

Experimental study of resistance of aerial bundled cables with different hydrophobic coatings to hoar frost and soft rime.

D. Titov, K. Volkhov, N. Ivanov, A. Melnikov and P. Vorobev

Skolkovo Institute of Science and Technology, Nobel St. 3, Moscow 143026, Russia

d.titov@skoltech.ru

Abstract — The resistance of aerial bundled cables with and without different composite hydrophobic coatings to hoar frost and soft rime has been investigated. A new lab setup as well as testing methodology were developed for reproducing conditions, close to real. To achieve that goal, the processes of cooling and moistening of the air are separated in the lab setup. Series of tests were conducted aiming at subjecting wires with various coating types to induce soft rime and hoar frost icing in the laboratory conditions. The density and intensity of ice formation are examined and described.

Keywords — *icing on overhead power lines, icing lab setup, soft rime, hoar frost, condensation, desublimation, dew point, frost point*

I. INTRODUCTION

The accumulation of ice and snow on overhead power lines (OPL), especially in combination with wind, can pose a real threat to the reliability of the power supply to consumers. In the icy regions of Russia, the permitted icing loads on the conductors can range from 1.7 kg / m to 6 kg / m, with actual loads frequently exceeding this standard. Probably, the world's largest ice load on power lines with weights as high as 305 kg / m (Fig.1) was observed in 1961 in Norway [1]. The key parameters that determine the ice accumulation and ease of it's removal are adhesion force between ice and surface of the conductor and mechanical properties of the conductor.



Fig. 1 Icing on a 22-kV line in Norway

There are 4 anti-icing (AI) and de-icing (DI) methods to combat ice accretion on the surface of conductors [2]: mechanical methods based on breaking ice, thermal methods based on ice melting, active coatings and devices and passive methods. The first two methods are actively used in Russia

and require the organization of tracking ice conditions [3]. Active coatings and devices require some electrical energy to combat ice accretion. Most of the active coating methods are neither available commercially nor widely in use. Active coatings and devices were described in detail in the CIGRE TB 438 brochure [2].

The passive methods do not require an external source of energy but use only natural forces such as wind, gravity or solar radiation. An example of passive method use is a device of limiting the subspan oscillation. Among the widely used methods in Russia are counterweights, such as eccentric loads or pendulum type, phase-to-phase standoff insulators based on polymer long rod insulator [4]. The use of wires with icephobic and hydrophobic coatings, as well as with desired mechanical properties: high modulus of elasticity, tear-resistance, increased torsional stiffness, reduced diameter while maintaining electrical resistance, also refers to the passive method of dealing with icing [5]. The use of such wires in Russia is ad hoc due to the increased cost of such wires.

At the same time, the production of aerial bundled cables (ABC)¹ for various voltage classes up to 110 kV (SIP-7 conductors and analogs) is actively developed due to overall reduction in accident rate of OPL and the narrowing of their security zone. Since the wires are covered by insulation, their collision with each other and/or with falling trees in icy conditions does not lead to short circuits and disconnections. Moreover, the low dielectric constant of the polyethylene insulator surface reduces the effect of electrostatic forces, thus reducing the chemical adhesion [6], slowing down the icing process. On the other hand, the increased weight and dimensions of ABC, as well as the impossibility of melting on ABC, can cause damage to the supports during severe icing events. Therefore, studies of icing on such wires and the applicability of various icephobic and hydrophobic coatings on the polymer surface are relevant.

The objective of this paper is to reveal the impact of various composite insulating materials with hydrophobic properties on ice formation on ABC with the aim to assess their resistance to icing. For this, we have designed a laboratory setup which reproduces air conditions, close to real-life, and conducted tests on aerial bundled cables with and without different composite hydrophobic coatings to study their

¹ - self-supporting system consists of three cores of hard-drawn stranded and compacted aluminum conductors of equal cross-section and insulated with carbon-loaded XLPE to ensure UV protection.

resistance to icing. The obtained results and further research are discussed.

II. BRIEF SUMMARY ABOUT ICING PROCESS

Atmospheric icing is a generic term used to describe all types of accretion of frozen water substance, generally belonging to two main categories: precipitation icing and in-cloud icing [7]. The most famous models for assessment of icing intensity are models of Makkonen [8], Lozowski [9] and MRI-model [10].

Precipitation icing is caused by rain drops or snowflakes that freeze or stick to the icing body. This type of icing usually does not lead to any serious consequences for OPL in Russia - the accreted ice mass is, in most cases, much lower than the loads power lines are designed for. The wet or dry snow is usually blown away by wind and does not cause serious damage. Most of the icing associated accidents in the central regions of Russia in 2010 (the year of severe freezing rains [11]) were caused not by the icing itself, but rather by the tall trees near the wires, with their iced branches touching the wires.

In-cloud icing, which is caused by supercooled, suspended cloud water droplets, is the more dangerous type of ice accretion. It's intensity is determined by the cloud liquid water content (LWC), the size distribution of the cloud droplets, wind speed, air and conductor surface temperatures, etc. The typical in-cloud icing processes are condensation and desublimation. Condensation occurs when the temperature of the wire surface drops below the value of dew point. In turn, desublimation occurs when the temperature drops below the value of frost point [12]. The summary of condensation and sublimation processes characteristics are given by Table I.

TABLE I. THE TYPICAL PROCESSES OF IN-CLOUD ICING

Process	Density (kg/m ³)	Ice type
Condensation (deposition and freezing of super cooled droplets of vapour)	700-900	Glaze ice
	300-700	Hard rime
Desublimation (formation of ice crystals bypassing the liquid phase)	100-300	Soft rime
	less than 100	Hoar frost

Condensation and desublimation are processes that are inseparably linked with each other - the boundaries of the processes in Table I are conditional. Depending on the prevailing process, the density of ice deposits can be different by almost an order of magnitude (Table I). However, the intensity of each process varies differently with changing meteorological parameters and operating conditions of lines (mostly, wire temperature), which leads to shift in the prevailing process and, consequently, to change in ice density. The description of the main factors, influencing the intensities of condensation and desublimation are summarized in Table II.

As can be seen from Table I, glaze ice and hard rime are the densest types of deposits, therefore, they were mostly studied in the previous literature [1]. Soft rime and hoar frost, on the contrary, were not given much attention in the scope of studies of power lines icing. Nevertheless, these types of deposits are

important and they should be modeled within the scope of experiments because their density and adhesion forces increase as the temperature rises. Even small amount of such deposits can pose a serious problem to OPL because it increases the collision efficiency with droplets from the atmosphere, increases the wire sail area, and serve as a new surface for further deposition. Moreover, under the conditions of low or absent wind, hoar frost and soft rime are the prevalent processes, and can later develop into denser type of ice formations. In addition, the growth rates of both hoar frost and soft rime are highly dependent on whether the line is powered or not: both increases greatly if the wire is under voltage (see Table II).

TABLE II. FEATURES OF THE INFLUENCE OF SOME FACTORS ON DESUBLIMATION AND CONDENSATION PROCESSES

Factor	Features of influence
Wind speed	The wind speed greatly influences ice formation intensity with effects, such as turbulent flows causing qualitative changes in icing process as the wind speed increases. In addition, the wind accelerates the process of heat removal from the deposition surface, thus increases the intensity of the icing process. Even a weak wind can blow off crystals on the surface of the wire, so desublimation is usually not observed in windy weather, but deposition and freezing of super cooled droplets of vapour is preserved.
Air temperature, droplet size, LWC	The air temperature greatly affects the density of ice, which is proved by research results [13]. Low air temperature limits the droplet size as well as LWC. This leads to a decrease ice density with decreasing temperature.
Wire temperature	The level of intensity of condensation and desublimation unequally depends on absolute humidity and the temperature difference between wire surface and ambient air. Mathematical description of these processes is presented in sources [14, 15].
Voltage of line	The electric field strength of a conductor increases the intensity of ice formation due to polarization of droplet near the conductor. Trial tests on OPL 400 kV and laboratory tests in wind tunnel showed, that the desublimation intensity of the conductor with electric-field strength of 25 kV/cm is increased by 16.5 times (droplet diameter 2-5 μ m). For comparison, the intensity of glaze formation in the same electric field increases only 1.3 times [3].

Due to the prevalence of soft rime and hoar frost, as well as the risk of accidents during their intensive growth, the authors modeled these deposits on ABC with different hydrophobic coatings in order to reveal the influence of hydrophobic coatings on the growth of ice crystals on their surface.

III. INVESTIGATION OF ICE ACCRETION ON CONDUCTORS

A. Description of the lab installation

The installation for conducting necessary experiments was developed at the Skolkovo Institute of Science and Technology. To reproduce natural conditions of air flow during icing the set up consists of wind tunnel, two thermostats, blower, air cooler, additional heat-exchange unit,

moisture evaporator, compressor with air storage tank and vortex tube.

The icing process occurs inside the wind tunnel, while the rest of the setup is required for air preparation. A schematic picture of the installation is given by Fig. 2.

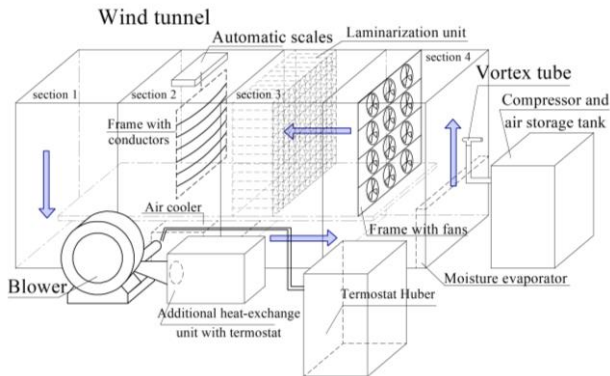


Fig. 2 Scheme of lab installation. The air movement inside the wind tunnel is indicated by the blue arrows.

Wind tunnel (Fig. 3) consists of four sliding sections moving on wheels along guides. Sections are securely pressed to each other with special locks. The air flow is induced by the 14 fans, 100 W each, that create the wind speed up to 8 m/s. To avoid turbulent air flows, the wind tunnel is additionally equipped with the laminarization unit (Fig. 4).



Fig. 3 Wind tunnel: dimensions 5x2.4x2 m

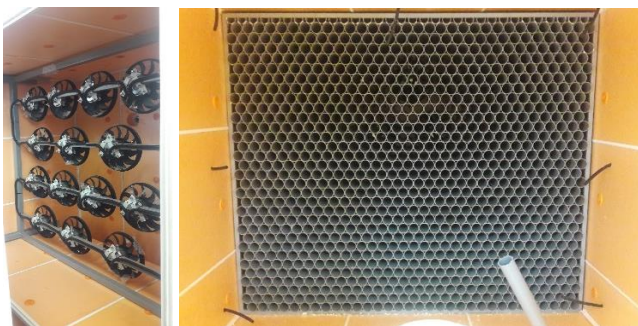


Fig. 4 Frame with fans (left) and laminarization unit (right)

To create the required temperature regime, in the lower part of the second section (under the tested conductors), there is a heat-insulated air cooler with corrugated tubes 20 meters in length arranged in it through which the refrigerant circulates from Huber Unistat 530w thermostat (Fig. 5). The position of the air cooler inside the wind tunnel reduces the loss of cold.



Fig. 5 Air cooler (left) and Huber thermostats (right)

Up to 160 m³/hour of air is supplied to the air cooler from the K11 MD blower. Before entering the blower, the air is pre-cooled and dried in the additional heat-exchange unit by the second thermostat (Fig.6).

Before the setup achieves steady-state conditions, vortex tube is used, which additionally blows cold air at a temperature of up to -16 °C through the wind tunnel. At the entrance to the vortex tube, the air with the pressure of 0.76 MPa is injected with an industrial compressor (Fig. 7). The air circulates around the perimeter of the wind tunnel from the top to the bottom, etc., mixing with the air cooled to -35 °C from the air cooler. Overpressure in the wind tunnel is avoided due to the presence of a hole in the lower part of the second section of the wind tunnel.



Fig. 6 Blower (left) and additional heat-exchange unit (right)



Fig. 7 DRB 40 D compressor with air storage tank and vortex tube (model 3250 thru 3299)

Ultrasonic and heating evaporators create the necessary level of humidity in the wind tunnel. Total water consumption of the setup is up to 4 liters per hour. In the upper part of the second section of the tunnel a frame with up to 6 conductor segments (1.2 meters in length each) is suspended (Fig. 8). The scales are mounted on the roof of the tunnel to weigh the frame with conductors during the experiment. The wind tunnel

is also equipped with moisture sprinklers, which were not used during the experiments.



Fig. 8 Frame with conductors

Space-distributed temperature and humidity sensors, wind direction and speed sensors, as well as scales, send data to a computer in real time to monitor the experiment conditions. Accurate adjustment of the rotational speed of the fans and the blower, as well as the temperature of the refrigerant, help to maintain a steady-state system operation. The sequence of drying the air in the compressor and the additional heat exchanger, cooling the air in the cooler and the vortex tube, as well as humidifying the air inside the wind tunnel, make it possible to avoid reducing the efficiency of the installation, since the cooling surface is practically not overgrown with ice. The air accumulated in the cooler for 3-4 hours of the experiment is blown during 5-7 minutes with a blower at a speed of about 18 m/s while heating the corrugated tubes by thermostat. At the same time, ice and warm air come out in a special hole without heating the air inside the wind tunnel.

B. Description of used conductors

In the experiments, we used ABC with outer diameter 17.4 mm for 20 kV without special hydrophobic coatings and with two types of coatings based on composite materials:

1. with a bacteriostatic effect.
2. with enhanced antiadhesive properties. It is designed with low content of solvents for the treatment of porous surfaces, rubber products, and plastics.

The coating has multifunctional polymer composition with enhanced hydrophobic properties without mechanical impurities for application on a clean surface as a film for complex protection (moisture protection, protection from dust, corrosion) in air chemically aggressive environment. The compositions impart a uniform hydrophobic chemisorbed film (pile) effect to the surface to retain the lubricating layer. The thickness of the protective layer is 100 nanometers. Compositions form a single chemical entity with the surfaces (due to chemisorption bonds), creating a surface that is absorbed by the fluorine particles, which significantly reduces the coefficient of friction along the contiguous surfaces. Do not change their performance in the temperature range from -80 °C to +420 °C).

C. Description of experiments

² - at the time of the experiments, the high-voltage installation was not configured.

³ - the current load is absent. As a result, the wire temperature has minimal value. Such conditions enhance the intensity of condensation and

To study the effect of various coatings on the desublimation intensity five cables without special hydrophobic coatings with a length of 1.2 m were first placed in the wind tunnel during an experiment (fig.7). A data-collection system, thermostats, blower, fans and compressor with vortex tube were started to enter the temperature regime -16 ... -15 °C inside the wind tunnel.

After the supply of moisture, both temperature and humidity in the tunnel stabilize at -8 °C and 99 % respectively, and after that the experiment was run for two hours. The second experiment was carried out with the same conductors but with the steady-state temperature of -2 °C. The experimental conditions are summarized in Table III.

TABLE III. THE DESCRIPTION OF EXPERIMENT CONDITIONS

Parameter	Value
Wind speed	About 1-2 m/s
Voltage ²	~ 0 kV
Current load ³	0 A
Air temperature	-2°C and -8°C
Dispersion of droplets (source of moisture)	About 2-10 μm (hypersonic moisture evaporator)
The angle between wind and wire axis ⁴	90°
Relative humidity	more than 90%
Duration of the experiment	2 hours after process stabilization

The experiment with the same conditions was also conducted for ABC with two types of coatings. The equivalence of experimental conditions for all the tests was ensured by controlling stability of the evaporator moisture consumption, rotational speed of the fans, air temperature inside the wind tunnel, temperature of the refrigerant in the thermostat circuit, and surface temperature of the wire.

The comparison criteria for conductors with different coatings are as follows:

- time before the appearance of visually distinct deposits, min;
- rate of deposit growth with time (determined by weighing the frame with the wires during the experiment with a resolution of 1 measurement in 20 seconds);
- density of the ice deposit (determined by calculation based on the average deposit diameter at the end of the experiment).

D. Results

The results of all the experiments in the wind tunnel at temperatures of -8 °C and -2 °C are summarized below (Figs. 9-12 and Table IV).

desublimation. Such an operating condition is close to night mode of operation when the maximal intensity of icing is observed.

⁴ - angle between wind flux and wire axis influence on intensity and form of deposits. The maximal intensity is during right angle.

TABLE IV. THE NUMERICAL RESULTS OF EXPERIMENTS
(-8 °C / -2 °C)

Parameter	Units	Without cover	Cover 1	Cover 2
The time before the appearance of distinct visual deposits	min	38/16	35/25	37/25
Mass of deposits at the end of the experiment	kg	1.1/1.43	1.04/1.33	1.05/1.37
Estimated density	kg/m ³	130/560	140/540	130/600

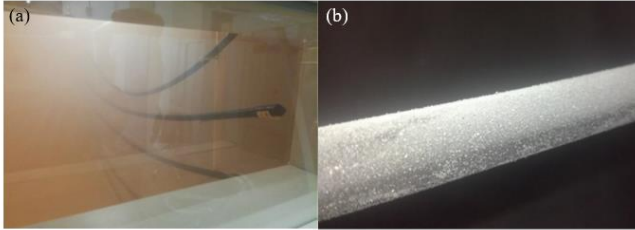


Fig. 9 (a) – a fog under negative temperatures; (b) – the appearance of visually distinct deposits on a wire

Fig. 10 shows that at lower temperatures (-8 °C) the time before the appearance of visually distinct deposits is almost the same for all types of coatings – 35-38 minutes. During this time, individual crystals are deposited on the surface, but do not cover the surface of the wire with a continuous layer.

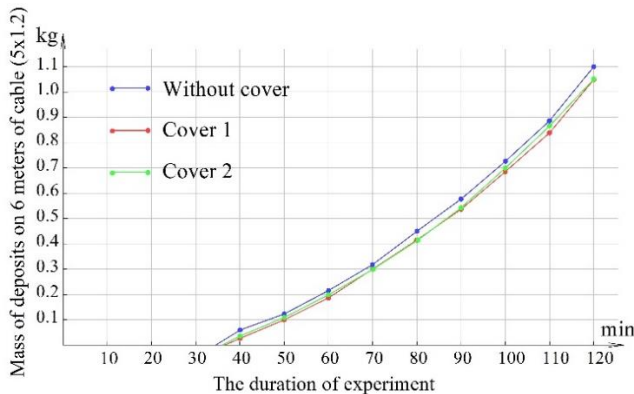


Fig. 10 Deposits growth rate at the temperature of -8 °C

During the experiment, the process of deposit growth is accelerated, because accreting surface increases and air is supersaturated with moisture. In some places, the thickness of loose deposits was up to 15-17 mm at the end of the experiment. Estimated deposit density is about 130-140 kg/m³.

At temperatures close to 0 °C, however, the process of icing on an uncoated wire was initiated sooner (around 16 mins after the experiment start) than for the coated ones (25 mins) (Fig. 11). However, with time, the intensity of deposit growth and deposit density became very similar for all wires.

Despite the large increased mass of ice on the wires 1.33-1.43 kg, average equivalent radial thickness of deposits was 5.3 mm. The resulting deposits are significantly denser than for the lower temperature experiment, which can be explained by the predominance of the condensation process at higher

temperatures. Graphs comparing deposit growth at different temperatures are shown on the Fig. 12.

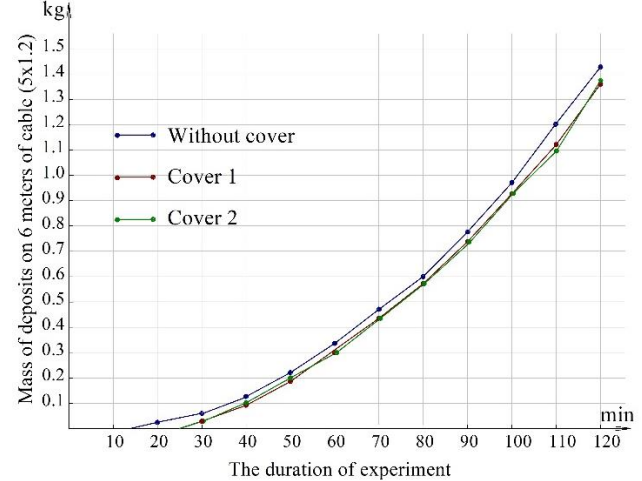


Fig. 11 Deposits growth dynamics at the temperature of -2 °C

Obviously, the air temperature has a much stronger effect on the process than the presence of used hydrophobic coatings. The difference in growth rate of ice deposits is also caused by different values of absolute humidity at the temperature -8 °C and -2 °C.

The presence of composite coatings slightly slows down the process of deposit growth at the very initial stage because its hydrophobicity decelerates the process of condensation. However, the composite coating has no particular effect on the process of desublimation.

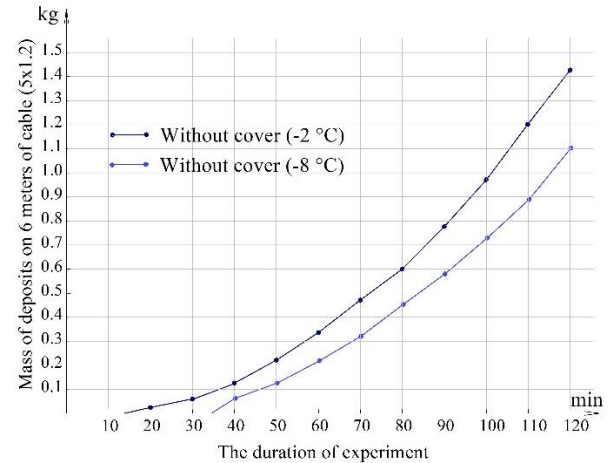


Fig. 12 Deposits growth dynamics on ABC without any covers at the temperature of -2 °C and -8 °C

Compacted desublimated deposits become a new surface for ice accretion, which speeds up with time. Thus, one can say that the use of these types of coatings does not always help during icy conditions, especially when the surface deposition temperature is below the desublimation point.

IV. CONCLUSIONS

We have developed a new testing methodology to study ice formation on aerial bundled cables with different types of hydrophobic coatings. A laboratory setup for conducting tests was developed and experiments were performed to investigate the resistance of cables with different coating types (and with no coating) to formation of hoar frost and soft rime. The main findings of the experiments are the following:

1. It was experimentally established, that hydrophobic coatings based on composites have very little effect on ice formation on aerial bundled cables. Hydrophobic coatings can reduce the intensity of condensation at an early stage of the process, but have virtually no effect on the desublimation process, which leads to formation of soft rime and hoar frost. We assume that this phenomenon can be explained by the fact that a film of crystalline ice accumulates due to ice deposit on the wire surface. This accretion does not depend on the angle of surface moistening. The deposit has an accretion of a different nature which is governed by other physical laws. The crystals become a new surface of deposition changing anti-icing properties of the wire.

2. An efficient way to avoid the formation of ice crystals on the surface is to raise the surface temperature above the frost point. The frost point at normal atmospheric pressure, even during worst fog (supersaturation of water vapour in moist clean air) does not exceed the air temperature by 1-2 °C. Increasing the surface temperature of the wire will also reduce the rate of condensation. At that, the collection and accretion efficiencies will decrease and the collision efficiency will remain unchanged. The icing intensity can also be reduced by hydrophobic coatings, as was shown during our study.

3. The results indicate the promising application of high-voltage insulated wires with hydrophobic coatings, the development of insulating coatings with high thermal conductivity, providing an increased surface temperature of the wire to minimize the process of desublimation, as well as improving measures for the timely preventive heating of insulated wire. The combined use of these solutions can be a good strategy for minimizing power outages in the ice period in networks up to 110 kV.

Further research will include the effects of various hydrophobic coatings on the polymer surface on the strength of ice accretion, as well as the effects of electric field strength, wind direction and speed, the droplet size on the intensity of the icing process.

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