Experimental measurements of charge separation under wet growth conditions

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In this work we present the results of experimental measurements of the charge transferred to simulated graupel under wet growth conditions. The range of temperature was between $-7$ and $-18^\circ$C. The speeds of collision employed in the measurements were between 8 and 13 m/s with the goal of representing graupel of different initial densities. The aim of this study was to corroborate the existence of charge transfer under wet growth. The results show the presence of positive charge when graupel reaches partial wet growth, and the magnitude of this charge is comparable to the charge transferred under dry growth conditions. On the other hand, when total wet growth is reached no charge transfer is registered. This leads to the conclusion that the non-inductive mechanism could be working under partial wet growth conditions when the ice crystals collide with the dry regions of the graupel surface and then bounce off.

KEYWORDS
charge transfer, cloud electrification, ice crystal–graupel interaction, wet growth
et al. (1991) and Jayaratne (1993), using the heat balance equation (Macklin and Payne, 1967), concluded that the measurements of Takahashi were carried out with the graupel under wet growth conditions. Based on these results, Williams et al. (1991) suggested that ice crystals could bounce off a hailstone under wet growth conditions, charging it positively.

Recently, Jayaratne and Saunders (2016) reported a significant positive charge transfer when ice crystals interacted with a simulated hailstone in wet growth. In this study, the magnitude of the charge transferred to the simulated hailstone when ice crystals collided against it, under wet growth conditions, was experimentally measured. The hailstone was simulated by a stainless steel rod of 32 mm length and 4 mm diameter. The experiments were carried out at an ambient temperature of $-10^\circ$C and at two different speeds of collision: 12 and 20 m/s. They reported a charge transferred per ice crystal of 20 fC at 12 m/s and 50 fC at 20 m/s, assuming that 1 in 100 ice crystals rebounded off the hailstone surface. They suggested that some regions of the hailstone surface remained dry even under wet growth conditions and that in those regions the non-inductive mechanism could work thus explaining the charge acquired by the hailstone.

Based on the experimental evidence that under wet growth the graupel acquires a positive charge, the main goals of this work are to study the performance of the non-inductive mechanism under wet growth conditions, extending the conditions studied by Jayaratne and Saunders (2016), and to corroborate the suggestion that the charge separated is due to the interaction of ice crystals with dry zones of the graupel surface.

2 | EXPERIMENTS

2.1 | Experimental set-up

The measurements were carried out using the experimental set-up shown in Figure 1. The main components of the experimental device are: the Ice Crystals Chamber (ICC), the Cloud Chamber (CIC), the wind tunnel and the target. The experimental device was placed inside a Cold Chamber with controlled temperature capable of reaching temperatures down to $-30^\circ$C.

The ICC, where the ice crystal cloud was generated, consists of a metallic box with dimensions 1.8 m height and 0.6 m by 0.9 m$^2$ base. The CIC, where the cloud of supercooled water droplets was generated, consists of a metallic box of 60 cm with a showerhead placed inside. The supply of water for the showerhead was contained in a reservoir (R) placed outside the Cold Chamber (Figure 1). The CIC and the ICC were connected by a wind tunnel to an air pump capable of enabling and disabling the airflow into the tunnel and regulating its speed.

The target consists of a brass sphere of 1 cm diameter which simulates a graupel. It was placed inside the wind tunnel as can be observed in Figure 1. The target was connected to a current amplifier with 1 pA precision. The current sensed by the amplifier is a measure of the charge acquired by the target during its interaction with the ice crystals in the presence of the supercooled droplets.

Adjusting the power of the air pump, the speed of the airflow was controlled. The measurements were carried out at three different ranges of speeds: 8 to 10, 10 to 12, and 12 to 13.5 m/s. Different collision speeds were selected to represent graupel of different initial densities. The lower
Experimental procedures

To perform the measurements of the charge transferred to the graupel during its interaction with ice crystals in the presence of supercooled droplets, the next steps were followed:

1. The cold chamber was set at the desired temperature.
2. The water in the reservoir was heated up to the desired temperature.
3. Distilled water droplets were introduced in the ICC with the nebulizer for about 3 min.
4. The ice crystals were nucleated and they grew by vapour deposition for about 60 s.
5. The water from the reservoir R was released to form the supercooled droplet cloud. Ten seconds later the air flow was initiated by turning on the pump.

On average, measurements lasted 100 s. Secondary experiments were performed and they showed that ice crystals inside the ICC lasted for at least 300 s assuring a nearly constant ice crystal concentration during the entire measurement and discarding the possibility of null charge current (CC) as a consequence of the absence of ice crystals.

3 EXPERIMENTAL RESULTS AND DISCUSSION

Measurements of the charging current to the simulated graupel during ice-crystal collisions in the presence of supercooled droplets under wet growth conditions were carried out at temperatures between $-7$ and $-18 \degree C$ at a range of impact speeds between 8 and 13 m/s.

Figure 3 shows the sign of the charge current to the graupel as a function of the ambient temperature and the rime accretion rate ($RAR$) under wet growth conditions. Open circles represent a positive charge acquired by the graupel while black circles represent conditions where the graupel charging current was zero. The $RAR$ combines the effect of the effective liquid water content ($EW$) with the impact velocity ($RAR = EW \times V$). From Figure 3 it can be observed that the sign of the non-zero charge current was always positive. In addition, some measurements of the graupel charge under conditions in which the air flow contained only supercooled droplets were performed. Under these conditions no appreciable current ($>1 \mu A$) was detected on the graupel. Therefore, it can be assumed that the graupel current registered was

The samples were taken around 90 s after seeding. Figure 2 shows the sign of the charge current to the graupel as a function of the ambient temperature. Open circles represent a positive charge acquired by the graupel while black circles represent conditions where the graupel charging current was zero. The $RAR$ combines the effect of the effective liquid water content ($EW$) with the impact velocity ($RAR = EW \times V$). From Figure 3 it can be observed that the sign of the non-zero charge current was always positive. In addition, some measurements of the graupel charge under conditions in which the air flow contained only supercooled droplets were performed. Under these conditions no appreciable current ($>1 \mu A$) was detected on the graupel. Therefore, it can be assumed that the graupel current registered was
to the graupel is zero. Solid and broken lines represent theoretical limits for wet growth conditions. Open circles represent a positive charge acquired by the graupel at a temperature of $-5 \degree C$ (C (broken line)). The $-5\degree C$ temperature is reached for graupel temperature below 0 $\degree C$ (List et al., 1989). These theoretical curves were derived using the heat balance equation (Macklin and Payne, 1967) for a spherical collector of diameter 1 cm. Therefore, values of $\text{RAR}$ and ambient temperature above the theoretical curves should indicate conditions of wet growth of the graupel.

From Figure 3, it can be observed that almost all measurements were performed under wet growth conditions, according to the theoretical curves, and zero current to the graupel under such conditions was expected (Saunders et al., 1991; Saunders and Brooks, 1992). However, most of the measurements showed a positive current to the graupel during ice crystal interactions. These results are in agreement with the results reported by Takahashi (1978) and Jayaratne and Saunders (2016) who also found a positive charge transfer to the graupel under wet growth conditions.

Experimental and theoretical studies (List et al., 1989; Nasello et al., 1992) have shown that the mean surface temperature of an accreting graupel is not enough to describe the superficial conditions of the graupel. Therefore, given that the theoretical curves shown on Figure 3 are based on the mean temperature over the graupel surface, the information that they provide seems to be inadequate as an indicator of wet growth conditions over the entire graupel surface.

List et al. (1989) carried out experiments where they determined the temperature of the equator (stagnation point) and pole (90° from stagnation point) of a rotating spherical graupel growing by accretion. In those experiments, the graupel was inside a wind tunnel at an ambient temperature of $-15\degree C$. The measurements were carried out for different values of liquid water content with a wind speed of 19.8 m/s. They found that when graupel reached wet growth, the surface graupel temperature was always below 0 $\degree C$. They also discovered a considerable difference between the surface temperatures at the equator and pole, which depended on the liquid water content at the same values of wind speed and ambient temperature. They concluded that heat transfer needs to be treated as non-homogeneous and non-isotropic and that the surface temperature of the graupel cannot be considered as one single value. In later experiments, List et al. (1995) determined the surface temperature variations of gyrating hailstones. They found that the growth by accretion of hailstones under certain cloud conditions was characterized by a dry and cold regime at the poles and a wet and warmer regime at the equator. From direct observations they associated dry regions with opaque ice and wet regions with transparent ice.

Nasello et al. (1992) did a theoretical study which showed that there was a surface temperature distribution for ice accreted on a cylindrical collector which had a maximum value on the stagnation point and decreased to the sides. They arrived at these results after considering that it was necessary to include in the equations of heat exchange the factors that take into account the thermal conductivity of the entire graupel.

Therefore, in order to identify the graupel surface conditions during the experiments, visual examinations of the graupel surface were realized after each measurement. From the examinations of the graupel surface, it was possible to relate the measurements with zero charging current with the observations of totally transparent graupel, which indicates that the entire graupel surface was wet. On the other hand, the measurements with non-zero current were coincident with observations of a graupel surface with both transparent and opaque areas. The transparent areas indicate a wet growth
regime while the opaque areas indicate dry growth conditions. So, it may be possible that ice crystals collide with these areas under dry growth conditions and bounce off, allowing the non-inductive mechanism to operate, as was suggested by Jayaratne and Saunders (2016).

In general, it was observed that the accretion thickness around the stagnation point was thicker than the thickness closer to the equator. Assuming that the air speed around the sphere is approximately constant, it was expected that the edges would have lower local RAR than the top of the target. These could be the regions that the charging mechanism is working on.

The visual examinations of the graupel surface have shown that theoretical curves are not enough to determine the growth conditions of the entire graupel surface, as was reported by List et al. (1989) and Nasello et al. (1992). Reaching partial or total wet growth seems to depend on the liquid water content, collision speed and ambient temperature. As can be observed from Figure 3, total wet growth is reached mostly at ambient temperatures higher than −10 °C while at lower temperatures the environmental conditions used in the experiments are not enough to achieve this growth condition.

Figure 4 shows the charge current (CC, upper panel) and the temperature of the target (TT, lower panel) as functions of time for a measurement where partial wet growth was reached. The measurement corresponds to an ambient temperature of −13.5 °C, a collision speed of 12 m/s and an EW of 2.13 g m⁻³. During the first 10 s of the measurement, CC is zero since there was no air flow in the wind tunnel and therefore, there were no ice crystals interacting with the target. At 10 s, the air pump was turned on. The negative peak between 10 and 20 s corresponds to charge transfer due to collisions between ice crystals and the metallic surface of the target which is not covered by ice at the beginning of each measurement. Then, the accretion process initiates and the target temperature begins to increase due to the latent heat of fusion and then the CC begins to increase. The CC value remains constant until the end of the measurement when the air pump is turned off at 80 s. CC between 20 and 50 s corresponds to interactions under dry growth conditions of the graupel while CC between 50 and 80 s corresponds to interactions under partial wet growth conditions of the graupel. As can be observed, the magnitude of CC during both growth conditions have the same order of magnitude, indicating that the charge acquired by the graupel under partial wet growth conditions could be relevant to the electrification mechanism.

An estimation of the charge transferred to the graupel per individual collision can be estimated from:

\[ q = \frac{CC}{p(EcN)VA}, \]

where A is the cross-sectional area of the target and V is the collision speed. Ec is the average collision efficiency of the target for ice crystals, which is defined as the ratio between the number of ice crystals that collide with the collector and the number of ice crystals within its path, and p is the probability that an ice crystal collides with the target and bounces off. The value of (Ec N) is the number of ice crystals per unit of volume that hit the target. From the Formvar samples, the value of (Ec N) was estimated as (3 ± 2) ice crystals per cm³ assuming that the target and the glass strip, used as sampler, have the same collision efficiency. Given that the magnitude of CC under wet growth conditions varied between 1 and 6 pA, the charge transferred per collision also varied between 1 and 3 fC if we assume a value of p of unity (all the ice crystals that collide with the target, rebound). However, under wet growth, a percentage of the ice crystals that collide remain stuck to the graupel. If we suppose that only 10% of ice crystals collide and rebound from the graupel (p = 0.1), then the charge transfer per collision will increase to 10 fC and so on. These values of charge transferred are similar to those reported by Jayaratne and Saunders (2016) with a collision speed of 12 m/s. Our values are also in agreement with those found by Takahashi (1978) in the wet growth region who reported a charge per collision of 30 fC.

4 | SUMMARY AND CONCLUSION

Novel experimental measurements of the charging current of a simulated graupel, under wet growth, during ice crystal interactions were performed. The measurements were realized at temperatures between −7 and −18 °C in a range of impact speeds from 8 to 13 m/s.
Visual observations of the graupel surface showed that the graupel presented some areas with dry growth and others with wet growth conditions. On the dry areas, ice crystals could impact without sticking and charge could be transferred between the interacting ice particles.

The results show that the graupel charging current during wet growth was always positive and had the same order of magnitude as the current during dry growth. Also, it can be estimated that mostly for warmer temperatures, if the EW value increased enough, the total wet growth would be reached eventually and, as a consequence of this, the graupel charging current would be zero.

Finally, a charge transferred per collision of 10–30 fC was estimated for a p value of 0.1, which is in concordance with previous values reported.

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