THE EQUIVALENT THERMAL CONDUCTIVITY OF SNOW SLEEVES ON OVERHEAD TRANSMISSION LINES

C. Zhang*[1], M. Farzaneh[1, 2], L. Kiss[2] and P. Montpellier[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]Réseau de transport d'électricité (RTE), Paris, France
*E-mail: czhang@uqac.ca

Abstract**—**The equivalent thermal conductivity of the snow, i.e. heat transfer capability of the snow sleeve, is investigated in this paper. Besides snow density, the strong influences of microstructure and vapor on the thermal conductivity were taken into account in this model.

First, a microstructure model for dry snow was developed. Snow was classified into four categories according to the shape of snow grain. Two geometry factors were then introduced and their influence on snow density was discussed in detail. Second, these results were compared with those of prior research, showing good agreement. Dependence on the microstructure and other factors was also studied. Finally, a set of experiments was conducted and their results were compared with those of the model.

1. INTRODUCTION

Snow is a porous, permeable aggregate of ice grains. Its thermal characteristics depend upon various factors such as thermal conductivity of constituent phases, porosity, and size of particles.

2. RESULTS AND DISCUSSION

Ref. [2] discussed three shapes of grain: sphere, cylindrical and cubical. The snow consisting of plate ice crystals can be modeled as two plates plus a connection column, as is shown in Figure 1.

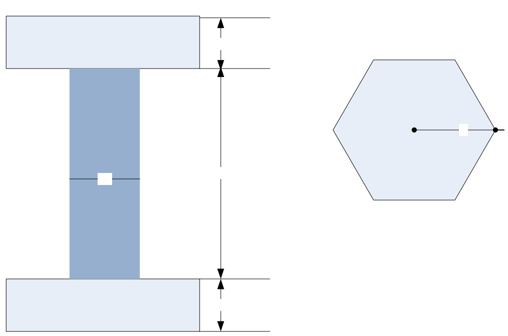

Figure 1. Geometrical model for hexagonal column

The equivalent thermal conductivity $\boldsymbol{k_e}$ of dry snow can be calculated by

$$k_e = k_g\left(1 + ra_1\right)\frac{1}{\dfrac{ra_1}{1 + mA_g^{'}} + \dfrac{1}{1 + mra_2A_g^{'}}} \quad (1)$$

where the ratio of $2\boldsymbol{h_g}$ and $\boldsymbol{l}$ is defined as $\boldsymbol{ra_1}$, the ratio of $\boldsymbol{A_b}$ and $\boldsymbol{A_g}$ is $\boldsymbol{ra_2}$, the ratio of conductivity of ice and gas is $\boldsymbol{m}$, and $\boldsymbol{k_g}$ is the thermal conductivity of the saturated gas (including dry air and vapor).

Kingery suggested that the value of $\boldsymbol{ra_2}$ mainly depends on the temperature [1]. $\boldsymbol{A_g}'$ depends on the snow grain shape. $\boldsymbol{A_g}'$ is a constant for a given shape as shown in Table 1.

Table 1: Shape factors $\boldsymbol{A_g}'$

Shape	A_g'	Snow
Hexagonal plate	$3\sqrt{3}/8$	Fresh
Sphere plate	1/6	Rounded grains
Cylinder plate	π/4	Faceted grains
Cube plate	1	Faceted grains

3. CONCLUSION

A snow microstructure model was developed to estimate the equivalent thermal conductivity of dry snow. The equivalent thermal conductivity is a function of the snow temperature and the shape factors $\boldsymbol{ra_1}$ and $\boldsymbol{ra_2}$.

The results of this model agree with the results from [9].

The thermal equivalent conductivity of dry snow increases with increasing temperature, especially as temperature is above 260K. Conductivity increases faster when the temperature is above 260K, which is due to the fact that saturated water vapor is more conductive at a higher temperature and that the saturated vapor pressure increases exponentially with temperature. When the temperature is near 0°C, about 20% of the heat is moved by vapor.

A set of experiments were conducted at the CIGELE laboratories. It was found that the scatter of the experimental data at a given density was due to the strong influence of the microstructure on the thermal conductivity and that the snow sleeves reproduced in laboratory consisted of multiple types of snow grain.

4. REFERENCES

[1] Kingery, W. D. (1960) Regelation, surface diffusion and ice sintering. J. appl. Phys. 31, 833-838.

[2] Janko Gravner, David Griffeath, Modeling snow crystal growth: a three-dimensional mesoscopic approach, 2008.

[3] M. Sturm, J. Holmgren, K¨ onig M and K. Morris K, 1997, The thermal conductivity of seasonal snow; J. Glaciol. 43(143) 26–41.

P. K. Satyawali, A.K. Singh, Dependence of thermal conductivity of snow on microstructure, 2008.

THE EQUIVALENT THERMAL CONDUCTIVITY OF SNOW SLEEVES ON OVERHEAD TRANSMISSION LINES

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 Quebec à Chicoutimi,
Chicoutimi, Qc, Canada

P.Montpellier
Réseau de transport d'électricité (RTE),
Paris, France

***Abstract*— The equivalent thermal conductivity of the snow, i.e. heat transfer capability of the snow sleeve, is investigated in this paper. Besides snow density, the strong influences of microstructure and vapor on the thermal conductivity were taken into account in this model.**

First, a microstructure model for dry snow was developed. Snow was classified into four categories according to the shape of snow grain. Two geometry factors were then introduced and their influence on snow density was discussed in detail. Second, these results were compared with those of prior research, showing good agreement. Dependence on the microstructure and other factors was also studied. Finally, a set of experiments was conducted and their results were compared with those of the model.

Keywords: the equivalent thermal conductivity; dry snow; weather

I. INTRODUCTION

Heat transfer within snow is one of the most essential processes characterizing a variety of snow properties, and plays an important role in snow technology and science.

The first formal measurement of the thermal conductivity of snow dates back to at least 1886 [11], the method and devices were demonstrated in detail for measuring the equivalent thermal conductivity of snow [1][9]. In these investigations, the observed data of thermal conductivity vary within a wide range. Also, it is usually assumed that the equivalent snow conductivity is almost independent of temperature and other snow properties snow except density.

Snow is a porous, permeable aggregate of ice grains that can predominantly consist of single crystals or close groupings of several crystals. Its thermal characteristics depend upon various factors such as thermal conductivity of constituent phases, porosity, shape factor, size of particles, etc. Ref. [1] proposed a kind of multi-composition model and applied it to dry snow research.

Recently, more research has focused on the microstructure of snow. Several papers estimate snow conductivity by setting up a two-dimensional or three-dimensional grid of ice particles. A two-dimensional model was also proposed to estimate the equivalent thermal conductivity of snow [7]. Ref. [10] proposed a three-dimensional model including various geometrical shapes which have an influence on thermal conductivity.

The aims of this research are:

a) to develop a microstructure model to estimate the equivalent thermal conductivity of dry snow;

b) to analyze the thermal conductivity dependence on the microstructure and other factors such as temperature and vapor;

c) to experimentally validate the microstructure model.

II. THE EQUIVALENT THERMAL CONDUCTIVITY OF SNOW

As temperature changes, snow exhibits a dynamically complex process represented by three fractions continuously changing their ratios: ice particles, water and gaseous phase (including air and water vapor). Therefore, heat transport of snow is more complex than that of a single-phase substance. It has three main components:

a) conduction through the ice lattice;

b) conduction through the air in the pore spaces;

c) latent heat transport across the pore spaces due to vapor sublimation and condensation.

Based on an elegant experiment, De Quervain estimated that the ice skeleton for his snow samples carried 55-60% of the heat, the rest moving across the pores as sensible or latent heat [2][3]. Reviewing the literature on vapor diffusion in snow, S. C. Colbeck (1993), concluded that 30-40% of the heat is moved by vapor transport because the vapor gradient enhancement predominates over the blocking effect of the ice skeleton.

III. Snow Component Properties

Dry snow can be described as a porous medium consisting of air and two water phases (ice and vapor).

The equivalent thermal conductivity for saturated gas $\boldsymbol{k_g}$ is composed of two parts: conduction through the air and diffusion of water vapor carrying the latent heat of sublimation along the vapor-pressure gradient.

The conductivity of gas (0.047) is almost twice as large as that of pure air (0.024) at 0^{o}C. At -50^{o}C, however, the difference between the conductivity of air (0.020083) and gas (0.020353) can be neglected.

The conductivity of ice decreases as temperature increases. Even at 0 ^{o}C, the conductivity of ice is 50 times greater than that of saturated gas.

IV. Thermal Conductivity Model Development

In this section, a microstructural model for dry snow is proposed.

A. Microstructural model

In [5], several shapes of grain (hexagonal, cylindrical and cubical) are discussed. This may be a better model for the computation of thermal resistance.

A basic type of ice crystal can be used to model a certain type of snow. For example, snow consisting of plate ice crystals can be modeled as two plates plus a connection column, as is shown in Figure 2.

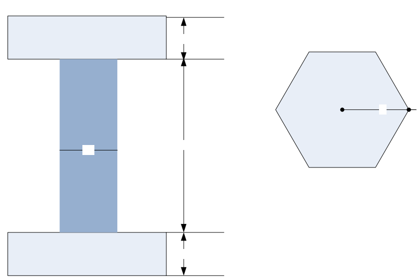

Figure 2. Geometrical model for hexagonal column

The equivalent thermal conductivity can be obtained from the following:

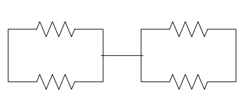

Figure 3. Equivalent thermal circuits for snow grain

$$k_e = k_g\left(1 + ra_1\right)\frac{1}{\dfrac{ra_1}{1 + mA_g^{'}} + \dfrac{1}{1 + mra_2A_g^{'}}} \qquad (1)$$

where the ratio of $2\boldsymbol{h_g}$ and $\boldsymbol{l}$ is defined as $\boldsymbol{ra_1}$, the ratio of $\boldsymbol{A_b}$ and $\boldsymbol{A_g}$ is $\boldsymbol{ra_2}$, the ratio of conductivity of ice and gas is $\boldsymbol{m}$, and $\boldsymbol{k_g}$ is the thermal conductivity of saturated gas (including dry air and water vapor).

$\boldsymbol{A_g}$ depends on the snow grain shape. $\boldsymbol{A_g^{'}}$ is a constant for a given shape as shown in Table I.

TABLE I. SHAPE FACTORS A_g

Shape	A_g	$A_g^{'}$	Snow
Hexagonal plate	$\left(\frac{3\sqrt{3}}{2}\right)r_g^2$	$\frac{3\sqrt{3}}{8}$	Fresh
Sphere plate	$\left(\frac{2}{3}\right)r_g^2$	1/6	Rounded grains
Cylinder plate	πr_g^2	π/4	Faceted grains
Cube plate	$4r_g^2$	1	Faceted grains

Therefore, for a given shape of snow grain at a given temperature, $\boldsymbol{k_e}$ is only a function of $\boldsymbol{ra_1}$ and $\boldsymbol{ra_2}$:

$$k_e = f\left(ra_1, ra_2\right) \qquad (2)$$

In [6], the ratio of the bonding area between ice crystals to the size of the crystals was directly determined as shown in Table II.

TABLE II. RELATIONSHIP BETWEEN TEMPERATURE AND $\boldsymbol{ra_2}$

Temperature(°C)	ra_2
-5	0.010 - 0.0256
-27	0.007 – 0.018
-88	0.0004 – 0.0001

V. Results and Discuss

A. Comparisons with experimental data

The results at obtained from Aggarwal (2004), M. Sturn et al (1997) [9] -5°C and (1) are shown in Figure 4.

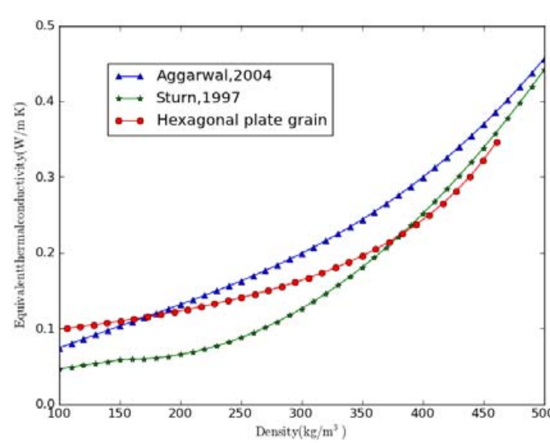

Figure 4. Variation of equivalent thermal conductivity with density at -5°C. Δ, Aggarwal;*, [9]; o, hexagonal plate grain from (1)

The data are in good agreement as the snow density is less than 500 kg/m3.

B. Effect from grain shape

The effective snow conductivity for several types of snow grains at -5°C for ra_2=0.0256 is plotted as a function of density in Figure 5.

At a higher snow density, there are more ice grains and they are in closer contact, which leads to a higher value of snow conductivity (see Figs. 4, 5). The dependency of thermal conductivity of snow on density is nonlinear, as seen in these figures.

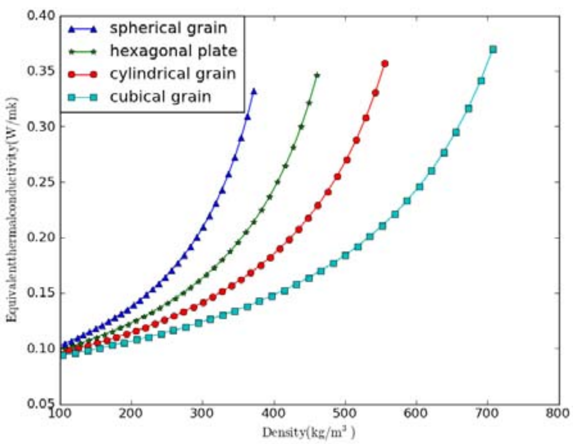

Figure 5. Variation of equivalent thermal conductivity with density at -5 °C and ra_2=0.0256. Δ, spherical grain; *, hexagonal plate; o, cylindrical grain; □, cubical grain

C. The effect of temperature

Figure 6 shows a variation of the thermal conductivity with temperature for spherical, cylindrical and cubical grains, respectively. In this figure, three densities were selected.

It can be seen the equivalent thermal conductivity increases with increasing temperature, especially as temperature is above 260 K. The nonlinear increase in conductivity with increasing temperature above 260 K is due to the fact that saturated water vapor is more conductive at a higher temperature and that the dependency of saturated vapor pressure with temperature is exponential.

D. Effect from water vapor

The water vapor plays an important role in the calculation of snow conductivity, especially when the temperature is near 0°C. A series of snow conductivity values at -5°C are shown in Figure 7. Taking the vapor effect into account, the snow conductivity is 20% higher than that of dry air, i.e. as about 20% of the heat moved by vapor.

When the temperature of snow is very low, such as -50°C, the difference between dry air and the saturated gas is only around 1%, meaning that the effect of vapor can be neglected when the temperature less than -50°C.

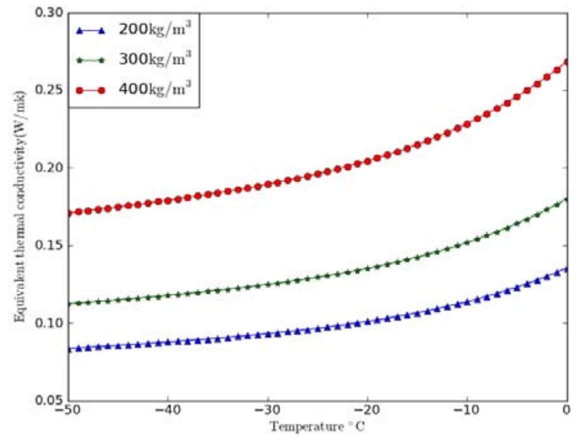

Figure 6. Temperature dependence of the equivalent thermal conductivity for hexagonal column grain. Δ, density of snow ρ_s = 200 kg/m³, *, ρ_s = 300 kg/m³; o, ρ_s = 400 kg/m³

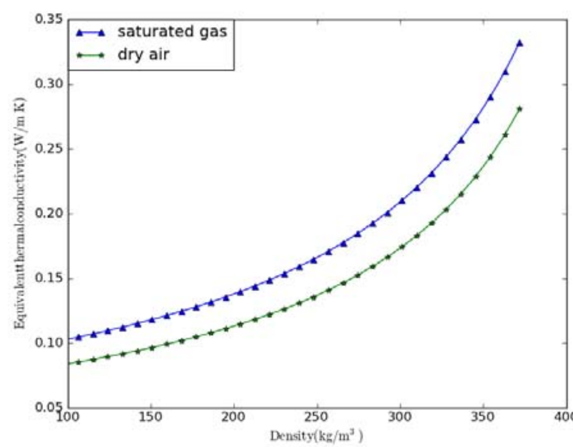

Figure 7. Snow conductivity with (Δ) and without (*) water vapor affect. ra_2=0.0256 at -5℃

VI. THERMAL CONDUCTIVITY MEASUREMENT

A. Experimental set-up

Figure 8 shows the instruments needed to measure the thermal conductivity of snow. Two thermal couples are placed at different positions within the snow sleeve. The temperature of air is set below 0°C and the electric current at 50-100A.

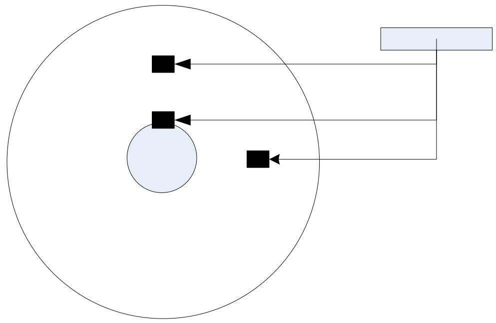

Figure 8. Schematic diagram of experiment set-up

B. *Calculation process*

As the heat flux from the cable is constant, conductivity can be obtained by measuring the temperature gradient within the snow.

Assuming the value of the conductivity of snow $\boldsymbol{k_e}$ to be constant, $\boldsymbol{k_e}$ can be obtained by [4]

$$k_e = I^2 R_T \frac{\ln(r_1 / r_2)}{2\pi L(T_1 - T_2)} \qquad (3)$$

where $\boldsymbol{r_1}$ and $\boldsymbol{r_2}$ are the radius of the inner and outer semicouple positions respectively; $\boldsymbol{T_1}$ and $\boldsymbol{T_2}$ are the temperatures measured by the inner and outer semi-couple respectively; $\boldsymbol{I}$ is the electric current (A), $\boldsymbol{R_T}$ is the resistance of the conductor at any temperature ($\boldsymbol{T}$).

C. *Results and discussion*

The experimental data and the equivalent thermal conductivity for solid prism grain type are plotted in Figure 9. It can be seen that there is agreement with the solid prism type for a few results. The scatter of the experimental data at a given density is due to the strong influence of the microstructure on the thermal conductivity. As the snow used in the experiments was collected from ground accumulation, it was difficult to estimate the shape of the snow grains and it is reasonable to assume that the snow was a mixture of several types of snow grains.

Some experimental data show higher conductivity values than empirical equations. The snow sleeves used in these particular tests was made up of wet snow. When the test was performed at an early stage, the ambient air temperature was not low enough to keep most part of the snow below 0 ºC, i.e. there existed wet snow within the sleeve. The presence of water and vapor in wet snow causes the equivalent thermal conductivity of snow to increase.

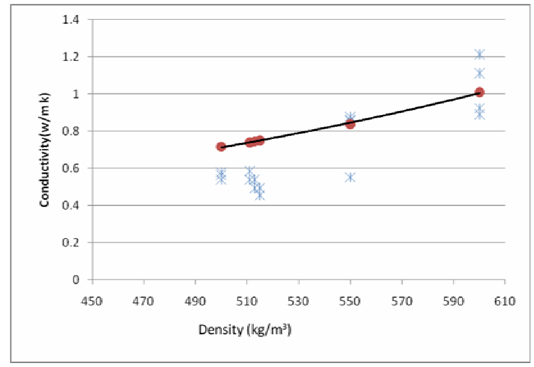

Figure 9. Experimental snow conductivity vs density. *, experimental data; o, result of (1), air temperature -4°C

VII. CONCLUSIONS

The equivalent thermal conductivity of dry snow is investigated in this paper. Besides snow density, the strong influences of microstructure and vapor on the thermal conductivity were taken into account in this model. The main results are the following ones:

1) A microstructure model for dry snow was proposed to estimate the snow equivalent thermal conductivity. The equivalent thermal conductivity is a function of the snow temperature and the shape factors $\boldsymbol{ra_1}$ and $\boldsymbol{ra_2}$.

2) The equivalent thermal conductivity of dry snow increases with increasing density due to the fact that the conductivity of pure ice is at least 100 times larger than that of saturated gas.

3) The snow was classified into four types by its grain shape: spherical, hexagonal, cylindrical and cubical. As snow has the same density values, cubical grains have larger values of equivalent thermal conductivity than cylindrical and spherical grains.

4) The results of this model agree with previous investigations.

5) The equivalent thermal conductivity of dry snow increases with increasing temperature, especially as temperature is above 260K. The nonlinear increase in conductivity with increasing temperature above 260 K is due to the fact that saturated water vapor is more conductive at higher temperature and that the dependency of saturated vapor pressure on temperature is exponential.

   About 20% of the heat is moved by vapor when the temperature is near 0°C. When the temperature of snow is very low, such as -50°C, the effect of vapor can be neglected.

6) A set of experiments were conducted at the CIGELE laboratories. The scatter of the experimental data is due to the strong influence of the microstructure on the thermal conductivity and the snow sleeve reproduced in laboratory consists of multiple types of snow grain.

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] D. Pitman, B.Zuckerman, Effective thermal conductivity of snow at -88ºC, -27ºC and -5ºC, 1966.

[2] DE QUERVAIN, M.R. On Metamorphism and Hardening of Snow under Constant Pressure and Temperature Gradient, IUGG General Assembly of Toronto, IASH Publication No. 46, pp 225-239. 1958.

[3] DE QUERVAIN, M.R., Snow Structure, Heat and Mass Flux Through Snow (Theme paper) International Symposia on the Role of Snow and Ice in Hydrology, Symposium on Properties and Processes, Banff, 1972.

[4] Frank P. Incropera and David P. DeWitt, Introduction to Heat Transfer, fourth edition, 2002.

[5] Janko Gravner, David Griffeath, Modeling snow crystal growth: a three-dimensional mesoscopic approach, 2008.

[6] Kingery, W. D. (1960) Regelation, surface diffusion and ice sintering. J. appl. Phys. 31, 833-838.

[7] L S Verma, A K Shrotriya, Ramvir Singh and D R Chaudhry, 1991 Thermal conduction in two phase materials with spherical and non-spherical inclusions; J.Phys.D:Appl.Phys. 24 1729–1737.

[8] M. Sturm, J. B. Johnson, Natural Convection in the Subarctic Snow Cover, JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 96, NO. B7, PP. 11,657-11,671, 1991.

[9] M. Sturm, J. Holmgren, K¨ onig M and K. Morris K, 1997, The thermal conductivity of seasonal snow; J. Glaciol. 43(143) 26–41.

[10] P. K. Satyawali, A.K. Singh, Dependence of thermal conductivity of snow on microstructure, 2008

[11] Thomas Andrews, Observations on Pure Ice and Snow, Proc. R. Soc. Lond. January 1, 1886 40:544-549.