A SEMI-EMPIRICAL ICING MODEL FOR ENERGIZED CONDUCTORS

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Abstract: Preliminary freezing rain experiments have been performed on fixed, heated conductor samples. The data, which complements previously reported data for analogous unheated conductor samples, provide an experimental basis for developing a refined icing model. Consequently a simple semi-empirical model is proposed that incorporates the effect of Joule heating on the weight of ice formed on an overhead power line due to a continuous freezing rain. The model's predictions are checked against available field observations with promising corroborations.

1. INTRODUCTION

A reliable estimate of the extreme ice load is essential in the design and maintenance of a power system in an ice prone area. Due to the lack of long term field observations on ice loads, historical weather records, which are available from local weather stations, are often used to find the extreme ice weight. Such a practice requires a model to compute the ice weight from known weather conditions. Extensive experimental investigations were made previously on fixed, unheated conductor samples by using an outdoor freezing rain simulator. It was found that the simple model of Goodwin et al. [1] agrees surprisingly well with experimental data [2] (even though the assumed cylindrical icing may be invalid).

However a power line, which is somewhat resistive, normally carries electricity, which produces Joule heating. Thus preliminary freezing rain experiments are reported here that assess the effect of Joule heating on short, stationary conductor samples. The data is used to develop a simple, semi-empirical icing model that incorporates Joule heating. Predictions are checked against available experimental data and field observations and the model appears to be promising.

2. RESULTS

Based on the limited experimental data on heated conductor samples, as well as fairly extensive experimental data on un-heated conductor samples, the following semi-empirical icing equation is proposed to account for Joule heating

$$\mathrm{d}b^*/\mathrm{d}t^* = 0.5 \quad (\text{if } 0 \leq I_w' \leq 2) \tag{1a}$$

$$\mathrm{d}b^*/\mathrm{d}t^* = 0.55 - 0.025\, I_w' \quad (\text{if } 2 \leq I_w' \leq 18) \tag{1b}$$

where b^* is the dimensionless ice thickness; t^* is the dimensionless time; and I_w' is the modified wetness index.

Fig. 1 summarizes the experimental correlation between k (i.e. $\mathrm{d}b^*/\mathrm{d}t^*$) and I_w' as compared with the predictions from Eq. (1). Here the data noted as "Expt-NH" are the results from unheated conductor samples reported previously [2], and the data noted as "Expt-H" are the results from heated conductor samples reported presently. The predictions are shown by the two straight lines.

This figure suggests that Goodwin's model is reasonable if an ice growth is not overly wet ($I_w' \leq 2$). Otherwise, a reduction is necessary, depending on the degree of the ice wetness.

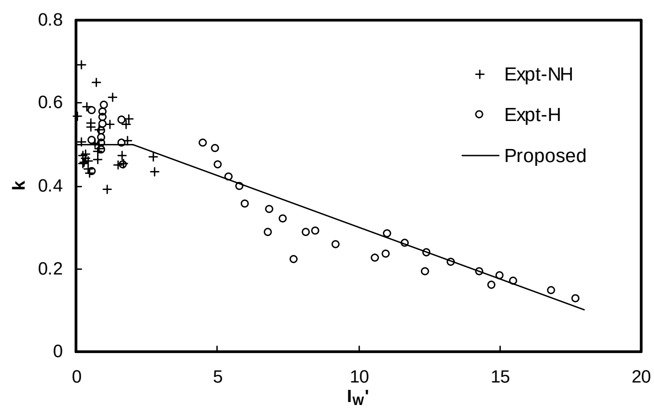

Figure 1. Experimental correlation between k and I_w'.

3. CONCLUSION

A simple, semi-empirical, icing model was proposed that accounts for the Joule heating effect in simulated conductor samples. It was validated against limited experimental data for heated conductor samples, as well as more extensive experimental data from unheated conductor samples. However, further corroborations are required to validate or refine the proposed model.

4. REFERENCES

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***Abstract*—Preliminary freezing rain experiments have been performed on fixed, heated conductor samples. The data, which complements previously reported data for analogous unheated conductor samples, provide an experimental basis for developing a refined icing model. Consequently a simple semi-empirical model is proposed that incorporates the effect of Joule heating on the weight of ice formed on an overhead power line due to a continuous freezing rain. The model's predictions are checked against available field observations with promising corroborations.**

Keywords-component; conductor; freezing rain; icing model; Joule heating; overhead power

I. INTRODUCTION

A reliable estimate of the extreme ice load is essential in the design and maintenance of a power system in an ice prone area. Due to the lack of long term field observations on ice loads, historical weather records, which are available from local weather stations, are often used to find the extreme ice weight. Such a practice requires a model to compute the ice weight from known weather conditions. Extensive experimental investigations were made previously on fixed, unheated conductor samples by using an outdoor freezing rain simulator. It was found that the simple model of Goodwin et al. [1] agrees surprisingly well with experimental data [2, 3] (even though the assumed cylindrical icing may be invalid).

However a power line, which is somewhat resistive, normally carries electricity, which produces Joule heating. Thus preliminary freezing rain experiments are reported here that assess the effect of Joule heating on short, stationary conductor samples. The data is used to develop a simple, semi-empirical icing model that incorporates Joule heating. Predictions are checked against available experimental data and field observations and the model appears to be promising.

II. TEST PROGRAM

A. Freezing rain simulator

The freezing rain simulator is located outdoors to take advantage of a naturally cold ambient air temperature. The freezing rain is simulated by spraying pre-cooled water droplets, having an approximately 1 mm diameter, about 10 m almost vertically into the air through fine nozzles. A fairly uniform, constant side wind is generated by using an axial flow fan. A heated conductor sample is perpendicular to the airflow, and is held horizontally by fixing its ends. The weight of ice accreted on a sample, as well as the vertical and horizontal precipitation rates, are measured half hourly. The ambient air temperature and the wind speed are monitored over the duration of a continuous test. See [2, 3] for more details.

B. Sample preparation

An internally heated conductor was emulated by replacing the inner steel core of an approximately 0.8 m long conductor section with a tightly fitting, resistor type heater, as illustrated in Fig. 1. Both ends of the sample were wrapped with electrical tape so that the heat loss on the ends was minor. The Joule heat produced by an electrical current passing through a conductor was simulated by an equivalent amount of heat generated by the heater rod located within the conductor sample. Different levels of Joule heating were obtained by adjusting the input voltage of the variable DC power source. The outside diameters of 2.86 cm, 1.25 cm, and 2.1 cm were used as they are representative of overhead power lines.

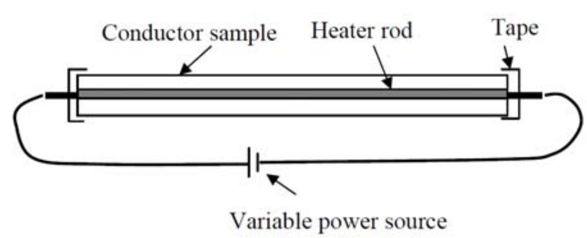

Figure 1. Schematic of a heated conductor sample.

C. Test conditions

Tests were performed when the ambient air temperature was between -1 to -12 ^{o}C and the outside wind speed was less than 1 m/s. A simulated side wind to a conductor sample was a moderate 5 m/s or so. The precipitation rate of the simulated freezing rain was deliberately taken to be a relatively high 1 cm/hr or so in order that a test's total duration could be limited to around 3 hours with a fairly representative precipitation. An extra-high-voltage (EHV) transmission line can produce Joule heat per unit conductor length, Q_J, in the range of 5 to 100 W/m [4], as seen in Fig. 2. Thus, the heat used for different tests was within this range. An overview of the test conditions is presented in Table 1. The status of an ice growth in the last column of Table 1 was determined visually from the absence or presence and extent of water on the surface of an icing. In general, a wet ice growth is defined for a shape of pendant icicles and a dry growth corresponds to a crescent ice shape. In addition, a transition between the wet and dry ice growths could be identified by an airfoil like shape. Ice shapes which represent these three categories are illustrated in Fig. 3 [3]. However, a transition growth was not observed in the present limited tests.

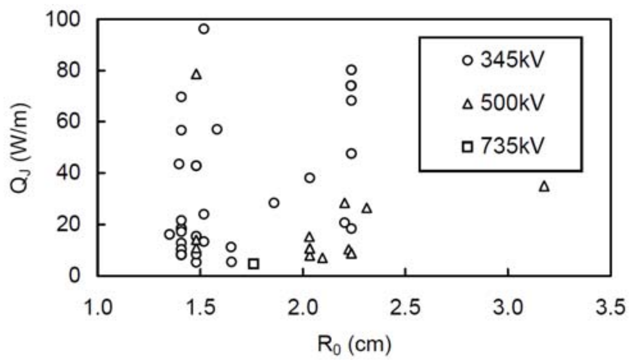

Figure 2. Joule heating on EHV transmission lines.

TABLE I. TEST CONDITIONS.

No.	R_0 (cm)	V_W (m/s)	T_a (°C)	P_v (cm/hr)	P_h (cm/hr)	t_{max} (hr)	Q_C (W/m)	Status
JH1	1.43	5	-5.5	1.35	0.39	2.43	46.0	Wet
JH2	1.43	5	-5.5	1.03	0.26	2.38	22.5	Wet
JH3	1.43	5	-2.0	1.45	0.24	2.38	14.4	Wet
JH4	1.43	5	-3.5	1.12	0.26	2.08	25.0	Wet
JH5	1.05	6	-2.7	0.65	1.02	2.00	20.0	Wet
JH6	1.43	5	-11.0	0.91	0.13	2.67	25.0	Dry
JH7	0.63	5	-8.5	1.31	0.17	2.64	16.0	Dry

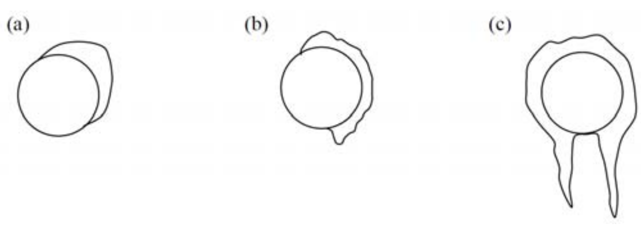

Figure 3. Representative ice shapes for: (a) dry ice; (b) transition; and (c) wet ice growths. Not drawn to scale.

D. Results

Test results are expressed in terms of a dimensionless ice thickness, b^* over a dimensionless time, t^*, as shown in Fig. 4. The b^* is the ratio of an equivalent radial ice thickness, b, to a bare conductor's radius, R_0, at any instant t from the freezing precipitation's start [2, 3]. On the other hand, t^* is defined by [2, 3]

$$t^* = 2\frac{\rho_w}{\rho_i}\frac{Pt}{\pi R_0} \tag{1}$$

where ρ_w and ρ_i are the mass density of water and ice, respectively. In addition, P is the combined precipitation rate defined as [2, 3]

$$P = \sqrt{P_v^2 + P_h^2} \tag{2}$$

in which P_v and P_h are the vertical and horizontal components, respectively.

Results from Goodwin's model [1], which correspond to unheated samples, are also plotted in Fig. 4 for comparison. This figure indicates that Joule heating tends, not surprisingly, to reduce the ice weight for a wet ice growth. The tests for JH1 through JH5 show a reduction of upto 50%. On the other hand, Joule heating appears to be insignificant for a dry ice growth, as evidenced by JH6 and JH7 in Fig. 4.

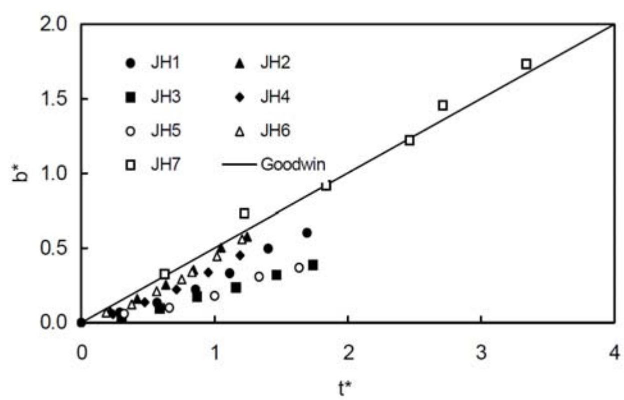

Figure 4. Summary of test results.

III. ICING MODEL

A. Basic formulation

The basic formulation for a dry ice growth involves a simple mass balance which can be found elsewhere [6]. On the other hand, a wet ice growth, which occurs when water droplets do not freeze immediately upon contact with an external surface, requires an additional heat balance. By neglecting the frictional heating of air, the kinetic energy of the impinging water droplets, as well as the heat loss due to radiation and a conductor's conduction, the heat balance equation over a short time interval, dt, for an icing surface having a unit length [5], is

$$Q_f + Q_J = Q_c + Q_e + Q_w\,. \tag{3}$$

Here Q_f is the latent heat released during freezing; Q_J is the Joule heat released from the energized (heated) conductor; Q_c is the loss of sensible heat to air; Q_e is the heat loss due to evaporation; Q_w is the heat loss in warming the impinging water from its own original temperature (which is assumed to be the ambient air temperature T_a) to the temperature of the icing surface T_S (which is taken as 0 °C for a wet ice growth). These components are determined, individually, from [6]

$$Q_J = \alpha_J I^2 R\mathrm{d}t \tag{4}$$

$$Q_f = \pi\rho_i D_C L_f \alpha_f \mathrm{d}b \tag{5}$$

$$Q_c = \pi D_C h(T_S - T_a)\mathrm{d}t \tag{6}$$

$$Q_e = \frac{0.622 hL_e}{c_p p_a l^{2/3}}(e_S - e_a)\pi D_C \mathrm{d}t \tag{7}$$

and

$$Q_w = D_C \beta P \rho_w C_w (T_S - T_a)\mathrm{d}t \tag{8}$$

where D_C is the equivalent diameter of an iced conductor; L_f is the latent heat of ice (334 kJ/kg); α_f is the latent heat efficiency, which is used to accommodate the time delay between a water droplet's contact with a conductor's surface and the complete release of the droplet's latent heat; α_J is the Joule heating efficiency used to measure the percentage of the Joule heat actually transferred to the icing surface; I^2R is the Joule heat per unit conductor length with I being current and R being the conductor's resistance; L_e is the latent heat of evaporation of water (2500 kJ/kg); c_p is the specific heat of air at a constant pressure (1 kJ/kg/°C); p_a is the atmospheric pressure; l is the Lewis number (0.876); e_s and e_a are the saturation vapor pressures over water at T_s and T_a, respectively; C_w is the specific heat of water (4.2 kJ/kg/°C); β is the ratio of the effective width of the iced conductor facing the impinging freezing raindrops to D_C. In addition, h is the convective heat transfer coefficient which may be estimated from [6]

$$h = N_u k_a / D_C \tag{9}$$

where k_a is the thermal conductivity of air (0.024 W/m²/°C). Furthermore N_u is the Nusselt number which is related to the Reynolds number, R_e, by [7]

$$\mathrm{Nu} = 0.117\mathrm{Re}^{0.68} \tag{10}$$

where

$$\mathrm{Re} = V_W D_C / \mu_a \tag{11}$$

and V_W is the wind speed. Also μ_a is the kinetic viscosity of air which is assumed to be 1.3×10^{-5} m²/s.

Eq. (7) can be approximated by

$$Q_e = 0.75 h(T_S - T_a) 2\pi (R_0 + b)\mathrm{d}t. \tag{12}$$

Substituting Eqs. (5) through (12) into Eq. (3) leads to

$$\frac{db}{dt} = \left[\frac{\left(1.75h + \frac{C_w \beta P \rho_w}{\pi}\right)(-T_a)}{\rho_i \alpha_f L_f} - \frac{\alpha_J I^2 R}{2\pi(R_0 + b)\rho_i \alpha_f L_f} \right] \tag{13}$$

or, in dimensionless form,

$$\mathrm{d}b^* / \mathrm{d}t^* = 1/(2\alpha_f I_W') \tag{14}$$

where I_w' is the modified wetness index given by

$$I_W' = I_W / [1 - \frac{\alpha_J q_J}{(1+b^*)q_C}] \tag{15}$$

The I_W in Eq. (15) is the wetness index defined by

$$I_W = \frac{P\rho_w L_f}{\pi(1.75h + C_w \beta P \rho_w / \pi)(-T_a)\alpha_I} \approx \frac{11 P D_C^{0.32}}{V_W^{0.68}(-T_a)} \tag{16}$$

where a_I is an empirical correction coefficient. It is taken to be 0.6 to match the experimental data (as discussed in subsection *B*).

In addition,

$$q_J = I^2 R / (2\pi R_0) \tag{17}$$

$$q_C = (1.75h + C_w \beta P \rho_w / \pi)(-T_a) \approx 44 \frac{V_W^{0.68}}{D_C^{0.32}}(-T_a) \tag{18}$$

In the simplified Eqs. (16) and (18), P, D_C, V_W, T_a and q_C are in cm/hr, cm; m/s, °C and W/m², respectively.

Clearly, I_w' will reduce to I_w if Joule heat is not present.

B. Experimental verification of the wetness index I_W

Without Joule heating, a dry (wet) ice growth occurs if $I_W < 1$ ($I_W > 1$). Previously reported experimental data for non-heated conductor samples [3] are used to assess this categorization. Fig. 5 gives the estimated values of I_W for the three ice categories illustrated in Fig. 3, based on the experimental data from [3]. Here a_I is taken to be 0.6 so that a transition state will correspond to $I_W \approx 1$.

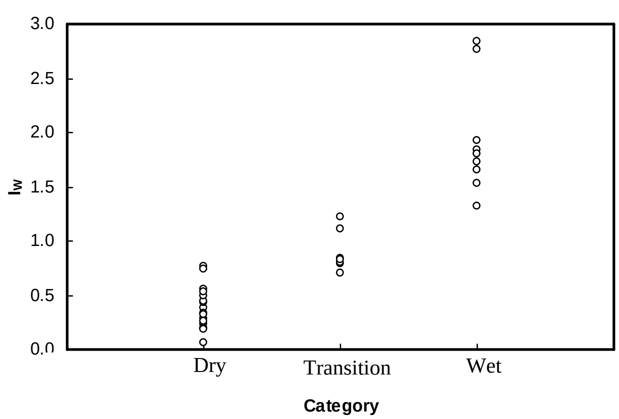

Figure 5. Comparison with experimental results from unheated conductor samples in terms of the wetness index, I_W.

Fig. 5 shows that the categorizations for moderate icings can be determined approximately from the wet index value.

That is, a dry ice with crescent ice shape (Fig. 3a) most likely occurs if $I_W < 0.8$; a wet ice with pendent icicles (Fig. 3c) most likely occurs if $I_W > 1.2$; a transition ice with D-like ice shape (Fig. 3b) most likely occurs otherwise.

C. *Experimental correlation between k and I_w'*

Denote db^*/dt^* as k. Eqs. (14) and (15) indicate that k is a function of I_w'. Experimental data is now used to identify the correlation between k and I_w' (so that a_f is found indirectly).

Fig. 6 summarizes the result of experimental correlation between k and I_w'. Here the data noted as "Expt-NH" are the results from unheated conductor samples reported previously [3], and the data noted as "Expt-H" are the results from heated conductor samples reported presently. It is assumed in preparing Fig. 6 that $\alpha_J = 1$, $\beta = 1$. For clarity, the data in Fig. 6 for $I_w' < 2$ is zoomed to give Fig. 7.

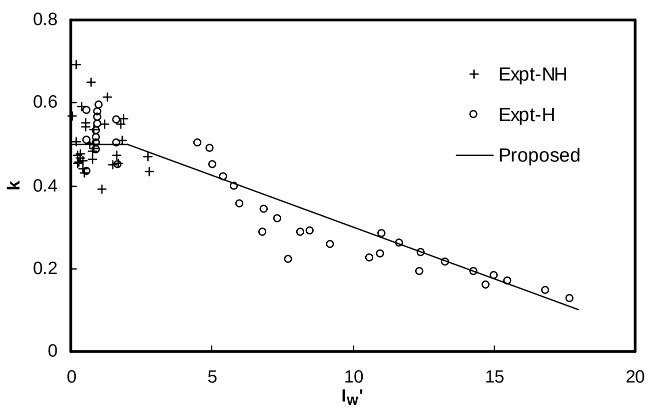

Figure 6. Experimental correlation between k and I_w'.

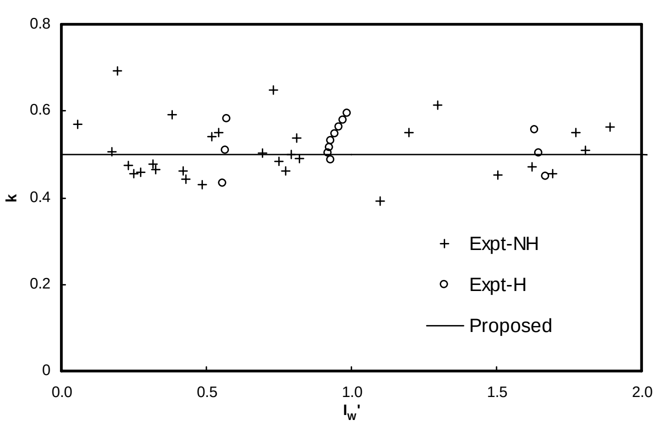

Figure 7. Zoomed experimental correlation for $I_w' < 2$.

D. *Icing model considering Joule heating effect*

Based on the limited data presented in Fig. 6 (as well as Fig. 7) the following semi-empirical icing equation seems to reasonably account for Joule heating

$$\mathrm{d}b^*/\mathrm{d}t^* = 0.5 \quad (\text{if } 0 \leq I_w' \leq 2) \tag{20a}$$

$$\mathrm{d}b^*/\mathrm{d}t^* = 0.55 - 0.025\, I_w' \quad (\text{if } 2 \leq I_w' \leq 18) \tag{20b}$$

The above equation corresponds to the two lines denoted as "Proposed" in Fig. 6.

This figure suggests that Goodwin's model is reasonable if an ice growth is not overly wet ($I_w' \leq 2$). Otherwise, a reduction is necessary, depending on the degree of the ice wetness.

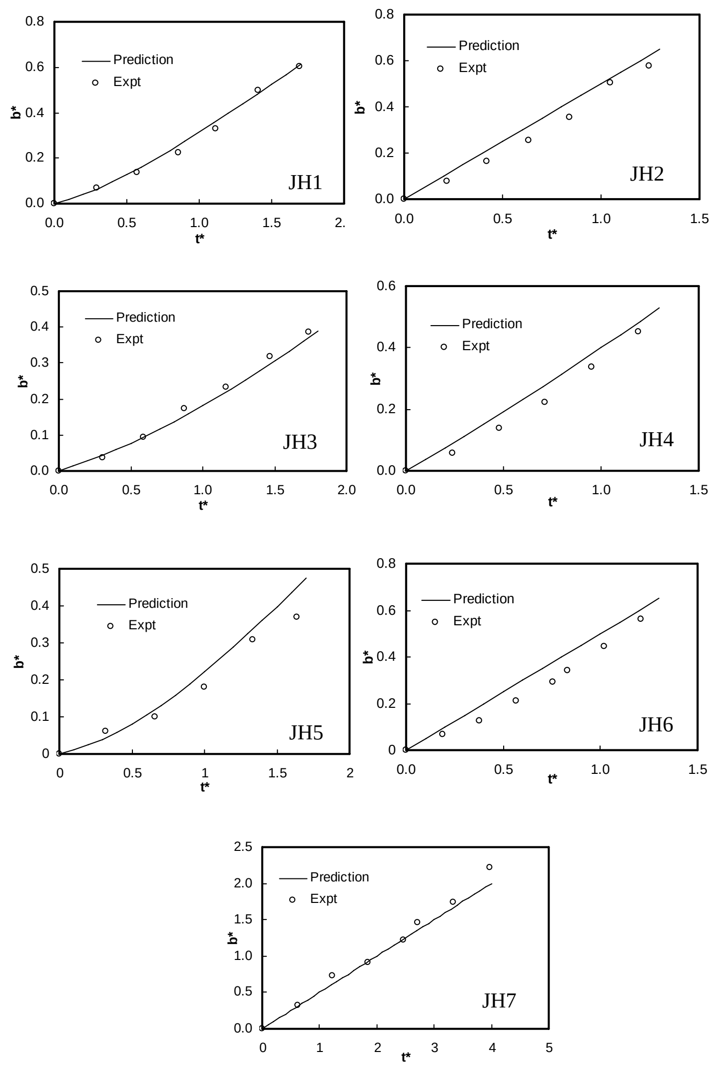

Figure 8. Comparison between the predicted and experimental results for the seven heated conductor samples.

IV. VALIDATION

Fig. 8 shows fairly good agreement between the experimental results and predictions from Eq. (20) for the seven heated conductor samples listed in Table 1.

Field observations from real energized power lines [8] are compared next in Fig. 9 with the proposed icing model. The results from Goodwin's model are also presented in the figure. The solid line in Fig. 9 corresponds to the situation where a measured ice thickness, b_m, coincides with its calculated counterpart, b_c. Fig. 9 shows that in general a better agreement with the field observations is achieved by using the present model than Goodwin's model.

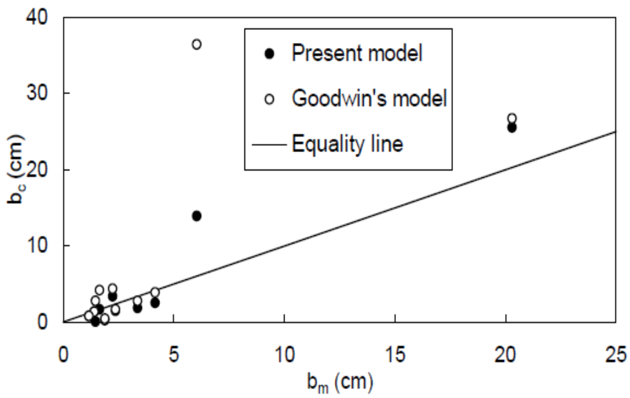

Figure 9. Comparison of calculated ice thickness, b_c, with the ice thickness, b_m, that is measured on energized, field lines.

V. Conclusions

A simple, semi-empirical, icing model was proposed that accounts for the Joule heating effect in simulated conductor samples. It was validated against limited experimental data for heated conductor samples, as well as more extensive experimental data from unheated conductor samples. However, further corroborations are required to validate or refine the proposed model.

References

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