Cold Regions Science and Technology 129 (2016) 96–103

Contents lists available at ScienceDirect

Cold Regions Science and Technology

journal homepage: www.elsevier.com/locate/coldregions

Experimental study on the thermal conductivity for transmission line icing

Yongcan Zhu [a], Xinbo Huang [b,*], Jianyuan Jia [a], Yi Tian [a], Long Zhao [b], Ye Zhang [b], Yuntao Cui [b], Xiaobo Li [c]

[a] *School of Electro-Mechanical Engineering, Xidian University, Xi'an 710071, China*
[b] *School of Electronics and Information, Xi'an Polytechnic University, Xi'an 710048, China*
[c] *Xi'an Modern Control Technology Institute, Xi'an 710065, China*

ARTICLE INFO

Article history:
Received 7 January 2016
Received in revised form 26 April 2016
Accepted 25 June 2016
Available online 28 June 2016

Keywords:
Transmission line
Icing
Thermal conductivity
Icing density
Thermal equilibrium
De-icing

ABSTRACT

Both practices and experiments have shown that the thermal conductivity of icing has an obvious influence on ice-melting process, but it is ignored by most of the existing models which set the simulation parameter as a constant. In this paper, an experimental study is conducted to investigate the thermal conductivity for overhead transmission line icing. Based on the test data in artificial icing laboratory, a quadratic equation of thermal conductivity and icing density is presented. And then, the equation of icing thermal conductivity is employed to simulate the critical ice-melting current and ice-melting time. The results of the experiment and simulation show that the thermal conductivity can improve the prediction accuracy in thermal de-icing projects, with the mean error of 4% and 14%, respectively.

1. Introduction

Transmission line icing is a highly hazardous natural phenomenon to power grid safety, which arises from supercooled water droplet or wet snow. The severe ice load, wind load and dynamic aspects (mechanical traveling waves) have provoked a number of serious problems, such as flashover, structural failure, and even breakdown of the electricity grid (Makkonen, 1984; Makkonen, 2000; Personne and Gayet, 1988; Savadjiev and Farzaneh, 2004). In April 1961, a severe ice storm occurred in Norway. The greatest elliptic cross-section diameter was measured at 1.4 m and the smallest at 0.95 m. In the disastrous Ice Storm of 1998 in Canada, >1300 transmission towers and 35,000 distribution structures were destroyed (Farzaneh, 2008). In early 2008, a severe ice storm hit southern regions in China. At least 7000 overhead transmission lines above 10 kV and 800 substations above 35 kV were out of service, and >120,000 transmission towers above 10 kV were damaged. The ice storm brought a direct economic loss of >130 billion RMB (Shukai and Jie, 2008; Yi, 2008). In order to solve the problem, a number of investigators have made both experimental and theoretical studies on icing growth models and de-icing methods (Farhadi et al., 2011; Farzaneh et al., 2008; Fikke, 2005; Huneault et al., 2005; Lébatto et al., 2015; Lozowski et al., 2000; Makkonen, 1998; Makkonen, 2000; Makkonen, 2013; Péter et al., 2008; Xingliang et al., 2010).

In general, most of de-icing models are based on thermal equilibrium equations. Icing thermal conductivity is a basic parameter of thermal equilibrium equations, which has a great influence on ice-melting current and ice-melting time. Literatures (Péter et al., 2008; Sadov et al., 2007; Xingliang et al., 2010) presented the thermal de-icing method for iced transmission lines based on high current impulses or DC current, and set the simulation parameter of icing thermal conductivity as a constant between 2.03 and 2.22 W/m °C. However, the thermal conductivity of practical icing layer is a variable, which depends on a variety of parameters, such as icing density and icing structure.

Generally speaking, higher icing density results in greater thermal conductivity. As shown in Table 1, transmission line icing can be distinguished into several forms by density and appearance, and named glaze, hard rime, soft rime, wet snow, and hoarfrost (Farzaneh, 2008; Makkonen, 2000; Songhai et al., 2011). Glaze icing grows in a transparent, smooth structure with almost no air bubbles, and can be thought to be the pure ice with thermal conductivity range of 2.0–2.2 W/m °C. Frost forms when water vapor changes directly into solid ice with ultra low density, and it may cause corona losses and gradually become soft rime on overhead power transmission cables (Farzaneh, 2008; Makkonen, 2013). Frost is a familiar and detrimental phenomenon in refrigeration and spaceflight as well. For this, academics and scientists have made both experimental and theoretical studies of the heat and mass transfer in an effort to obtain the effective thermal conductivity, and presented the feasible empirical formulae for the unique icing with low density (Ahmet, 2000; Fukusako, 1990; Östin

---

* Corresponding author at: 19 South Jinhua Road, Xi'an, CN, China.
E-mail address: huangxb1975@163.com (X. Huang).

http://dx.doi.org/10.1016/j.coldregions.2016.06.009

Table 1
Principal properties of transmission line icing.

Type of icing	Appearance	Density (kg/m)
Glaze	Transparent, almost no air bubbles	800–900
Hard rime	Opaque to transparent, with air bubbles	600–800
Soft rime	White with many air bubbles	300–600
Wet snow	White with many air bubbles	400–600
Hoarfrost	White featherlike	<300

and Andersson, 1991; Shin et al., 2003; Yonko and Sepsy, 1967). Moreover, literatures (Ratcliffe, 1962; Slack, 1980) presented that lower temperature results in higher ice thermal conductivity, and the thermal conductivity of pure ice are 2.14 W/m °C and 2.4 W/m °C when ice-layer temperatures equal to 0 °C and −23 °C. Engineers may employ literature data on icing thermal conductivity, because it has been under investigation for more than fifty years. However, literature expressions may lead to a great deal of confusion. On the one hand, almost all of the test data and numerical results in literatures are based on the conditions of ice crystals growth on a cold plate or cold fin–tube, then, the type of ice crystal structures may be different from that of the transmission line icing. On the other hand, the empirical equations related to frost and snow are not appropriate for high-density icing, such as hard rime and glaze.

Objectives of the present study on transmission line icing are: (1) to design a method for measuring the thermal conductivity of transmission line icing; (2) to investigate the relational expression between thermal conductivity and icing density; and (3) to employ the thermal conductivity equation in the thermal de-icing model, and verify it in the artificial icing laboratory.

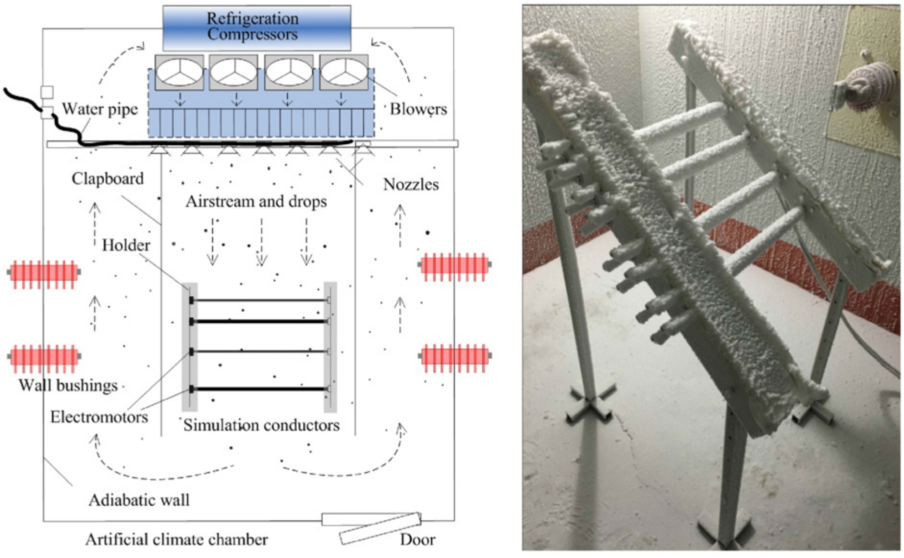
2. Experimental apparatus

2.1. Artificial icing laboratory

As shown in Fig. 1(a), the artificial icing laboratory is composed of thermal insulation material with thickness, width, height and length of 15 mm, 3.2 m, 2.2 m, and 4.2 m, respectively. The real experiment region (simple wind tunnel) is a rectangular duct of 1.5 m widths, 0.8 m height cross-section and overall length of 2.5 m. Two refrigeration compressors with the capacity of 2.5 kW and 8.0 kW are available, and the appropriate one will be selected to provide the desirable ambient temperature within −25–0 °C. A group of blowers are placed in the rear part of the real experiment region and connected to the power supply through variable-frequency devices. Such a design provides constant wind velocity in the range of 0–12 m/s. The auto spray device includes compressor, air filter, water filter, pressure regulator and seven nozzles, which are employed to adjust the parameters of droplets such as liquid water mass per unit volume (LWC) and median volume diameter (MVD). As shown in Fig. 1(b), simulation conductors consist of several aluminium tubes with thickness of 2.5 mm and overall length of 1 m. As shows in Fig. 2, a nickel-chrome sheet of 0.1 mm thickness and 10 mm wide is helically stuck on the aluminium tube surface. Surely, the aluminium tube and nickel-chrome sheet are completely separated by 0.05 mm thickness surface insulating coating. The final diameter of simulation conductor is 20 mm with electrical resistivity equal to 6 Ω/m. Simulation conductors are connected to low-speed electromotors through some special bearings. Such a design provides constant rotation speed of simulation conductor in the range of 0.01–1 *r*/min. By changing the experimental parameters of artificial icing laboratory, various icing samples will be obtained with different density and thermal conductivity.

2.2. The experimental apparatus of icing thermal conductivity

After the measurement of diameter and weight, the test sample (simulation conductor covered with icing) is horizontally placed on a wooden bracket. As shows in Fig. 2, the output of the adjustable DC power supply is connected to the end of the nickel-chrome sheet, used as DC power system. At the beginning of every test, the temperature of test sample is equal to the ambient value, and it increases rapidly as suitable current flows through. Eight sensors are utilized to the acquisition of surface temperature value along the simulation conductor, which are respectively installed at the 1/3, 2/3 of the overall length. The average reading of temperature sensors is assumed as the real temperature of the simulation conductor. Installation sensors are covered by the thermal paste with thermal conductivity of 10 W/m °C, thus to ensure the reading of sensors in accordance with the simulation conductor. Another two temperature sensors are used for the ambient temperature near the test sample. And then, all the temperature sensors are connected to a data acquisition system with save data every 10 s. Moreover, in the experimental process, it should be noted that the temperature of test sample and environment must always be lower than 0 °C, so as to avoid icing structural changes.



(a) Schematic of artificial icing laboratory (b) Simulation conductors covered by icing

Fig. 1. Experimental apparatus (a) Schematic of artificial icing laboratory (b) Simulation conductors covered by icing.