Texture and fabric characteristics of atmospheric ice deposits on overhead power lines

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***Abstract*—At atmospheric pressure and temperatures, the stable phase of ice is hexagonal ice, I_h. An ice monocrystal of this type is a transversely isotropic material having its hexagonal symmetry about its c-axis. The c-axes of crystals in polycrystalline ice can exhibit various degrees of alignment, thereby providing a definite crystallographic fabric to the solid. In this study, the three distinct textures of atmospheric ice observed on power lines are qualitatively described. They are characterized by columnar, feathery and granular textures, each having its own c-axes orientation and mechanical behavior.**

I. Introduction

Atmospheric ice deposits are naturally formed by accretion of supercooled water droplets on cold substrates. The most frequent types of atmospheric ice deposits on electrical transmission lines are glaze and hard and soft rime, each having a different texture and growth conditions. Glaze is a transparent deposit with a density very close to that of pure ice. It can be accreted during a freezing rain event where the bigger droplets, normally between 0.5 and 5mm, have enough time to cover a surface area prior to freezing (wet regime type of ice accretion). Hard rime is less transparent with a density between 0.7 to 0.9 g/cm^3, as compared with soft rime which is white and opaque with a density as low as 0.6 g/cm^3. Rime deposits are naturally produced during an in-cloud riming event where smaller supercooled droplets freeze on a cold substrate (dry regime type of ice accretion).

II. Ice sample preparation

In this research work, in-cloud riming events were simulated in the horizontal refrigerated wind tunnel of the CIGELE laboratory, while the freezing rain simulation was performed at the icing precipitation simulation laboratory. The texture and air-bubble content of the two sets of ice samples were qualitatively studied using a low magnification microscope equipped with transmitted light and polarized filters.

A. In-cloud riming simulation in wind tunnel

For the purpose of this simulation, a rime deposit was accreted on an aluminum cylinder, 35.1 mm in diameter and 400 mm in length, placed in the middle of the test section of the refrigerated horizontal wind tunnel. The cylinder was insulated on both sides by two pieces of Teflon, each with an approximate length of 300mm. The cylinder was cleaned with alcohol and set in place for two hours while the system was cooling down. The controlling factors for simulating the meteorological conditions in the wind tunnel were: (a) air speed ranging from 5 to 20 m/s; (b) conductor rotating speed, from 1 to 5Hz; (c) air temperature, -3 to -9°C; (d) Spray System Co. nozzle type, fluid cap 2050, air cap 67147; and (e) water to air pressure ratio, typically around 53/40.

This research was mainly concerned with the transition conditions from wet to dry regimes, in order to produce a more uniform ice structure. For each combination of the affecting factors, both the liquid water content (LWC) and the water droplet spectrum were measured. The median volume diameter (MVD) of droplets was calculated from the water droplet spectrum. The droplet size distribution was measured by exposing a glass slide covered by a film of silver colloid at the middle of the test section for a short period of time. The droplets were then counted and measured as to their size under microscope to provide the data for the droplet spectrum. MVD was calculated from the spectrum, which covers the natural range of in-cloud and drizzle icing, up to 100 µm. LWC was measured using the single rotating cylinder method, ranging from 0.4 to 2.0 g/m^3, to simulate conditions close to natural precipitations.

B. Freezing-rain simulation in the precipitation laboratory

In order to obtain more uniform and thicker ice deposits for the freezing-rain simulations, the ice deposits were accumulated on an aluminum plate (3/8”- 110×400 mm^2) with the same volume per length as a conductor, as shown in Fig. 1.

The plate was insulated from underneath to simulate the symmetry boundary condition existing at the center of the conductor. It should be noted that an aluminum plate was used to try simulating the thermal conditions of an aluminum cylinder as closely as possible. However, a genuine simulation for the cylinder would be much more complex, if not impossible.

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Fig. 1. Insulated aluminum-plate and air-speed anemometer

Water droplets were sprayed using a single flat-spray nozzle (airless nozzle model H1/4VV-2501) producing larger droplets up to 1mm. A time-delay system was designed to interrupt the nozzle movement, causing the precipitation rate to vary independently from water droplet size. Therefore, the controlling factors were (a) air temperature, ranging from –3 to -9°C; (b) water pressure, from 20 to 85 psi (138 to 586 kPa); and, (c) the time-delay between each nozzle cycle, 1 to 30 seconds. The main reason for using the interrupting system is that it makes it possible to simulate precipitation rates close to the normal range of a natural freezing rain event by varying the spraying time interval. As an example, the vertical component of the natural precipitation rate in a freezing rain event normally varies in the range of 0 to 5 mm/hr. The controlling parameters had an influence on the droplet size distribution in addition to the precipitation rate. The droplet size distribution was obtained using the same techniques as those of the riming simulation, as shown in Fig. 2.

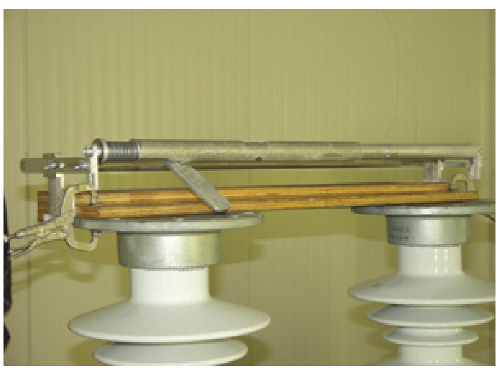


Fig. 2. Glass slide exposure device for obtaining the water droplet spectrum

The precipitation rate was measured by collecting the water sprayed during a certain period of time, as shown in Fig. 3. The calibration charts for the variation of the precipitation rate versus the nozzle water pressure and interrupt time are shown in Fig. 4.

Fig. 3. Standard device for precipitation rate measurements

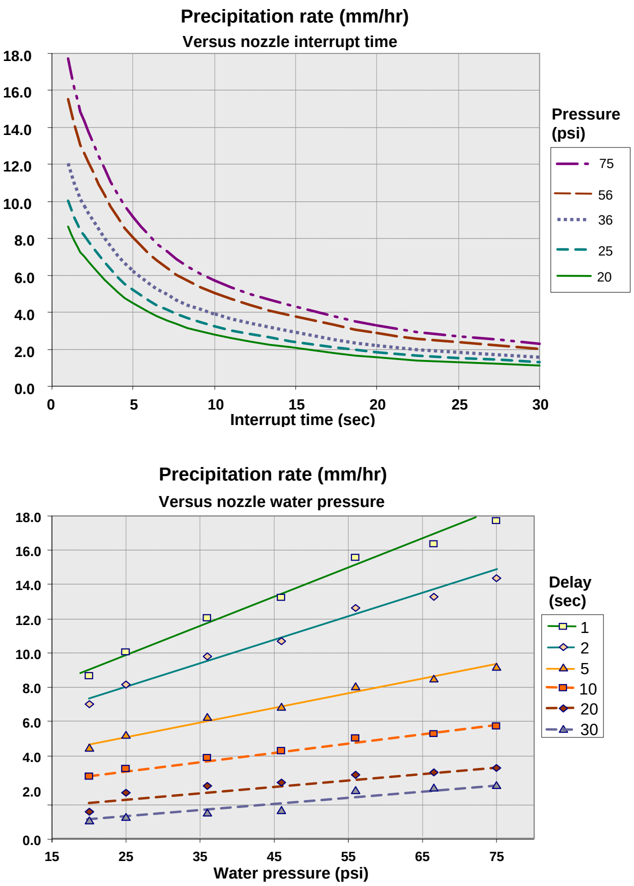


Fig. 4. Precipitation rate versus water pressure and interrupt time

III. TEXTURE OBSERVATION

A. Thick-section preparation

The grain size and air-bubble content for both the radial (vertical) and the transverse (horizontal) directions were qualitatively analyzed. First, rough ice sections were cut off along the cylinder using a band saw, as shown in Fig. 5. From these, two 15 mm thick sections were prepared, one in the radial and the other one in the transverse direction. Then, the thick sections were cut in sizes adequate for the microtome stage plate. The band saw and microtome were placed in a cold chamber for a few hours before they were used to cut the samples.

Fig. 5. Thick section preparation using a band saw

B. Thin-section preparation

The bottom surface of each resized thick section was processed through the microtome to remove the cutting marks from the band saw. First, a 4 mm surface layer was cut off by microtoming a number of 10 µm thick layers. Then, a 0.6 mm surface layer, followed by another 0.4 mm one, for a total of 5 mm, were likewise cut off by microtoming 5 µm, and 2 to 1 µm layers respectively [1]. Before cutting each layer, the microtome blade was wiped clean with a soft tissue paper. The thick section was then mounted on a clear glass plate using freezing drops of water at its edges. Applying a slight pressure on the sample ensured that no water remained on the contact surface. At that point, it became possible to start using the microtome on the top surface of the thick section by removing successive 10 µm layers until a thickness of about 2 mm was finally reached. This was followed by shaving off another 1 mm, first removing 5 µm layers, and then 2 to 1 µm ones, to a final thickness of 0.5mm. This procedure provided a smooth, clean and reflective surface.

The prepared thin section was then placed on the rotating-stage of a normal microscope equipped with a color camera for texture and bubble size observations. With ordinary light, the bubble size distribution of the thin section was obtained using the AVM software, which was calibrated prior to each measurement. On the other hand, the texture and crystallographic orientation of ice sample were also examined by placing the thin section between crossed Polaroid filters illuminated with white light. Depending on the ice type, each crystal of the thin section had a different color and brightness.

IV. Classification of Atmospheric Ice Texture

From a macro scale point of view, ice is assumed to be a grain structured material whose texture depends on growth processes and thermo-mechanical histories. Michel and Ramseier established a classification system based on grain texture and crystallographic c-axis orientation of saline sea ice, river, lake and fresh water ice in 1971 [2]. Later in 1976, Ramseier presented a detailed analysis of this classification [3]. The crystallographic orientation of such materials is normally represented by a stereographic projection, also called a Wulff net. Following the rules set by Michel and Ramseier, the texture of atmospheric ice deposits on power lines is classified in four major categories that are described as follows from higher deposit temperatures down.

A. Columnar ice

This texture is common under a wet growth regime when the deposit temperature is zero or very close to the melting point. In this case, the droplets have enough time to spread into a thin water film before freezing. The small air bubbles escape from the water film producing a very clear ice deposit containing a relatively limited number of large bubbles causing the density to be very close to the corresponding value of pure ice, usually higher than 0.9 g/cm^3. The c-axis orientation, grain size, bubble size and concentration depend mainly on LWC and droplet size. Under very wet growth regimes, ice is clear and may contain some large spherical bubbles. The c-axes are randomly oriented in a transverse plane (Fig. 6). This type of ice has almost the same structure as fresh water ice (S2 ice) with medium to large grains normally less than 5 mm in diameter. This type of ice may be considered as a transversely isotropic material. In this case, the air temperature (Ta) and deposit surface temperature (Ts) are higher than -6°C and 0°C, respectively.

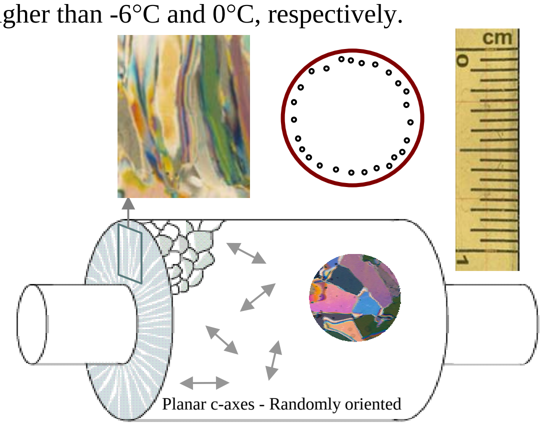


Fig. 6. Texture, fabric and Wulff net of typical columnar atmospheric ice, accreted at Ta=-5°C and Precipitation rate=2.5 mm/h

B. Feathery ice

The crystal structure becomes finer and more complex with a feathery appearance at the starting stages of a dry growth regime (hard rime) (Fig. 7). In this case, the droplets do not have enough time to spread, and small air bubbles are trapped inside the ice deposit. Therefore, the resulting ice is opaque and contains a large number of small bubbles causing the density to vary between 0.7 and 0.9 g/cm^3. The c-axis orientations are almost vertical. However, they spread randomly as air and deposit temperatures decrease. This type of ice has a structure which is columnar to granular so that it should be considered as a material being between transversely isotropic (hard rime) and nearly isotropic (rime). Feathery ice is formed usually at air temperatures below -10°C under a dry growth regime when the deposit temperature is far enough from the melting point.

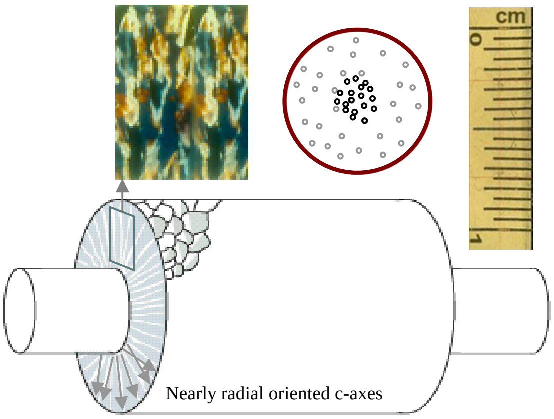


Fig. 7. Texture, fabric and Wulff net of feathery atmospheric ice, accreted at Ta=-10°C, LWC=1.0 g/m^3, and air speed=10m/s

C. Granular ice

The texture and c-axes orientation of granular ice is shown in Fig. 8. The c-axes are randomly oriented, so it can be considered as an isotropic material. This type of ice may be found under a very dry growth regime producing a very fine structure as seen in soft rime structures. In this situation, ice has a very rough and opaque appearance, and contains many air bubbles, with a density usually less than 0.6 g/cm^3. Granular ice is formed at very low air temperatures, usually below
-15°C, and at low deposit temperatures, normally below -10°C.

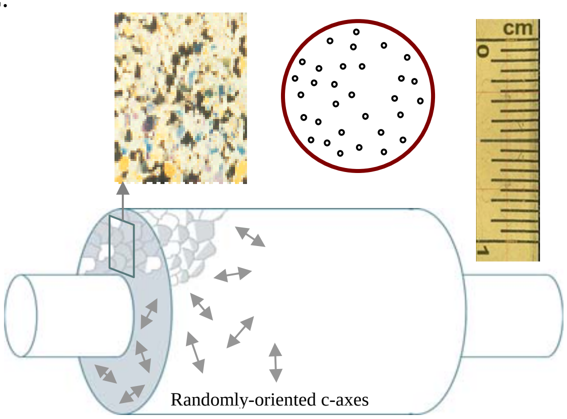


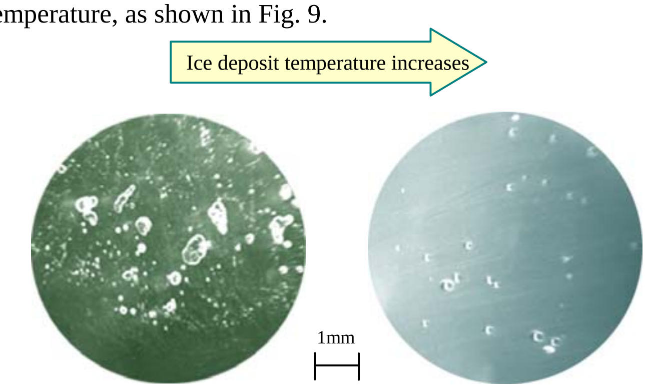
Fig. 8. Texture, fabric and Wulff net of granular ice, accreted at Ta=-20°C, LWC=0.5 g/m^3, and air speed=5m/s

D. Agglomerate texture

This texture is a combination of various types of atmospheric ice. It is observed in presence of water flow or when the formation conditions are found to vary during the accretion event.

V. Air Bubbles in Atmospheric Ice

The bubbles nucleate when the concentration of dissolved air in the liquid reaches a critical value at the growth front. Therefore, the air bubble content of atmospheric ice deposits depends on growth conditions including air temperature, droplet size, and LWC. It may also be related to ice deposit temperature, as shown in Fig. 9.



(a) (b)

Fig. 9. Air bubble content at two various deposit temperatures
(a) Transition from dry to wet growth regime, deposit surface temperature slightly bellow 0°C,
(b) Wet growth regime, deposit surface temperature 0°C

VI. Conclusions

Atmospheric ice is classified as granular, feathery or columnar ice based on its grain shape. Glaze belongs to the family of columnar ice, while soft rime might be considered as granular ice. Hard-rime, on the other hand, has a feathery structure sometimes more similar to columnar ice, but is sometimes more likely granular. The grain structures up to a maximum width of a few millimeters were observed for different growth conditions. The size of grains was very fine for dry regime of ice accretion. However, it increased as the rate of growth slowed down. The air-bubble content of atmospheric ice varied from a very low level for glaze to the finer bubbles and higher air-content level which is the characteristic of rime deposits.

VII. Acknowledgment

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VIII. References

[1] *A. Derradji-Aouat*, "Mathematical modeling of monotonic and cyclic behavior of fresh water ice" Ph.D. dissertation, Dept. Civil Eng., Univ. Ottawa, 1992.

[2] *B. Michel and R.O. Ramseier*, "Classification of river and lake ice, Canadian Geotechnical Journal", vol. 8, pp 36-45, 1971.

[3] *R.O. Ramseier*, "Growth and mechanical properties of river and lake ice" Ph.D. dissertation, Dept. Civil Eng., Univ. Laval, Quebec, 1976.