A WET SNOW FAILURE MODEL FOR PREDICTING SNOW SHEDDING FROM AN OVERHEAD CABLE

C. Zhang*[1], M. Farzaneh[1,2], L. Kiss[2] and L. Pellet[3]
[1]NSERC / Hydro-Quebec / UQAC Industrial Chair on Atmospheric Icing of Power Network Equipment (CIGELE) and Canada Research Chair on Atmospheric Icing Engineering of Power Networks (INGIVRE), www.cigele.ca
[2]International Research Centre on Atmospheric Icing and Power Network Engineering (CENGIVRE)
Université du Québec à Chicoutimi (UQAC), Chicoutimi, Qc, Canada
[3]Électricité de France (EDF), Recherche et développement, Clamart, France
E-mail: czhang@uqac.ca

***Abstract*—**In this paper, an analytical model for predicting the shedding of wet snow sleeves from overhead conductors is proposed. This model is based on a dry snow failure model and on experimental tests carried out at CIGELE laboratories. This model takes into account into the effect of the water flow within the sleeve. The results show that the time of snow shedding occurrence decreases nonlinearly as initial volume water content, air velocity and electric current intensity increase. This model can provide a fast estimation of the required Joule heat or wind to trigger snow shedding from the cable.

1. INTRODUCTION

The effective initial porosity of wet snow, Φ_{es}, was introduced and can be obtained as a result of multiplying the initial snow porosity, Φ_{ini}, by the function f_{vp}.

$$\phi_{es} = f_{vp}\phi_{ini} = \left(a + be^{cW_{ini}+dQ_l}\right)\phi_{ini} \qquad (1)$$

where a, b, c, and d are constants, w_{ini} is the initial volume water content (IVWC), and Q_l is the heat flux at the snow surface per unit length of cable (w/m).

The function f_{vp} represents the effects resulting from the water flow and depends on wet snow properties such as the geometry and size of the snow grains.

The snow shedding occurrence time T_s can be defined by the following equation:

$$T_s = \frac{\phi_{sc} - \phi_{es}}{V_v} \qquad (2)$$

where V_v is the volume variation rate. The failure strength under double shear condition occurs as the snow porosity approaches the critical value Φ_{sc} of 0.556 [2].

2. RESULTS AND DISCUSSION

Data fitting was carried out based on (1) and the results of experiment carried out at the CIGELE laboratories.

Within the domain of melted water percolation, snow shedding can be classified into two categories as to the driving force of snow melting: Joule heating with natural air convection and forced air convection. Heat transfer coefficient calculation was carried out at a constant surface temperature condition using CFD software FLUENT [1].

The empirical equations for wet snow shedding are shown in Table 1.

Table 1: Empirical equations for f_{vp}

Type	Equation
Electric heating	$f_{vp} = 3.74 - 3.15be^{-0.5W_{ini}-0.03Q_l}$
Forced air convection	$f_{vp} = 1.19 - 0.263be^{-1.14W_{ini}-0.0656Q_l}$

The results of electric heating type are shown in Figure 1.

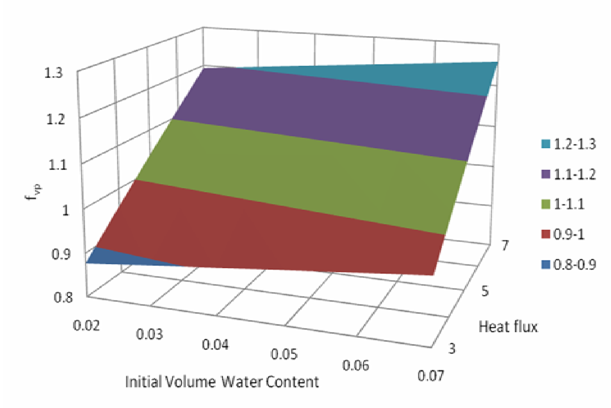

Figure 1. The relationship between f_{vp}, IVWC, and the heat flux

3. CONCLUSION

An analytical model was developed to predict the time of the snow shedding occurrence on an overhead cable. This model is based on a modified empirical dry snow model and experiments carried out at the CIGELE laboratories.

The effective initial porosity increases nonlinearly with increasing IVWC and outer heat flux. As a result, the time of wet snow shedding occurrence decreases nonlinearly with increasing IVWC, air velocity and electric current intensity.

As compared to dry snow failure, at lower melting rates the presence of water delays the occurrence of snow shedding due to the water-strengthened adhesion force between neighboring grains. However, a further increase of the melting rate produces more water resulting in a weakening of the cohesive and adhesive forces, thus accelerating the occurrence of snow shedding.

4. REFERENCES

[1] C. Zhang, M. Farzaneh and L. Kiss, A Numerical Study of Forced Convection around a Snow Sleeve in a Cross Flow of Air, IWAIS XIII, September 8 to 11, 2009.

[2] G. E. H. Ballard and R. W. McGAW, A theory of snow failure, U.S.Army Cold Regions Research and Engineering Laboratory, Research report, 137(1965).

A WET SNOW FAILURE MODEL FOR PREDICTING SNOW SHEDDING FROM AN OVERHEAD CABLE

C. Zhang[1], M. Farzaneh[1,2], L. Kiss[2]
[1]*NSERC / Hydro-Quebec / UQAC Industrial Chair on Atmospheric Icing of Power Network Equipment (CIGELE) and Canada Research Chair on Atmospheric Icing Engineering of Power Networks (INGIVRE), www.cigele.ca*
[2]*International Research Centre on Atmospheric Icing and Power Network Engineering (CENGIVRE)*
Université du Québec à Chicoutimi (UQAC), Chicoutimi, Qc, Canada

Université du Quebec à Chicoutimi,
Chicoutimi, Qc, Canada

L. Pellet
Électricité de France (EDF),
Recherche et développement,
Clamart, France

Abstract— **In this paper, an analytical model for predicting the shedding of wet snow sleeves from overhead conductors is proposed. This model is based on a dry snow failure model and on experimental tests carried out at CIGELE laboratories. This model takes into account into the effect of the water flow within the sleeve. The results show that the time of snow shedding occurrence decreases nonlinearly as initial volume water content, air velocity and electric current intensity increase. This model can provide a fast estimation of the required Joule heat or wind to trigger snow shedding from the cable.**

The results show that the effective initial porosity increase with an increase in the initial volume water content (IVWC) and outer heat flux, so that the time of snow shedding occurrence decreases nonlinearly with increasing IVWC, air velocity and electric current intensity.

As compared to dry snow failure, at lower melting rates the presence of water delays the occurrence of snow shedding due to the water-strengthened adhesion force between neighboring grains. However, a further increase of the melting rate produces more water resulting in a weakening of the cohesive and adhesive forces, thus accelerating the occurrence of snow shedding.

Keywords: wet snow shedding; effective initial water content

I. INTRODUCTION

Predicting the time of snow shedding (failure) occurrence is particularly important because snow shedding from overhead cables may induce potential safety risks.

Observation of snow shedding from overhead cables is rare and not well documented. Therefore, it is not surprising that sophisticated theoretical models of wet snow failure have not been fully developed.

The mechanisms of viscoelastic flow ([4], [5], [6]), heat transfer by vapor, and surface and volume diffusion lead to a stress distribution balance and make the snow failure process much more complex.

A general model of dry snow failure based on ice strength and laboratory tests was proposed in [2] and [3]. Water in wet snow has an obvious effect on snow shedding, but little work ([7],[8]) has been carried out in this field due to the complexity of the effects of water percolation. Snow failure or shedding always starts from a weak part of the snow sleeve. Such weakness may come from the sleeve creation process, but is more likely to be formed by the melted water flow or the wind-induced cable vibration. These random factors can hardly be simulated and predicted in any accurate way.

The aim of this paper is to develop an analytical model based on empirical results in order to predict the occurrence time of wet snow shedding.

II. EXPERIMENTAL STUDY

A set of experiments were carried out at the CIGELE laboratories. At the beginning of each test, a snow sleeve was fabricated as a homogeneous circular cylinder shape around a suspended cable at the center of the sleeve. As the snow in contact with the cable surface melted, a hole was formed by the cable moving through the snow sleeve.

When the wet snow sleeve is at a temperature higher than melting point, water migrates towards the bottom of the sleeve with time, and the bottom part of the sleeve becomes saturated. Experimental observations showed that the liquid water content (LWC) at the bottom increased with time, and then remained approximately constant during a relatively longer period during which the water seeped out of the sleeve.

For dry snow below the melting point, melted water refreezes quickly after it is produced. However, a hole with a smooth surface is also produced into the sleeve by the cable.

As shown in Figure 2, the upper section of the snow sleeve above the cable was detached from the snow sleeve as snow shedding happened.

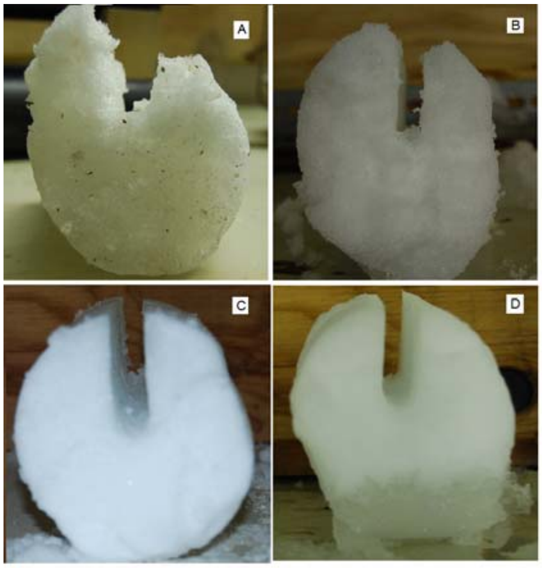

Figure 2. A, B and D: Wet show shedding; C: Dry snow shedding.

III. WATER FLOW EFFECT

One of prerequisites of wet snow accretion on overhead cables is the presence of liquid water within the snow, this fbeing responsible for the strong adhesion of wet snow to the cable and the cohesiveness of snow grains. However, a further increase of LWC results in the weakening of the cohesive and adhesive forces, leading to shedding.

Natural processes such as free or forced air convection and artificially controlled conditions like Joule heating may cause water flow within a snow sleeve. Water percolation influences the snow properties in several ways:

a) it changes the size and shape of the snow grains;

b) it changes the size and shape of the bond between neighboring snow grains;

c) it produces fissures (imperfections).

Effects a) and b) lead to the microstructure changes and increase the stiffness of the ice matrix. Eeffect c) always results in the development of weakness within the sleeve, helping to trigger shedding. However, it is very difficult to predict precisely the occurrence of such weakness or the failure strength of the ice matrix because of the uncertainty of the water flow and the irregularity and uneven distribution of pores within the snow.

IV. ASSUMPTIONS

Since predicting snow shedding is highly complex, some assumptions are needed for describing the governing water percolation process. These assumptions are as follows:

1. The deformation of the ice matrix of the snow sleeve boundary is neglected.
2. Snow melting only occurs at the sleeve surface.
3. Though instability of water flow has been observed under a variety of natural conditions, it is still assumed that there is no channel flow or fingering due to the local concentration of water. Thus for any small piece of snow, it is assumed that the snow is homogeneous and isotropic.
4. No heat conduction occurs within the snow.

V. WET SNOW SHEDDING MODEL

It is reasonable to assume that some correlation exists between dry and wet snow. Therefore, an analytical model based on dry snow failure and experimental data is presently being developed.

A. Dry snow failure

Ref. [2] proposed the following empirical equation for the double shear condition

$$\sigma_f = 2.16 \times 10^5 \times \left(1 - \frac{\phi_{ds}}{0.556}\right) \tag{3}$$

where $\boldsymbol{\sigma_f}$ is the failure strength and $\boldsymbol{\Phi_{ds}}$ is the porosity of dry snow.

It can be shown that the snow failure strength increases when increasing the snow density and the failure strength occurs as the snow porosity approaches the critical value $\boldsymbol{\Phi_{sc}}$ 0.556. The snow shedding occurrence time, $\boldsymbol{T_s}$, can thus be expressed by the following equation

$$T_s = \frac{\phi_{sc} - \phi_{ini}}{V_v} \tag{4}$$

where $\boldsymbol{\Phi_{ini}}$ is the snow porosity at the initial state and $\boldsymbol{V_v}$ is the volume variation rate.

B. Wet snow failure

It is not surprising that the results obtained from (3) show much divergence from observed data of wet snow shedding as this equation is only valid for dry snow. In order to be applicable to wet snow, (3) must be modified and extended.

For this purpose, parameter $\boldsymbol{\Phi_{es}}$, depending on wet snow properties such as the geometry and size of the snow grains, is introduced to describe the effect of the water flow.

$$\phi_{es} = f_{vp}\phi_{ini} = \left(a + be^{cW_{ini} + dQ_l}\right)\phi_{ini} \tag{5}$$

where $\boldsymbol{a}$, $\boldsymbol{b}$, $\boldsymbol{c}$, and $\boldsymbol{d}$ are constants, $\boldsymbol{w_{ini}}$ is the initial volume water content (IVWC) and $\boldsymbol{Q_l}$ is the heat flux at the snow surface per unit length of cable (w/m).

So, the time for wet snow shedding is given by:

$$T_s = \frac{\phi_{sc} - \phi_{es}}{V_v} \tag{6}$$

VI. SNOW MELTING RATE

The heat flux $\boldsymbol{Q}$ (w) at sleeve surface is defined as

$$Q = Q_a + Q_j \tag{7}$$

where $\boldsymbol{Q_a}$ is the heat convection by ambient air, and $\boldsymbol{Q_j}$ is the Joule heat from an electric conductor. Heat transfer coefficient was carried out under a constant surface temperature condition using CFD FLUENT [1].

The average volume variation rate $\boldsymbol{V_v}$ (1/m s) is

$$V_v = \frac{Q}{H_f \rho_s} \frac{1}{\pi\left(r_s^2 - r_c^2\right)} \tag{8}$$

where $\boldsymbol{r_s}$ and $\boldsymbol{r_c}$ are the diameters of the snow sleeve and the cable, respectively; $\boldsymbol{H_f}$ is the fusion heat of water (334×10^3J/kg, and $\boldsymbol{\rho_s}$ is the snow density.

VII. DATA FITTING

The data fitting was carried out based on Equation (6) and results from experiments carried out at the CIGELE laboratories.

Concerning the melted water percolation, the outer conditions were subdivided into two types: forced air convection and Joule heating. Under the former conditions, melted water percolates through all areas within the snow sleeve and the rate of snow melting is not consistent due to local heat transfer coefficient variation along the snow sleeve surface. Under the latter conditions, melted water concentrates on the lower section of the snow sleeve.

A. Electric heating

1) Water flows

Melted water flows due to the Joule heating concentrate near the top surface of the line conductor, as shown in Figure 3. Natural air convection occurs all around the snow sleeve surface, but is dominant on the heat flux as the ambient air temperature is high enough.

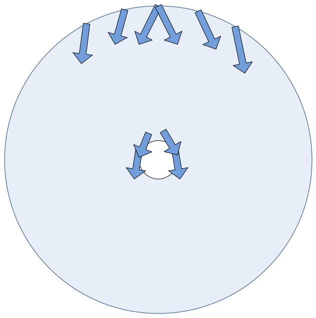

Figure 3. Schematic of water flow under electric heating

2) Data fitting

The following equation is obtained by data fitting based on the experimental results

$$f_{vp} = 3.74 - 3.15be^{-0.5W_{ini} - 0.03Q_l} \tag{9}$$

The relationship between $\boldsymbol{f_{vp}}$, $\boldsymbol{W_{ini}}$, and $\boldsymbol{Q_l}$ is shown in Figure 4. It can be seen that $\boldsymbol{f_{vp}}$ increases with $\boldsymbol{W_{ini}}$ or $\boldsymbol{Q_l}$. Furthermore, $\boldsymbol{f_{vp}}$ is less than 1 when $\boldsymbol{W_{ini}}$ or $\boldsymbol{Q_l}$ are small enough. The time for wet snow shedding is longer than that for dry snow when $\boldsymbol{f_{vp}}$ is less than 1. This result is in agreement with the hypothesis that a little water consolidates the wet snow cohesive force but that a further increase of liquid water weakens the cohesive and adhesive forces and leads to snow shedding.

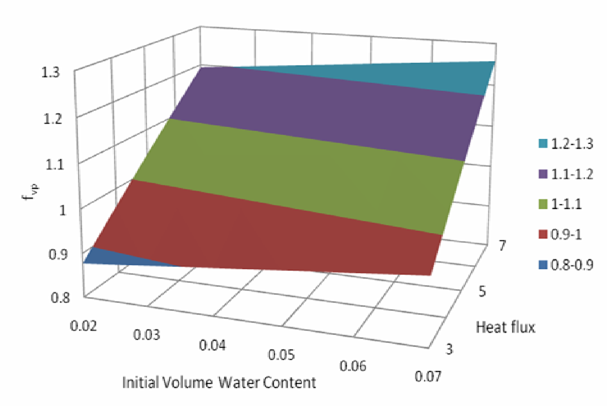

Figure 4. The relationship between f_{vp}, IVWC, and the heat flux

B. Forced air convection

1) Water flow

Melted water is produced by forced air convection and water flow concentrates near the top surface of a snow sleeve, as shown in Figure 5. It should be noted that the water flow is uneven due to the uneven distribution of the heat convection.

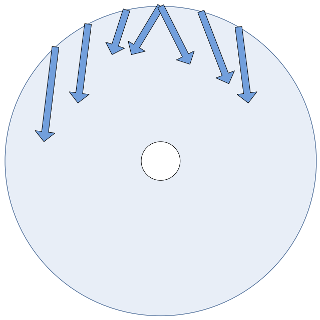

Figure 5. Schematic of the water flow under forced convection

2) Data fitting

The following equation is obtained by data fitting based on the experimental results.

$$f_{vp} = 1.19 - 0.263be^{-1.14W_{ini} - 0.0656Q_l} \tag{10}$$

In Figure 6, 7 and 8, it can be seen that $\boldsymbol{f_{vp}}$ increases when $\boldsymbol{W_{ini}}$ or the $\boldsymbol{Q_l}$ are increased. Compared to the prior equation (9) under Joule heating, $\boldsymbol{f_{vp}}$ is always larger than 1.

Therefore, the time for wet snow shedding is shorter than that of dry snow failure. As the values of the heat flux due to a forced convection are much higher than those of a prior kind, the effects from a forced convection become dominant in determining the effective initial snow porosity.

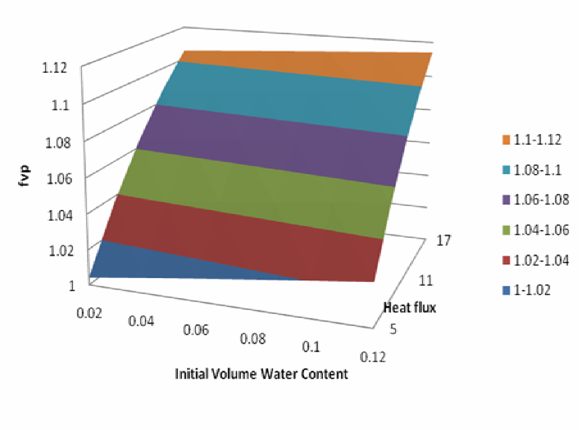

Figure 6. The relationship between f_{vp} and IVWC, forced air convection

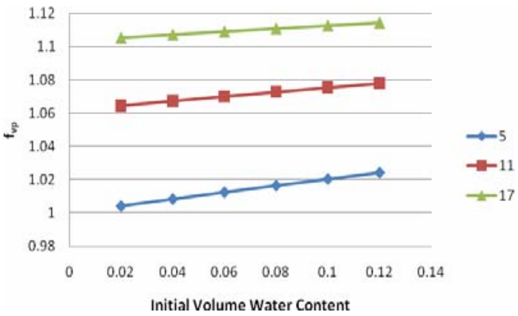

Figure 7. f_{vp} increases as IVWC is increased. Heat flux: Δ, 17w/m; □, 11w/m; ◊, 5w/m.

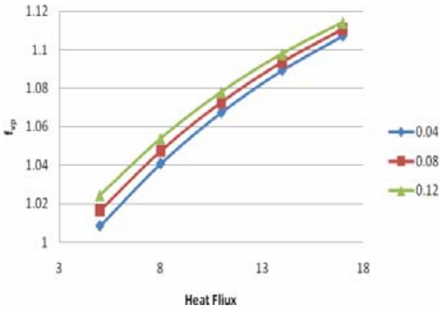

Figure 8. f_{vp} increases as heat flux is increased. IVWC: Δ, 0.12; □, 0.08; ◊, 0.04.

VIII. CONCLUSION

The water flow inside a snow sleeve influences its shedding in many ways, such as changing the shape and size of the snow grains. Generally, snow shedding starts at a weak part (imperfection) caused by the water flow but this cannot be simulated and predicted in any accurate way.

Under certain assumptions, an analytical model was developed to predict the time of the snow shedding occurrence. This model is based on a modified empirical dry snow model and on experiments carried out at the CIGELE laboratories. The main results are the following ones:

- A parameter, the effective initial porosity, was introduced to describe the effects resulting from the water flow within a wet snow sleeve. Its value depends on the wet snow properties such as the geometry of the snow grains.
- Concerning the melted water percolation, the outer conditions were subdivided into two types: forced air convection and Joule heating with natural air convection.
- The parameter values were calculated from experiments conducted at the CIGELE laboratories.
- The effective initial porosity increase with increasing IVWC and outer heat flux, so that the time of snow shedding occurrence decreases nonlinearly with increasing IVWC, air velocity and electric current intensity.
- As comparing with dry snow failure, the presence of water delays the occurrence of snow shedding at lower melting rates due to the water-strengthened adhesion force between neighboring grains. However, a further increase in melting rate produces more water, which will weaken the cohesive and adhesive forces, and accelerate the occurrence of snow shedding.

ACKNOWLEDGEMENTS

This study was carried out within the framework of the NSERC/Hydro-Québec/UQAC Industrial Chair on Atmospheric Icing of Power Network Equipment (CIGELE) and the Canada Research Chair on Engineering of Power Network Atmospheric Icing (INGIVRE) at the Université du Québec à Chicoutimi. The authors would like to thank all CIGELE partners (Hydro-Quebec, Hydro One, Réseau Transport d'Electricite (RTE) and Electricité de France (EDF), Alcan Cable, K-Line Insulators, Tyco Electronics, Dual-ADE, and FUQAC) whose financial support made this research possible.

REFERENCES

[1] C. Zhang, M. Farzaneh and L. Kiss, A Numerical Study of Forced Convection around a Snow Sleeve in a Cross Flow of Air, IWAIS XIII, September 8 to 11, 2009.

[2] G. E. H. Ballard and R. W. McGAW, A theory of snow failure, U.S.Army Cold Regions Research and Engineering Laboratory, Research report, 137(1965).

[3] G. E. H. Ballard and ED Feldt,A theoretical consideration of the strength of snow, J. Glaciology 6, 159-170 (1966).

[4] Jean Pierre Navarre, Jacques Meyssonnier and Alexandre Vagnon, 3D numerical model of snow deformation without failure and its application to cold room mechanical tests, Cold Regions Science and Technology Volume 50, Issues 1-3, November 2007.

[5] Jurg Schweizer, Laboratory experiments on shear failure of snow. Ann. Glaciol., 26, 97–102. 1998.

[6] Jurg Schweizer, Review of dry snow slab avalanche release. Cold Reg. Sci. Technol., 30(1–3), 43–57. 1999.

[7] László E. Kollár , Ossama Olqma,, Masoud Farzaneh, Natural wet-snow shedding from overhead cables, Cold Regions Science and Technology 60 (2010) 40–50.

[8] P. Admirat “Wet Snow Accrestion on Overhead Lines” in book by M. Farzaneh “Atmospheric Icing of Power Networks”, 2008.