Collisions in Washout[1]

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ABSTRACT

The collision of a falling drop with a small particle has been studied by high-speed photography. The trajectory of the particle relative to the center of the drop and relative to a fixed point has been determined under various conditions. The effect of electrostatic charges on drop and particle has been studied.

1. Introduction

Washout of airborne particulates by precipitation or by sprays has applications to the cleaning of air in atmospheric and industrial processes and to the growth of atmospheric hydrometeors. It has been studied very extensively in the past with a view to such applications. Our work in this field relates to the fact that most of the atmospheric radioactive debris collected at ground level is carried to the ground by precipitation.

There are several mechanisms for the scavenging of atmospheric dust by hydrometeors. Collisions with falling raindrops is one such mechanism, and this is the subject of the present paper.

The case under consideration is that of rain falling through the atmosphere, the raindrops colliding with and scavenging dust particles present in the atmosphere. An obvious approach to this subject is to consider the collision of a single drop with a single particle. This approach has been taken by several theoreticians, but it has not been taken in any previous experimental work to our knowledge. We have done this, using high-speed photography for observation. The film gives the position of the particle in a vertical plane through the particle and the center of the drop as a function of time. The experiments continue toward extending the ranges of the parameters, but the results already obtained permit some conclusions.

Recent measurements in partially glaciated clouds have shown that growing ice particles may assume very large charges, e.g., 1 esu for a 1-mm particle (MacCready and Baugham, 1968; Berg and Gaukler, 1968; Stow and Latham[2]). This suggests decisive effects of electrostatic forces upon collisions. Very small particles that lack inertia would follow the air flow around the drop, and would therefore not be scavenged unless attracted by electrostatic forces. This subject was studied by Kraemer and Johnstone (1955), who measured the collection efficiency for particles $<1\ \mu$ in a wind tunnel. The collection efficiency was almost zero in the absence of charge but reached a value of 100 in the presence of charge. The relative velocity was small, 6 cm sec^{-1}, in those experiments.

The large charges on growing ice particles would make them effective scavengers. Rosinski (1966, 1967a,b) Rosinski *et al.* (1969), and Rosinski and Kerrigan (1969) have analyzed hailstones with respect to dust particles and related the scavenging effect to their growth. Rosinski's observations include the collision effect and also peculiar effects associated with growth, e.g., the Facy effect. It appears, however, that the electrification that accompanies growth would be a major scavenging effect.

2. Experimental technique

The experimental technique is illustrated in Fig. 1. A water drop falls off a hypodermic needle and is charged by induction in a field between two parallel plates. It falls through a hole in the bottom plate toward a particle suspended in an electric field to be described later. The drop intercepts a light beam and thereby triggers a relay that disconnects the field so that the particle falls freely. The same relay opens the shutter of the high-speed camera. In order to locate the particle with respect to the drop in a vertical plane normal to the film plane, a picture is taken with a still camera at right angle to the main optical axis.

In order to facilitate the mathematical treatment of the event, we are using spherical particles, 15–30 μ glass beads. They have turned out to be hollow, and it is therefore necessary to determine the density of each particle used in the experiment. This is done by determining the free fall velocity of the particle and applying Stokes' law. The suspension field is disconnected manually, and the free fall of the particle is recorded with the high-speed camera. The field is then switched

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[2] Stow, C. D., and J. Latham, 1967: Airborne studies of the electric properties of convective clouds. Paper presented at Fourth Intern. Conf. Universal Aspects of Atmosphere Electricity, Tokyo.

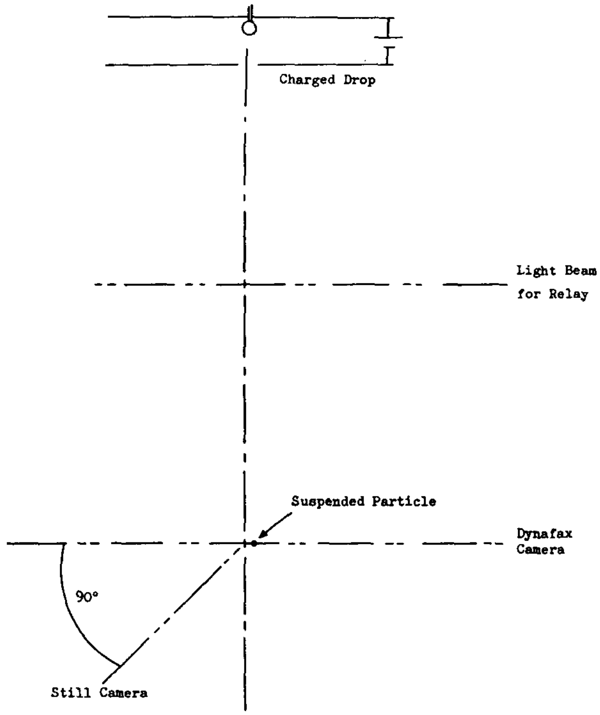

FIG. 1. Diagram of the apparatus.

on again so that the particle is retrieved and available for the main experiment.

Fig. 2 shows the device used for the suspension of the particle (Berg and George, 1967; Berg and Gaukler, 1969). An ac voltage applied as shown in Fig. 2 produces a non-uniform ac field. A charged particle introduced in this field takes a position, at which the field is strong enough to support its weight, and oscillates vertically around this position. The net force required for suspension is produced by the interaction of the oscillating

TABLE 1. Values of the parameters for the data shown in Figs. 4–12 and 16.

Experiment no.	184	122	165	203
Figure no.	4, 5, 6	7, 8, 9	10, 11, 12	16
Particle diameter d (μ)	26.3	24.0	19.6	46.0
Particle terminal velocity v_{po} (cm sec^{-1})	1.99	2.78	1.81	3.32
Particle density (gm cm^{-3})	0.96	1.60	1.57	0.52
Particle mass m (gm)	9.13×10^{-9}	11.6×10^{-9}	6.18×10^{-9}	27.0×10^{-9}
Particle charge to mass ratio q/m (esu gm^{-1})	4.04×10^{4}	4.97×10^{4}	7.11×10^{4}	2.55×10^{4}
Particle charge q (esu)	3.68×10^{-4}	5.76×10^{-4}	4.39×10^{-4}	6.90×10^{-4}
Drop diameter D (cm)	0.255	0.261	0.242	0.250
Drop velocity v_D (cm sec^{-1})	242	260	242	154
Drop charge Q (esu)	0	−0.0645	0.0648	−0.324
Initial distance from center line r_0 (cm)	0.198	0.178	0.233	0.227

field and the oscillating particle. The field also provides horizontal containment. The horizontal forces on the particle are so small that no perceptible oscillation is required for containment. By means of a superimposed dc field (also as shown in Fig. 2) the particle can be lifted to the center of symmetry. In this position the particle does not oscillate, and the ac field merely provides horizontal containment and a vertical restoring force. The dc voltage is proportional to the mass-to-charge ratio for the suspended particle. The diameter of the particle is determined by taking a photograph of the particle at a magnification of 40 at the film and an additional magnification of 15 in projection of the film. The error of measurement is probably less than one percent.

Typical values of the parameters are given in Table 1.

3. Theory

The particle is too small to affect the motion of the falling drop or even the flow of air around the drop. The

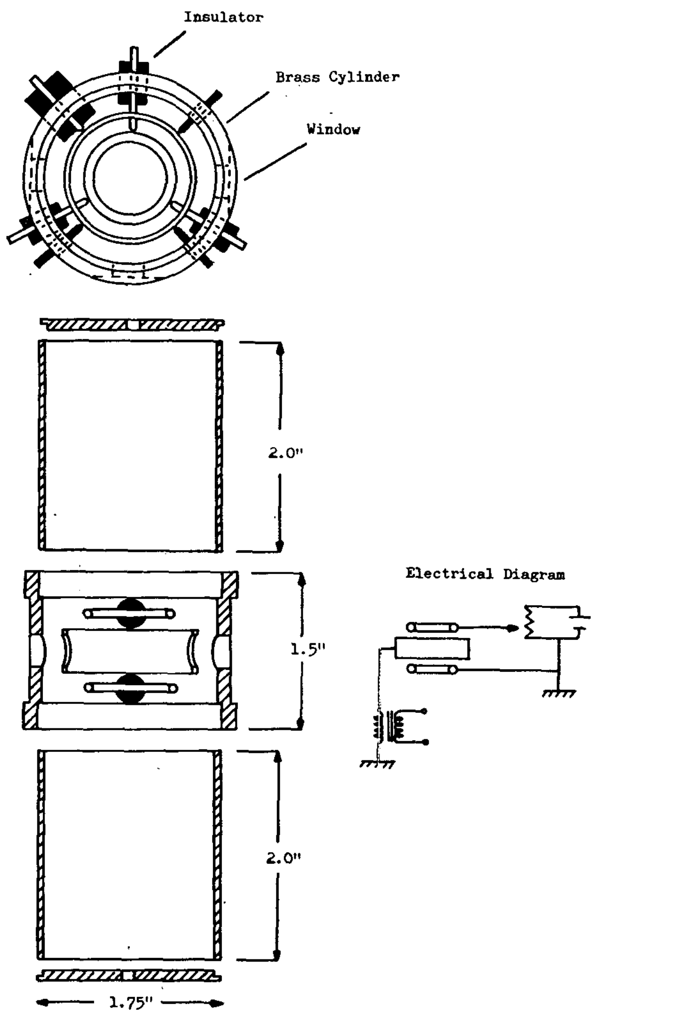

FIG. 2. The suspension chamber.

forces acting on the particle are aerodynamic forces, electrostatic forces and inertia. Assuming, for simplicity, potential flow of the air, the potential is

$$\phi_a=-v_D\frac{D^3}{8}\frac{z}{2R^3},\qquad (1)$$

with the notation being given in Fig. 3 and with v_D the drop velocity.

The equations of motion in the z and r directions may be written in the form

$$\frac{dv_{pz}}{dt}=g-\frac{g}{v_{po}}v_{pz}+\frac{g}{v_{po}}v_D\frac{D^3}{16R^3}\left(\frac{3z^2}{R^2}-1\right)+\frac{qQz}{mR^3}-\frac{Q^2dz}{2mR^4},\qquad (2)$$

$$\frac{dv_{pr}}{dt}=-\frac{g}{v_{po}}v_{pr}+\frac{g}{v_{po}}v_D\frac{3D^3}{16}\frac{rz}{R^5}+\frac{qQr}{mR^3}-\frac{Q^2dr}{2mR^4},\qquad (3)$$

where g is the acceleration of gravity; D, Q, v_D the diameter, charge and velocity of the drop; and d, q, m, v_p, v_{po} the diameter, charge, mass, velocity and terminal velocity of the particle.

In the simple case $r=0$ there is no horizontal deflection of the particle, and the equation of motion is

$$v_{pz}=g-\frac{g}{v_{po}}v_{pz}+\frac{g}{v_{po}}v_D\frac{D^3}{8}\frac{1}{z^3}+\frac{qQ}{mz^2}-\frac{Q^2d}{2mz^3}.\qquad (4)$$

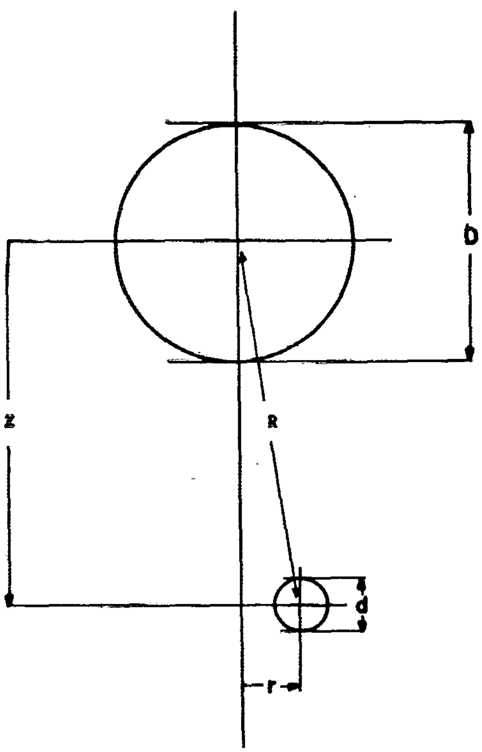

FIG. 3. The coordinate system.

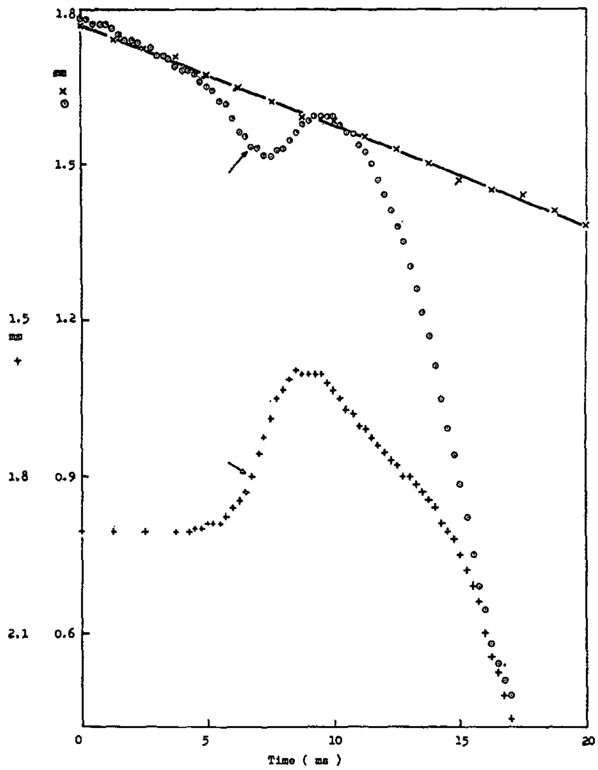

FIG. 4. Vertical positions of a particle in free fall (crosses) and the vertical (circles) and horizontal (plus marks) positions of the same particle in the presence of a falling, uncharged drop for experiment 184. The parameters are listed in Table 1. The arrow marks the instant when the particle is at the level of the center of the drop.

This equation can be integrated to give v_{pz}. It can then be integrated numerically one step further to give the deviation from the free fall caused by the presence of the falling drop.

The general equations of motion (2) and (3) cannot be solved in terms of tabulated functions. They can be solved by numerical integration, however.

In the case $r=0$ the aerodynamic force and the image force depend upon the distance in the same way. The image force is greater than the aerodynamic force when

$$Q^2>\frac{mgv_DD^3}{4dv_{po}}=\frac{3\pi}{4}\eta D^3v_D,\qquad (5)$$

where η is the viscosity of air. Thus, for uncharged particles or particles so small that their charge is negligible, there is a net force of attraction when the inequality (5) is satisfied. In the general case $r\neq 0$ the corresponding formula is

$$Q^2>\frac{3\pi}{4}\eta D^3v_D\frac{z}{R}.\qquad (6)$$

Clearly, (6) is satisfied, if (5) is satisfied. It is noteworthy that the condition for attraction depends upon

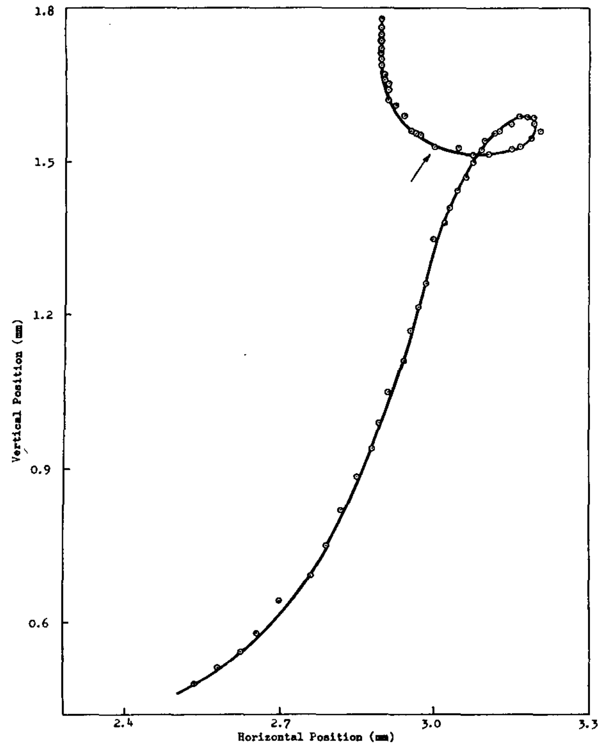

FIG. 5. The data in Fig. 4 replotted to show the trajectory of the particle relative to a fixed point. The arrow marks the instant when the particle is at the level of the center of the drop. The horizontal coordinate of the center of the drop is 0.93 mm.

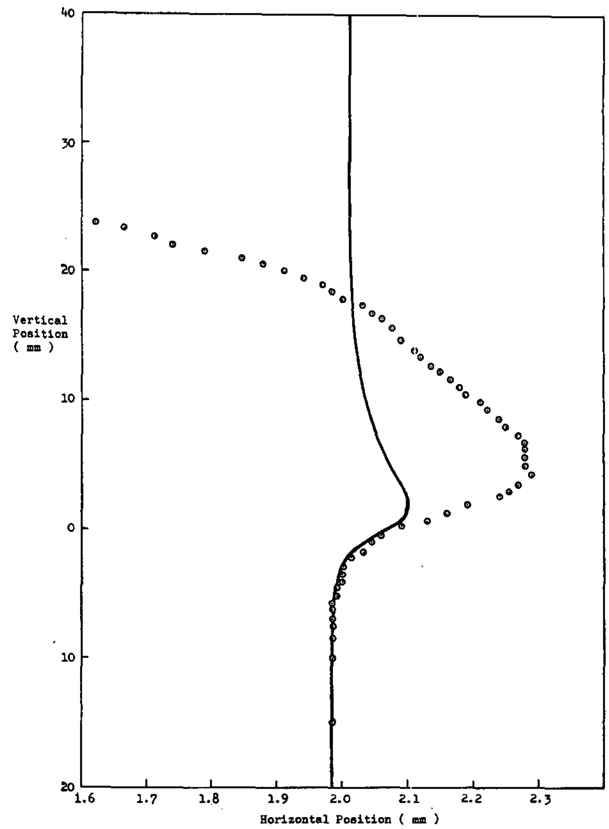

FIG. 6. The data in Fig. 4 replotted to show the trajectory of the particle relative to the center of the drop. The curve is a calculation based on theory; the points are experimental values.

the properties of the drop alone, independent of the properties of the particle.

When the particle size goes toward zero and the drop velocity is small enough, the collision efficiency goes toward infinity if the inequality (5) or (6) is satisfied, and toward zero if the inequality (5) or (6) is not satisfied. When the particle size approaches infinity, the collision efficiency approaches unity because the inertia then predominates.

It follows from this reasoning that the scavenging of small particles is most effective when the scavenger is strongly charged and falls slowly, e.g., when the scavenger is a snow flake. For large and strongly charged particles the Coulomb force predominates, especially at large distances.

4. Experimental data

The films were evaluated by measuring the vertical and the horizontal coordinates of the particle on a sequence of frames relative to the edge of the frame. Typical plots of such data are given in Figs. 4, 7 and 10. The data were then replotted to give the trajectory of the particle with respect to a fixed point, typical plots being given in Figs. 5, 8 and 11. The data were finally plotted with respect to the drop center as the

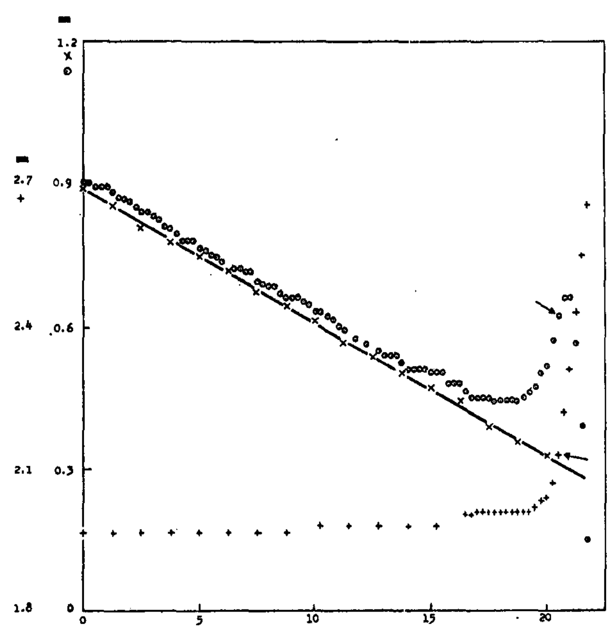

FIG. 7. Same as Fig. 4 except for experiment 122 involving a falling drop charged to the opposite polarity as compared to the particle.

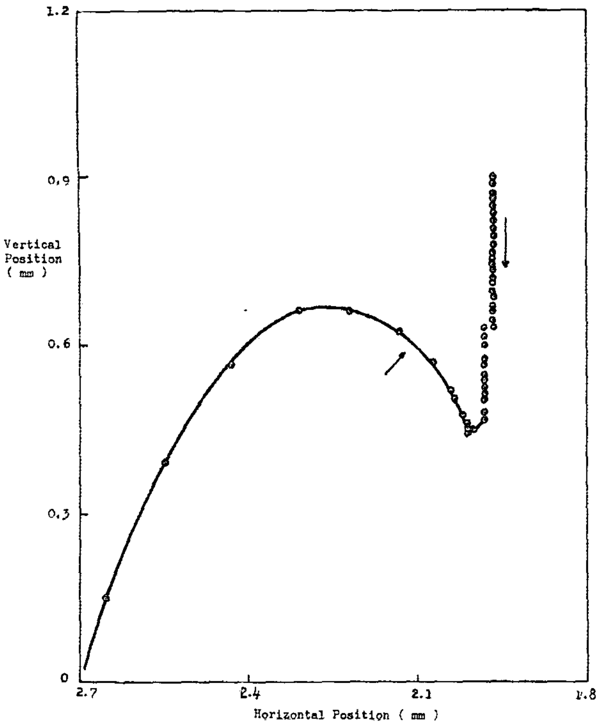

FIG. 8. The data in Fig. 7 replotted to show the trajectory of the particle relative to a fixed point. The arrow marks the instant when the particle is at the level of the center of the drop. The horizontal coordinate of the center of the drop is 3.76 mm.

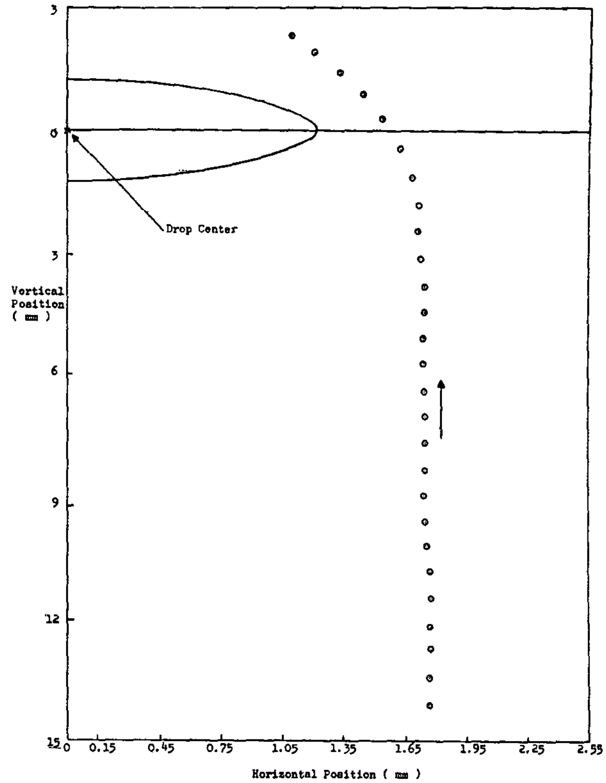

FIG. 9. The data in Figure 7 replotted to show the trajectory of the particle relative to the center of the drop.

origin of the coordinate system; typical particle trajectories relative to the drop are given in Figs. 6, 9 and 12. Figs. 4, 7 and 10 also give plots of the free, undisturbed fall of the particle in the absence of a falling drop, i.e., the vertical position of the particle as a function of time. The slope of this line gives the terminal velocity of the particle in free fall.

Experiments were first conducted with the particle on the center line through the drop, i.e., $r=0$ in Fig. 3. The vertical deflection from the free fall trajectory was calculated from Eq. (4) and from the experimental data. Typical results are presented in Figs. 13, 14 and 15. The agreement between theory and experiment shows the validity of the potential flow. It is noteworthy that the product force Qq was not used in the calculation of the curve in Fig. 15 for the case of opposite polarities of drop and particle. It was found that the particle loses its charge by a discharge when it is close enough to the drop. Similar observations have been reported by Sartor (1967).

Values of the parameters used in the comparison between theory and experiment are shown in Table 2.

Eq. (2) shows that the aerodynamic force is negative, i.e., attractive, when $3z^2/R^2<1$. This effect is clearly shown in Fig. 5. Not only does the particle reverse its direction upward but it also makes a loop, which, ap-

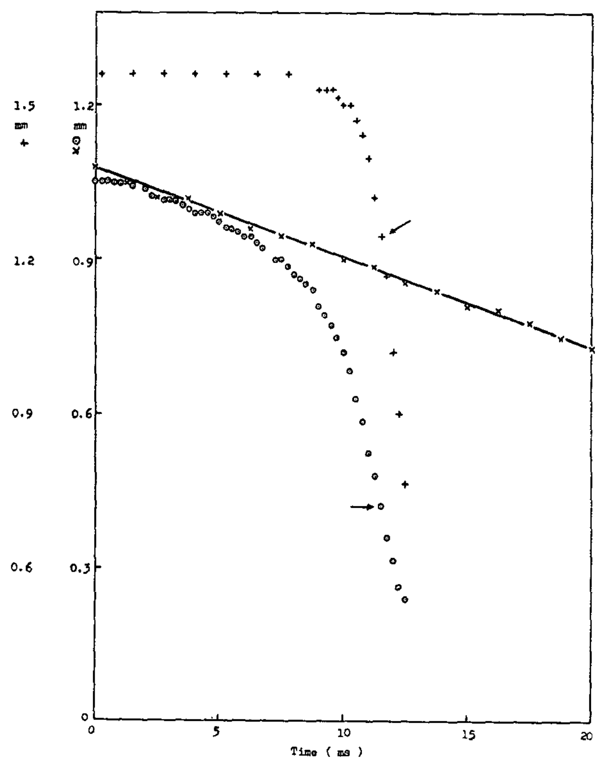

FIG. 10. Same as Fig. 4 except for experiment 165 involving a falling drop charged to the same polarity as the particle.

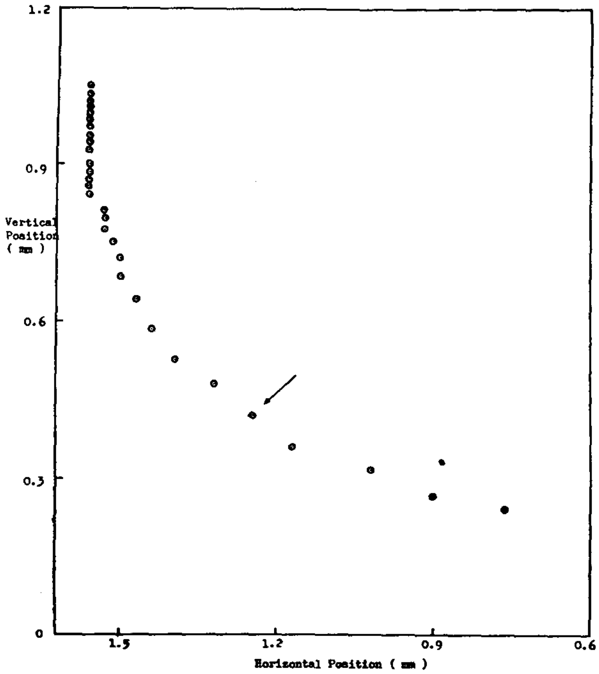

FIG. 11. The data in Fig. 10 replotted to show the trajectory of the particle relative to a fixed point. The arrow marks the instant when the particle is at the level of the center of the drop. The horizontal coordinate of the center of the drop is 3.6 mm.

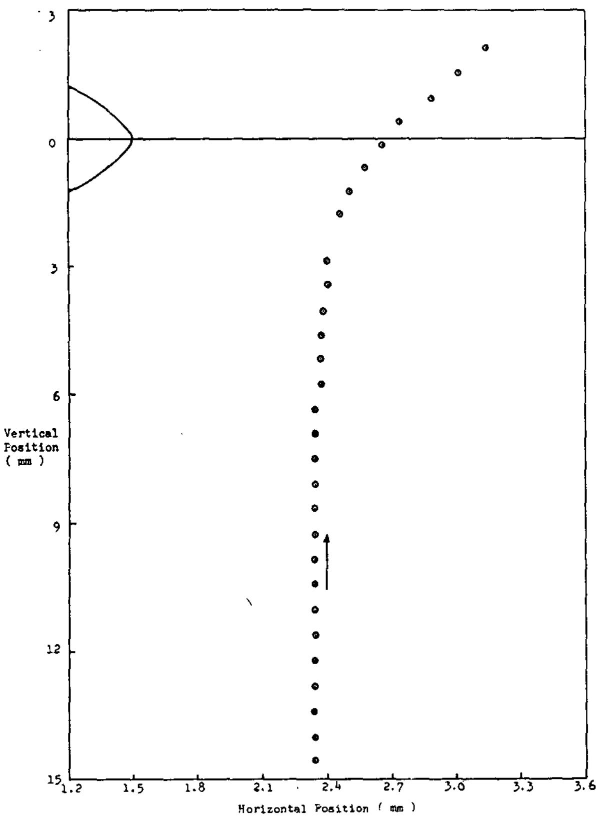

FIG. 12. The data in Fig. 10 replotted to show the trajectory of the particle relative to the center of the drop.

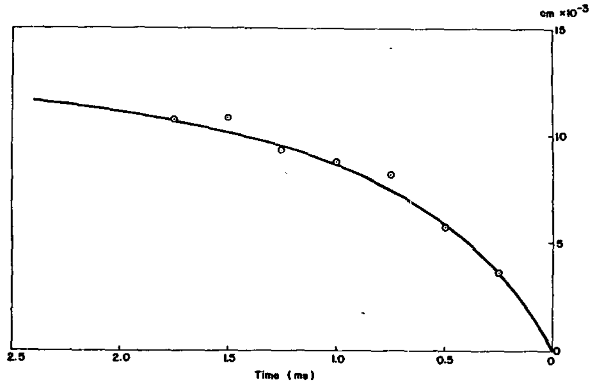

FIG. 13. Vertical deflection of the particle by the drop for experiment 54, where time zero is at collision. The curve is a calculation based on theory; the points are experimental values. The parameters are given in Table 2.

parently, gives it a spin. When the particle trajectory is calculated from (2) and (3) neglecting the spin, the calculated deflection is much smaller than that observed. Furthermore, when the particle goes back toward the center line through the drop, it passes its original position, which is contrary to theory for a particle without a spin. It thus, appears, that the spin may be decisive to the particle trajectory. This effect remains to be investigated.

Most of the data were taken with a 2.5-mm drop at a fall velocity of 2.5 m sec^{-1}. The size is that of a drop falling by its own weight off a hypodermic needle. We have produced smaller drops under these conditions,

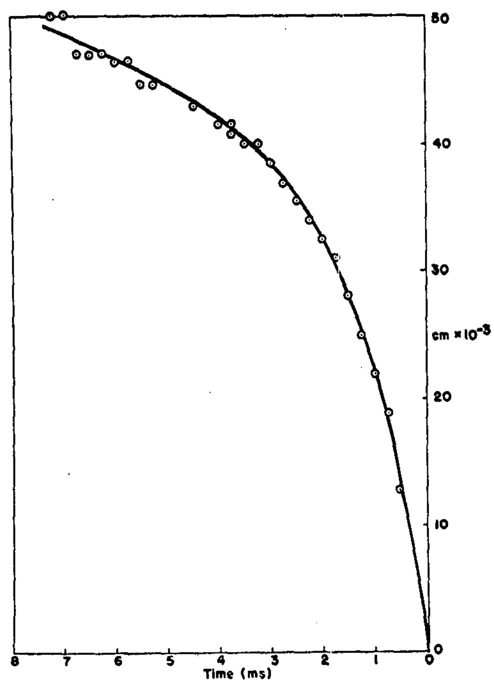

FIG. 14. Same as Fig. 13 except for experiment 88.

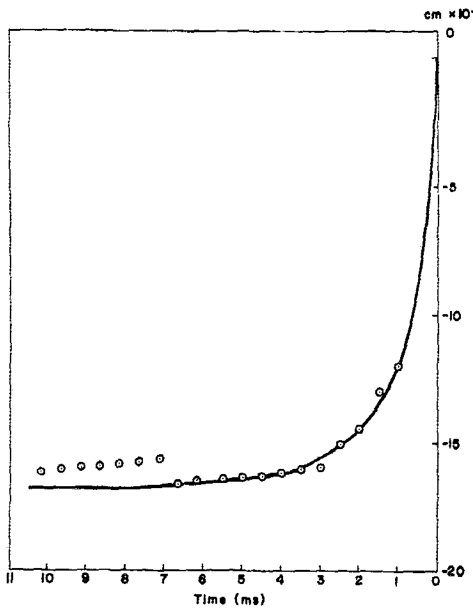

FIG. 15. Same as Fig. 13 except for experiment 92. The jump at 7 m sec is probably caused by loss of particle charge by discharge.

but they cannot be accurately aimed. The fall velocity is considerably smaller than that in free fall. However, the velocity changes very little during the event under study. The drop charge was in most cases no more than 0.065 esu, corresponding to a charging voltage of 1000 V. Under these circumstances there was never a collision at the back side of the drop. Merely reducing the drop velocity to 1.5 m sec^{-1} did not suffice to produce such a collision, but when the charging voltage was also increased to 5000 V, i.e., a drop charge of 0.3 esu, collisions just behind the equator could occasionally be seen, but only when the particle had a grazing incidence that just missed the front side of the drop. Fig. 16 shows such a particle trajectory.

In the case shown in Figs. 7, 8 and 9 the particle was accelerated by the drop from a free fall velocity of 2 cm sec^{-1} to a velocity of 100 cm sec^{-1}, but the particle did not catch up with the drop that fell at 2.5 m sec^{-1}.

TABLE 2. Values of the parameters used in comparisons between theory and experiment.

Experiment no.	54	88	92
Figure no.	13	14	15
Particle diameter d (μ)	25.0	19.8	28.2
Particle terminal velocity (cm sec^{-1})	3.27	1.87	1.67
Particle density (gm cm^{-3})	1.75	1.59	0.701
Particle mass (gm)	14.28×10^{-9}	6.47×10^{-9}	8.23×10^{-9}
Particle charge to mass ratio q/m (esu gm^{-1})	2.21×10^{4}	5.05×10^{4}	6.37×10^{4}*
Particle charge q (esu)	3.15×10^{-4}	3.27×10^{-4}	5.24×10^{-4}*
Drop diameter D (cm)	0.248	0.248	0.252
Drop velocity v_D (cm sec^{-1})	254	248	248
Drop charge Q (esu)	0	0.0648	−0.0645

* Initial values; the charge was lost by discharge.

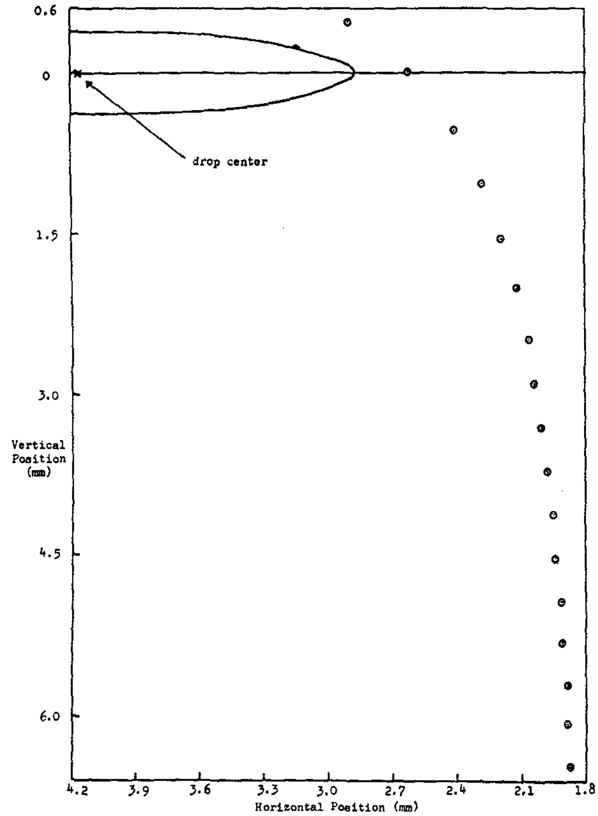

FIG. 16. The trajectory of the particle relative to the center of a falling drop charged to the opposite polarity as compared to the particle (experiment 203). The parameters are given in Table 1.

5. Discussion

The effects of electrostatic charges upon collisions in washout are shown by (2) and (3), or more simply, by (4). The product force depends least upon the distance,

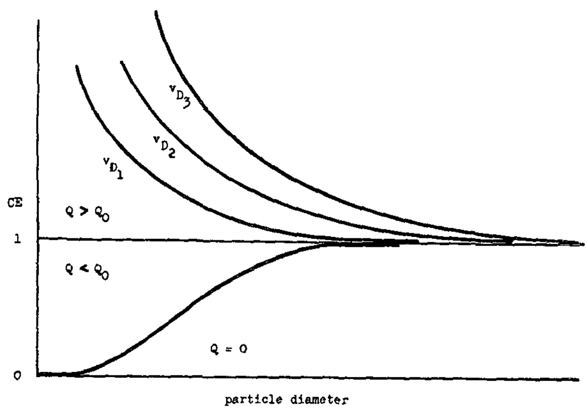

FIG. 17. The collision efficiency for uncharged particles and a charged scavenger: $v_{D1}>v_{D2}>v_{D3}$.

and this force therefore predominates at large distances. However, the particle charge is likely to be lost by a discharge when the particle comes close to the drop. It may, therefore, not be decisive to collision. The image force of attraction depends upon the distance in nearly the same manner as does the aerodynamic force of repulsion, and one predominates over the other according to (6). For a 2.5-mm drop falling at terminal velocity the image force predominates if $Q>0.07$ esu. Raindrops are usually not so strongly charged, and they are therefore poor scavengers of small particles. However, since snowflakes and hailstones may be much more strongly charged and also have a smaller fall velocity, they are generally more effective scavengers of small particles.

The fall velocity of the scavenger at a given force of attraction determines the time available for the acceleration of the particle and the particle velocity required to reach the scavenger before it has gone by. Of course, if the scavenger had no velocity relative to the particle, the collision efficiency would be infinite. But the acceleration also depends upon the particle mass, and small particles are therefore more affected by charges than are large particles.

Fig. 17 shows schematically the collision efficiency as a function of particle diameter. Collision efficiencies larger than unity could only be expected for $Q>Q_0$, Q_0 denoting the limiting value according to (6), and for small fall velocities.

6. Conclusion

The problem posed in this paper and its theoretical and experimental study are simple and straightforward. The experimental study was well worthwhile, however, because of the need to determine the effects of the several assumptions necessary for the theoretical treatment, e.g., the nature of the flow around the drop, the discharge of the charged particle, and the rotation of the particle.

On the other hand, the approach taken to the problem leads to considerations that may otherwise not be apparent, and also to their experimental investigation. One such consideration is the scavenging by a strongly charged hydrometeor when falling slowly, e.g., a snowflake, as contrasted to scavenging by a rapidly falling drop as a result of inertia and impaction. It appears that the electrical effect predominates in the scavenging of very small particles.

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