discussed.

2. Experimental arrangement

A vertical wind tunnel of Blanchard's type (1955) was mounted over a blower enclosed in a wooden box (Fig. 1). The box had two vents that could be adjusted to vary the wind speed. The wind tunnel was made with a converging shape which helps in reducing eddies in the wind profile. To help smooth the airflow, a wire mesh screen was fixed in the wind tunnel, and above this screen plastic drinking straws each 0.6 cm in diameter were packed vertically in a hexagonal pattern.

An electrode made of copper mesh screening was fixed at the top of the tunnel. The edges of this screening were rolled around a rectangular frame of copper rod so as to increase the corona threshold. Above this electrode another similar, but smaller, elliptical wire mesh electrode (see Fig. 1) was suspended on nylon threads. After soldering and smoothing the connections, we found that when a potential of up to 40 kV was applied to these electrodes (10 cm apart) corona current, if it existed, was less than 0.1 μÅ.

To avoid the various complications of working with ice and maintaining low temperatures, it was decided to use copper spheres to simulate the collisions of smaller droplets and precipitation particles in thunderstorms. The larger sphere (used in place of a precipitation particle) was suspended with teflon tubing 0.5 mm in radius, passing through the upper electrode and coming between the two electrodes. Another teflon tube (0.17 cm in diameter) was fixed with one end coming up from beneath the lower electrode and the other end coming out of one side of the wind tunnel. The smaller sphere was placed in this lower tube, and air pressure was slowly applied until it was expelled into the air stream and collided with the larger sphere.

The region around the larger sphere was illuminated with a 75 W filament projection lamp, and the before- and after-impact trajectories of the smaller sphere were photographed with open-shutter photography. An *f*1.2 lens camera with close-up lenses and ASA 400 black and white film were used.

3. Results

A constant vertical air stream of 8 m sec^{-1} was maintained. Smaller spheres of radii 100, 150 and 200 μ ($\pm 10\ \mu$) were allowed to collide with a larger sphere of 2 mm radius under various values for the electric field. Before each collision the spheres were exposed to a radioactive Po^{210} source of 500 μCi for $\sim$1 min to neutralize any residual charge on them. Although the smaller sphere coming out of the teflon tube may subsequently have acquired some contact electrification charge, this should not affect the after-impact trajectories, since the maximum charge that a particle of 100–200 μ in radius can carry is less by about an order of magnitude than the induced charge on the lower half of the 2-mm sphere in a field of about 3 kV cm^{-1}. In other words, the charge carried by the smaller sphere after the collision will be only very slightly affected by the charge it carried before the collision.

The presence of the upper wire mesh electrode above the wind tunnel (see Fig. 1) produced some horizontal divergence in the wind profile between the two electrodes. This horizontal divergence was clearly evident from the trajectories of some smaller spheres that never collided with the larger sphere. Such spheres had a trajectory moving away from the center of the apparatus as they moved up between the two electrodes. Thus,

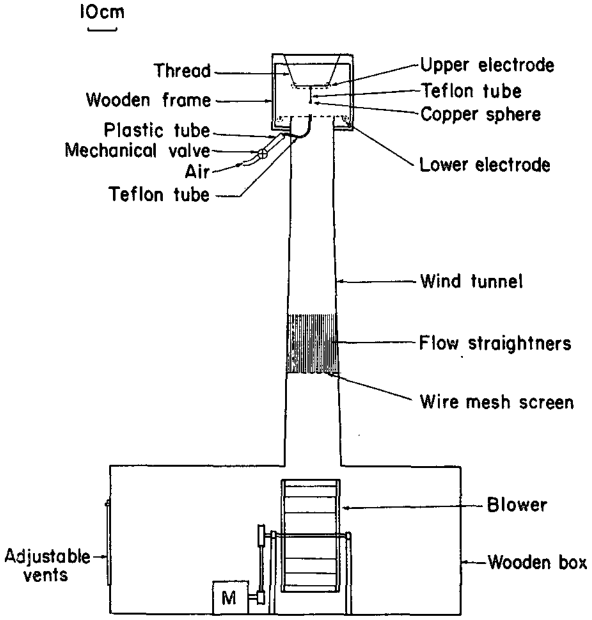

FIG. 1. Wind tunnel.

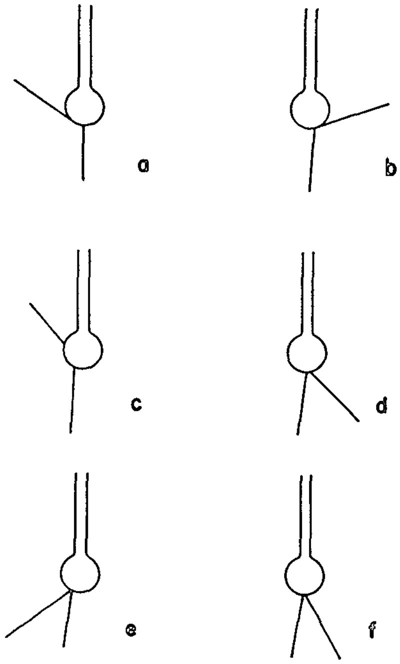

FIG. 2. Trajectories of spheres of 200 μ radii before and after collision with a sphere of 2 mm radius in electric fields of 0, 1.6, 1.7, 1.8, 1.9 and 2.0 kV cm^{-1}, a.–f., respectively.

FIG. 3. Trajectories of spheres of 200 μ radii before and after collision with a sphere of 2 mm radius in electric fields of 1.9 kV cm^{-1}, a., and 2.0 kV cm^{-1}, b.

after the collision, the smaller sphere experiences two forces—one electrical force acting vertically downward, and the second aerodynamic force acting upward, but considerably diverted from the vertical direction. As a result of these two forces, the smaller sphere moves upward or downward, but at the same time moves away from the center, as we shall see in Figs. 2 and 3.

Fig. 2 shows the trajectories of 200 μ spheres before and after the collision with the larger sphere. It may be noted that for fields <1.7 kV cm^{-1}, the smaller sphere moves up after the collision, but in fields >1.8 kV cm^{-1}, the smaller sphere comes down after the collision under the influence of electric forces. The similar transition points for the 150 and 100 μ radii spheres were found to be at 2.2 and 2.8 kV cm^{-1}, respectively. The numerical values of these transition points should not, however, be taken very strictly because they represent only the values where most of the spheres change their direction of after-impact trajectory in our experiments. Sometimes, however, when the collision took place near the periphery of the larger sphere, the smaller sphere moves up instead of coming down, as would be expected in that particular strength of field. For example, Fig. 3 represents two cases of collisions of 200 μ spheres in electric fields of 1.9 and 2.0 kV cm^{-1}. The collisions are clearly occurring far away from the bottom of the sphere; therefore, the spheres are moving up.

It is appropriate to emphasize here that the directions of motion of small spheres after their collision with the larger one are not the result of the elastic bounce-off. It was only in the high electric fields, i.e., above the transition point for a particular size group of spheres, that most of the spheres moved down after the collision, instead of going up as always happened in no- or below-transition electric fields. This would not have happened had these been merely the result of elastic collision. Repeated observations of collisions in different electric fields near the transition points (where the smaller sphere, after the collision, reverses the direction of motion) confirmed the idea that it was the electric field that determined the direction of motion of the smaller sphere after the collision.

4. Theoretical aspects

The equation of motion of a sphere of radius a and mass m moving with a downward velocity v in a vertical electric field E can be written as

$$m\frac{dv}{dt}=qE-6\pi\eta av\left(\frac{C_D\,\mathrm{Re}}{24}\right)+mg, \tag{1}$$

where q is the charge on the sphere, η the viscosity of the medium, C_D and Re the drag coefficient and Reynolds' number, respectively, of the sphere, and g the acceleration due to gravity. Therefore, for a constant vertical velocity v,

$$v=\frac{qE+mg}{6\pi\eta a\left(\dfrac{C_D\,\mathrm{Re}}{24}\right)}. \tag{2}$$

Latham and Mason (1962) have shown that the charge transferred after the impact between a smaller and a relatively much larger uncharged sphere is

$$q=\tfrac{1}{2}\pi^2Ea^2\cos\theta, \tag{3}$$

where θ is the angle of collision with respect to the direction of the electric field. From (2) and (3)

$$v=\frac{\tfrac{1}{2}\pi^2E^2a^2\cos\theta+mg}{6\pi\eta a\left(\dfrac{C_D\,\mathrm{Re}}{24}\right)}. \tag{4}$$

Thus, the precipitation particles will separate from smaller particles only if v, the velocity of smaller particles under the electrical force, is smaller than the difference of their fall velocities, under the gravitational force, which is generally taken as 8 m sec^{-1}. This value of 8 m sec^{-1} may, however, be much lower if the electrical force acting on precipitation particles is also taken into account. However, here we shall ignore the electrical force on precipitation particles and take the separation velocity of precipitation and smaller sized particles as 8 m sec^{-1}. From Eq. (4) we shall calculate the minimum electric field required for smaller particles of different radii to obtain this velocity of 8 m sec^{-1} under the electrical force. To do this, we first calculate the Reynolds' number for spheres (taking their velocity as 8 m sec^{-1}) of different radii and then obtain their corresponding drag coefficients from a curve by Wieselsberger (Prandtl and Tietjens, 1957). Taking the angle of collision to be zero, Eq. (4) gives the minimum electric fields required for particles of different radii to attain a velocity of 8 m sec^{-1} (taking $\eta=1.8\times10^{-4}$ poise). These are shown in Fig. 4. In the case of smaller particles (which are ice crystals in these calculations), the mass term is negligible, while for copper spheres in our experiment, its effect is obvious from the figure. It is clear that most of the ice crystals can attain, under the electrical force, a velocity of 8 m sec^{-1} when the electric fields are from 4–6 kV cm^{-1}.

The experimental value of the transition point for a 200 μ sphere is in agreement with the calculated one. That the experimental values are lower than the calculated ones for 150 and 100 μ spheres may be the result of the development of horizontal divergence in the wind profile, as pointed out earlier.

5. Applicability of the results to thunderstorms

It is important to determine the effect of the collision of precipitation and cloud particles in thunderstorms on the development of the electric field. Due to the lack of exact meteorological and electrical data in the mature stages of thunderstorms, it is difficult to assess the quantitative importance of our observed results. It is, however, possible to draw some conclusions on the basis of the observations and some reasonable speculations.

Direct measurements of electric fields inside thunderclouds by Gunn (1948) showed a maximum value of 3.4 kV cm^{-1}. Evans (1969) found electric fields only up to 500 V cm^{-1}. However, his method of measurement has many limitations, as pointed out by Vonnegut (1969). Apparently, there are no reliable measurements available at the present time of electric fields inside thunderclouds. Many scientists, however, believe that electric fields of 5 kV cm^{-1} or even higher may exist. Moreover, it may be possible that in some localized regions of thunderstorms, such as near the lower positive charge pocket, which many authors believe triggers the lightning discharge, much larger electric fields might exist. In such regions, therefore, charged cloud particles can attain much higher velocities, due to the electric force, than in other parts of the thunderstorm; under these conditions their gravitational separation from precipitation particles would be questionable.

Quite a large size spectrum of cloud particles is known to exist in thunderclouds. Since the charge acquired and thus the electrical force acting on small cloud particles increases with their size, the relatively larger particles will acquire much higher velocities under electrical forces. As shown in Fig. 4, in electric fields of about 4–6 kV cm^{-1}, cloud particles of radii 50–200 μ should not separate from precipitation particles. However, even lower electric fields will considerably slow down the separation of cloud and precipitation particles. Thus, the rate of charge separation will be considerably reduced.

Doubt may be raised about the possibility of application of these results obtained with copper spheres to those of collisions of cloud and precipitation particles in clouds. The main difference between the two cases seems to be that of their different densities and electrical conductivities. The difference in densities has already been taken into account by including drag force and the weight of the sphere in Eq. (1), and the effect is explained from Fig. 4. With regard to the difference in their electrical conductivities, if the time of contact between the cloud and precipitation particles is long compared to the relaxation time of the water and ice, there should not be any serious doubt about their analogy to copper spheres.

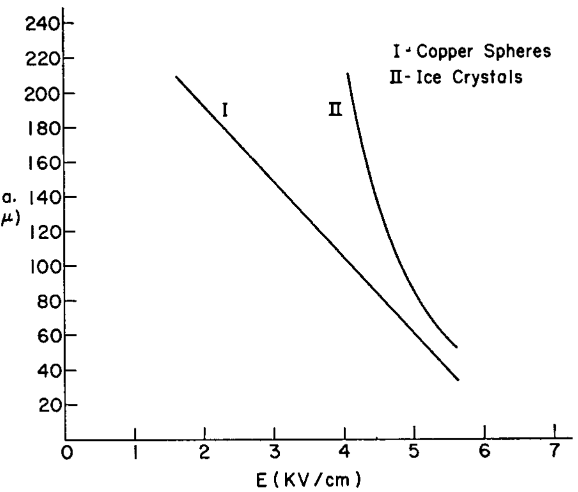

Fig. 4. Values of minimum electric fields for particles of different sizes to attain a velocity, under the electrical force, of 8 m sec^{-1}.

6. Conclusions

While the exchange of induced electrical charges between cloud and precipitation particles can lead to the build-up of low electric fields, our observations indicate that in high electric fields and with the particle sizes that we have investigated (100–200 μ), this mechanism can act in the opposite direction and can reduce the electric field. Whether or not this occurs in thunderstorms will depend on whether the cloud particles and the electric fields are sufficiently large. Even in the case that the size of the particles and the magnitude of the field are small enough so that charge separation can occur under the influence of gravity, electrical forces may reduce significantly the rate of charge separation within the cloud and should not be neglected.

The considerations made in this paper impose a general limitation on the maximum electric field and on the rate of growth of the electric field by a charge-generating mechanism based on the charge separation resulting from falling precipitation particles. Some thunderstorms exhibit many flashes per second, which require a very high rate of charge separation. If these thunderstorms have high electric fields, as many scientists believe, it is questionable whether a charge-generating mechanism based on charge separation resulting from falling precipitation particles can be claimed as the principal mechanism in these very active thunderstorms.

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