AN ANALYSIS OF SELECTED ICE ACCRETION MEASUREMENTS ON A WIRE AT MT. WASHINGTON

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ABSTRACT

Although numerical models have been developed to predict the increase in load on transmission lines due to atmospheric icing, there are very few data available with which to verify them experimentally. The accretion of ice on a wire is a complex three-dimensional phenomenon involving torsion of the wire under the accretion weight, vibration, and breaking of some of the ice. In particular, the Mt. Washington test site used for our experiments experiences strong winds that cause high loads, vibrations, and breaking of ice chunks. Load measurements for a few wire-icing events are analyzed to determine the functional relationship between icing load and time, and how this compares with the predictions of some available numerical models. Results indicate that loads for steady icing conditions tend to increase exponentially with time.

INTRODUCTION

Atmospheric ice accretion on structures is a major design factor for overhead transmission lines in northern regions. The complexity of the ice accretion process and the scarcity of accretion data make it difficult to calculate realistic ice loads for design purposes (Brown and Krishnasamy, 1984). Ice accretion models have recently been developed (Makkonen, 1984) to take into account some characteristics of wire icing. One major difference between wire icing and icing of a fixed structure is the torsion of the wire due to ice loads (McComber, 1984; Smith and Baker, 1983; Egelhofer et al., 1984). However, other factors that also play important roles have not yet been fully addressed, as, for example, wire geometry (span, sag, height from ground), wind-induced vibrations, Joule heating, and the electrical field on a conductor (Nikiforov, 1983). Wire icing data need to be collected in sufficient quantity to permit the development and testing of more complete models. However, some of the data already available should be sufficient to verify at least semi-empirical models.

In this paper ice load measurements on a wire obtained during a few icing events at Mt. Washington are used to verify a proposed simple model, and the functional relationship between ice load and time is compared with the predictions of some other climatological models.

THEORETICAL ANALYSIS

The icing intensity I $(kg/m^2 \cdot h)$ on a wire is found by the following relation (Makkonen, 1984):

$$I = 3.6\ E\ w\ V_m \qquad (1)$$

where E is the net collection efficiency, $w(g/m^3)$ the liquid water content, and $V_m(m/s)$ the wind speed normal to the wire. The factor 3.6 is used to make the units consistent in Eq. 1.

To obtain the ice load as a function of time, the following equation must be integrated:

$$\frac{dM}{dt} = I(t)\ A(t) \qquad (2)$$

where M is the ice load per unit length (kg/m), t is the time (h), and A is the cross section per unit length (m). For a perfectly cylindrical and smooth shape, the cross-sectional area per unit length is the diameter D (m). However, for a more general shape the cross-sectional area per unit length, A, can be regarded as a characteristic diameter of the accretion.

In an icing event the ice load increases, and if the breaking of large chunks of ice is not considered, the average size increases and the icing rate is positive:

$$dM/dt > 0 \quad \text{and} \quad dD/dt > 0 \ . \qquad (3)$$

Makkonen (1984) has reviewed a few existing simulation models for ice accretion events. One of the important differences of these models, illustrated in Figure 1, is the change of the icing rate with time. Since the icing loads are obtained by integration of the icing rate, the variation of the icing rate with time is critical to a realistic simulation. This is especially important for safety considerations so that the model will not underestimate the true icing rate.

An exponential relationship between the icing rate and the characteristic diameter of the accretion can be used to compare the convexity of the different curves in Figure 1:

$$\frac{dM}{dt} = k\ D^n \qquad (4)$$

In Eq. 4, k is considered constant for steady meteorological parameters and n is an exponent that takes into account the effects of changing accretion size on the icing rate.

Starting with the lowest value of exponent n, for $n < 0$ by derivation $d^2M/dt^2 < 0$ is obtained, since $dD/dt > 0$ is always positive. This results in a convex curve and a decreasing icing rate with time. The model suggested by Makkonen (1984) is of this type. The main factor causing the decreasing icing rate is to be found in the calculation for the collection efficiency. The calculated collection efficiency E_c is obtained mathematically for a two-dimensional flow around a smooth cylinder and using a calculated average diameter with the Langmuir and Blodgett (1946) method. As the size D of the accretion increases, the collection efficiency E_c decreases. Equations fitted to these numerical data were reviewed by Horjen (1983), and his recommended expressions (not reproduced here) are used below for the calculation of the collection efficiency.

For n = 0 the icing load increases linearly with time, and a constant icing rate model is obtained. Even if this is the simplest of the possible models, it does not seem to have been proposed in the literature.

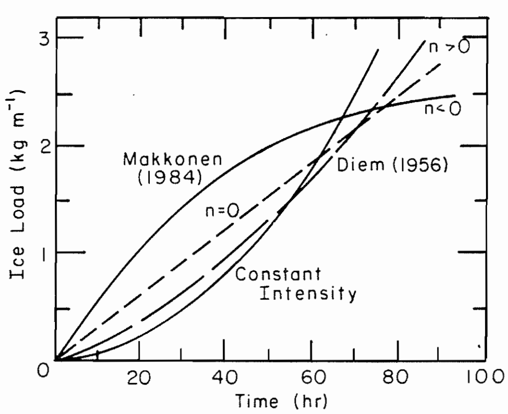

Figure 1. Approximate evolution of the ice load on a 0.5-cm wire as predicted by different models (V = 10 m/s; w = 0.2 g/m^3; d = 20 μm; ρ = 0.6 g/m^3; t_a = -5°C; E = 0.1 for the constant E models). (After Makkonen, 1984).

A simulation model with n = 1 predicts a concave curve and hence an increasing icing rate with time: $d^2M/dt^2 > 0$. This is the constant intensity model:

$$\frac{dM}{dt} = I_o D \ . \qquad (5)$$

The only empirical model shown in Figure 1 is the one from Diem, for which Makkonen (1984) gives the expression $M = I_o t^{1.4}$. It is interesting to note that it results in an increasing icing rate with time. However, none of the above models could be easily fitted to the Mt. Washington data, where an increasing icing rate with time was also observed. In order to be able to make use of linear regression with these experimental data a semi-logarithmic plotting of the data proved useful. A theoretical justification for this type of model is presented in the next section.

THE EXPONENTIAL GROWTH MODEL

A stranded wire or a wire with an initial accretion does not have a smooth, cylindrical shape. It does have a surface roughness which can be quantified by a roughness parameter ε(m) proportional to the heights of the various roughness irregularities. On the other hand, since smaller accretions have a higher collection efficiency the effect of the roughness irregularities will be to increase the overall collection efficiency by a certain factor. In a first approximation it can be assumed that the calculated collection efficiency E_c must be multiplied by a factor of the order of magnitude 1 and proportional to the roughness: $C\,\varepsilon$. This factor is nondimensional. Eq. 2 becomes

$$\frac{dM}{dt} = (E_c\, C\, \varepsilon)\, w\, V_m\, D = E_c\, C\, \frac{\varepsilon}{D}\, w\, V_m\, D^2 \ . \qquad (6)$$

$E_c C \varepsilon$ can be considered the net collection efficiency E. Also, it can be argued that the relative roughness ε/D remains fairly constant during the time of the accretion. This is justified by the fact that due to a feedback or cumulative effect, the roughness increases with the size of the accretion D, so that the relative roughness ends up almost constant. With these considerations Eq. 6 becomes

$$\frac{dM}{dt} = \frac{E\, w\, V_m}{D_o} D^2 \qquad (7)$$

where D_o is used to indicate an initial average size held constant during the icing event.

The ice load M is related to the characteristic diameter D by

$$M = \frac{\pi D^2}{4} \rho_i \qquad (8)$$

where ρ_i is the ice accretion density (kg/m^3).

By combining this expression with Eq. 7 the following equation is obtained:

$$\frac{dM}{M} = \left[\frac{4\, E\, w\, V_m}{\pi\, \rho_i\, D_o}\right] dt \ . \qquad (9)$$

In Eq. 9 the parameters assumed to have a constant average value during an icing event are combined in a constant k:

$$k = \frac{4\, Ew\, V_m}{\pi\, \rho_i\, D_o} \ . \qquad (10)$$

The new parameter $k(h^{-1})$ is in fact a relative icing rate:

$$k = \frac{dM/dt}{M} \tag{11}$$

and can be thought of as giving the fractional increase in ice load per hour. A k equal to 0.04 indicates that the load increases by 4% every hour. Since k is taken constant during an icing event the resulting model can also be considered to be a constant relative icing rate model. In Eq. 10 the characteristic thickness of the accretion D_o can be calculated from the initial ice load M_o.

Equation 9 is integrated to give:

$$\ln\left(\frac{M}{M_o}\right) = k\ t \qquad \text{or} \qquad \frac{M}{M_o} = e^{kt}\ . \tag{12}$$

Using this type of model for an icing event means that the data can be plotted on a semi-logarithmic scale, and linear regression can be used to find the value of the slope k. An experimental value of the relative icing rate k is then obtained and it can be compared to the one calculated from the meteorological parameters.

ICE LOAD MEASUREMENTS ON A WIRE AT MT. WASHINGTON

The test site in 1978 was located 9 m northwest of the Observatory Building near the summit of Mt. Washington (elevation 1954 m). For the measurements of 1980 it was on the flat roof of the Sherman Adams Building, just north of the summit. Figure 2 is a photograph of the 1980 wire set-up. Two 1.5- x 1.5- x 1.5-m steel cribs filled with rocks provided a solid foundation for the 15-cm H-beams that supported the test wire. The end supports were 6 m apart (10 m in 1980) and the wire was attached to each end approximately 2.5 m from the surface. The wire was oriented north-south, which is normal to the prevailing winds. The test wire was ordinary 0.64-cm (1/4-in.) stranded steel cable. The amount of slack varied from one season to the next but the catenary angle was measured and used in the calculations to find the ice loads. One end of the wire was attached to an axial load cell, which was rigidly fixed to the support.

An electrically heated, vaned pitot static tube located on a mast on the corner of the southernmost crib at the height of the test wire was used for wind measurements.

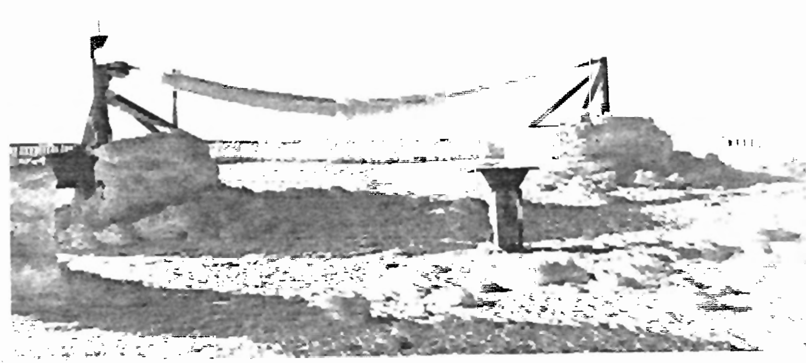

Figure 2. Photograph of the wire set-up for ice load measurements at Mt. Washington Observatory.

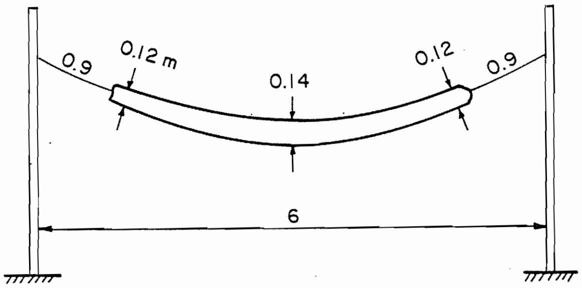

Figure 3. Schematic description of the ice accretion shape at 1500 hr, 1 May 1978.

The liquid water content w and droplet size d (μm) were measured using the rotating multicylinder method (Langmuir and Blodgett, 1946). This method gives the average volumetric droplet diameter d and a general characterization of the diameter distribution shape.

Visual observations were made during icing events and the maximum accretion diameter was usually recorded. The winds during icing events were always above 20 m/s. This resulted in considerable vibration of the wire in various modes. Figure 3 shows a typical schematic of an ice accretion shape on the wire obtained in these conditions. After a certain time the cross section became almost cylindrical due to the torsional vibrations. The vibrations are also responsible for the continuous crushing and breaking of the rime near the ends which kept the wire free of ice near the ends. On the ice-covered part of the wire the accretion is broken into chunks 15 cm long or longer that often rotated independently of each other.

The value of the ice load used in the analysis was obtained from the recorded output of the tension load cell. The vibration of the wire resulted in vibrations of the tension signal with a frequency of approximately 1 Hz. An average of the tension signal can, however, be easily interpolated from the recording. No attempts were made to eliminate the average wind effect on the tension signal, which has been studied by Govoni and Ackley (1983). Since a constant velocity is assumed during the events for the analysis, the load M is effectively multiplied by a constant factor. This results in an upward shift of the straight line on the semi-logarithmic scale but does not affect the slope k which is obtained with the linear regression.

DESCRIPTION OF THE FIVE ICING EVENTS AND RESULTS

Five icing events were chosen for analysis. The choice was based on the availability of high quality data from the single-axis load cell and reasonable monitoring of the ice events.

The first event took place between 0400 hr 1 May 1978 and 0900 hr 2 May 1978. Rime was formed on the wire. According to the records the temperature rose during the event from -16°C to -8°C, and the average wind speed normal to the wire was 24.6 m/s. During the event the measured liquid water content was 0.45 g/m^3 with a median droplet diameter of 13 μm. The wire was vibrating during icing and there were large chunks of ice in the center of the span with decreasing diameter going towards the supports. Approximately 0.9 m of wire was free of ice on each end. Average loads were read every half hour from the pen recordings of the load cell; the load curve is plotted in Figure 4. Linear regression was used to determine the best straight line fit on the semi-logarithmic plot. A slope of k=0.06605 was obtained for the event, with a correlation coefficient of 0.9872.

The second icing event was recorded from 0430 hr 10 May 1978 to 0600 hr the next day. Again, rime formed on the wire. The two ends of the wire were free of ice due to the wire movement. Temperatures were close to the freezing point, increasing to -1°C at 1800 hr, and it was observed at that time that icicles were formed on the accretion. The liquid water content was measured twice during this event. The first run was taken at 1120 hr on 10 May and the second at 2300 hr on the same day. The values obtained were 0.4 g/m^3 with a droplet diameter of 13 μm and 0.7 g/m^3 with a droplet diameter of 20 μm, respectively. The observed weather was fog with wind speeds of 21.5 m/s, gusting to 24.5 m/s. Figure 5 shows

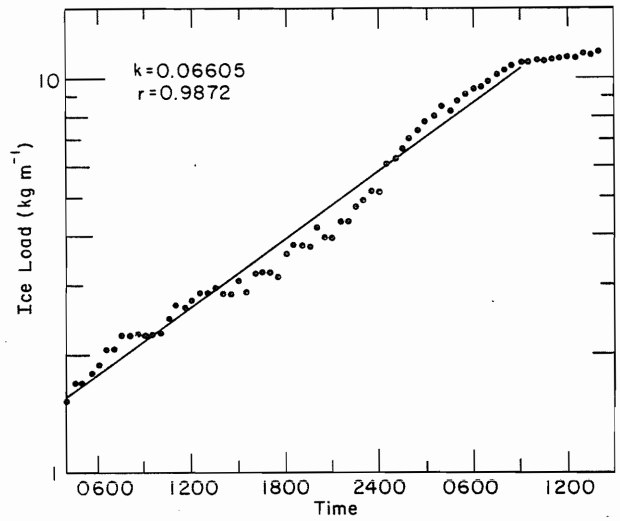

Figure 4. Ice load measurements, 1 May 1978.

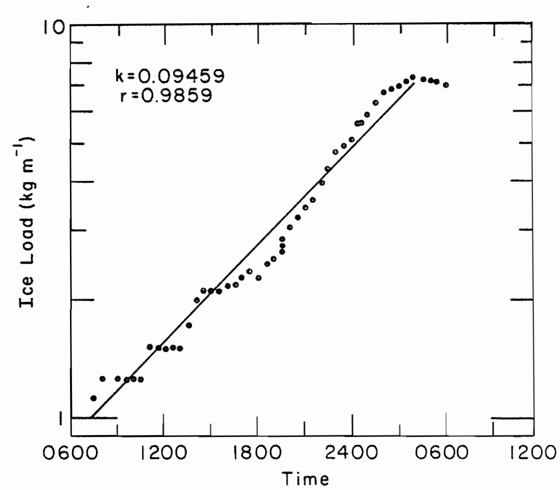

Figure 5. Ice load measurements, 10-11 May 1978.

the best fit curve obtained for the loads read from the continuous recordings. The slope obtained by linear regression is k = 0.09459, with a coefficient of correlation of 0.9859.

The third event was monitored on 22 and 23 February 1980. Rime formed on the wire from about 2000 hr on 22 February to 1200 hr on 23 February. During the accretion of ice the mean temperature was −9.5°C and the wind averaged 20.1 m/s. As usual, ice was broken off near the ends at both sides, and a maximum diameter of 15 cm was measured in the center of the wire. The liquid water content and droplet diameter were not measured for this event. The results of the ice load measurements and the best fit curve are shown in Figure 6. A slope of k = 0.10164 was obtained, with a correlation coefficient of 0.9952.

The fourth icing event took place from 0800 to 2300 hr on 28 November 1978. Again, rime formed on the wire. The temperature was −18°C at the end of the measurements. The wind velocity measured was around 22.4 m/s. No measurements of liquid water content and droplet sizes were obtained.

The results of this run are shown in Figure 7. A slope of 0.10175 was obtained, for a correlation coefficient of 0.9859.

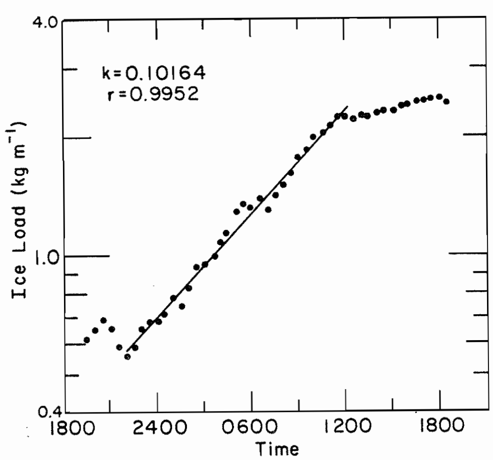

Figure 6. Ice load measurements, 22-23 February 1980.

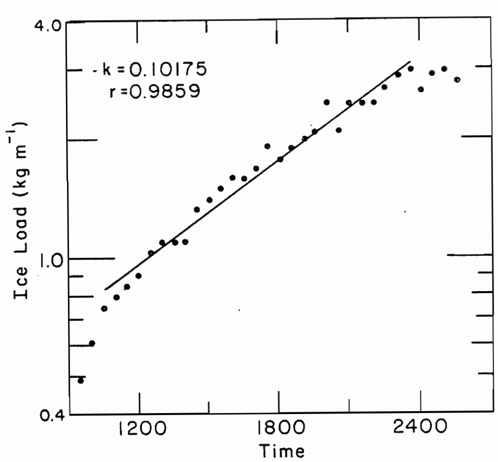

Figure 7. Ice load measurements, 28 November 1978.

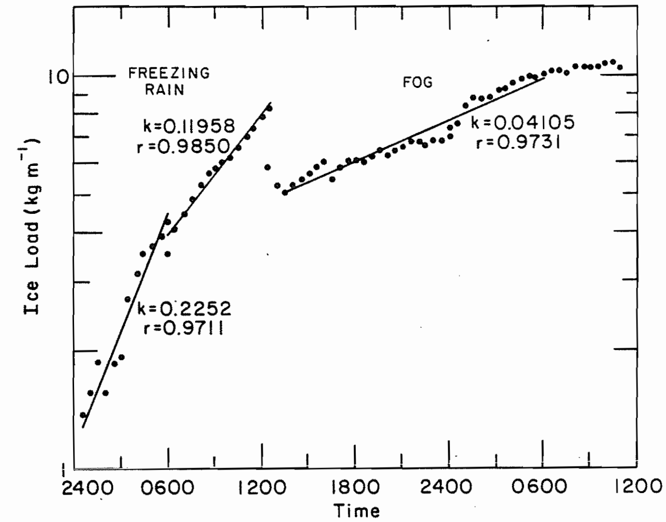

Figure 8. Ice load measurements, 5-6 April 1978.

The fifth and last event analyzed took place on 5 and 6 April 1978. Icing occurred from 0030 hr on 5 April to 1200 hr the next day. At first a mixture of freezing rain and ice pellets was observed, resulting in clear ice on the wire. A multicylinder run made at 0810 hr on 5 April indicated a liquid water content of 1.4 g/m^3 and a droplet size of 17 µm, at a temperature of -5°C. The wind speed around this time averaged 22.4 m/s. At 1200 hr it was observed that the average speed of the wind had increased to 34 m/s. At this time nearly half of the ice on the wire broke off. After this the build-up continued as rime in the fog and strong winds. Another liquid water measurement made at 0330 hr on 6 April gave 0.57 g/m^3 with a droplet diameter of 14 µm. The wind velocity at that time was around 26.8 m/s. At the end of the run the average icing diameter in the center of the span was measured to be 25 cm for an ice chunk 0.53 m in length.

The resulting loads for this event are plotted in Figure 8. Because of the break-up in the ice, and also because of significant differences in the weather conditions (the transition from freezing rain to fog), the complete event is divided into three curves. The first one has a slope of k = 0.2252 with a correlation coefficient of 0.971; the second has a slope of k = 0.11958 with a correlation coefficient of 0.985; and the third has a slope of 0.04105 and a correlation coefficient of 0.9731.

DISCUSSION

The five curve fittings in Figures 4-8 indicate that the exponential growth model can be used to describe the accretion of ice on a wire. The fit is fairly good, considering the complexity of this phenomenon as well as the varying meteorological parameters during the time of the icing event.

In order to make a comparison of the slope obtained on semi-logarithmic graphs with the values of the measured meteorological parameters the value of the collection efficiency was first calculated for the different cases using the method of Horjen (1983). It can be seen in Table 1 that there is not very good correlation between the slope calculated with this collection efficiency and the one measured. Instead of using this value of collection efficiency an average collection efficiency was calculated for all cases using an average of the different meteorological parameters, V = 23.4 m/s, D = 0.095 m and d = 14.4 µm. With these values a collection efficiency E = 0.0430 was obtained.

The values of $4\ w\ V/\pi D_o\ \rho_i$ were plotted against k and a best fit curve was obtained by linear regression. The slope obtained can be considered the best average of the net collection efficiency for the icing events reported. A value of E = 0.0306 was obtained. With this value a calculated value of k was obtained and plotted with respect to the experimental values in Figure 9.

Table 1. Comparison of different parameters measured or calculated during the icing events.

Date of icing event	D_o m	w g/m³	d μm	V_m m/s	ρ_i g/m³	E_{calc}	k_{exp} h⁻¹	r	$\frac{4\,w\,V_m}{\pi\,D_o\,\rho_i}$ h⁻¹	k_{calc} h⁻¹
1 May 1978	0.089	0.48	13	24.6	0.38*	0.0357	0.0661	0.987	1.62	0.0495
10 May 1978	0.068	0.55	16	22.4	0.38*	0.1077	0.0946	0.986	2.22	0.0678
2 Apr 1980	0.054	0.48*	12*	14.9	0.38*	0.0301	0.1016	0.995	1.62	0.0495
28 Nov 1978	0.075	0.48*	12*	20.1	0.25	0.0238	0.1017	0.986	2.37	0.0722
5 Apr 1978	0.066	1.4	17	22.4	0.38*	0.1329	0.2252	0.991	5.80	0.1773
5 Apr 1978	0.129	1.4	17	33.5	0.38*	0.0752	0.1196	0.985	4.45	0.1362
6 Apr 1978	0.185	0.57	14	26.1	0.38*	0.0052	0.410	0.9731	0.99	0.0301

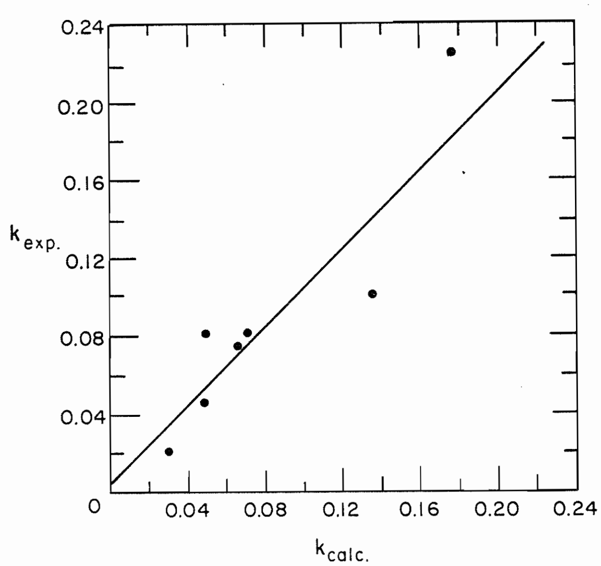

Figure 9. Comparison of the experimental and calculated relative icing rate k.

The principal consequence of this correlation is the conclusion that the collection efficiency does not seem to show a decrease as the size of the accretion increases. But the correspondence of the average collection efficiency with the one obtained experimentally should not be considered too important in view of the fact that the loss of ice due to the almost continuous breaking of the accretion is not included in the calculation for E. This should in fact indicate that the real collection efficiency, without accounting for the break-up of ice, would be higher than the 0.04 used. Under the conditions of icing at Mt. Washington the wind is always high enough to induce strong movements of the wire, and hence significant crushing and breaking of the ice.

The wind velocity has an important effect on the signal. Considering the average angle of deflection of the wire that was observed during the test, the tension due to the ice weight might be overestimated by as much as 30% in some cases. However, assuming as we did an average value of wind velocity during accretion means that the load due to ice is multiplied by a constant factor. In such a case on the semi-logarithmic graphs the multiplication of the load by a constant factor results in a shifting of the curves upwards without a change in the slope. This obviously does not affect the exponential model as such.

CONCLUSION

An exponential growth model was used to approximate the building-up of ice on a wire at Mt. Washington. The analysis of five different events shows that this is an adequate model that can be used to approximate the ice load's variation as a function of time, using average values of the meteorological parameters. The use of this model indicates a constant relative icing rate, which results in larger load with time than the decreasing icing rate predicted by some previously proposed models.

The use of this model implies that there is no important reduction in the collection efficiency with increasing size of the accretion as predicted by the mathematical calculation made for two-dimensional smooth cylinders. This could indicate that the surface roughness increases the collection efficiency significantly. Since this roughness increases with the size of the accretion this effect could balance out the decrease in icing rate due to increasing average size of the accretion.

Because of the complexity of the phenomenon of ice accretion on a wire, especially during strong winds as on Mt. Washington, more tests need to be performed before an adequate model can be verified. One of the most important factors to study would be the relative importance of the breaking-up of the ice during an accretion and the different factors that could increase this breaking-up in an actual situation. This in fact could result in a low-cost means of reducing the damage caused to power lines by in-cloud or fog icing.

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