Artificial snow laboratory for indoor snow-phobicity testing

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Abstract— **Ice and snow accumulation poses a significant threat to the reliability of the electrical system. For Italian transmission and distribution system the main issue is represented by wet snowfall events, occurring at temperatures close to 0°C, with snow density reaching up to 300 Kg/m^3. Ice-phobic and snow-phobic coatings are one of the most promising ways for hindering ice and snow accumulation.**

Many studies report of icing and freezing phenomena and many methods have been developed over time to assess ice-phobic performances of coatings, mainly measuring ice adhesion (eg. shear stress testing, centrifuge testing etc.) and freezing delay. Many mechanisms have been consequently proposed to explain ice-phobic properties of tested coatings, according to their chemical composition and mechanical properties.

On the other hand, snow offers a considerable complexity and factors such as crystal structure, density, and liquid water content (LWC) can vary sharply with weather conditions. These properties have significant implications on the adhesion of snow on surfaces and inferring snow-phobicity of coatings from their ice-phobic performances can be misleading. For practical reasons it is somehow difficult to deal with snow for indoor performance testing and the tests are commonly delegated to outdoor activities. Outdoor testing of coatings is however affected by external uncontrollable factors such as the occurrence of snowfall events and their intensity, the presence of wind, air humidity and the presence of condensed water on surfaces.

To overcome these problems and to achieve a stricter measurement of the snow-phobic properties of coatings, RSE has recently put into operation the first artificial snow laboratory in Italy. This facility is capable of simulating snowfall with controllable flow, and to produce both dry and wet snow, with an LWC up to about 35%. The snow production is performed inside a cold chamber with settable air flow and temperature, down to -10°C, and measured relative humidity.

For the testing of snow-phobic coatings deposed on segments of conductors and ground wires, the laboratory is equipped with a custom-made apparatus capable of slowly rotating them, allowing the growth of artificial snow sleeves. The process, reproducing the sleeve accretion on overhead lines (OHL), is monitored through a camera and quantified with load cells that record the weight of the accumulated snow over time. It is thus possible to measure the snow-phobic behavior of coatings, in terms of delaying the formation of the snow sleeve and/or facilitating an earlier detachment. The laboratory is also equipped with a universal tensile strength machine to develop shear stress test with snow on flat surfaces.

All depicted tests can be performed with varying snow properties and environmental conditions of cold chamber, to assess the performances of coatings under different simulated snowfall scenarios.

The artificial snow laboratory is thus a valuable tool for the measurement of snow-phobic properties of surfaces and for a deeper comprehension of adhesion and detachment mechanisms, helping to provide valuable hints for further research and development.

Keywords— ***wet snow, overhead lines, indoor snow testing, snow-phobicity***

I. INTRODUCTION

During winter season several areas in Italy, mainly in Alpine and Apennine ridges, experience outages due to ice and snow accumulation. Italian OHLs of transmission and distribution are mainly threatened by wet snowfalls, occurring when air temperature is above 0°C and with a high relative humidity.

As the development of ice-phobic materials is pursued to deal with icing phenomena and is commonly regarded as a promising solution, many methods have been developed over time to measure ice adhesion for assessing their performances. On the other hand, snow offers a considerable complexity as, for instance, snowflakes have different adhesive properties to surfaces based on their LWC: the sticking efficiency on conductors, which is the tendency of snowflakes to stick to a cylindric surface after impact, is reported to rapidly increase with increasing LWC [1]. Snow, and in particular wet snow, is also hard to consistently recreate and to handle on a laboratory scale. Few works thus deal with the adhesion of snow to surfaces [2] and with the measurement of snow-phobic performances.

To achieve a rigorous testing of snow-phobic performances, a dedicated artificial snow laboratory (snow-lab) has been developed and is operational in the RSE facilities in Italy. The snow production machine of the snow-lab can produce snowfalls with different LWC inside a temperature-controlled chamber. The snowfalls can be used to test coating performances on OHL components directly under a snow flux or to measure the adhesion of snow samples to flat surfaces, by means of a dedicated strength testing machine for tensile and compression tests.

For a reliable snow-phobicity testing on OHL components, since comparisons among coated and uncoated surfaces should be made, a homogeneous snow flow must be ensured on all the OHL components under test. Since an effect of snow-phobic coatings can be observed in a delayed accretion or in an earlier shedding of the snow sleeve with respect to an uncoated, it can only be quantified if a reasonably comparable growth rate on all the segments is achieved.

A thorough setup process has thus been performed in the artificial snow-lab to seek the operating parameters to reliably reproduce snow with the required LWC meanwhile ensuring a homogeneous accretion rate of the sleeves on OHL components. Three different snowfall scenarios differing in the LWC of the snowflakes, in the snow flux and in the environmental parameters of cold chamber, are reproduced to mimic both dry and wet snow.

In this paper the main results of activities held in snow-lab, related to snow sleeve growth on conductors, are presented and discussed, with reference to a proposed cylindric accretion model [3]. Results obtained on coated samples for snow-phobicity assessment are also presented and their evaluation is briefly discussed.

II. SNOW-LAB DESCRIPTION AND EXPERIMENTAL SETTING

The testing area of the snow-lab is a 8 m^2 cold chamber (fig. 1-A) in which snow is produced by a snow machine. Briefly, snow is obtained by scraping, with metallic teeth, the ice layer which is continuously formed on the surface of a refrigerated rotating drum. The LWC of produced snow is controlled mainly acting on drum speed and temperature. The snow machine (fig. 1-B) is fed with liquid softened water collected in a basin placed in contact with the drum. Air blades fed with compressed air, located below the drum, can be activated to allow the detachment of the snow from the teeth.

The snow machine is attached to the ceiling of the cold chamber and snow falls from a height of about 1.8 m. An electromechanical linear conveyor can move back and forth the snow machine on a 2 m length rail: as the drum is 1 m in width, the snow-covered area can reach about 2 m^2.

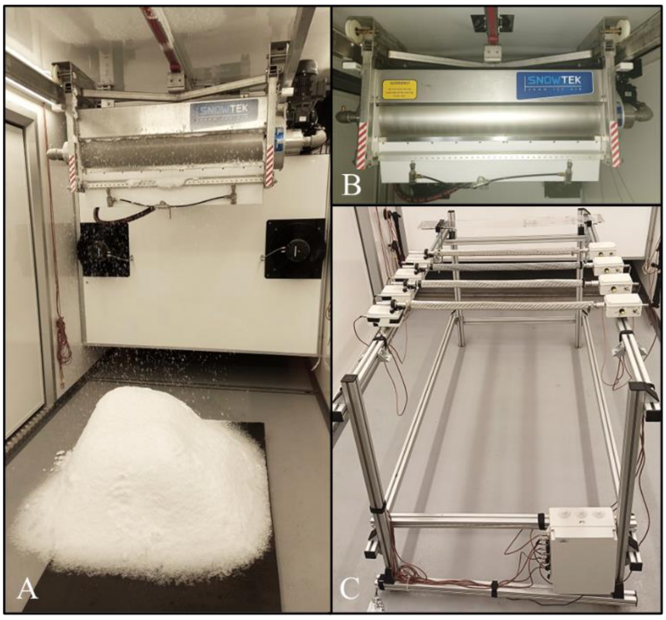

Fig. 1 A: view of the cold chamber with snow in production; B: detail of the snow machine; C: apparatus for components testing, with attached 31.5 mm diam. and 72 cm long aluminum conductors.

The maximum rate of snow production is 18 Kg×h^{-1}, corresponding to a precipitation flux of about 18 mmeq×m^{-2}×h^{-1} and the lowest settable temperature of the air in the cold chamber is -10°C.

By varying the operating parameters of snow machine and cold chamber conditions different types of snowfall events can be simulated. Snow with LWC up to about 35% and a corresponding density of about 300 Kg×m^{-3} can be produced.

Snow-chamber is equipped with temperature probes (PT100 resistance thermometer) for the continuous measurement of temperature in 9 different spots of the snow chamber and with a hygrometer for relative humidity (RH%) measurement. A high-resolution camera is used to periodically record images inside the cold chamber.

For snow-phobicity testing on components of OHL, a home-made exposure apparatus (fig. 1-C) has been developed and is operational inside the cold chamber. The apparatus consists of a modular aluminum frame on which it is possible to attach segments of conductors and ground wires, up to 2 m in length and with different diameters. In both the attachment points of the apparatus are located load cells (sensitivity: 1g, max load: 10 Kg) for the real-time measurement of the weight of segments. A dimmable 12V motor, placed in one of the two attaching points, allows to slowly rotate the segments up to about 1,5 rpm: during artificial snowfall events, rotation is imposed to allow the regular growth of snow sleeves on their surfaces. The apparatus is equipped with 8 load cells and 4 motors and can thus host 4 segments at the same time.

LWC measurements on produced snow are performed with a calorimetric method [4]: when hot water, at temperature T_1, is added to wet snow (an ice-water mixture at 0°C), the heat lost by the mass of hot water is equal to the heat absorbed by the ice fraction melting added to heat needed to bring the whole mass of water from 0°C to the final temperature T_2. LWC, expressed as mass fraction, is given by:

$$LWC = 1 - \frac{c_{P,w}}{L_f}\left[\frac{m_w}{m_{sn}}(T_1 - T_2) - T_2\right] \qquad (1)$$

where, $C_{p,w}$ is water specific heat at constant pressure, L_f is the ice melting latent heat, m_w is the mass of hot water; m_{sn} is the mass of snow. A centesimal thermometer is used for temperature measurements and a dewar vessel is used as a container: a correction is applied considering the heat exchanged by the container when varying in temperature, assessed with the method reported in [5]. Snow density is measured by weighing a container of known volume when filled with the produced snow. LWC and density are checked periodically during tests, sampling in different spots of the deposed snowpack.

III. SNOW SLEEVES ACCRETION ON CONDUCTORS

Target of the setup stage is to achieve a homogenous growth rate on 4 conductor segments simultaneously under 3 distinct snowfall scenarios. Snowfalls with about 0% (dry snow), 15% and 35% of LWC in the snowflakes, respectively named G0, G15 and G35, are reproduced.

Stranded aluminum conductors with a diameter of 31.5 mm and a length of 72 cm are used. Segments are obtained from the respective ACSR (aluminium-conductor steel-reinforced) cable. The internal steel strands and an inner layer of aluminum strands are removed and replaced with a rigid aluminum pipe of 1.5 cm diameter. Consequently, the conductors are only composed of the two outer concentric layers (24 and 18 wires respectively) of 3 mm diameter strands. This adaptation is required to properly accommodate the segments to the attaching points of the components testing apparatus. The configuration of the apparatus is chosen with the segments exposed in the transversal direction respect to the direction of movement of the snow machine. The height of apparatus is set to 1 m from the floor and snowflakes thus collide with conductors with a 0.8 m fall height.

The testing facilities effectively allow to grow cylindrical snow sleeves - on the segments.

The setup activities allowed to find out the parameters of snow machine, cold chamber, and exposure apparatus to be set. Relevant parameters of snow machine are reported in Table I., together with cold chamber environmental parameters and with the measured properties of snow produced.

Table I. Snow laboratory settings for homogeneous growth on conductor segments with dry (G0), 15% LWC (G15) and 35% (G35) LWC snowfalls

	G0	G15	G35
Snow production rate (Kg×h^{-1})	16.4	13.9	17.0
Surface covered (m^2)	1.1	1.8	1.8
Snow deposition rate (Kg×m^{-2}×h^{-1})	14.9	7.7	9.4
Rotation speed of segments (rpm)	1	1	1
Snow LWC – average (%)	1.6	14.3	34.8
Snow density – average (Kg×m^{-3})	122	216	417
Cold chamber T – average (°C)	-1	-0.5	-0.5
Relative humidity - average (%)	65	70	68

Setup tests were prolonged until at least a detachment of one snow sleeve was observed (for snowfall scenarios G0 and G15) or until 6 hours (for G35).

LWC and density measured on the snow, reported the graph of Fig. 2, were found to be substantially steady during testing periods under snowfalls G0, G15 and G35.

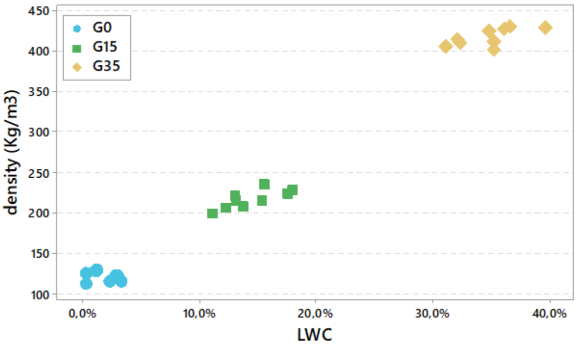

Fig. 2 LWC and density measured on snow during G0, G15 and G35 testing

A homogeneous accretion rate of the snow sleeves is achieved on all 4 segments under the 3 snowfall events, as can be observed in the graphs of Fig. 3 reporting their mass over time.

The trend of mass versus time curves found is in agreement with snow accretion models [3] and outdoor observations [6]. As expected, the observed rate of mass accretion increases with the increasing of the diameter of snow sleeve, as newly deposed layers of snow intercept more and more snow.

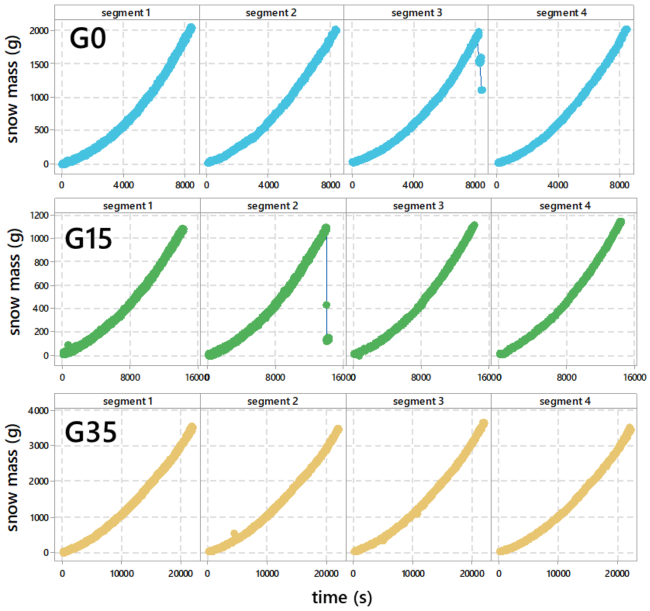

Fig. 3 snow masses accreted over time on the 4 segments under the three snowing conditions G0, G15 and G35. The shedding occurred in G0 (segment 3) and in G15 (segment 2) is visible

The mass accretion rates in the three scenarios are shown in Fig. 4 where is plotted the average mass of the snow sleeves against the snow deposed in the testing area in Kg×m^{-2} (approximately equivalent to mmeq).

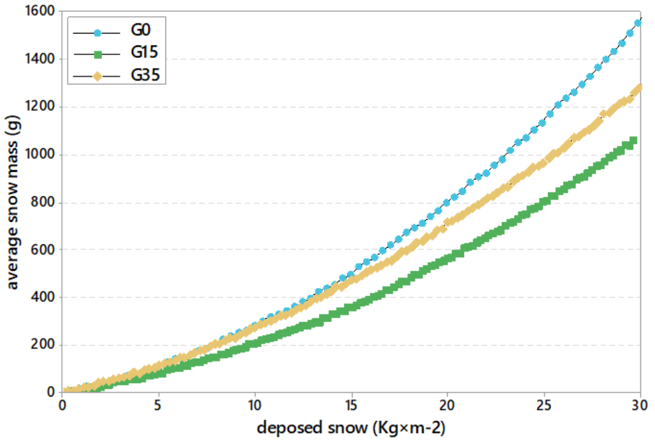

Fig. 4 accretion of snow sleeves in the different scenarios

Snow sleeve accretion rates for the three scenarios, in decreasing order are G0>G35>G15. The higher mass accretion rate observed under dry snowfall G0 is unexpected since higher sticking efficiency is reported for wet snow [1]. It must be however considered that different settings of snow machine are required to produce dry and wet snow: specifically, air blade activation is required to detach wet snow from the drum (while is not required for dry snow) leading to different impact speed on conductors. As tests are performed separately under the three snowfall scenarios, this is not expected to a critical issue for snow-phobic testing.

A comparison is performed also in terms of diameters of the snow sleeves. From the averages data of snow mass recorded (M), the snow sleeve diameter (D) is calculated at each time interval (i), according to [3], with the following equation:

$$D_i = \sqrt{\left[\frac{4(M_i - M_{i-1})}{\pi \rho_s} + D_{i-1}^2\right]} \qquad (2)$$

and using as ρ_s the average of the snow density measured. The diameters are also estimated from the images acquired at regular time intervals during accretion tests, visually measuring 3 distinct points on the segment for each image. A further comparison can be thus done, in the graphs of Fig. 5, between experimental data and data from model.

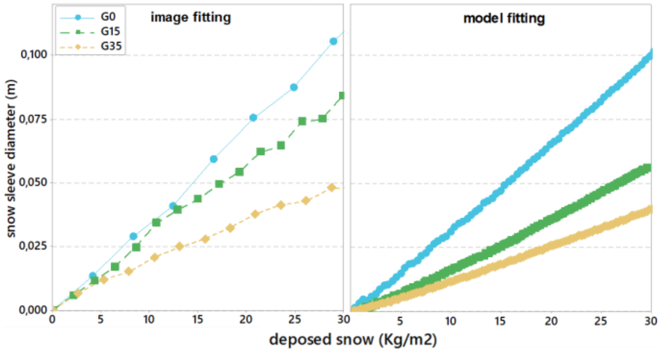

Fig. 5 left: results of diameter estimation based on image processing; right: results based on calculation according to equation 2

A linear accretion of the snow sleeve is observed if diameter is considered. Both data from images and from model agree that diameter accretion rate is, in decreasing order, G0>G15>G35, which is consistent with the increase of density of involved snow. Calculated and measured diameters are similar for the three scenarios, indicating a good consistency between theoretical and experimental data. Slightly lower diameters are however systematically calculated with the model. Possibly, the stacking of the snowflakes on the conductors under rotation is not as efficient as on a flat steady surface. This is suggested by camera images: in Fig. 6 the snow sleeves of present a jagged profile, with presence of local deposits of snowflakes and empty valleys. As a result, lower snow densities on the segments are expected and thus larger diameters are measured.

For diameter measurement, it should also be noticed that a degree of asymmetry is observed in the form of the snow sleeves, not reaching a perfect cylindric shape. This is likely due to a spatially unbalanced production rate of snow machine. The asymmetry, based on the difference in cell load readings between the two attachment points of each segment, is calculated in about 15% in G0, 10% in G15 and about 6% in G35 testing.

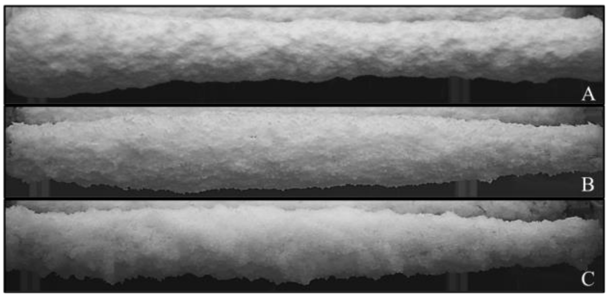

Fig. 6 camera images of snow sleeves on segments under G0 (A), G15 (B), G35 (C) snowfall scenarios

IV. SNOW-PHOBICITY TESTING AND EVALUATION

An example of testing on snow-phobic coatings is reported to briefly discuss the assessment of snow-phobic properties based on the snow-lab results.

The coatings under test, described elsewhere [7], and denoted as sample 1 and 2 are directly deposed on 31.5 mm diameter ACSR segments. Tests in snow-lab are performed simultaneously on both the coated segments, with two uncoated segments as reference. Test duration is set to 5 hours with the above-mentioned setup under snowfall G15. Snow masses on the segments over time are reported in Fig. 7.

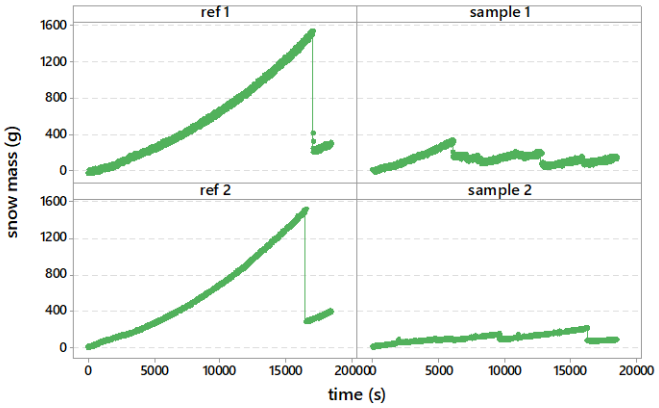

Fig. 7 snow masses of coated (sample) and uncoated (ref) ACSR segments under G15 testing up to 5 hours

The reduced snow load on samples is clearly visible in the graph, especially by the comparison with snow loads on the references. The experimental system is thus proven to be capable of evidencing differences in snow accumulation trends among segments treated with different coatings.

For a numerical quantification of snow-phobic properties, several parameters describing data results can be used, and some of them are listed below:

- average snow mass during test: M_A
- maximum snow mass: M_{max}
- snow mass at time i (hours): M_i
- shedding number during test: S_N
- average snow mass at shedding: M_{AS}

The parameters, calculated for the test hereby presented are reported in Table II.

TABLE II. PARAMETERS DESCRIBING DATA RESULTS OF THE SNOW-PHOBICITY TEST

	M_A	M_{max}	M_1	M_2	M_3	M_4	M_5	S_N	M_{AS}
Ref 1	566	1530	149	413	750	1160	250	1	1530
Smp 1	129	339	160	123	190	71	132	6	207
Smp 2	102	217	70	101	108	168	78	4	136
Ref 2	581	1520	172	428	779	1230	375	1	1520

Data generated during tests can however account for different snow-phobic behaviour of tested components, such as the hindering of snow sleeve accretion or the complete or partial shedding from the segments, that may not be fully witnessed by listed parameters. Specific performance indicators should be developed and applied for snow-phobicity results.

V. CONCLUSIONS

A dedicated snow-lab is operational for snow adhesion testing on surfaces and for snow-phobicity assessment of coatings directly deposed on OHL components. For OHL testing an experimental setup has been developed to consistently depose snowflakes on ACSR segments. A homogenous growth of snow sleeve has been observed on 4 different segments under 3 distinct snowfall scenarios, ensuring a reliable snow-phobicity assessment. The experimental accretion rate of diameters of snow sleeves on segments has been found to be basically in agreement with a commonly accepted cylindrical accretion model.

Testing on segments treated with snow-phobic coatings has shown that, based on the comparison with untread segments, the proposed experimental setting is able to clearly point out snow-phobic properties, in terms of snow sleeve accretion delay and early shedding.

As few tests on snow-phobicity are reported and a lack of common practices and performance indicators is experienced in this field, snow-lab can be a useful source of experimental data for evaluation of snow-phobic performances.

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