Charging of Aircraft: High-Velocity Collisions

W. D. Keith* and C. P. R. Saunders†
University of Manchester Institute of Science and Technology, Manchester, England, United Kingdom

A laboratory investigation into the charge transferred to a metal target during high-speed collisions with ice crystals has shown that the charge separated at a speed of 25 m s^{-1} is greater than the charge separated at higher speeds under the same cloud conditions. It is suggested that the reduction in charge transfer at high speeds is because of the reduced contact time between the interacting particles. The sign of the charging is negative in conditions of zero liquid water content at all temperatures; the charging is positive at warm temperatures in the presence of liquid water. Thus, aircraft may charge negatively at high altitudes and positively at lower levels when they encounter water droplets.

Introduction

SINCE the beginning of aviation there have been reports of lightning strikes to aircraft as they flew through or near thunderclouds. There is still controversy as to the effect of the aircraft itself: Does it trigger the lightning or simply happen to be in its path? Does self-charge on the aircraft promote lightning strikes? The purpose of this work was to determine the charging of a metal target during high-velocity interactions with water droplets and ice crystals in the laboratory to simulate the charging of an aircraft in the atmosphere. The work is a continuation of experiments to investigate the charging of soft hailstones as they fall and interact with supercooled droplets and ice crystals in thunderclouds.[1-3]

Experimental Procedure

The experiments described here were performed in a 3-m-high cloud chamber situated within a large cold room.[2] The cloud was formed by introducing vapor from a boiler through a hole in the floor of the lower chamber that was 2-m high. The power to the boiler could be controlled from outside the cold room, thus enabling control of the liquid water content of the cloud. At a liquid water content of 1 g m^{-3}, the drop-size distribution had a maximum size of 33 μm and a modal diameter of 12 μm. When the cloud liquid water content was about 2 g m^{-3} there was an unavoidable temperature gradient of 1°C m^{-1} over the height of the cloud chamber, but the region where the experiments were performed was well mixed and so had a uniform temperature. A droplet cloud in the upper chamber was produced by an ultrasonic nebulizer situated on a shelf outside the cold room.

Ice crystals could be produced by seeding the cloud in the lower chamber with a wire that had been dipped in liquid nitrogen. The wire was introduced quickly into the chamber that nucleated the cloud, and as the environment was supersaturated with respect to ice, the ice crystals grew at the expense of the water droplets. The ice crystals could be seen as "dust" in a light beam and could be sampled to determine their sizes and concentration. The maximum crystal size that could be produced in this way was about 130 μm. Larger ice crystals up to 800 μm were produced by seeding the cloud in the top chamber, levitating the growing crystals, and eventually allowing them to fall through the supersaturated environment of the lower chamber.

The soft hailstone was simulated by a metal target of diameter 5 mm and length 2 cm situated inside a tube of diameter 2 cm that protruded a short distance into the lower cloud chamber. A regenerative pump drew the cloud past the target at speeds of up to 110 m s^{-1}. At this impact speed, two sets of experiments were performed with a cloud consisting purely of ice crystals; the first with a clean metal target and the second with a previously rimed target. Further experiments were performed to determine the charge transfer in the riming case. The apparatus was modified slightly to allow the cloud to be drawn past three targets simultaneously (of diameter 1.6 mm) at different velocities so that direct comparison of the charging currents could be made. The impact velocities used were

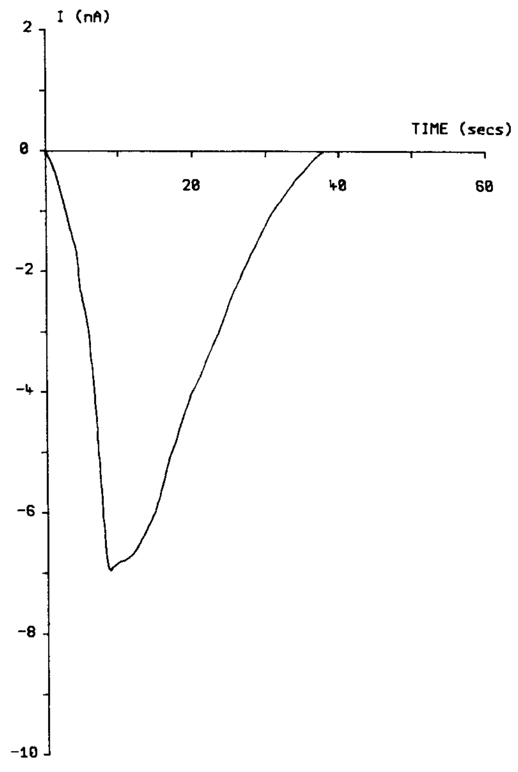

Fig. 1 Charging current vs time at 110 m/s.

Received July 30, 1988; revision received July 18, 1989.

*Research Assistant, Department of Pure and Applied Physics; currently Scientific Officer, British Nuclear Fuels, Capenhurst, Cheshire, England, United Kingdom.

†Professor, Head of Atmospheric Physics Research Group, Department of Pure and Applied Physics.

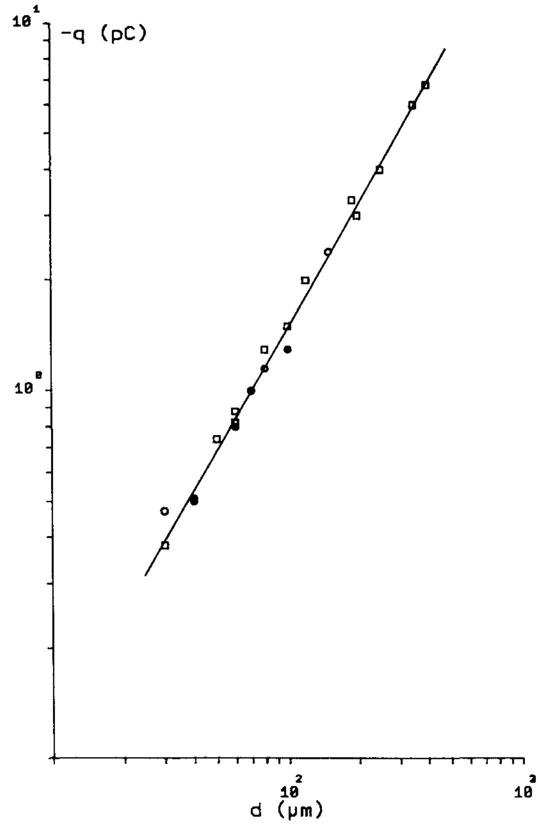

Fig. 2 Charge per event vs crystal size at 110 m/s.

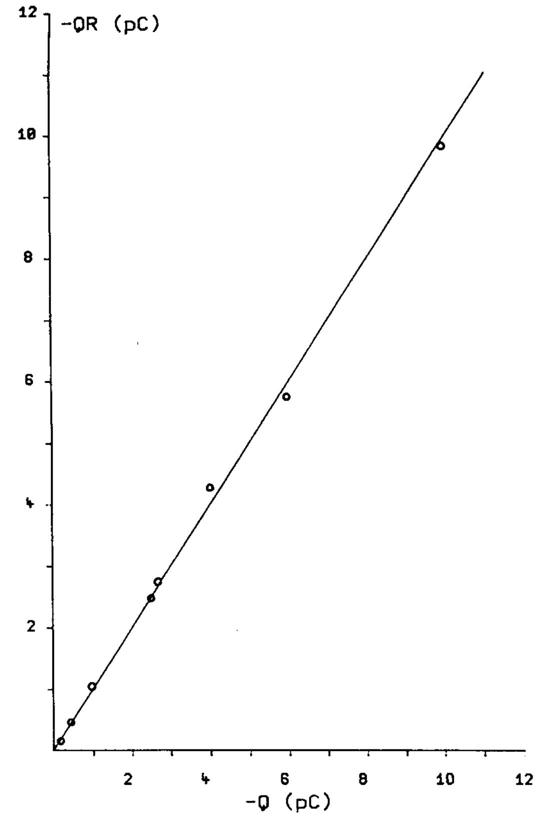

Fig. 3 ***Q*** **vs** ***QR*** **at 110 m/s.**

75, 50, and 25 m s^{-1} and 50, 25, and 10 m s^{-1}. The charging was investigated at cloud temperatures of −15 and −25°C.

The targets were connected to Earth via a sensitive charge amplifier having a sensitivity of 1 mV ≡ 10^{12} A; charge flowed to Earth with a time constant of 1 s. In the previous low-velocity experiments, a higher sensitivity was used, but the higher charge transfers here saturated the amplifier. Chart recorders were used to record the net multiple charge transfers as charging currents.

Results

A cloud of ice crystals, of concentration about 104 m^{-3}, was drawn past a 5-mm-diam metal target at a speed of 110 m s^{-1}. The crystal concentration was determined from a formvar-covered microscope slide just before the pump was switched on. It was assumed, by comparing the volume flow past the target and the total volume of the cold room, that the crystal concentration drawn past the target for the first 10 s of a run was constant, after which time the crystal concentration became depleted. The charge per crystal separation event is calculated from the crystal concentration and value of the initial negative current peak. At these speeds, the collision efficiency was unity and the event probability[4] (collision × separation efficiencies) was also found to be unity as there was no evidence of any crystals on the target at the end of a run. Strong negative charging was measured at all temperatures and all crystal diameters in agreement with the results of Jayaratne et al., who found that an evaporating ice-covered target always charged negatively. Figure 1 shows a typical run at −15°C; the charging is negative and quickly returns to zero as the crystal cloud is depleted. Figure 2 shows the charge per event against crystal diameter at a speed of 110 m s^{-1}. This figure illustrates that the charge transfer is independent of temperature and that large amounts of charge are being separated, for example, a 500 μm crystal separates about −10 pC, which is three orders of magnitude greater than the charge measured at 3 m s^{-1}. These experiments were repeated with a previously rimed target that also charged negatively. The target was rimed by drawing supercooled water droplets past it for a few seconds; the cloud was then seeded and the experiments conducted as before at 110 m s^{-1}. Figure 3 plots points from the two sets of experiments at equal values of crystal size that range from 20 to 450 μm. There was no effect due to the presence of the rime as indicated by the close 1:1 relationship between the charge per event of the rimed target QR with that of the unrimed target Q.

The foregoing experiments were conducted without any water droplets being present in the chamber, but this is not representative of natural conditions and so experiments were performed at high speed with a mixed cloud. The apparatus was modified so that the cloud could be drawn simultaneously past three targets at different speeds, which enabled the direct comparison of results at three speeds under the same cloud conditions. The target diameter was 1.6 mm and the flow speeds used initially were 75, 50, and 25 m s^{-1}. The event probability is unity for all crystal diameters at these velocities. The shapes of the three current-time graphs were similar, which verified that the targets were experiencing the same cloud conditions. Other experiments were performed at 50, 25, and 10 m s^{-1} at −15°C to investigate the velocity dependence further. Figure 4 shows the charge per event against diameter for these four velocities; the charge separated is a maximum at 25 m s^{-1}.

The apparatus was also used at a temperature of −25°C; the sign of the charging was negative but the same pattern of velocity dependence was observed. The shape of the current vs time graph was the same for all the targets, thus confirming that they experienced the same cloud conditions. Figure 5 shows the charge per event against crystal diameter with a maximum value at 25 m s^{-1}. The gradient of the lines is 0.7

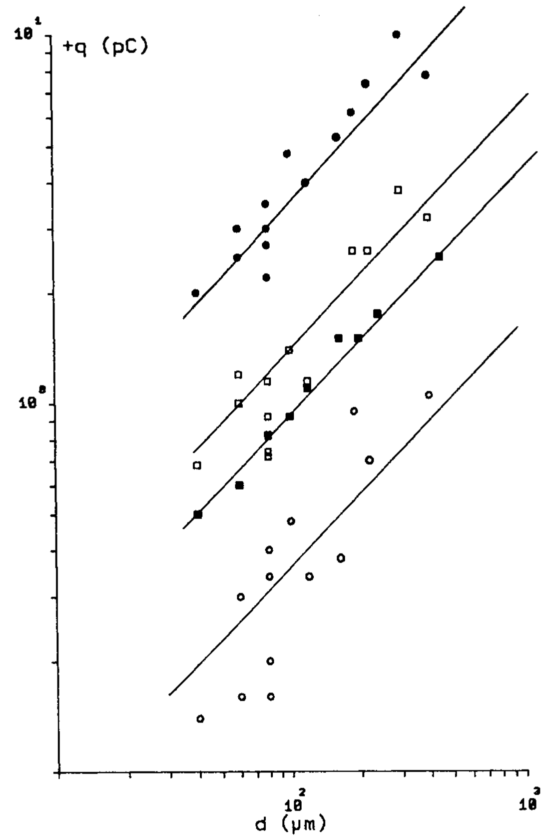

Fig. 4 Charge per event vs crystal size for different impact velocities at −15°C; ○ = 75 m/s, □ = 50 m/s, ● = 25 m/s, ■ = 10 m/s.

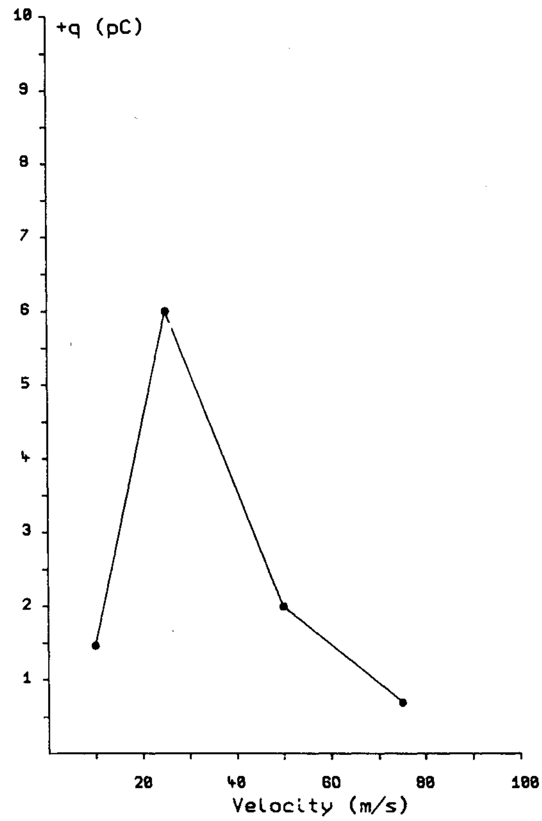

Fig. 6 Charge per event vs speed for a 200 μm crystal at −15°C.

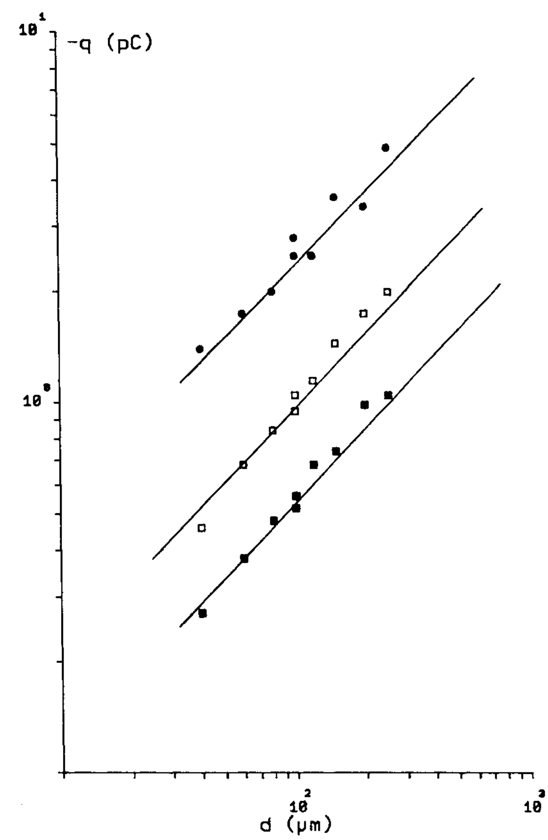

Fig. 5 Charge per event vs crystal size for different impact velocities at −25°C; □ = 50 m/s. ● = 25 m/s, ■ = 10 m/s.

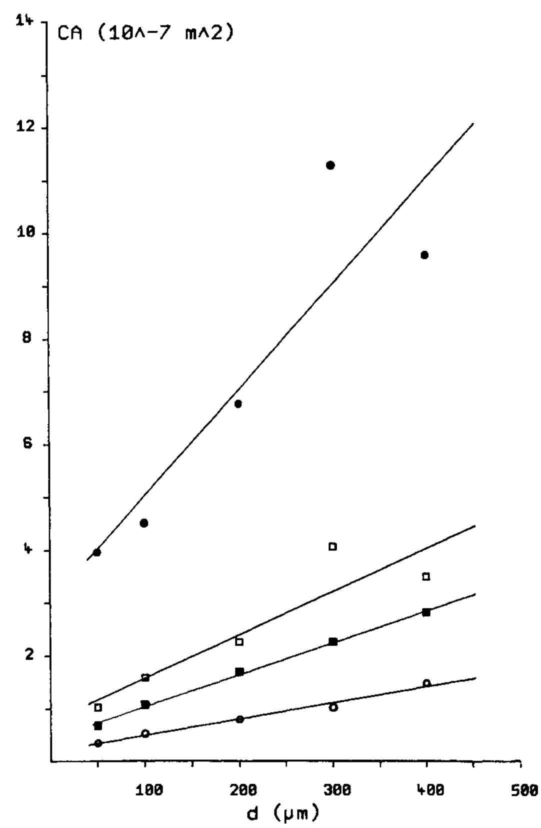

Fig. 7 Contact area vs crystal size for different impact velocities at −15°C; ○ = 75 m/s, □ = 50 m/s, ● = 25 m/s, ■ = 10 m/s.

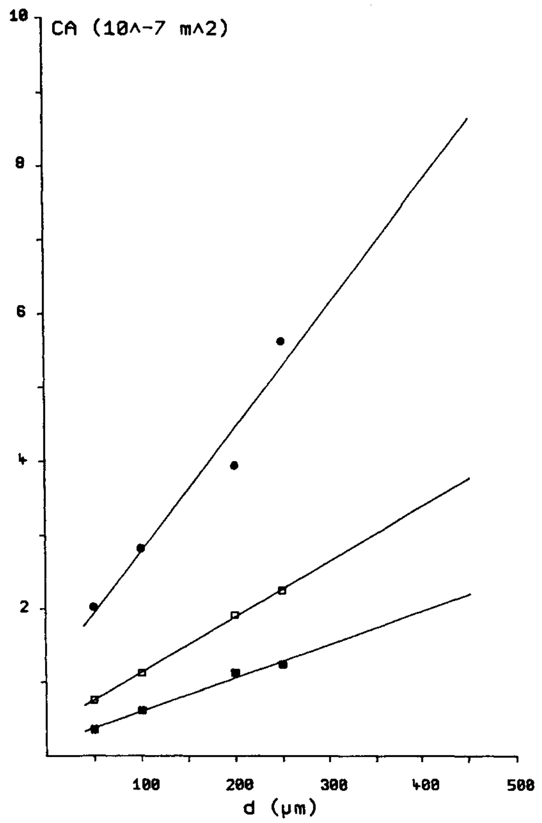

Fig. 8 Contact area vs crystal size for different impact velocities at −25°C; □ = 50 m/s, ● = 25 m/s, ■ = 10 m/s.

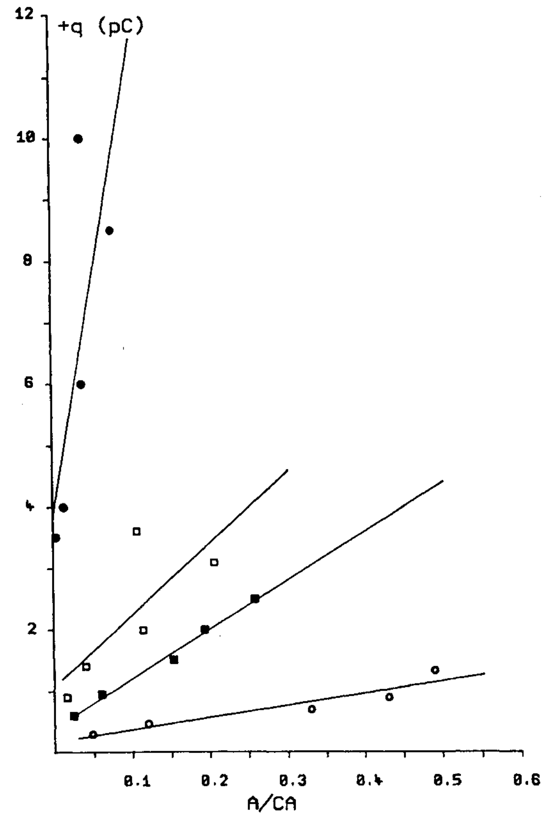

Fig. 10 The ratio of contact area to crystal area vs charge for positive charging; ○ = 75 m/s, □ = 50 m/s, ● = 25 m/s, ■ = 10 m/s.

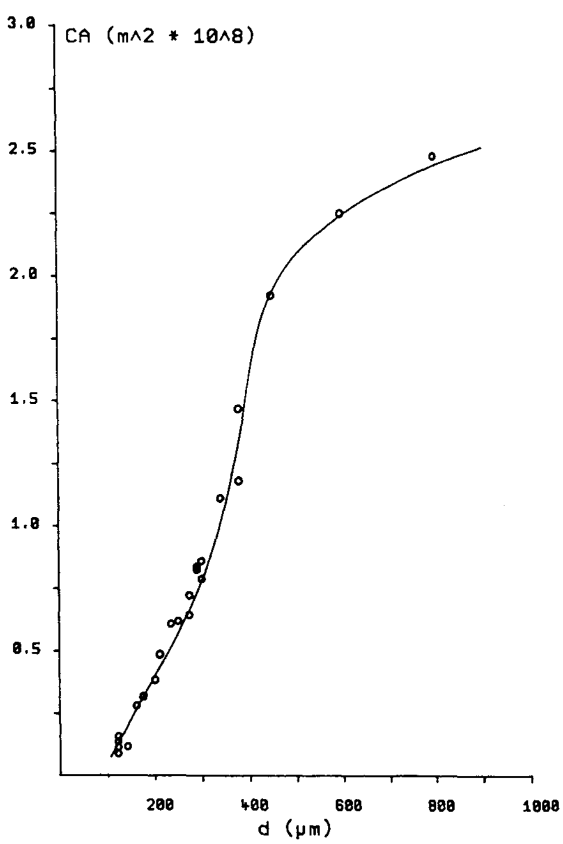

Fig. 9 Contact area vs crystal size at 3 m/s (from Ref. 6).

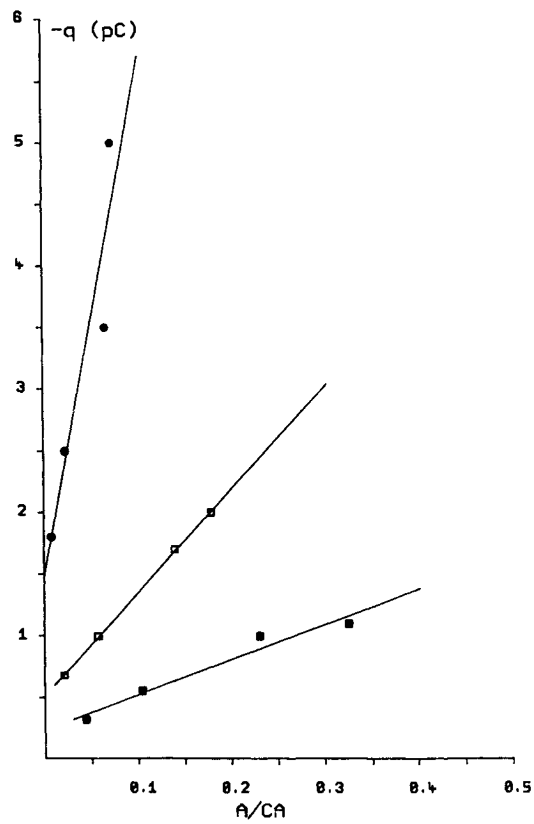

Fig. 11 The ratio of contact area to crystal area vs charge for negative charging; □ = 50 m/s, ● = 25 m/s, ■ = 10 m/s.

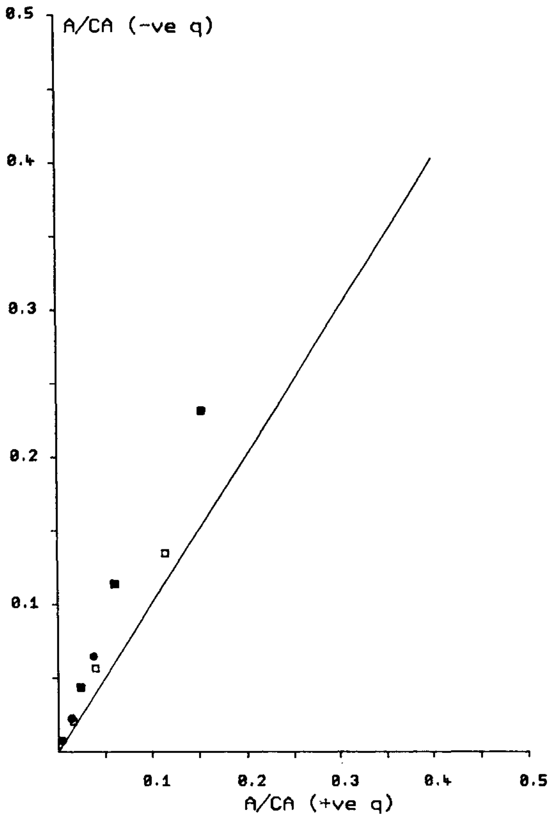

Fig. 12 The ratio of contact area to crystal area for positive charging vs the ratio for negative charging; □ = 50 m/s, ● = 25 m/s, ■ = 10 m/s.

for both positive and negative charging and is independent of the speed. A possible explanation for the velocity dependence is discussed in the following section.

Discussion

The high-speed collision experiments were designed to simulate the charging of an aircraft as it flies through a cloud of ice crystals. In regions of zero liquid water content, the target charged negatively at all temperatures. However, the collection efficiency for water droplets at these speeds is such that even a very low liquid water content can give an appreciable rate of rime accretion, which was shown by Jayaratne et al.[1] to lead to positive charging. This was the case with the 1.6-mm targets; under cloud conditions that gave negative charging to the 5-mm target, the smaller target collected more water droplets and rime ice, leading to positive charging. Thus, it was quite difficult to insure a zero liquid water content in the crystal-only experiments with the 1.6-mm targets.

The velocity dependence was opposite to that expected in that the high velocities produced less charge than the lower velocities. Figure 6 illustrates the charge per event for a 200 μm crystal against air speed that shows the charge per event is maximum at about 25 m s^{-1}. This can be explained in terms of contact time and adhesion efficiency. Initially, as the contact time between the hailstone and ice crystal increases with increased velocity, the charge transfer also increases. However, above a certain velocity, the particles bounce off more readily and then the charge transfer decreases because of reduced contact time. When ice crystals rebound from an ice target, corona breakdown occurs, leading to light emission.[5] This implies that the local electric field at the point of contact is sufficient to cause breakdown, giving a limit to the magnitude of the charge transfer. By using Gauss's law and assuming a breakdown field value of 10^6 V m^{-1}, the contact area of interaction can be calculated from the formula $CA = Q/8.8 \times 10^{-6}$ (m^2), where Q is the magnitude of the charge transfer and CA the area of contact between the target and ice crystal. The contact area of the crystals was determined from Figs. 4 and 5 for the positive and negative charging regimes and is shown in Figs. 7 and 8 against the crystal diameter. It can be seen that there is little variation in the contact area with crystal size. At low impact speeds, the contact area increases with crystal diameter[6] as shown in Fig. 9. The ratio of the crystal area A and the contact area CA is plotted against the charge per event for both positive and negative charging (Figs. 10 and 11). At low-impact speeds, the contact area is approximately one-fifth of the crystal area,[6] whereas Figs. 10 and 11 show that the contact area at high speeds can be up to five times the crystal area. The ratio of the crystal area to contact area for negative charging at $-25°$C was plotted against the ratio for positive charging at $-15°$C and is shown in Fig. 12; there is a close 1:1 relationship. Also, the dependence of the charge per event on the crystal diameter ($d^{0.7}$) is the same for both positive and negative charging. These two results could indicate that the same unknown charging mechanism is operating at the two different temperatures, and given the large contact area, frictional charging may be a dominant process.

Conclusions

The work presented here shows that the charge per collision does not increase with impact velocity above a certain speed. In these experiments, the limiting speed is around 25 m s^{-1}, but this speed may be dependent on the liquid water content.

In relation to aircraft, the charging is strongly dependent on the liquid water content, and so at high altitudes where liquid water is scarce, the charging will be predominantly negative. At lower levels the charging may be a combination of both positive and negative and at speeds above 100 m s^{-1} may be reduced to even smaller values than detected in the experiments. It may be that there is no significant charging of high-speed aircraft and rockets by collisions with cloud particles.

Acknowledgment

This work was supported by the U.S. Air Force.

References

[1]Jayaratne, E. R., Saunders, C. P. R., and Hallett, J., "Laboratory Studies of the Charging of Soft Hail During Ice Crystal Interactions," *Quarterly Journal Royal Meteorological Society,* Vol. 109, No. 459, 1983, pp. 609–630.

[2]Keith, W. D., and Saunders, C. P. R., "The Charging of Soft Hail by Large Ice Crystal Interactions," *Atmospheric Research* (to be published).

[3]Keith, W. D., and Saunders, C. P. R., "The Effect of Centrifugal Acceleration on the Charging of a Riming Hailstone," Journal of Meteorology and Atmospheric Physics, Vol. 41, 1989, pp. 55–61.

[4]Keith, W. D., and Saunders, C. P. R., "The Collection Efficiency of a Cylindrical Target for Ice Crystals," *Atmospheric Research*, Vol. 23, 1989, pp. 83–95.

[5]Keith, W. D., and Saunders, C. P. R., "Light Emission from Colliding Ice Particles," *Nature,* 1988, pp. 362–364.

[6]Keith, W.D., "Thunderstorm Electrification," Ph.D. Thesis, Univ. of Manchester Institute of Science and Technology, Manchester, UK, 1987.