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Static charging of aircraft by collisions with ice crystals (+)

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Résumé. — Des expériences de laboratoire, mesurant le transfert de charge lors de collisions de cristaux de glace avec diverses cibles métalliques, ont montré que l'effet dominant, sur l'amplitude et le signe de la charge, est le travail de sortie du métal. La différence de charge entre deux alliages utilisés en aéronautique atteint un facteur deux. D'autres expériences seront nécessaires pour caractériser la charge des matériaux composites.

Abstract. — Laboratory experiments measuring the charge transferred when ice crystals collide with various metal targets have shown that the primary influence on the magnitude and sign of the charging is the work function of the metal. The magnitude of the charging of two alloys used for aircraft manufacture varied by a factor of two. Further experiments are needed to characterise the charging of composite materials.

1. Introduction.

When aircraft fly through clouds they generally charge up negatively because of the triboelectric or frictional charging occurring as water or ice particles collide with the material on the surface of the aircraft. Field measurements have been made of the charging currents to aircraft in various meteorological conditions, and using this knowledge effort has been directed towards finding efficient methods of discharging the aircraft. In this paper we report results of laboratory experiments of the charge transferred to various materials when ice particles impact upon them. Modern aircraft made from composites may have different charging properties from those constructed out of conventional materials, and an increased susceptibility to precipitation static may give rise to interference in modern digital control systems. Such laboratory tests should enable the charging properties of proposed materials to be characterised.

2. Summary of previous work.

There have been several studies of currents to aircraft during flights through clouds. Tanner [1] has reported current densities for aircraft to be in the range $50\text{--}100\ \mu\text{A m}^{-2}$ for cirrus clouds, $100\text{--}200\ \mu\text{A m}^{-2}$ for stratocumulus, and $300\ \mu\text{A m}^{-2}$

for snow. Boulay and Laroche [2] measured the current to probes covered with conducting paint on a Meteor aircraft flying at $200\ \text{m s}^{-1}$, and confirmed these values. They estimated that the overall capturing area of the aircraft was about $8\ \text{m}^2$ and calculated the maximum charging current to be $3\ \text{mA}$, which compared well with the highest discharge current recorded of over $2\ \text{mA}$. On only one occasion, in liquid precipitation near the ground, did they record positive current. In an investigation which extended to higher speeds, Nanevich [3] also measured current in the range $100\text{--}200\ \mu\text{A m}^{-2}$, but, in addition, observed the ice crystal concentration. At mach 1.2 he estimated that each ice crystal collision transferred about $50\ \text{pC}$, the value was slightly higher at $200\ \text{m s}^{-1}$, but at mach 1.9 the charge per interaction was reduced by about 50 %.

We have previously described [4] laboratory experiments in which individual ice particles typically of size $100\ \mu\text{m}$ were accelerated to speeds between 10 and $80\ \text{m s}^{-1}$ and the charge transfer measured as each particle collided with various metal targets at $-10\ ^\circ\text{C}$. The charges transferred in successive apparently identical collisions followed a log-normal distribution with a wide scatter, so at least 50 interactions were analysed to form a meaningful average. Three principle conclusions were drawn from this study :

(a) The average charge transfer per collision was proportional to the velocity of impact for a given target material and a constant ice particle size. As shown in figure 1 this relationship extended to at least $80\ \text{m s}^{-1}$.

(+) Cet article a fait l'objet d'une communication à la Conférence Internationale sur la Foudre et l'Electricité Statique (Paris, 10-15 juin 1985).

Fig. 1. — The charge transferred to magnesium (x) and nickel (O) targets as a function of velocity by 100 μm ice particles at -10°C .

(b) The charge depended upon the square of the size of the ice particle for a given target and impact velocity (see Fig. 2).

Fig. 2. — The charge acquired by a nickel target as a function of the square of the size of the ice particle. (x) 60 m/s ; (O) 10 m/s.

(c) When different targets were used, but the particle size and impact velocity were kept constant, the primary influence on the magnitude and sign of the charging appeared to be the work function of the metal target. Figure 3 from Caranti, Illingworth and Marsh [5] shows this work function dependence for 100 μm ice particles impacting upon targets at 10 m s⁻¹. Most common metals charged negatively, a notable exception being magnesium which has a low work function and acquired positive charge.

Fig. 3. — Average charge transfer (q) at -10°C of 100 μm ice spheres plotted against the work function of the target (W). 10 m/s.

Liquid supercooled drops also resulted in positive charging of the target.

The measured negative charging of most common metals and paint covered targets is consistent with the negative charging observed with aircraft. Direct quantitative comparison of the laboratory studies with aircraft measurement involves an assumption of the typical size and concentration of ice particles in clouds. The charge per interaction for a 100 μm particle in the laboratory was typically -1 pC at 80 m s^{-1} . From the derived velocity and size dependence this would suggest that a 200 μm particle at 200 m s^{-1} would charge a target by about -10 pC . If the concentration was 100 per liter then the current would be about $200\text{ }\mu\text{A m}^{-2}$, in agreement with most densities reviewed above. Boulay and Laroche [2] recorded one occasion of positive charging in rain, which is compatible with the laboratory findings on liquid drops. Nanevich [3] found a charge per crystal of about -50 pC at much higher velocities. Trinks and ter Haseborg [6] have carried out experiments with 20 mm diameter ice projectiles to simulate the effect of hailstone charging. Such large particles were totally pulverised when they hit metal targets at speeds in the range 35 to $1\,000\text{ m s}^{-1}$. The target acquired negative charges of up to 10 pC per interaction, but the total number of these violent collisions in a cloud should be low. In natural ice clouds such large particles are rare and the concentration of smaller ice particles is so many orders of

magnitude higher than these smaller particles will be responsible for the observed charging. In this study we report further measurements of charge transfers when $100\text{ }\mu\text{m}$ ice particles collide with targets made from different materials.

3. Apparatus.

The apparatus for studying individual collisions of ice particles with various metal targets is shown in figure 4. Water droplets in the size range $50\text{--}200\text{ }\mu\text{m}$ with a controllable charge (0 to $\pm 250\text{ fC}$) were produced at the rate of about 1 Hz by a droplet generator on top of the cold room. Each droplet then froze slowly as it fell down a tube into the cold room and collided with a tenuous cloud of minute ice crystals, which was formed by cooling a short section of the tube. The time for the particle to pass between two induction rings placed just below the freezing section then enabled the terminal velocity of each particle to be determined, and hence the size estimated to better than $10\text{ }\mu\text{m}$. In these experiments the particle size was kept close to $100\text{ }\mu\text{m}$ and the temperature of the cold room was -10°C . The thermal relaxation of a drop of this size is about 0.06 s ([7], Eqs. (13-68)), and the freezing time about 1 s ([7], Eqs. (16-20)). After falling a further 45 cm at terminal velocity of 25 cm s^{-1} the particles, completely frozen, entered the wind tunnel and were accelerated to 10 m s^{-1} . Examination of the ice particles under the microscope revealed that they had the spherical shape expected of frozen droplets. The ice particles then reached the working section (shown enlarged in the Fig.) where they passed through a final induction ring before hitting the target. The target was a cylinder 4 mm in diameter and was easily removable so that the charging properties of different materials could be investigated.

Separate amplifiers were placed as close as possible to both the induction rings and the target to reduce microphonic and 50 Hz pick up to the equivalent of less than 2 fC . The amplifier outputs were summed, recorded, and subsequently replayed and examined on a digital storage oscilloscope.

Fig. 4. — The apparatus for studying individual collision of ice particles with various metal targets.

Because the amplifier has a rise time of $3\text{ }\mu\text{s}$ but a long (100 ms) decay time for any charge deposited on the target, it was possible to differentiate between the rapidly varying induced charge caused by approaching and departing charged particles, and the long 100 ms exponential decay when charge was transferred to the target. Considerable information on the nature of the interaction could be derived from the shapes of the waveforms as discussed in detail in Caranti and Illingworth [8]. Figure 5 shows a simple unambiguous waveform. The first pulse is the passage of the ice particle through the induction ring with its initial label charge, q_i , which is $+8\text{ fC}$ in this case. Twelve milliseconds later the particle travelling at 10 m s^{-1} collides with the target initially inducing the label charge q_t on the target, and then on actual contact transfers q_t (-24 fC in this example) to the target. The subsequent slow (100 ms) exponential decay clearly identified this as a net charge transfer rather than the more rapidly varying charges induced on the target by the movement of charged particles in the proximity.

The label charge on the ice particle might be considered to be an unnecessary complication, however, its presence was most important :

(a) The size measurement of the particle relies on detecting the passage time between two induction rings. Because the charge transfer on collision is known to vary as the particle size squared, an unknown variation in the size of the particle could easily obscure a systematic difference in the charging properties of two different targets.

(b) Only charge transfers preceded by a label of the correct size were accepted as valid interactions. Occasional extraneous events were observed which interrupted the regular series of waveforms resulting from the succession of $100\text{ }\mu\text{m}$ particles carrying the same initial charge arriving at a rate of one per second. These were especially common at the beginning of a run when the introduction of moist air into the apparatus lead to the temporary production of a dense cloud of small ice crystals in the freezing section which would subsequently sediment out and on occasion impact upon the target. Although the charge transfers from such interactions were excluded from the analysis because of the absence of the correct label charge, it was reassuring to note that the sign of the charge transfers resulting from the collisions with vapour grown crystals was in agreement with the sign for the frozen droplets, indicating that the charging properties of the particles used do reflect those of natural crystals.

An extensive series of experiments (Caranti and Illingworth [8]) has established that the presence of electric charge on the particle before collision does not affect the value of the charge transferred and so the term « label » is appropriate. Presumably in the short contact time available the initial charge on the ice particle is not able to migrate along the surface of the ice to the area of contact of the ice and metal where it could affect the charge transfer. The interaction with a particular target always resulted in

a predominant polarity of charge transfer, and so the opposite sign of label was chosen as in figure 5. If the signs were the same then an ambiguous waveform similar to the one displayed in figure 6 could result. In this case because both q_i and q_t are $+5$ fC the particle has either hit the target, and stuck to the target — « a collection » ; or it has hit the target, transferred charge to it and left carrying no net charge.

Occasionally waveforms of the shape in figure 7 were observed. In this case after the collision the ice

Fig. 5. — Negative charging when a $100\text{ }\mu\text{m}$ ice particle collides with a H15 target. Horizontal scale 100 ms per division. Vertical 10 fC per division.

Fig. 6. — An ambiguous waveform. The label and the transfer have the same magnitude. This could be a collection or a valid transfer of charge. Scales as for figure 5.

Fig. 7. — A negative charge transfer following a positive label detection. The excursion superposed on the exponential decay indicates a bouncing impact. Scales as for figure 5.

particle has rebounded upstream and then been re-accelerated and passed within « electrostatic range » inducing the blip superposed on the exponential decay. Such waveforms are indicative of « head-on » rather than grazing collisions.

4. Results.

The experiments were carried out at temperatures of -10°C . To aid comparison with previous work on collisions with different metals and also to simplify the experimental procedure an impact velocity of 10 m s^{-1} was used. The results plotted in figure 1 show that the average charge per collision was proportional to the velocity of impact for a given target material for velocities of up to 80 m s^{-1} , and a limited amount of data obtained at 100 m s^{-1} showed that the increase in charging with velocity appeared to extend to this higher speed. In the absence of laboratory data for higher speeds we assume that this linear increase extends to 200 m s^{-1} , to make comparisons with the charging currents measured to the Meteor aircraft. The droplet diameter was kept as close to $100\text{ }\mu\text{m}$ as possible, but the actual size was continually monitored by recording the passage time through the induction rings of the sizer. For each experiment the conductivity of the water used to make the droplets was measured and was always below $1.5 \times 10^{-6}\text{ mho cm}^{-1}$.

Table I displays the average charge transferred for at least one hundred impacts against three materials used for the surface of aircraft. Over 95 % of H15 and H30 is aluminium but the exact composition is given in table II together with the related non-British equivalent specifications. The third material, stainless steel, contains 10 % nickel and 18 % chromium. Although the chemical composition of H15 and H30 is virtually identical the average charge transferred in run 2 to the H30 target seemed significantly larger than run 1 for H15 ; subsequent experiments on different days confirmed this trend and runs 4 and 5, for slightly larger particles, are shown at the foot of the table. A histogram of

Table I. — Charge transfers to H15, H30 (composition, see Tab. II) and stainless steel at -10°C . Impact velocity 10 m s^{-1} , n number of events, q average charge transfer, σ standard deviation, $\sigma/\sqrt{n}$ standard error of the mean. Runs 4 and 5 are $110\text{ }\mu\text{m}$ ice particles, 1 and 2 for $90\text{ }\mu\text{m}$.

	Material	n	q	σ	$\sigma/\sqrt{n}$
1	H15	166	-14.0	± 6.8	± 0.5
2	H30	211	-21.6	± 11.1	± 0.8
3	Stainless Steel	121	-19.6	± 9.7	± 0.9
4	H15	157	-27.8	± 15.9	± 1.3
5	H30	166	-80.1	± 46.5	± 3.6

Table II. — *Composition (per cent). Unless indicated all limits are maxima.*

	Al	Cu	Mg	Si	Fe	Mn	Zn	Cr
	%	%	%	%	%	%	%	%
H15	Rem	3.9/ 5.0	0.2/ 0.8	0.5/ 1.0	0.7	0.4/ 1.2	0.2	0.10
H30	Rem	0.10	0.5/ 1.2	0.7/ 1.3	0.5	0.4/ 1.0	0.2	0.25

EQUIVALENT STANDARDS

UK	America	Canada	France	Germany	Italy	Sweden	Switzerland	ISO
BS	AA	CSA	NF	DIN	UNI	SIS	VSM	ISO
H30	6 082	GS11N	A-SGM	3.2315	P-LSIMGMN P-AlCu 4.4	144 212	10 850.EAlSiMg	AlSi1MgMn 6 351
H15	2 014	CS41N	A-U4SG	3.1255 AlCuMgPb	SiMnMg	144 338		AlCu4SiMg 2 014

Fig. 8. — Histogram of the charges transferred to H15 (dotted) and H30 (solid line). Runs 4 and 5 in table I. Vertical Scale 5 events per division.

individual charge transfers in runs 4 and 5 is plotted in figure 8, and clearly demonstrates the different charging patterns of the two materials. Table I summarises the mean charge transfers, the standard deviation, and the standard error of the mean for an assumed normal distribution. This standard error is an underestimate because the distributions are skew, and more importantly, because systematic errors will be larger. These errors arise because of variations in particle size and position of impact upon the cylindrical target. It should be appreciated that accelerating a 100 μm ice particle to 10 m s^{-1} so that it hits a target 4 mm in diameter 3 m distant is quite difficult. On the day when runs 4 and 5 were performed collisions were more head on because many « boun-

cing » waveforms similar in character to figure 7 were observed. Runs 1 and 2 were carried out on a day when the collisions with target appeared to be more grazing and this may account for the lower average charges observed with both materials on this day.

Previous work had revealed that magnesium targets charged positively. According to the theory, as displayed in figure 3, magnesium charges positively because it has a work function of about 3.6 eV which is less than the apparent value of 4.1 eV for ice. Tin has a work function near to 4.4 eV and so should charge negatively. Although neither of these metals is used in its pure form in aircraft manufacture, they both have low melting points so that mixtures of the two metals can be prepared. A series of experiments was undertaken to see if the charging of the alloys changed linearly as the composition altered. The results are summarised in table III. Owing to the extreme reactivity of magnesium it proved impossible to prepare alloys containing more than 20 % magnesium without ignition occurring. However, the results in table III show that whereas the pure tin charged negatively with an average charge of -66 fC , the addition of 20 % magnesium was sufficient not only to cause positive charging, but the magnitude was greater than for pure magnesium. It appears that the addition of small proportions of metals can have a drastic effect on the charging properties. We will consider possible reasons for this in the next section.

Table III. — *Charge transfers for magnesium and tin and an alloy of the two. Symbols as for table I.*

Material		n	q	σ	$\sigma/\sqrt{n}$
—		—	—	—	—
1	Sn	48	-66.4	± 40.7	± 4.5
2	80 % Sn, 20 % Mg	84	$+144$	± 63.3	± 7.0
3	Mg	128	$+51.9$	± 46.6	± 4.1

5. Discussion.

The charging of pure metals on collision with ice does appear to be primarily influenced by the work functions of the metal, but the results reported in this paper indicate that the situation is more complicated when alloys are considered. In an extensive review of measurements on work functions Riviere [9] notes that there are not many measurements on the work function of alloys ; only a few simple alloys of two metals have been analysed. The results show that the change is only approximately linear when solid solutions occur, but on the appearance of intermetallic compounds sudden jumps occur, and values outside those found for the pure metals are often observed. Consideration of the electron energy levels and Fermi surfaces of the complex crystal structures shows that this behaviour is quite reasonable. It is quite possible that the behaviour in tables I and III is consistent with changes in the work function. The work function could be derived from the contact potential but unfortunately this was not measured in these experiments.

The materials H15 and H30 have, in spite of their similar chemical composition, quite different mechanical properties ; H15 has a tensile strength about twice that of H30. This may affect the mechanisms of the collision and lead to a larger contact area for H30, partially accounting for the larger transfers observed with H30.

6. Conclusion.

The charge transfers measured in the laboratory when individual ice particles collide with metal targets agree with the observed charging currents to

aircraft. For example, from our derived velocity and size dependence we predict that a $200\text{ }\mu\text{m}$ ice particle at 200 m s^{-1} would charge a target by about -10 pC . A concentration of ice particles of 100 per liter would lead to a current of $200\text{ }\mu\text{A m}^{-2}$ in agreement with most aircraft measurements reviewed in section 2. Laboratory experiments show that the charging of different alloys used in aircraft construction, having the same chemical composition but with differing mechanical properties, can vary by about a factor of two. The introduction of small amounts of magnesium into alloys can be sufficient to change the polarity of the charging. Such measurements may be explicable by changes in the work function of the alloys concerned, but no direct measurements were made in this study.

At this stage it is difficult to predict the charging properties of composite materials. This is because of their uncertain electronic structure. The lower electrical conductivity of the composites may introduce a further complication. Whereas the electrical relaxation time of metals is always much shorter than any collision contact time with ice crystals, this may not be the case with the composites. Measurements of the static charging of such composite materials in the laboratory by impacting ice particles would be an economical means of predicting how such materials would charge up in flight through natural clouds.

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References

- [1] TANNER, R. L., *et al.*, « Precipitation Charging and Corona-Generated Interference in Aircraft », Technical Report No. 73, Project No. 2494, Contract AF 19 (604) 3468, 1961.
- [2] BOULAY, J. L., LAROCHE, P., « Aircraft Potential Variations in Flight », Eighth Lightning and Static Electrification Conference (Fort-Worth) 1983.
- [3] NANEVICZ, J. E., « Flight-Test Studies of Static Electrification on a Supersonic Aircraft », Lightning and Static Electrification Conference (Culham) 1975.
- [4] CARANTI, J. M., ILLINGWORTH, A. J., MARSH, S. J., « Static Charging of Different Metals by Ice Crystals » International Aerospace and Ground Conference on Lightning and Static Electricity (Orlando, Florida) 1984.
- [5] CARANTI, J. M., ILLINGWORTH, A. J., MARSH, S. J., « The Charging of Ice by Differences in Contact Potential », *J. Geophys. Res.* **90** (1985) 6041.
- [6] TRINKS, H., TER HASEBORG, J. L., « Electric Charging by Impact of Hailstones and Raindrops », Eighth Lightning and Static Electrification Conference (Fort Worth) 1983.
- [7] PRUPPACHER, H. R., KLETT, J. D., *The microphysics of clouds and precipitation* Reidl (Dordrecht, Holland) 1978.
- [8] ILLINGWORTH, A. J., CARANTI, J. M., « Ice Conductivity Restraints on the Inductive Theory of Thunderstorm Electrification », *J. Geophys. Res.* **90** (1985) 6033.
- [9] RIVIERE, J. C., « Work Function : Measurements and Results » in *Solid State Surf. Sci.*, Ed. M. Green, Marcel Dekker (New York) 1969.