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Abstract*—The process of wet-snow shedding from overhead cables was simulated in cold-chamber experiments under different ambient conditions. The main objective of the study was to examine how cable sag influences the snow-shedding process. However, the effects of several other parameters were also considered, such as air temperature, solar radiation, snow-sleeve length, and periodic excitation of the cable. Periodic excitation was applied at the suspension point of the cable, leading to cable vibration which may simulate galloping. The two most important parameters related to wet snow adhesion to the cable, liquid water content and density, were measured as a time function along the entire snow sleeve until snow shedding occurred. The experimental observations were compared to data gathered in a recent study on snow shedding from cables with negligible sag. The main difference between negligible and large sag is that with the latter water migrates to the lower region of the sleeve in the middle of cable, and that droplets start dripping after the snow becomes locally saturated. The time when dripping began and the mass of dripping water were also measured. Forced cable vibration accelerated the shedding process; the relationship between the excitation amplitude and the time when shedding occurred were determined. Experiments also revealed that the maximum liquid water content of snow, which was reached when shedding occurred, depended on the initial snow density.

I. Nomenclature

T_1	Initial temperature of hot water in the adiabatic container (°C)
T_2	Temperature of snow sample = 0°C
T_3	Temperature of water after thermal equilibrium reached (°C)
m_1	Mass of hot water =0.5kg
m_2	Mass of snow sample (kg)
m_{2L}	Mass of liquid water in snow sample (kg)
c_w	Specific heat capacity of water = 4.187 kJ/(kgK)
c_{ice}	Specific heat capacity of ice = 1.84 kJ/(kgK)
C_{cont}	Heat capacity of adiabatic container (kJ/K)
λ	Ratio of heat capacities, C_{cont} / c_{ice} = 0.001 kg
L	Latent heat of melting/freezing = 333.51 kJ/kg

II. Background of Wet Snow Shedding and Objectives of this Study

A. *Wet Snow Shedding*

Power transmission lines in cold regions are endangered by snow accretion and shedding in several ways. The weight of accumulated snow can cause static overload on cables and on other line components. Snow shedding may also initiate high-amplitude vibrations and unbalanced load when a large mass is detached instantly. Therefore, it is important to predict when snow shedding from transmission line cables may be expected. However, this is not an easy task because natural snow shedding from cables is not well observed. So, there is relatively little information about the process and there exist no sophisticated theoretical models on it. A criterion of snow shedding was established in [1] based on a thermodynamic model of snow accretion. This criterion assumes that snow sheds from the cable when liquid water content (LWC) reaches 40%. This proposition seems a reasonable first approximation but field observations show that LWC sometimes reaches 55% when shedding occurs.

B. *In-Field Observations*

Accreted snow sheds when the cohesive force within snow and the adhesion force to cable are sufficiently low (very low or high LWC). Field observations show that shedding starts near towers and isolators when the snow sleeve is axial-type. This phase happens suddenly. Therefore the end region of conductor becomes bare and the remaining accretion is cylindrical. In the second phase, the cylindrical sleeve sheds randomly and partially by the effect of gravity and wind within 5-10 minutes [2]. In case of continuous wet snow precipitation, the wet snow accretion and shedding appear successively and lead to saw-tooth loading cycles.

In some cases partial shedding can generate a transverse wave which travels along the wire and induces shedding over the entire cable. However, a snow sleeve cannot shed entirely following a transverse wave because LWC and density are not uniform along the cable; consequently, the mechanical parameters are not uniform either.

Snow creep (Fig. 1) is one of the most significant causes of wet snow shedding. Snow creep is caused by the effect of gravity, wind, temperature, solar radiation and liquid precipitations [2]. A circular cavity zone is carved by the cable when the air temperature is close to 0°C and wind effect is significant. Due to the effect of gravity these sleeves fall down more easily.

Another form of snow creep (Fig. 2) occurs when the inclination of cable is more than 30-40°. In this case, the snow sleeve loses its adhesion from the cable and slide along it. This type of shedding was observed in mountainous areas of France [3].

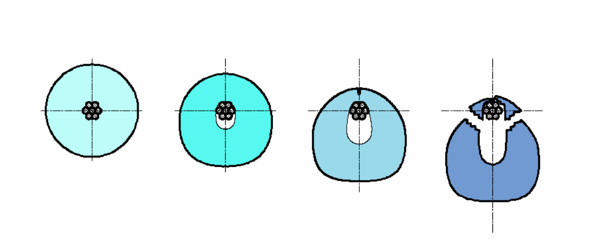

Fig. 1 Process of snow creep (re-draw from [2])

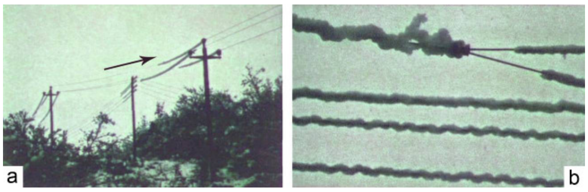

Fig. 2 Creep of a wet snow sleeve on a steep cable (from [3])

C. Wind Tunnel and Cold Chamber Observations

Wind tunnel experiments support the hypothesis that snow shedding is a random process. Sudden and partial shedding in short segments were both observed [4], showing that low density snow sheds more easily than high density snow when the cable is rigid (axial accretion). In case of cylindrical sleeves, snow sheds by the effect of gravity or wind alone when LWC is low. The shedding probability is higher when the LWC of snow is so great that the snow becomes saturated. The LWC increases due to the melting of ice particles in snow. The liquid water migrates into the lower regions of snow by the effect of gravity. Therefore, the water distribution in snow will be in the funicular regime at the bottom and creeps downward but the top of sleeve will have lower LWC and remains on the cable.

The two greatest problems of the wind tunnel experiments are the costs and the limit in cable length to be tested. In order to eliminate these problems, a cold chamber in CIGELE was used for this study. However, a snow sleeve cannot form naturally in cold chambers and the wind speed is more limited than in a wind tunnel.

A good technique to reproduce cylindrical wet snow sleeve was used in [2]. It was demonstrated that this method was valid to model the behaviour of natural wet-snow sleeves. In this study, wet snow shedding was investigated in the case of concentric, eccentric and hollow sleeves. No spontaneous shedding was observed along the entire span. Shedding was always observed to initiate at one end point along the cable and progressed at a measurable speed. Two trends were found under a similar heating effect. First, wet snow with higher initial density shed later than wet snow with lower density because the cohesion force was stronger. Second, wet snow with higher initial LWC shed faster, because LWC at which snow sheds was reached earlier. The strength of wet snow sleeve was also observed in his study in order to validate a finite element model of snow shedding from overhead wires.

Further observations on the CIGELE cold chamber were reported in [5], which contributed to a better understanding of the effects of ambient parameters such as heat radiation, air temperature and wind [6], as well as the effects of heating of cable by current [7] on snow shedding. A two-dimensional thermodynamic model was also developed in the cited studies, which can simulate the variation of snow LWC and density at the end section of snow sleeve and to predict how the same section turns downward resulting in shedding.

D. Objectives

The present study examines the effects of cable sag and periodic excitation of the cable on LWC and density of snow, which are the decisive parameters concerning snow shedding, under different ambient conditions and for different snow sleeve geometries. The parameters varied in the experiments are listed in Table I.

TABLE I: VARIED PARAMETERS

Varied parameters[1]		
Geometrical features		
Cable sag (sag-to-span ratio)	**800 mm (16%)**	**400 mm (8%)**
Length of snow sleeve	**2200 mm**	**4600 mm**
Environmental variables		
Air temperature	**5 °C**	**2 °C**
Radiation	**no**	**750 Lux**
Cable vibration	**off**	**on**

The sag-to-span ratios considered seem to be too high as compared to real transmission lines without ice accretion or snow deposit. However, the sag-to-span ratio of cables loaded by ice or snow accretion may exceed even the values chosen in this study. The main reason for choosing relatively high values is that they help to observe the effect of sag on the process of snow shedding.

III. MEASUREMENT PROCESSES AND EXPERIMENTAL SETUP

A. Wet Snow Preparation

The experiments were carried out in a cold chamber of CIGELE laboratories. The dry snow for the experiments was collected on the campus of the Université du Québec à Chicoutimi. Only the snow which has not experienced significant metamorphosis was collected for that purpose.

After being collected, the snow was left in the cold chamber at 5 °C air temperature, and regularly mixed to keep its density and LWC homogeneous. This phase lasted until the LWC of the snow reached the desired range for reproducing wet snow accretions, i.e. between 8 and 20%. The length of this period, which depends on the quality of collected snow, was in the range of 15 to 150 min. After that time, the cohesion in the snow was strong enough for preparing snow sleeves.

[1] In the following, the setting defined by the first column will be called “base setting”

B. Wet Snow Sleeve Molding

A semi-cylindrical mold was used to reproduce cylindrical natural wet snow sleeves. First, the mold must be positioned so that the cable is in the axis of the cylinder of the mold. Then the prepared wet snow was put into the mold and compressed by hand. When the entire mold was full of wet snow, the top of the sleeve was compressed and formed with a semi-cylindrical hand tool until the sleeve became cylindrical. After the sleeve had been prepared, the mold was removed carefully so as not to damage the sleeve. The finished sleeve had a uniform diameter of about 100 mm, and was assumed to be of uniform snow density and LWC at the beginning of the experiments.

C. Measurement of Liquid Water Content (LWC)

The most important parameter influencing adhesion of snow to the cable, and thereby snow shedding, is LWC. LWC is defined here as the ratio of the mass of liquid water (m_{2L}) to the total mass of snow (m_2)

$$LWC = \frac{m_{2L}}{m_2}$$

Wet snow is a mixture of ice particles, water and air. The mass of air is negligible; thus, the total mass of snow may be written as follows

$$m_2 = m_{2L} + m_{2S}$$

where m_{2S} is the mass of the ice particles.

The LWC of snow was measured in this study by a hot calorimeter [2, 8]. A snow sample was put into an adiabatic[2] container filled with hot water. After the snow melted and the thermal equilibrium was reached, the LWC was calculated from the heat balance equation of the system (water + wet snow + container):

$$m_1 \cdot c_w \cdot T_1 + C_{cont} \cdot T_1 + T_2 \cdot (m_{2L} \cdot c_w + m_{2S} \cdot c_{ice}) - m_{2S} \cdot L = T_3 (m_1 \cdot c_w + C_{cont})$$

where m_1, m_2 T_1, T_3, are the measured variables, and C_{cont} is obtained from calibration of the container [5]. T_2=0 °C is assumed because wet snow is a mixture of ice and water, and further parameters are constants. The heat balance equation is solved for the mass of the liquid water in the snow, m_{2L} :

$$m_{2L} = \frac{m_2 \cdot \left(\frac{c_{ice} \cdot T_2 - L}{c_w} - T_3 \right) - (m_1 + \lambda)(T_3 - T_1)}{\left(\frac{c_{ice} \cdot T_2 - L}{c_w} - T_2 \right)}$$

Finally, the LWC of the snow sample is expressed as follows:

$$LWC = \frac{\left(\frac{c_{ice} \cdot T_2 - L}{c_w} - T_3 \right) - \frac{(m_1 + \lambda)(T_3 - T_1)}{m_2}}{\left(\frac{c_{ice} \cdot T_2 - L}{c_w} - T_2 \right)}$$

D. Experimental Setup

Figure 3 presents the schematic drawing of the small-scale experimental setup. The cable was 5-m long, the maximal possible length in the cold chamber. The cable type was ALCAN Pigeon ACSR, with a diameter of 12.75 mm which is significantly lower than those used in transmission lines. The cable was suspended 1 m above the floor. The desired sag was set after preparing the snow sleeve on the closely horizontal cable. The cable was lowered very slowly and carefully in order to minimize the damage to the snow sleeve. However, the shock effect of cable hoist could not be totally damped.

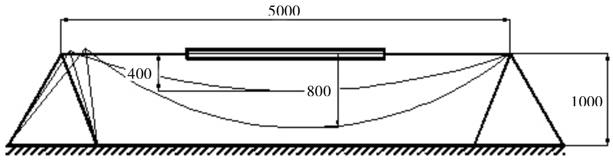

Fig. 3. Geometry of experimental cable with different sags

Two different sleeve lengths were used during the experiments. The snow sleeve geometry is shown in Fig.3. The snow sleeve ends were sometimes damaged during the preparation process, and one end was cut off to determine the initial LWC and density. Therefore, the snow sleeve lengths were not precisely equal in all experiments. The mean length was 2200 mm for the short sleeves and 4600 mm for the long ones. The maximum variation in the length was about 100 mm. At the end of each run[3], five samples were used along the snow sleeves to measure the LWC and density. The dots in Fig. 4 show the position of the sampling points when the cable is approximately horizontal as well as when the cable sag is 800 mm. Samples were taken from points 2-6 for the short sleeves, and from points 1, 2, 4, 6, 7 for the long ones.

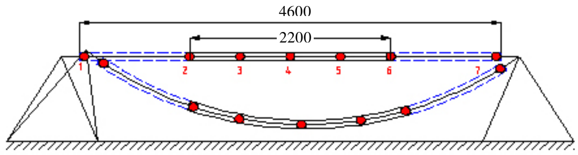

Fig. 4. Sleeve lengths and sampling points

In order to examine the effects of forced vibration on the snow sleeve, a DC-motor with a worm drive and an eccentric disc was fixed to one endpoint of the cable (see Fig. 5). The amplitude of excitation was 35 mm or 75 mm.

The lowest position of the cable was 200 mm above the ground. The maximal amplitude of the cable which depends on the excitation amplitude and frequency is indicated by *2A* on Fig. 5. Unfortunately, the motor was not strong enough to assure constant rotation speed during one period. Therefore, the excitation at this setting was nonlinear, but it was a low cost alternative to studying the effect of forced vibration with relatively high excitation amplitude.

The excitation frequency, excitation amplitude and maximal amplitude of cable in consecutive experiments are listed in Table III. The frequency and amplitude of the obtained motion fall in the range of frequency and amplitude describing

[2] This is reasonable to assume since during a 30-minute preliminary test the temperature drop was less than 1°C and the time in which the system reaches its equilibrium is about 5 minutes

[3] Unfortunately the snow sleeves had to be damaged for measuring LWC and density by this method, therefore only one measurement per run could be made along the cable at the end of each run.

galloping [9] or the effect of an external periodic force applied to remove accretion from the cable.

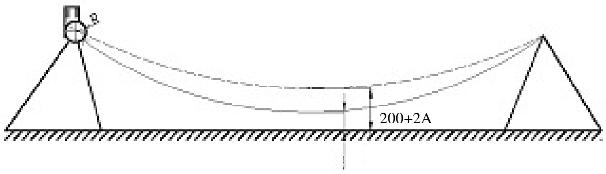

Fig. 5. Experimental settings with forced vibration

IV. Experimental Results

The cold chamber experiments showed that the shedding mechanism initiated at the end of the snow sleeves was similar to that of negligible sag [5, 6], except for long snow sleeves. Partial shedding of 20-30-cm sections was observed in all experiments, meaning that the dynamic effect of wet snow shedding was not significant.

The principal effect of sag appears in the nonuniformity of LWC and density along the cable, because the water content of the snow migrates due to gravitational force. Hours before shedding starts the water begins dripping from the lowest point of the snow sleeve which is a significant difference from the no-sag case. For better understanding of this phenomenon, the LWC and density were measured when water started dripping as well as at half of this time. Further measurements were made when shedding started, and the mass of dripping water was also weighted each 15 minutes until shedding. These measurements required different runs with the same initial parameters because the LWC and density could not be determined without damaging the snow sleeve. Consequently, differences occurred with the initial quality of the snow, which caused LWC and density deviations in some cases.

A. *LWC and Density Distributions along the Cable*

Even though LWC and density were assumed to be uniform along the cable at the beginning of an experiment, it was different in each run. The mean value of initial LWC together with the LWC distributions measured later are shown in Fig.6.

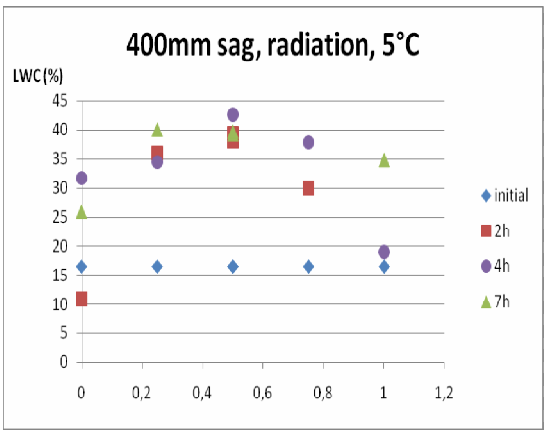

Fig. 6. Typical LWC distributions along the cable

During the experiments, water percolates toward the bottom of snow sleeve, as well as toward the lowest point of snow sleeve along the cable. Consequently, the LWC and density start increasing in the mid-span region until reaching a maximum when no more water can accumulate there, and the extra water starts dripping. After the LWC reaches its maximum value the snow cannot shed in the mid section for a while, because the inner cohesion forces and adhesion to cable is strong enough to hold the snow sleeve.

When the LWC also reaches its maximal value at the end of the cable, the shedding starts there in the case of short sleeves, because cohesion forces are weaker than in mid section due the free end. The water from the end section cannot migrate any more toward the mid section because the slope disappears at the end of the snow sleeve. As a result, the LWC increases rapidly at the bottom of the end sections and snow shedding begins. The complete wet snow shedding process is shown in Fig. 7.

As for the long snow sleeves, the process of water percolation is similar to that of short sleeves, except that the shedding mechanism is different. After the LWC reaches its maximal value at the bottom of the mid section, the snow starts creeping there because the pressure from other sections of the sleeve is higher than for the short sleeve. Consequently, cohesion and adhesion forces cannot hold the snow. The other reason of this difference is that the faster saturation in the mid region of the long sleeve does not give enough time to the snow matrix for metamorphosis. As a result, ice bonds are not as strong as in the short-sleeve case where saturation is slower.

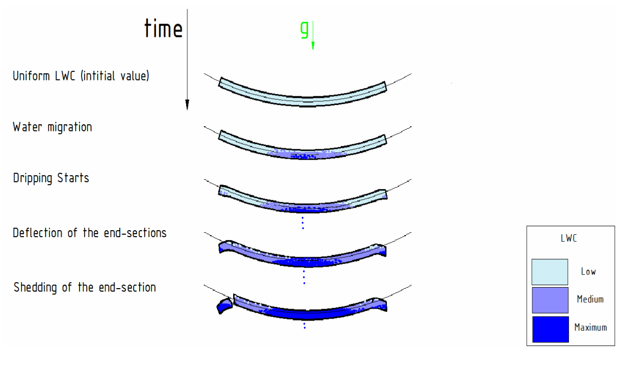

Fig 7 The process of snow shedding in case of short snow sleeve

B. *Effect of Cable Sag*

In order to understand the effect of sag, the LWC and density values as obtained for three different sags are compared with each other for different settings of the ambient parameters. The LWC and density results are obtained in the present study for sags of 400 mm and 800 mm. The data for the no-sag case were measured in [5]. Comparisons are made on the two segments of snow sleeve which are of the greatest interest: end section and mid-span section.

The initial LWC was in the same range for different sag cases except in the no-sag case for 2 °C without radiation (Fig. 8) where the initial LWC was very high.

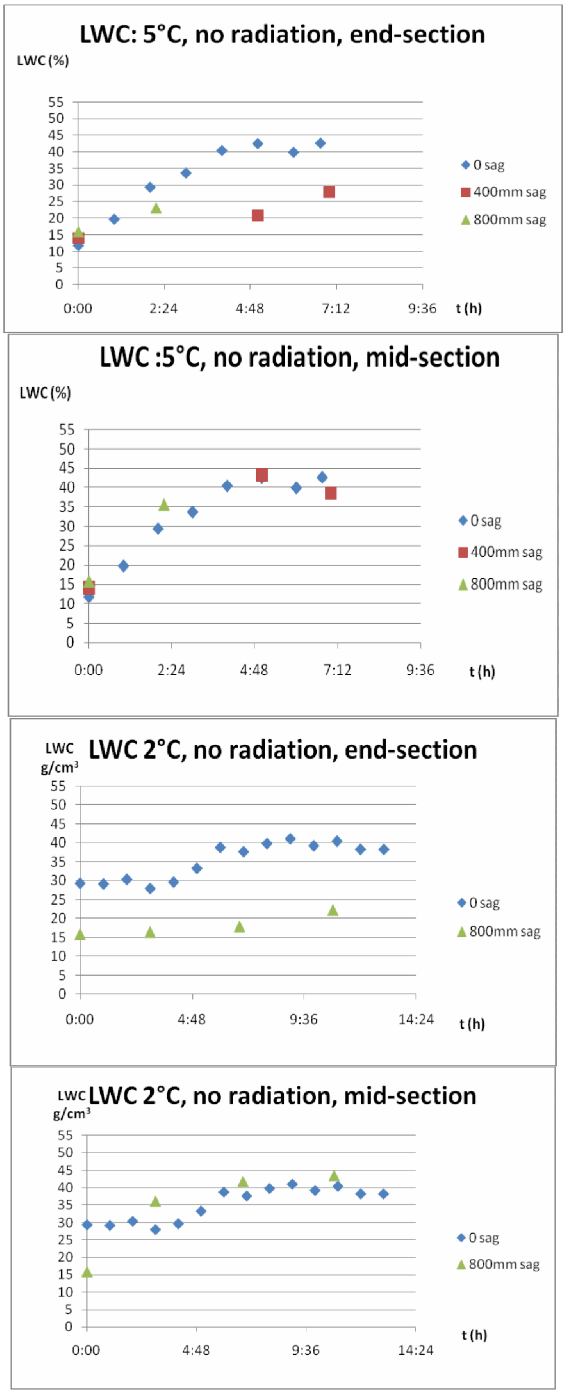

Fig. 8 Comparison of the increase in LWC for different sags

1) *End Sections*

The LWC of the end sections in a sagged snow sleeve is always lower than in a straight sleeve. This is not surprising because the water percolates into the lower regions along the cable whereas the water percolation is perpendicular to the cable axis in the no-sag case [5]. Variation of LWC in the cross section was not considered; average LWC was measured in each cross section in order to simplify comparisons. Significant difference between the LWC of the end sections in the 400 mm and 800 mm sag cases was not found. However, the LWC in the end sections is not independent of sag, since LWC increases faster in the end sections for the no-sag case. Consequently, the relation between sag and LWC in the end sections must be nonlinear because differences between lower sags are more significant than between high sags. In order to obtain a correct function between sag and LWC in the end section, more experiments should be made in the future.

2) *Mid Section*

The LWC in the mid section before dripping begins is little higher in the sagged cases than in the no-sag case. The difference is not big despite of water migration. The LWC values in the mid section become independent of sag after dripping starts because the excessive water drips and the LWC does not increase further.

C. *Dripping Water*

The process of water dripping is characterized by two parameters: the time when first droplet is observed and the mass of dripped water.

The time passed after the beginning of the experiment until dripping starts is shown in Table II for different conditions.

TABLE II: TIMES WHEN DRIPPING STARTS

Air temperature	Sag	radiation	length of sleeve	dripping starts
5 °C	800 mm	no radiation	short	2h10
	800 mm	radiation	short	1h50
	800 mm	no radiation	long	2h
	400 mm	radiation	short	2h
2 °C	800 mm	no radiation	short	6h50

The moment when dripping begins does not depends significantly on the sag of the cable, the radiation, or the sleeve length. The most influential parameter is the air temperature, which implies that convective heat flux is the most significant heat flux regarding wet snow shedding, which corresponds to the thermodynamic models of wet snow accretion [1, 10].

Significant effects of parameters other than air temperature

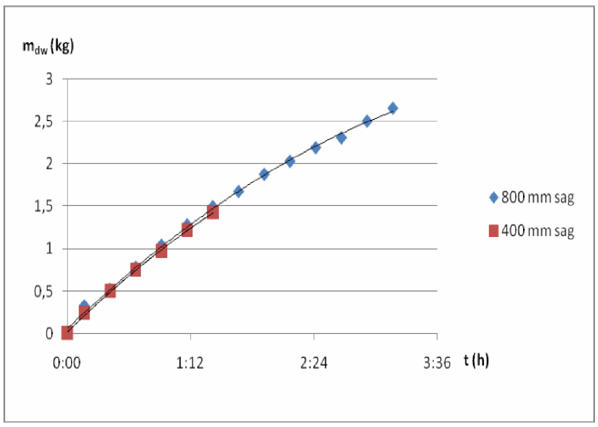

Fig. 9. Effect of sag on mass of dripping water

are not observed on the dripping time but on the mass of dripping water. Comparisons of the effects of different parameters are shown in Figs. 9-12. The t = 0:00 means the time when the first droplet was observed. Second order polynomial curves are fitted on the measured points. This type of approximation is very good as its correlation coefficients are above 0.98.

Figure 9 shows that the mass of dripping water is independent of the sag of the cable in the range of sags examined. However, this fact does not mean that independency is true for all sags. More observations should be made with different sags for finding a correct relation between sag and mass of dripping water.

Figure 10 reveals the effect of radiation which accelerates snow melting; therefore the mass of dripping water is higher than without radiation.

Dripping speed is much higher in case of long sleeves but the difference in total dripped masses of water before shedding is not significant (~15%) because shedding starts later in case of short sleeves (see Fig. 11).

If the mass of dripping water from the long sleeve is divided by the ratio of snow sleeve lengths, then the results show that the mass of dripping water is proportional to the lengths of snow sleeve (see Fig. 12). The little difference between the two curves comes from the measurement error in the snow sleeve length.

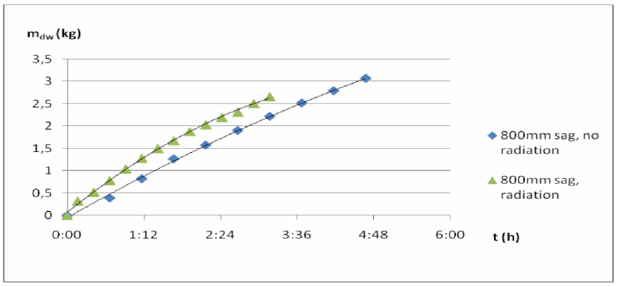

Fig. 10. Effect of radiation on mass of dripping water

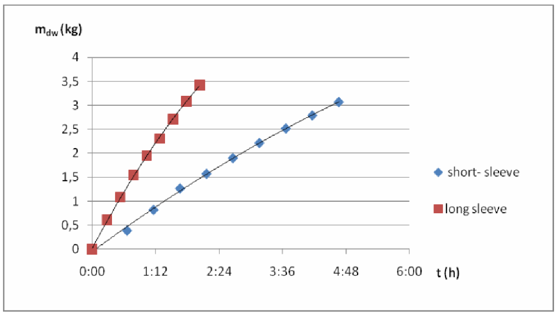

Fig. 11. Mass of dripping water as function of sleeve length

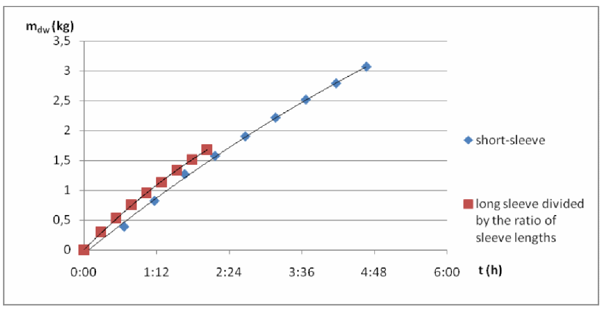

Fig. 12. Effects of sleeve length on the mass of dripping water

D. *Effects of Forced Vibration*

The effects of periodic excitation at one of the suspension points of the cable are presented in Table III. The time until snow sheds decreases when applying forced vibration. This decrease comes from the cyclic deformation of snow and strongly depends on the amplitude of vibration. The snow behaves differently from ice: it does not break and shed immediately. During the vibration within the used amplitude and frequency domain, shedding does not start before snow undergoes metamorphosis and LWC rises high enough. However, the vibrating motion accelerates water migration toward the mid section of cable and the LWC in mid section reaches its maximal value faster.

TABLE III: SHEDDING TIME AS FUNCTION AS VIBRATION PARAMETERS

Peak to peak amplitude 2A (mm)	Frequency [Hz]	Shedding starts
0	0	8:55
90	0.667	4:58
160	0.277	3:19
250	0.5263	2:40

The difference between LWC values at the end sections and LWC values at the mid section is higher than in the no-vibration case (Fig. 13). Unfortunately the used equipment did not make it possible to study the effect of amplitude and frequency independently.

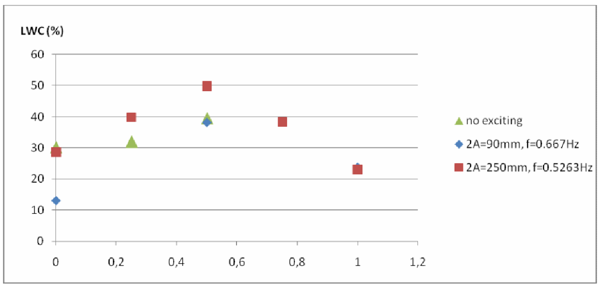

Fig. 13. LWC distribution along the cable with different vibration characteristics

Shedding from the vibrating cable starts in the mid section of the snow sleeve due to the water migrated there and due to the maximal snow deformation at that location.

E. *Relation between Initial Density and Maximal LWC of Snow*

An interesting phenomenon was observed during the analysis of experimental results. The maximum value of LWC when shedding occurs is not constant as was assumed in the accretion models [1, 10], but depends on the initial density of snow sleeve. The observed relation is shown on Fig 14. The maximal LWC which is measured when snow shed falls in the range of 38% to 55 %, and it decreases with increasing initial density. This fact may be explained by the microstructure of snow. The softer snow has more space between ice particles which may be filled by water. Thus, the LWC may increase higher until cohesion and adhesion are weakened so that snow sheds.

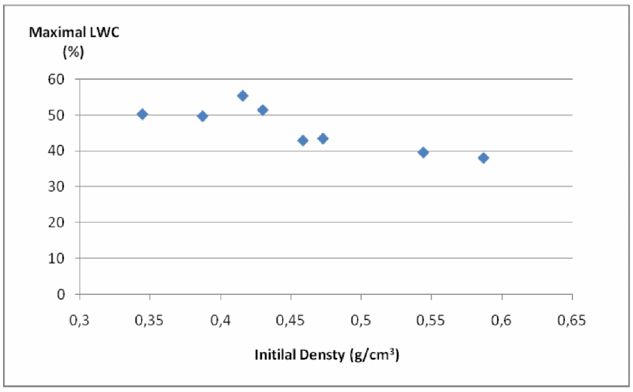

Fig. 14. Relation between initial density and maximal LWC of snow sleeve

V. Conclusions and Recommendations

This section summarizes the main results of the present study concerning wet snow shedding from overhead cables. This study is devoted to better understanding the process of snow shedding from sagged cables and to reveal the effects of some dynamic and thermodynamic parameters on this process. The cable geometry was not varied in the experiments, and snow shedding from bundled cables was not studied. Thus, the following conclusions are drawn for a single circular cable.

- The shedding mechanism from sagged cables is different of that from straight cables because water percolation occurs toward the middle of the span.
- The time of water dripping is longer, and the mass of dripping water before snow shedding from sagged cables is considerable, as opposed to the no-sag case.
- The shedding mechanism of short sleeves is different from that of long sleeves because snow shedding starts at the end for the former, whereas it starts at mid-span for the latter.
- Forced vibration decreases the shedding initiation time but the shedding mechanism remains the same.
- The maximum LWC of snow at shedding decreases with the initial density of snow.

Several further questions arise which should be investigated in future research:

- The relationship between the initial conditions of accreted snow and the maximal LWC value has to be determined experimentally for a more accurate prediction of shedding initiation.
- The development of a 3D numerical model taking water percolation into consideration would be a significant improvement in the modelling of wet snow shedding. More experimental results in the 0-15% cable sag domain are necessary to validate such a model.
- Testing the effects of different de-icing methods on wet snow removal would be very useful to find the optimal method, considering safety, cost and effectiveness.
- A non-destructive measurement technique is recommended in order to determine LWC without damaging the snow sleeves.
- There is very little information available on overnight freezing of snow sleeves, and they are from field observations only. The shedding mechanism of snow sleeves with frozen water may be studied in a cold chamber under varying ambient conditions.

VI. Acknowledgment

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