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Snow accretion on overhead wires

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Although snow accretion on overhead wires is a serious problem, recognized physical models have not yet been established. In this paper, attempts directed at understanding the mechanism of snow accretion on wires are reviewed. Fundamentals of the meteorological conditions under which snow accretes on wires, inferred mechanisms, mechanics and heat balance of snow accretion are briefly reviewed. A short historical review of research works throughout the world is given. Wind-tunnel tests aiming at examining the dependence of various parameters on the characteristics of accreted snow on wires are introduced and defects of such tests are discussed. Finally, attempts to establish snow-load design on power lines, with some results of observations under natural conditions, are briefly discussed. It should be emphasized that the present paper is characteristic of an interim report and summary about snow accretion on overhead wires, with the purpose of avoiding repetition of the same kind of research efforts and therefore accelerating further progress.

Keywords: snow accretion; wet snow; loading design; overhead wire; empirical modelling

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1. Introduction

Snow accretion on overhead lines is a type of icing classified as precipitation icing (see IEC 1991). For other types of icing, such as glaze due to supercooled rain droplets and rime ice due to supercooled cloud or fog droplets, good physical models have been developed. However, in the case of snow accretion, no satisfactory physical model has yet been developed. There are several reasons why this is so. Firstly, there are several physical mechanisms involved in the process of snow accretion. Secondly, there are difficulties encountered in simulating snow accretion under natural conditions within the laboratory. Thirdly, snow accretion occurs under a wide variety and combination of conditions which make observations difficult to assess, especially if some combinations occur only rarely. Finally, it is often difficult to observe natural snow accretion on wires after a snow event, since they might shed in a relatively short time or change their characteristics rapidly in contrast to other types of accretion.

Japan consists of a group of islands extending along the sub-tropical zone to a latitude of 45.5°, located at the boundary of the Pacific Ocean and the Asian continent. Thus, in every winter, snowfalls are experienced under various synoptic meteorological situations and, in particular, power lines suffer many types of fault due to snow at very early stages of commissioning. Such faults are mainly as follows.

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(1) Breakage of wires and collapse of support structures due to snow overload on wires.

(2) Flashover between phases or between shield wire and phase conductor due to unequal sag increase between spans and phases of line, or wire movement due to simultaneous shedding of accreted snow.

(3) Interphase flashover, or wear of fittings and members including bolts, caused by galloping motion of the wire due to aerodynamic instability when modified by snow accretion.

In addition, there are many problems experienced by overhead lines due to avalanche and snow cover settlement, but these are beyond the scope of the present paper and will not be discussed further.

Many of the above problems have been studied by many researchers and engineers in Japan and there now exists a considerable literature, but unfortunately most of this is written in Japanese (see discussion given in the paper by the Japanese Institute of Electrical Engineers 1965).

Over some 40 years as a power line engineer I have collected and assessed a large number of papers on icing from my own country and other major cold regions. Prior to 1982 only a few papers existed on snow accretion. At this time, regular meetings of the IWAIS (International Workshop on Atmospheric Icing of Structures) began and many papers on snow accretion became available, especially from France, Spain, Iceland and the US (Alaska) and, of course, Japan.

During the preparation of this paper, the author had another chance to assess these papers and again experience the worries concerning the present-day understanding of the physics of wet-snow accretion on overhead wires. The author presents in § 2 material which highlights many of the difficulties encountered in the study of snow accretion and how some of them may be overcome, especially from a practical point of view.

2. Fundamentals of snow accretion

(a) *Meteorological conditions under which snow accretion occurs*

In general, it has been considered that snow accretion on overhead lines occurs when 'wet snowflakes' adhere to wires, and this occurs at surface temperatures just above freezing. However, in practice, the phenomenon of snow accretion is experienced under a relatively wide range of combinations of meteorological parameters.

Figure 1 shows an example of the time history of meteorological parameters during snow accretion under positive temperature. These data were extracted from records of a nearby observatory when severe damage to power lines (including tower collapses) was experienced. In this case, precipitation started at 17:00 on 22 March 1986, in the form of rain when the surface air temperature was high (+5 °C). At about 21:00 on the same day the temperature fell to *ca.* +2 °C and the precipitation changed to snow via sleet, with the temperature almost constant near +0.5 °C until precipitation ceased at about 21:00 the next day. At the latter temperature the precipitation intensity was large, equivalent to more than 5 mm h^{-1} of water, which is extremely high for the winter season. In addition, wind speeds of *ca.* 5–10 m s^{-1} (ten minutes averaged) were observed during these adverse conditions. Although the

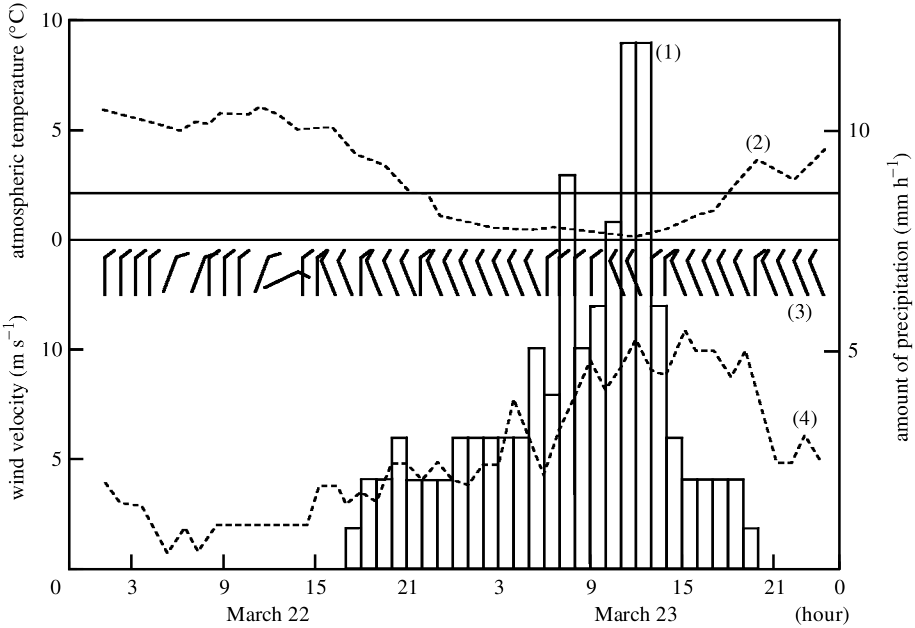

Figure 1. Meteorological data for the meteorological observation station.

exact mass of snow accreted on wires was not measured, there was a sufficiently heavy snow overload to promote the collapse of several towers.

On the other hand, figure 2 shows the time history of meteorological parameters during the observation of snow accretion on an Ishiuchi test line (Niigata Prefecture). The test line was constructed by the Central Research Institute of Electric Power Industry (CRIEPI), observed visually and monitored by various instruments, including video camera. Figure 3 shows the time history of the measured mass of snow accreted on wires. During this accretion period, the wind was calm and the speed could not be measured with an anemometer. Precipitation (snow) started at about 20:00 on 11 January 1986 and continued until 11:00 the next day. During the precipitation, the air temperature remained relatively constant, *ca.* $-4\,^{\circ}$C, and a snow mass of *ca.* 4 kg m^{-1} accreted on wires due to the accumulative precipitation equivalent to 30 mm of water.

These limited experiences of the meteorological conditions under which snow accretion occurs can be summarized as follows.

(a) Snow accretion on overhead wires may occur at air temperatures as low as $-7\,^{\circ}$C.

(b) Snow accretion at sub-freezing temperatures is limited to extremely low wind speeds ($V \leqslant 2$ m s^{-1}).

(c) At temperatures above freezing, snow may accrete under any wind speed.

(d) Characteristics and growing processes of snow accretion are significantly different above and below a certain boundary temperature. The boundary temperature differs slightly depending upon the altitude of location above mean sea level and the synoptic meteorological pattern causing snowfall.

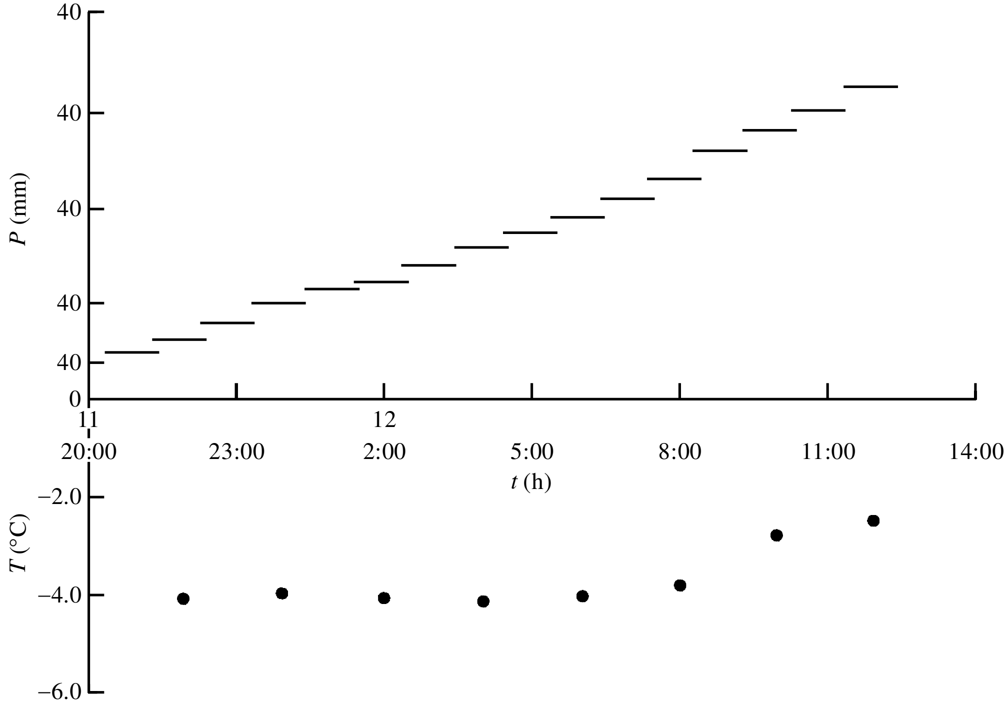

Figure 2. Air temperature and accumulated precipitation rate during snow accretion.

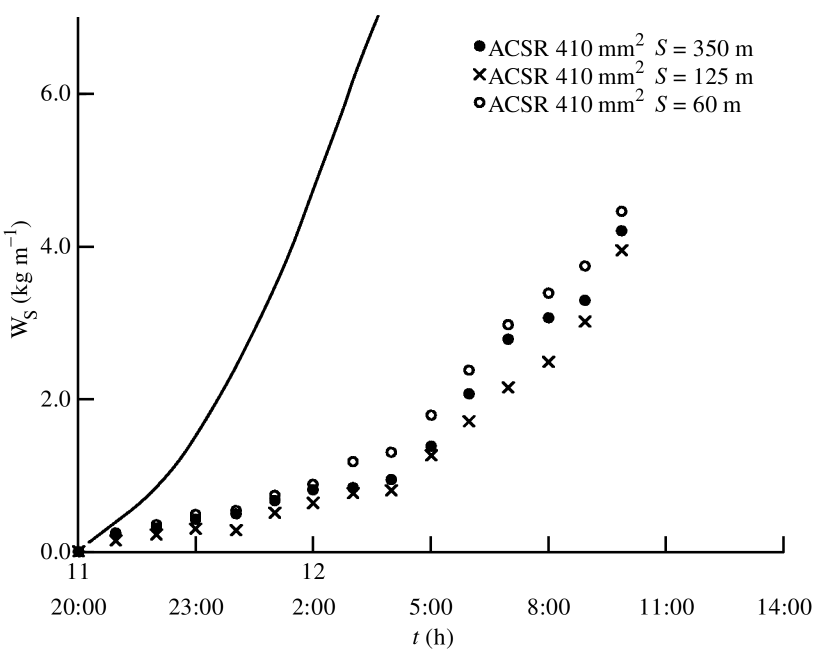

Figure 3. Time history of amount of snow accretion on wires.
Calculated using equation (3.1) $\rho_S = 0.1$ g cm^{-3}.

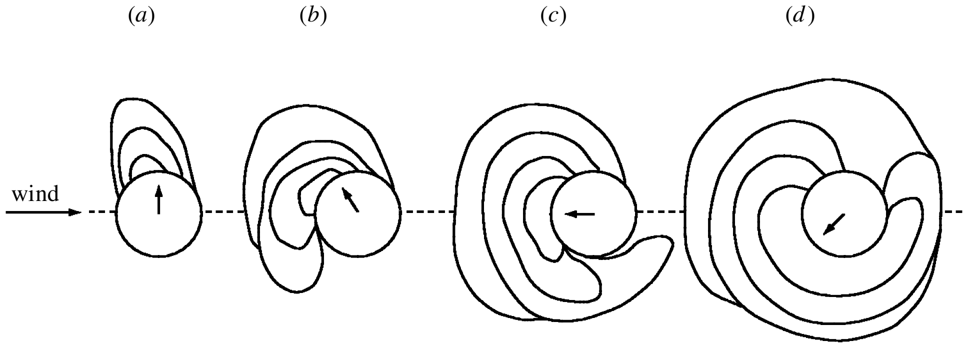

Figure 4. Growing process of a snow sleeve for dry-type accretion.

Because snow accretion giving rise to heavy load on power lines occurs at temperatures above freezing with superposed relatively high precipitation intensity (wet snow), this paper concentrates on the process of wet-snow accretion. However, in the following subsection, snow accretion at sub-freezing temperatures will be briefly described for completeness.

(b) *Snow accretion on overhead wires at sub-freezing temperatures*

In Ishiuchi, located in Niigata Prefecture (the Japan Sea side of the main island), where the test lines were installed, many cases of snow accretion on wires were observed for almost the same conditions as shown in figure 2 (see Sakamoto *et al.* 1990); the growing process was also recorded and is conceptually depicted in figure 4.

As shown in figure 4*a*, snow initially accumulates as a pile on wires. In this stage, snow piled on the wire will be blown off if the wind speed is over 2 m s^{-1}. If snowfall continues under calm conditions, the height of the snow piled on the wire increases gradually and the top of the piled snow is inclined toward the wind and the incoming snowflake trajectories. The snow piled on the wire now suddenly begins to creep into the wind (as shown in figure 4*b*). This is the second stage of the growing process. The speed of creep is in general relatively high, and when viewed from the downstream side of the wire the piled snow disappears from the top of the wire and reappears at the bottom within 5 min. If snowfall continues, the piling and creeping of snow repeats, and finally a cylindrical snow sleeve is formed via the processes depicted in figure 4*c*, *d*. It should be noted that the density of snow accreted during these processes at sub-freezing temperature is in general very low and never exceeds 0.1 g cm^{-3}; moreover, the adhesive force will be also very low.

The cases depicted in figure 4 are an example of ideal growth. In many cases, snow piled on wires drops spontaneously during the second and third stages of growth. This is especially true for wires of small size and low torsional rigidity, or under relatively high wind speed (for example, 1.5 m s^{-1}) when the wire begins to twist and piled snow tends to drop off, not allowing the creep stage to start. Consequently, growth of this kind of snow accretion under sub-freezing temperatures (dry-type snow accretion) will be limited to low- or medium-voltage lines having low height above ground and shielded against wind action. In addition, it is inferred that this type will scarcely give rise to high overload governing mechanical design of lines. However, it should be pointed out that even if it completes the growing process and a cylindrical snow sleeve is formed around the entire span of the wire, it tends to drop simultaneously, and may cause jumping of the wire due to transformation of the potential energy stored in the wire to kinetic energy through increased wire tension. Inferred mechanisms leading to snow accretion will be discussed in the following section.

(c) *Inferred mechanisms of snow accretion on overhead wires*

For snow accretion to form a cylindrical sleeve (causing heavy overload to power lines without shedding) there must be an adhesive force between the surface of the wire and the snow accumulation and between snowflakes themselves. Indeed, if these adhesive forces do not exist, then all snowflakes piled on the wire will be blown off by wind and not observed to adhere. In the cases in which heavy load on wires has been experienced, cylindrical snow sleeves have been observed without exception and the mechanism for such growth depends on adhesive forces. Some of the origins of adhesive forces between the surface of wires and snowflakes, and between snowflakes themselves, are as follows.

(1) Freezing (including pressure melting, re-freezing).

(2) Bonding through freezing of supercooled water droplets existing on the surface of snowflakes.

(3) Sintering.

(4) Condensation and freezing of vapour in the air.

(5) Mechanical intertwining of snowflakes.

(6) Capillary action due to liquid water included.

(7) Coherent force between ice particles formed through metamorphosis of snowflakes.

In general, the occurrence of freezing is limited to below 0 °C, and bonding action of supercooled droplets is also expected below 0 °C (although, in temperatures slightly above 0 °C, freezing can occur through dissipation of heat with evaporation and sublimation, but this effect is expected to be small).

Therefore, in cases where the air temperature is relatively low, adhesive mechanisms (2), (3), (4) and (5) are expected to dominate. Of course, the occurrence of freezing can be expected, but in sub-freezing temperatures it has been confirmed that the liquid-water content of snowflakes is very low. On the other hand, in cases where the temperature is higher, mechanisms (6) and (7) are expected to dominate.

Thus, dominant adhesive mechanisms are influenced by the liquid-water content of snowflakes, air temperature, humidity and speed of air carrying snowflakes. The action of wind is threefold: it compacts the accreted snow; it increases the impact speed of snowflakes on wires or snow sleeves; and it accelerates the metamorphosis of accreted snow.

Generally speaking, the liquid-water content of the snow is higher when the air temperature is higher. However, it is not true that there is no liquid water included in snowflakes in sub-freezing temperatures. This is because water is a substance that can be kept at liquid state at temperatures as low as −35 °C without ice nuclei and also it has a relatively high specific heat. The ice crystal itself is enriched in ice nuclei, and whether the liquid water contained in a snowflake is frozen or not is governed by the heat balance for the flakes. For example, when an atmospheric layer with a temperature above freezing exists over a near-ground sub-freezing layer, and when some portion of the ice inside the flakes is melted, liquid water will exist, even when the surface temperature is sub-freezing, until latent heat is dissipated by heat exchange. Therefore, strictly speaking, the boundary between wet snow and dry snow cannot be defined simply on the basis of the surface temperature.

As mentioned previously, the characteristics of accreted snow and growth processes are strongly dependent on adhesive mechanisms. However, the author considers that it is acceptable to distinguish wet snow from dry snow based on surface air temperature (that is, above or below freezing) from the standpoint of the phenomenon that occurs on power lines, rather than attempting to employ physical or meteorological arguments.

Indeed, the author suspects that for dry snow the dominant adhesive forces are pressure melting (re-freezing) and sintering (Sakamoto *et al*. 1990), and for wet snow, capillary forces due to liquid water and coherent forces between ice particles formed through the metamorphosis of snowflakes dominate. It should be noted that Colbeck & Ackley (1982) presented similar mechanisms for the formatting of wet-snow accretion.

In addition, it should be noted that if the temperature falls below freezing after wet snow has accreted on a wire, it will then freeze. When this happens, the adhesive force is significant, due to the hydrogen bond between the wire surface and the ice particles, and also bonding between ice particles will be enhanced due to freezing. In such instances, a wet-snow sleeve is hardly shed, even under strong winds, and may give rise to high combinations of snow and wind load, and may also cause galloping. When sleet falls are experienced, the solid-state ice contained in the sleet may be frozen on the wires through heat dissipation by evaporation and may result in galloping.

(*d*) *Mechanics of snow accretion on overhead wires*

The shape of snow accreted on overhead wires is governed by many factors, including: meteorological parameters such as temperature, humidity, wind speed and wind direction relative to lines; and line parameters such as material, size, stranding, supporting manner and span length. The shape of the accreted snow, as well as its orientation on a wire, may enhance the formation of cylindrical sleeve growth and lead to heavy overload, and it may also cause galloping.

Obviously, the shape of the wire effects the growing process. Although this problem has no direct relation to overhead-line loading, it nevertheless should be investigated so as to yield a better understanding of snow accretion on wires.

In Japan, it was assumed that wet-snow accretion is a phenomenon which occurs only under low wind speed. Shoda (1953) installed a test line in Shiozawa (Niigata Prefecture) and made observations under natural conditions over long periods. He reports that the growing process on a solid wire (a cylinder having a smooth surface) used mainly for communication lines was as follows.

(1) First stage: piling of snow on wire.

(2) Second stage: sliding of accreted snow on wire, without twisting of wire.

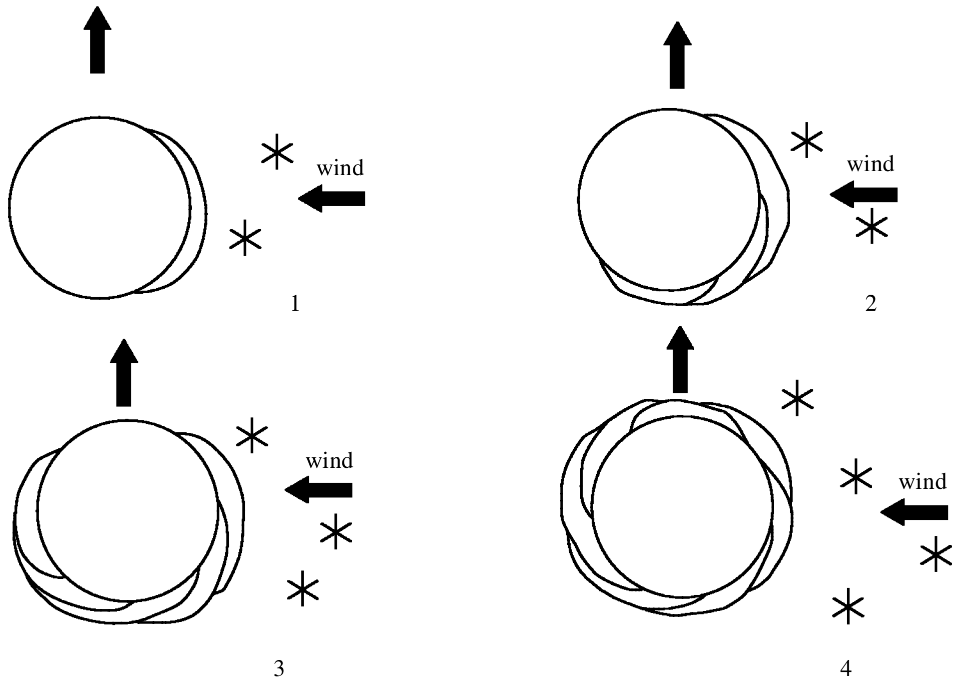

Figure 5. Wet-snow accretion on a smooth cylinder.

(3) Repetition of first and second stages.

(4) Formation of cylindrical snow sleeve without twisting of wire.

Growing processes in accord with his observations are illustrated schematically in figure 5. These processes have been confirmed for a larger size (diameter of 2 cm) smooth cylinder using wind-tunnel facilities to suggest a kind of countermeasure for reducing snow mass on wires. That is, when a tiny fin is placed around covered conductors, the snow piled on the wire cannot slip around the wire and the formation of cylindrical snow sleeves is prevented.

The development of cylindrical snow-sleeve growth on a stranded wire, as used for power lines, is completely different from the above (see Admirat *et al*. 1986; Admirat & Sakamoto 1988). Here, the growth rate depends on the torsion of the wire. The growing processes for a cylindrical snow sleeve around a stranded wire are shown schematically in figure 6.

In the centre of the wire span, where the wire is horizontal, there is no slippage or relative movement between the wire surface and accreted snow. Moreover, since the torsional rigidity of the wire, especially in centre portion of a long span, is relatively low, the wire is easily twisted around its axis due to the twisting moment induced by the eccentric weight of accreted snow. As discussed later, wet snow tends to accrete on the windward side of the wire under medium- or high-wind conditions, and the rotating of the wire is further increased by the effect of wind pressure. Also, the shape of the snow accreted on a wire differs as a function of locations along the wire span. This snow accretion problem is studied in detail in Poots & Skelton (1988, 1993)

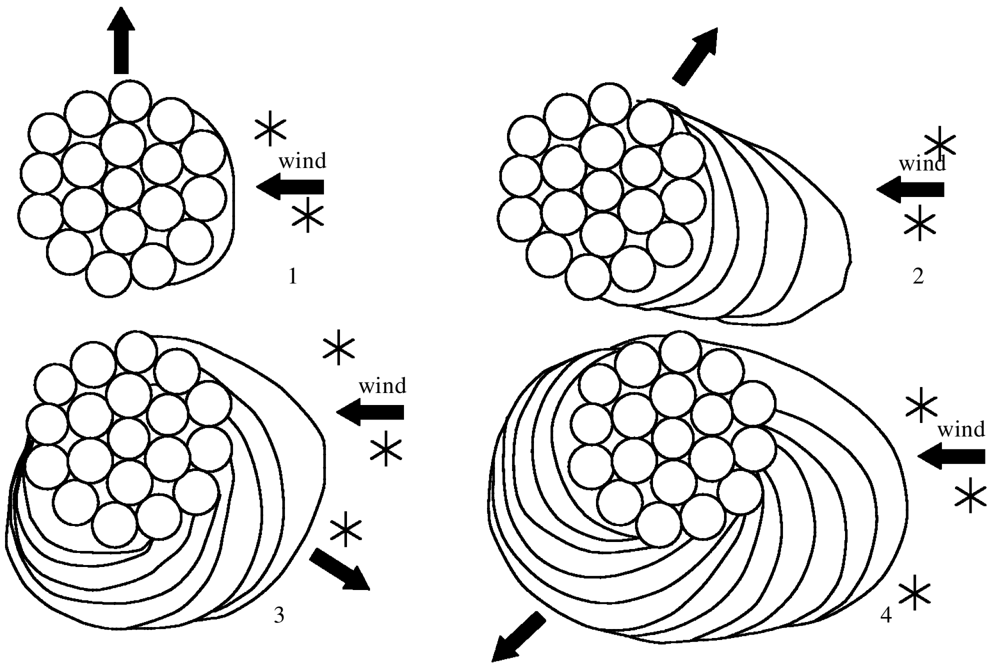

Figure 6. Wet-snow accretion on a stranded wire having low torsional rigidity.

and Poots (1996). Here, time-dependent models are developed which incorporate the effect of wind pressure and the torsional properties of the wire.

It has also been observed that, at least initially, snow accreted slightly above the centre of the windward side of the wire, and then suddenly the wire twisted more than 10° on further accretion. Thus the mass of snow accreted will be greater in the centre portion of the span and lesser closer to either end of the span. These observations suggest that when the torsional rigidity of the wire is increased, the mass of the accreted snow will decrease. Experiments on attaching counterweights to a span to increase the torsional rigidity of the wire have been undertaken in France and Japan and proved to be effective in reducing load in some cases; to date, the effectiveness of such countermeasures have not been fully evaluated in Japan. Wet-snow accretion on a torsionally rigid wire is shown schematically in figure 7. It can be seen that an increase of the area projected to the wind in which snow accreted further will be smaller, and the accretion efficiency will be smaller, due to the trajectories of snowflakes around the wire (see Wakahama 1979).

(*e*) *Heat balance during snow accretion*

The study of the heat balance for the accreted snow provides information on melting and the prevention of accretion by load current of power lines. This was first analysed by Grenier *et al.* (1986) and Admirat *et al.* (1988*a*) (see the summary of Poots 1996). The relevant heat fluxes incorporated in the heat balance during cylindrical-sleeve growth are as follows:

$$Q_{\mathrm{A}} = Jh(T_{\mathrm{A}} - T_{\mathrm{S}})\pi D, \tag{2.1}$$

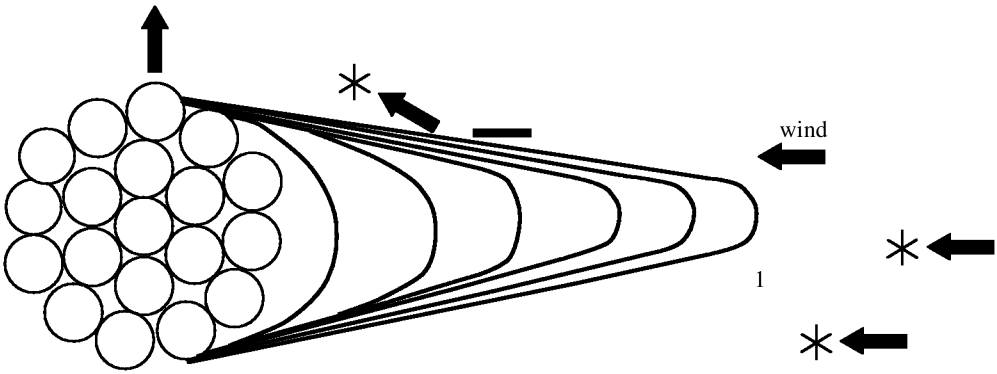

Figure 7. Wet-snow accretion on a torsionally rigid stranded wire.

where Q_A is the heat supplied through convection (W cm^{-1}), J is the mechanical equivalent of heat ($J = 4.186$ J cal^{-1}), h is the coefficient of heat transfer (cal cm^{-2} s^{-1} °C), T_A is the air temperature (°C), T_S is the temperature of snow surface accreted (°C), and D is the diameter of accreted snow (cm).

The coefficient of heat trasnfer (h) is related to the Nusselt number Nu, and is expressed as follows:

$$h = (\lambda/D)Nu, \tag{2.2}$$

where λ is the thermal conductivity of air. Furthermore, Nu is related to the Reynolds number Re, and Grenier *et al.* (1985) have proposed the following approximation:

$$Nu = 0.2Re^{0.61} \quad (\text{for } Re \leqslant 10^4). \tag{2.3}$$

The Reynolds number is defined by

$$Re = V\rho_A/\mu, \tag{2.4}$$

where V is the horizontal wind speed (cm s^{-1}), ρ_A is the density of air at temperature T_A (g cm^{-3}), and μ is the kinematic viscosity of air at temperature T_A (g cm^{-1} s^{-1}).

Substituting (2.2), (2.3) and (2.4) into (2.1) yields

$$Q_A = 2.63\lambda(\rho_A/\mu)^{0.61}(VD)^{0.61}(T_A - T_S). \tag{2.5}$$

In cases of wet snow, T_A is above freezing and hence ice and liquid water coexist; it follows that $T_A = 0$ °C. Employing the values $\rho_S = 1.293 \times 10^{-3}$ (g cm^{-3}) and $\mu = 1.73 \times 10^{-4}$ (g cm^{-1} s^{-1}) yields the following approximation:

$$Q_A = 0.52(VD)^{0.61}T_A \times 10^3. \tag{2.6}$$

For the case when T_A is negative (that is, sub-freezing), it may be assumed that $T_A = T_S$ and $Q_A = 0$.

Since the wire carries electric current, ohmic heating of the wire is supplied to the snow accreted by conduction. The Joule heat generated by current Q_J (W cm^{-1}) may be calculated as follows:

$$Q_J = I^2 R_{\mathrm{AC}\,T_C}, \tag{2.7}$$

where $R_{\mathrm{AC}\,T_{\mathrm{C}}}$ ($\Omega\,\mathrm{cm}^{-1}$) is resistance of wire for alternating current at temperature T_{C} and is given by

$$R_{\mathrm{AC}\,T_{\mathrm{C}}} = K_1 K_2 R_{\mathrm{DC20}} \times 10^{-5}\{1 + w_{20}(T_{\mathrm{C}} - 20)\}, \tag{2.8}$$

where w_{20} is the thermal coefficient of resistance of the wire at 20 °C, R_{DC20} is the resistance of the wire for direct current at 20 °C ($\Omega\,\mathrm{cm}^{-1}$), K_1 is the factor taking into account the skin effect of the wire, and K_2 is the factor taking into account the eddy current loss of the wire, including the ferrous component. K_1 and K_2 can be calculated by the following approximations:

$$K_1 = 1 + 1.56 \times 10^3\{0.05\sqrt{f}/R_{\mathrm{DC20}}\}^{3.93} \tag{2.9}$$

and

$$K_2 = \begin{cases} 1 & \text{for small ACSR,} \\ 1.025 & \text{for larger ACSR,} \end{cases} \tag{2.10}$$

where ACSR refers to aluminium conductor steel reinforced wire.

For wet-snow accretion, vapour pressure at the surface may be assumed to be at the saturated value, since ice and water are co-existent. If a difference exists between the saturated vapour pressure and the vapour pressure of the surrounding air, then evaporation or condensation occurs. Heat loss (or gain) due to evaporation (or condensation) is expressed as follows:

$$Q_{\mathrm{C}} = h(Pr/Sc)^{0.63}(L_{\mathrm{V}}/C_p)\varepsilon(\Delta P_{\mathrm{C}}/P)\pi D, \tag{2.11}$$

where h is the coefficient of heat transfer by convection ($\mathrm{cal\,cm^{-2}\,s^{-1}\,°C}$), Pr is the Prandtl number (equal to $\mu \times C_p/\lambda \approx 0.718$ at 0 °C), Sc is the Schmidt number (equal to $\mu/\rho_{\mathrm{A}} \times D_{\mathrm{B}} \approx 0.608$ at 0 °C), L_{V} is the vaporization heat of water (equal to 2500 J g^{-1}), C_p is the specific heat of air at constant pressure (equal to 0.24 cal g^{-1} °C), P_{C} is the difference between vapour pressure of air at T_{A} and saturated vapour pressure of air at 0 °C (Pa), P is the atmospheric pressure (Pa), D is the outer diameter of accreted snow (cm), and D_{B} is the diffusion coefficient of water vapour in air (equal to 0.22).

In the case when $P = 1000$ Pa, the value of Q_{C} is approximated by

$$Q_{\mathrm{C}} = 0.89(VD)^{0.61}\Delta P_{\mathrm{C}} \times 10^{-3}. \tag{2.12}$$

In addition to the above, heat will be dissipated due to melting of snow;

$$Q_{\mathrm{F}} = \alpha(1-\gamma)\beta PNL_{\mathrm{F}}D, \tag{2.13}$$

where Q_{F} is the heat loss due to melting of snow ($\mathrm{W\,cm^{-1}}$), α is the accretion efficiency (portion of snow contributing to accretion in the amount of snow passing around wire or accreted snow (discussed in later sections)), γ is the portion of liquid water in snowflakes, β is the portion of melted snow in accreted snow, P_n is the amount of snow accreted during unit time (discussed in a later section, see (3.2)), and L_{F} is the latent heat of fusion (equal to 335 J g^{-1}).

There are other effects which may contribute to the heat balance, such as heat radiated from surface of the accreted snow and solar radiation, but these are negligible during the growth of the snow sleeve.

The heat balance on the surface of the wire or accreted snow is now approximated by

$$Q_A + Q_J - Q_F + Q_E = 0. \tag{2.14}$$

When applied to practical cases, the current required to prevent or melt accreted snow can be deduced from the heat balance (see the theoretical model of Admirat *et al.* (1988*a*)).

In this context, it should be noted that the current required to prevent snow accretion is much smaller than that needed to melt the snow.

3. Estimation of wet-snow load

(*a*) *History and background*

Although snow accretion on overhead wires can occur under a wide range of meteorological conditions, the occurrence of heavy overload is confined to wet snow falling in a positive air temperature. In establishing appropriate design load of overhead lines, the ice (snow) load, having a certain long return period, should be determined and used (see IEC 1991).

Such research on design overloads continues in France, Norway, Iceland and the UK, etc. (see Ford 1986; Admirat *et al.* 1988*b*; Baldit *et al.* 1988; Finstad *et al.* 1990; Makkonen & Ahti 1993; Kiessling & Ruhnau 1993; Eliasson & Thorsteins 1993, 1996; Krishnasamy & Fikke 1998; Yukino *et al.* 1998).

In the early stages of such work in Japan, it was assumed that wet-snow accretion only occurred at low wind, as previously noted. Shoda (1953) proposed a method for estimating wet-snow load on communication lines, based on his observations and the assumption that all of the fallen snow passing within the horizontal projected area of the accreted snow (initially that of wire) will contribute and accrete on the wire as a cylindrical sleeve. The relationship between the diameter of the snow sleeve and the depth of new-fallen snow based on the above assumptions is given as follows:

$$D_S = N/\pi, \tag{3.1}$$

where D_S is the diameter of snow accreted on the wire (cm) and N is the depth of fallen snow (cm). In figure 8 the results and those predicted by (3.1) are displayed. Based on this relationship, it is now possible to calculate, in a simple manner, the diameter of the snow sleeve once the amount of fallen snow accumulated is known. Shoda (1953) also proposed to calculate the mass of snow using a density of 100 kg m^{-3}, since his observations were limited to low wind speeds. In fact, he assumed that the density of the accreted snow was the same as the new-fallen snow.

Based on his observations, he also concluded that, for large wires, growth to a cylindrical sleeve shape was less probable than in the case of small solid wire. This is because, for large wires, it takes longer for cylindrical-sleeve growth and, during this time, the possibility of spontaneous shedding is much higher. In further experiments to be discussed later, the growing process will be significantly different between the stranded wire usually used on power lines and the solid wire used for communication lines. In particular, the calculated results based on Shoda's method are a conservative estimate of snow load during low wind speed and irrespective of air temperature (as shown in figure 3 (solid line)). To this author's knowledge, the above is the earliest study of snow accretion undertaken in Japan.

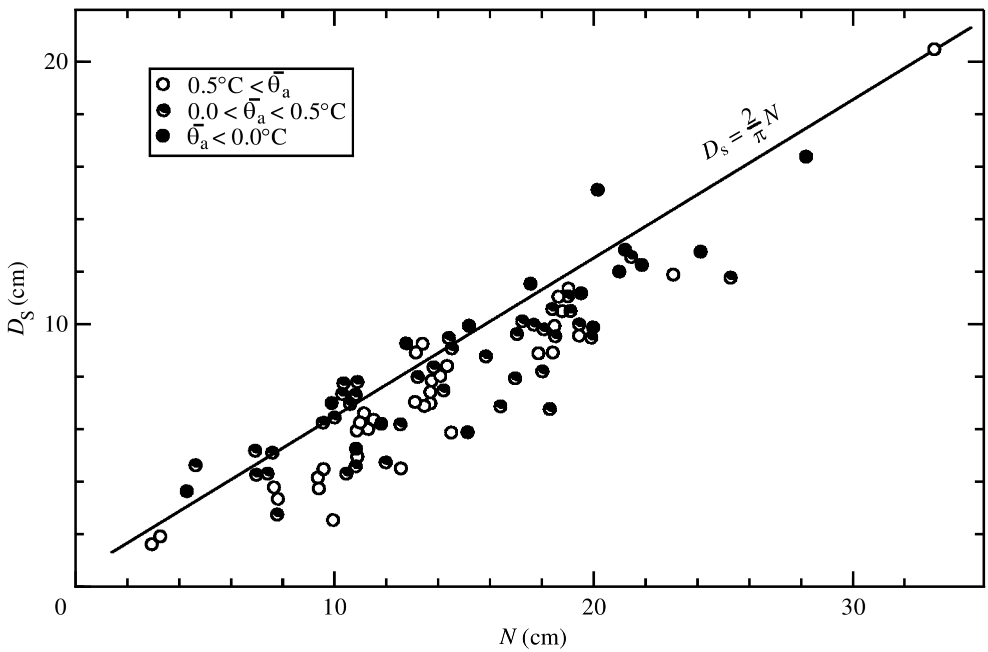

Figure 8. Relationship between depth of newly fallen snow (N) and diameter of accreted snow (D_S). $\bar{\theta}_a$ is ambient temperature during accretion.

Since the Japanese utilities experienced severe damage to their power lines, including many tower collapses, in 1963, 1972 and 1981, a great deal of research has been undertaken to understand wet-snow accretion and to develop methods for estimates for snow load on power lines. Methods for decreasing snow loads on wires has also been done by all utilities and associated organizations such as CRIEPI.

As mentioned previously, the author is unaware of any satisfactory physical model of snow accretion. Many problems remain to be solved and research efforts continue in many countries. In the following sections, results so far obtained will be briefly described in the hope that this is useful in avoiding repetition of research efforts.

(*b*) *Wet-snow accretion on wires under windy conditions and the cylindrical-sleeve model*

Shoda's (1953) study dealt mainly with snow accretion at low wind speeds. As described above, the utilities of Japan experienced severe damages to power lines under conditions where wind action could not be neglected. Thus Sakamoto & Ishihara (1984) developed a new method based on the use of the cylindrical-sleeve model. That is, when wind action is taken into account, the value of the snow precipitation intensity P_n is approximated by

$$P_n = P\sqrt{1 + (V \sin\theta/V_N)^2}, \tag{3.2}$$

where P is the intensity of precipitation observed on ground surface (g cm^{-2} s^{-1}), V is the wind speed (cm s^{-1}), V_N is the falling speed of snowflake (cm s^{-1}), and θ is the angle between the axes of wire and wind direction.

Now, if it is assumed that the amount of snow accreted on the wire is P_n multiplied by α (where α is an accretion factor), and that the snow accreted on the wire is cylindrical in shape, it follows that

$$2\pi R\rho_{\mathrm{S}}\,\mathrm{d}R = \alpha P_n 2R\,\mathrm{d}t, \tag{3.3}$$

where R is the radius of accreted snow (cm) (radius of wire + thickness of accreted snow $= R_0 + r$), ρ_{S} is the density of accreted snow ($\mathrm{g\,cm^{-3}}$), t is the time (s), r is the thickness of accreted snow (cm), and R_0 is the radius of the wire (cm).

The sleeve thickness now becomes

$$\mathrm{d}R = \frac{\alpha P_n}{\pi\rho_{\mathrm{S}}}\,\mathrm{d}t \tag{3.4}$$

and the mass of snow accreted, $\mathrm{d}W$, per unit length of wire is

$$\mathrm{d}W = 2\pi R\rho_{\mathrm{S}}\,\mathrm{d}R, \tag{3.5}$$

where W is measured in $\mathrm{g\,cm^{-1}}$.

Integrating (3.4) and introducing initial conditions yields

$$R - R_0 = t = \int_0^t \frac{\alpha}{\pi\rho_{\mathrm{S}}} P_n\,\mathrm{d}t = \frac{\bar{\alpha}}{\pi\bar{\rho}_{\mathrm{S}}}\bar{P}_n t, \tag{3.6}$$

where the bar denotes average value of quantities taken over a time interval of accretion.

The outer diameter of the snow sleeve is $D = 2(R_0 + t)$ and, using (3.6), it follows that

$$D = \frac{2\bar{\alpha}}{\phi\bar{\rho}_{\mathrm{S}}}\bar{P}_n t + D_0. \tag{3.7}$$

The mass of snow accreted is given, on integration of (3.5), as

$$W = \int_{R_0}^{R} 2\pi R\bar{\rho}_{\mathrm{S}}\,\mathrm{d}R = \pi\bar{\rho}_{\mathrm{S}}(R^2 - R_0^2) \tag{3.8}$$

and, on using (3.6), it follows that during cylindrical growth the mass of snow accreted is given by

$$W = \frac{\bar{\alpha}^2\bar{P}_n^2 t^2}{\alpha\bar{\rho}_{\mathrm{S}}} + D_0\bar{\alpha}\bar{P}_n t. \tag{3.9}$$

Although this equation is based on the use of mean values of α, P_n and ρ_{S}, it is possible to divide one event of accretion into subsequences and calculate the mass of snow for each subsequence using representative mean values of them, especially when they change significantly with time.

In this equation, the quantities P_n and t are known or can be estimated if synoptic meteorological parameters are available and, of course, the diameter of the wire D_0 is known. However, the quantities ρ_{S} and α are unknown and have to be estimated from available data.

When this model was proposed, few data were available for deriving empirical relationship for ρ_{S} and α, and this indicated a need for further experimental and observational research to make the model useful from a practical point of view. This work is now discussed.

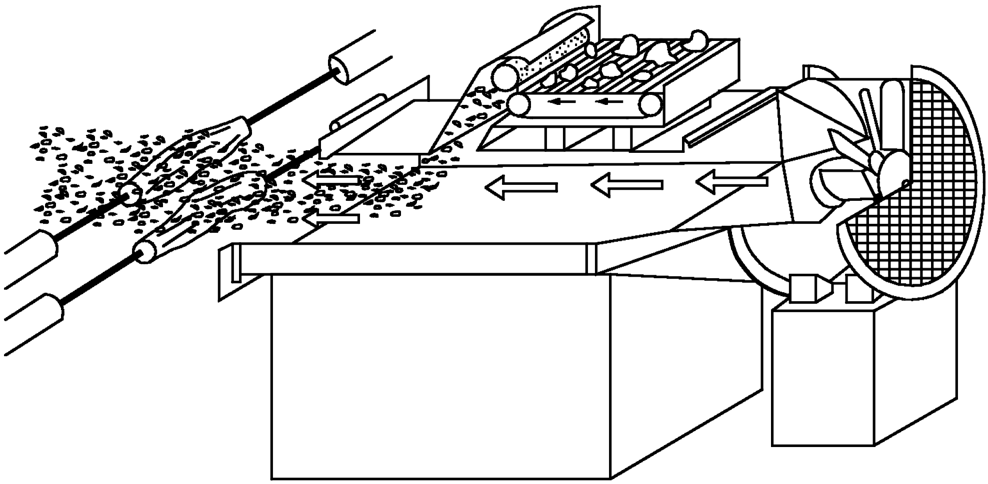

Figure 9. Arrangement of a wind-tunnel facility designed for producing wet-snow accretion under controlled atomospheric conditions.

(*c*) *Determination of the dependence of the density of snow sleeve* ρ_S *and accretion efficiency* α *on meteorological parameters using wind-tunnel facilities*

(i) *Purpose of experiments and facilities employed in the study of wet-snow accretion*

Although, as will be discussed later, artificial wet-snow accretion experiments have some important drawbacks in simulating natural wet-snow accretion, it is a useful tool for obtaining the qualitative dependence of wet-snow accretion on various meteorological parameters.

Of course, observations of natural snow accretion carried out in the field are ideal. However, in Japan, occurrences of heavy snow load at specific locations may be few; note also that the installation of test spans and supporting equipment for measuring mass and density, as well as meteorological parameters, is prohibitively expensive. Consequently, it was decided to construct empirical models for estimating ρ_S and α based on the limited results of measurements of natural cases. Such results contain some uncertainties and apply to a relatively narrow range of parameters, and for these reasons they are augmented with results of wind-tunnel experiments.

The wind-tunnel facility used for artificial wet-snow accretion experiments is shown in figure 9. The facility consists of a blower for generating wind (wind speed variable continuously), a rotating cylinder with many protrusions with which small pieces of snow may be scratched off from a mass of sample snow and fed into the airstream, a horizontal conveyor belt for carrying snow samples to the rotating cylinder, and wire samplers for capturing snowflakes blown off from the outlet of the tunnel. The length of the wire samplers was 2 m, and torsional springs were attached on each end for simulating torsional rigidity of the centre portion of wire spans with varying span length. The facility was installed in a hut in which the temperature could be controlled and kept relatively constant. Snowfall intensity was simulated by changing the amount of the snow sample carried by the horizontal belt conveyor.

Just prior to and after each experiment, the amount of snow passing around the wire sample (P_n) was measured using a specially designed capturing box with a heater. Each end of the wire sampler was supported via load cells and the increase in mass of accreted snow was recorded automatically. Rotation of wire samples with eccentric growth of accreted snow was measured with a potentiometer and also recorded.

In addition, the density and liquid-water content of the accreted snow and sample snow were measured by weighing samples removed by a small-size sampler and by use of a calorimeter, respectively.

In the experiments, several methods for obtaining 'wet snow' as realistically as possible were employed. For example, methods for injecting a water spray simultaneously with the snow sample and the heating of the snow sample using infrared lamps were tried. In the former method, it was verified that the water droplets injected into the airstream were blown off from the outlet separately, and in the latter method it proved difficult to heat the snow sample evenly. Consequently, both of these methods were unacceptable. Finally, the technique of lowering the speed of the conveyor belt carrying the snow samples was used, based on the inspection of microscopic photographs of snowflakes collected at the outlet of the wind-tunnel.

Experiments were conducted using fresh snow samples that had not experienced positive air temperature, solar radiation or rain after accumulation on the snow cover. Indeed, it was verified that results of the experiments differed significantly on using fresh or metamorphosed snow.

Experiments were carried out corresponding to a number of combinations of parameter ranges expected to occur in natural conditions.

In addition, the influence of Joule heat on the snow accretion was investigated yielding data on the lower limit of current necessary for preventing snow accretion and melting of the accreted snow sleeve.

The experiments were carried out as cooperative work between Electricité de France and CRIEPI for three winters.

(ii) *Density of accreted snow*

The results of experiments were analysed using the method of multiple regression analysis, taking density as the criterion variable and meteorological parameters as the functional variables, to yield the qualitative dependence of wet-snow accretion characteristics on meteorological parameters. The following equation, expressing the density of accreted snow as a function of the main parameters, was obtained:

$$\rho_S = 0.671V - 0.0103V^{1.1} + 0.0574T - 0.0107P_n - 0.048, \quad (3.10)$$

where ρ_S is the density of accreted snow ($\mathrm{g\,cm^{-3}}$), V is the wind speed ($\mathrm{m\,s^{-1}}$), T is the air temperature (°C), and P_n is the amount of snow passing around the wire per unit time.

The number of data used for deriving the equation was $n = 106$ and the multiple correlation coefficient was found to be $r = 0.87$.

Equation (3.10) introduces the second term to avoid overestimation of the density. The equation implies that increasing the wind speed and increasing the temperature have the effect of increasing the density. Moreover, increasing the amount of snow fed to the sleeve has the effect of decreasing the density. When considering the

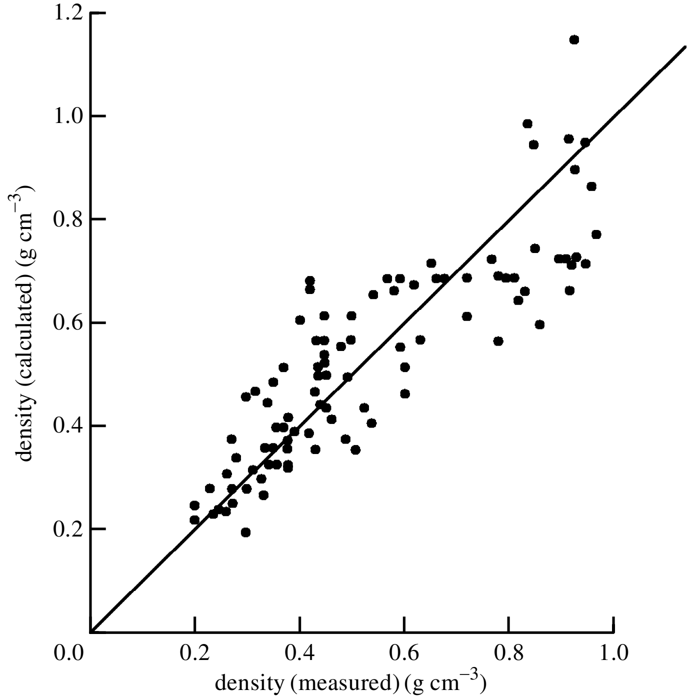

Figure 10. Comparison between measured and calculated densities (artificial) ($n = 106$, $r = 0.87$).

effect of changing ranges of parameters, it is clear that wind speed is the most significant. Since the density of water and ice are almost the same, the density of the snow sleeve is mainly governed by air contained in the structure and, if the wind speed is increased, greater compaction will take place. The density of accreted snow will, in principle, be at its maximum when the sleeve consists of liquid water and metamorphosed ice particles without the inclusion of air (see the photographs in Colbeck & Ackley (1982)). It can lie in the range 0.9–1.0 g cm^{-3}, and such cases have been observed at higher wind speeds (for example, 15 m s^{-1}).

Thus general trends expressed in (3.10) are physically acceptable. In figure 10, measured densities during experiments are compared with calculated measurements using (3.10).

(iii) *Accretion efficiency*

Since the mass of snowflakes is relatively high, the collision coefficient on a wire will be close to unity for wind speeds higher than, say, 5 m s^{-1}. This fact is shown clearly in experiments by Eeles *et al.* (1986), on using a water-tunnel simulation. However, not all impacted snowflakes on the wire or snow sleeve necessarily contribute to an increase in the mass of the sleeve. Some of the flakes will rebound and not accrete and some may melt. In addition, although the cylindrical sleeve model is useful from a practical viewpoint, it ignores the effect of the torsional rigidity of the wires and, moreover, for practical power lines, the accreted snow does not always keep this cylindrical shape. Recently, time-dependent models, taking into account the effect of the torsional rigidity of wire and yielding the shape of accreted snow along the span, have been developed by Poots (1996). Essentially, these models should be further developed with the aid of empirical models derived from experiments. In the following, the effect of torsional rigidity is assumed to be included in the observed accretion efficiency. It should also be emphasized that, when taking into account the effect of torsional rigidity of a wire span, the so-called accretion efficiency must also be a function of material, stranding and size of the wire, as well as the span length and locations along the span.

In many cases it has been observed that snow accreted on a wire can be shed spontaneously. This phenomenon is important in making a realistic estimate of snow load but, unfortunately, conditions and mechanisms for shedding are as yet not fully understood. It must be emphasized that the accretion efficiency used in practice ignores shedding and this could be critical in estimating the possible maximum snow overload.

From results of artificial accretion experiments in which cylindrical sleeves formed the accretion, efficiency was deduced from the measured mass of the sleeve and the density using (3.9). Multiple regression techniques were also completed, with the accretion efficiency taken as the criterion variable and meteorological parameters as functional variables. The following equation expresses the accretion efficiency as a function of the basic parameters:

$$\alpha = 0.624 \exp\{-0.0865(T - 3.27)^2\} \times \exp\{0.0621V - 0.744P_n\}. \tag{3.11}$$

Here, the same notation is used as in (3.10). The number of data used for analysis was $n = 52$, with the multiple correlation coefficient $r = 0.84$. The reason that the data used here were fewer than in the study of density is due to the rejection of data involving snow shedding.

This equation implies that the accretion efficiency has a maximum at $T = 3.27$, but this value is expected to overestimate the real values.

From a physical viewpoint, it is suspected that when the air temperature decreased close to freezing, the liquid-water content which aids the sticking process decreased and flakes tended to rebound; when temperature increased above the critical value, the heat flux induced by wind convection melted much of the snow.

The wind speed may have several effects on the accretion efficiency (for example, the change in snowflake trajectories, the collision speed on the sleeve, the change in heat flux), but to date the predominate effect has not been isolated. In figure 11, a comparison is given between calculated and observed values for the accretion efficiency (regarding the latter, see Tachizaki *et al.* (1988)).

In addition, the effects of the liquid-water content of the snow sleeve and that for the load current were investigated and analysed, but these results are not presented in this paper.

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(iv) *Defects of artificial experiments (lack of equivalency with natural cases)*

As previously pointed out in Sakamoto *et al.* (1988*a*), although artificial accretion experiments are a useful tool in understanding the role of the various parameters in the snow accretion phenomenon, it does not give the complete picture. First of all, it should be pointed out that there is a real difficulty in reproducing the relationship between the liquid-water content of snowflakes and the air temperature in natural

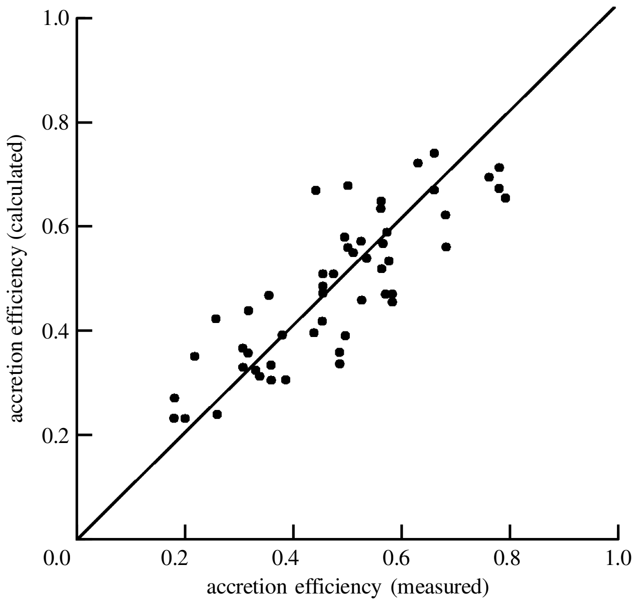

Figure 11. Comparison between measured and calculated accretion efficiencies (artificial) ($n = 52$, $r = 0.84$).

conditions. In a natural snowfall, snowflakes may travel a relatively long time through a positive temperature air layer in which the surface temperature is above freezing. However, in the case of artificially generated 'wet snow', much less time is available for heat exchange with the surrounding air. Attempts were made to lengthen the time prior to accretion on the wire sample but in practice it was difficult to do so; snow samples sticking everywhere on the facility, with increasing deficiencies in experimentation. Clearly, the liquid-water content of 'wet snow' under experimental conditions was suspected to be less than natural value at the same temperature.

Regarding questions of equivalency between conditions in the artificial experiments and the natural observations, further work must be undertaken before quantitative agreement can be established.

The difficulties involved are summarized as follows.

(1) The snowfall intensity selected for experiments was too high compared with natural values, thus shortening the time required in a sequence of the simulation. Consequently, in the experimental work, snow accretion on wire occurred for temperatures as high as 4–5 °C, which, under natural conditions, would have turned the precipitation to rain.

(2) Regarding wind speed, it was possible to reproduce any mean speed, but fluctuations and uneveness in speed with respect to vertical locations within the test area could not be eliminated.

(3) The relative humidity of air was kept above 80%, but it was thought that this value was slightly lower than in natural conditions, due to the fact that the temperature within the hut had to be kept higher than the outdoor value so as to obtain 'wet snow'.

It was concluded that heat exchange under natural conditions was not simulated exactly, and some caution must be exercised in the use of the above equations for density and accretion efficiency in real situations.

(*d*) *Derivation of empirical equations based on data of natural observations*

During the research projects, observations of natural snow accretion were requested from all utilities in Japan using a unified format for methods for observation and instruments used (see Sakamoto *et al*. 1988*b*). Measurements of the mass, density, shape and liquid-water content of accreted snow, as well as meteorological parameters such as air temperature, humidity, precipitation intensity, speed and direction of wind, were obtained. To facilitate this exercise, an observation manual including videotape instruction was prepared and distributed, so as to avoid errors due to the use of different procedures. Instruments for measurements were specified in detail. In particular, a common difficulty was encountered when measuring the diameter of snow sleeves on energized power lines when observed from the ground surface. For this, a special method using optical instruments with scale and distance meters was developed and specified for use.

Some results about natural wet-snow events were reported during the project, including results for operating lines and test spans. Some of the results are summarized in table 1, in which the observations for numbers 1–41 were obtained during the project and remaining ones were added from historical records and are thought to be relatively reliable.

Since these data were mainly observed on operating lines, some of the measurements relating to the mass of accreted snow involved estimation based on sag of span or direct measurements on short lengths of wire located close to line. Some of the data on density were measured after snow events or given by samples shed from the wires. Thus they include some uncertainty or unavoidable errors, as expected in such kinds of observations. In addition, meteorological parameters for some cases were made available from records of nearby observatories.

In table 1, the following notation is employed. V_{N} are mean values of the normal components of the wind speed to the line, using 10 min averages. T_{D} is the interface air temperature, which determines whether precipitation is rain or snow. The ratio of air temperature to T_{D} was taken because it has been found that T_{D} depends on altitude above mean sea level and the synoptic weather system under which precipitation was experienced, and it was thought that this interface temperature has an effect on whether the fallen snow is sticky (wet) or not. T_{D} has been analysed separately for representative synoptic weather systems such as monsoon-type and depression-type. For depression-type, T_{D} is expressed as a function of altitude above mean sea level H (measured in metres) as follows:

$$T_{\mathrm{D}} = 2.31 - 0.101 \times \ln(H). \tag{3.12}$$

Furthermore, P is the amount of precipitation water equivalent (measured in millimetres) during wet-snow conditions, P_n is the amount of snow passing around the wire (calculated from (3.2), $P_n t$ is the product of P_n and the duration time (in hours) of wet snow conditions, and α defines the calculated values for the snow accretion efficiency, deduced from density and mass measured using (3.9).

Table 1. *Summary of observations of wet-snow accretion on wires under natural conditions*

(Abbreviations in the column headings: no., number; ID, identification number of the company; alt., altitude; diam., diameter; wt, weight; AS, accreted snow; α, accretion rate (calculated). Data extracted from past records of faults of power lines. Refer to the text for a detailed explanation of the data.)

											meteorological parameters					
no.	ID	alt. (m)	date (dd/mm/yy)	diam. of wire (mm)	wt of AS (kg m^{-1})	size of AS (cm)		density of AS (g cm^{-3})	V (m s^{-1})	V_N	T	T/T_D	P	P_n	$P_n t$	α
1	1	30	6/4/84	18.2	5.0	10.0	10.0	0.7	7.0	4.9	1.7	0.86	1.8	8.8	10.50	0.86
2	1	7	6/4/84	11.1	5.5	10.0	10.0	0.7	7.0	4.9	1.9	0.90	3.4	16.9	13.50	0.739
3	1	5	10/2/85	7.8	(5.7)	11.5	9.0	(0.7)	11.8	11.5	0.6	0.28	0.9	10.4	15.53	0.673
4	1	14	20/2/85	18.2	0.5	(3.8	3.8)	(0.6)	9.0	8.3	1.3	0.64	2.0	16.8	6.69	0.300
5	1	5	10/2/85	13.5	0.7	5.0	3.0	0.7	7.0	2.7	0.8	0.37	3.4	9.9	6.91	0.419
6	1	8	21/2/85	13.5	0.6	4.0	4.0	0.54	5.0	3.7	0.4	0.19	0.7	2.2	3.36	0.712
7	2	5	19/2/83	10.5	1.2	5.0	5.0	0.64	7.2	6.5	0.1	0.05	0.6	3.8	9.09	0.446
8	2	5	19/2/83	10.5	1.6	6.0	4.5	0.77	7.2	6.5	0.1	0.05	0.6	3.8	9.09	0.507
9	2	5	19/2/83	18.2	1.1	5.5	5.3	0.52	7.2	6.5	0.1	0.05	0.6	3.8	9.09	0.355
10	2	5	19/2/83	18.2	1.1	6.0	5.5	0.47	7.2	6.5	0.1	0.05	0.6	3.8	9.09	0.342
11	2	5	19/2/83	18.2	0.5	4.0	3.5	0.60	7.2	6.5	0.1	0.05	0.6	3.8	9.09	0.281
12	2	5	19/2/83	18.2	1.0	6.0	5.5	0.43	7.2	6.5	0.1	0.05	0.6	3.8	9.09	0.321
13	2	5	19/2/83	18.2	0.8	5.0	4.5	0.55	7.2	6.5	0.1	0.05	0.6	3.8	9.09	0.296
14	2	5	19/2/83	18.2	0.6	4.0	4.0	0.62	7.2	6.5	0.1	0.05	0.6	3.8	9.09	0.252
15	2	5	2/3/83	18.2	2.3	6.5	5.8	0.86	6.3	5.8	−0.2	−0.09	2.2	12.8	7.65	0.809
16	2	5	2/3/83	18.2	2.2	6.0	6.0	0.85	6.1	5.8	−0.2	−0.09	2.2	12.8	7.65	0.783
17	2	300	20/4/84	18.2	(1.1)	(10.0	4.0)	0.39	2.0	1.4	1.3	0.75	2.5	4.3	6.02	0.482
18	2	100	10/2/85	18.2	1.9	7.6	6.0	0.57	7.8	7.6	0.5	0.27	1.2	9.9	20.72	0.227
19	2	100	11/2/85	10.5	(0.5)	(8.0	4.0)	(0.2)	1.1	0.2	−0.1	−0.05	1.8	1.8	4.96	0.303

Table 1. (*Cont.*)

no.	ID	alt. (m)	date (dd/mm/yy)	diam. of wire (mm)	wt of AS (kg m^{-1})	size of AS (cm)		density of AS (g cm^{-3})	V (m s^{-1})	V_N	meteorological parameters T	T/T_D	P	P_n	$P_n t$	α
20	2	100	11/2/85	16.1	(0.9)	(10.0	6.0)	(0.2)	1.1	0.2	−0.1	−0.05	1.8	1.8	4.96	0.497
21	2	280	21/2/85	18.2	(0.6)	(6.0	4.0)	(0.35)	1.1	0.8	−1.7	−0.98	1.2	2.2	2.39	0.795
22	2	280	21/2/85	18.2	(0.9)	(8.0	4.0)	(0.4)	1.1	0.8	−1.7	−0.98	1.2	2.2	2.39	1.081
23	2	80	19/2/83	7.8	3.6	12.0	12.0	0.32	0.4	0.4	0.7	0.38	2.5	2.7	9.04	0.628
24	2	350	14/3/83	7.8	1.9	10.0	10.0	0.24	0.2	0.2	−1.2	−0.70	2.1	1.8	3.61	0.978
25	2	200	14/3/83	18.2	2.3	12.0	12.0	0.21	0.2	0.2	−0.2	−0.11	2.1	1.8	3.57	0.967
26	2	10	26/12/83	7.8	1.5	7.0	7.0	0.40	4.7	2.7	0.6	0.29	1.8	4.8	5.77	0.680
27	2	40	19/2/83	18.2	(2.2)	(7.0	7.0)	0.62	1.8	1.5	0.6	0.32	1.7	3.9	5.41	0.980
28	2	40	19/2/83	10.5	(1.1)	(5.0	5.0)	0.62	1.8	1.5	0.6	0.32	1.7	3.9	5.41	0.702
29	2	200	20/2/83	18.2	2.1	8.0	6.0	0.55	0.4	0.2	0.1	0.06	3.0	3.2	13.32	0.370
30	2	200	20/2/83	18.2	1.0	6.0	6.0	0.34	0.4	0.2	0.1	0.06	3.0	3.2	13.32	0.195
31	2	60	14/3/83	34.2	0.7	4.7	3.3	(0.85)	0.8	0.6	0.4	0.21	1.7	2.0	3.18	0.624
32	2	10	14/3/83	13.0	0.6	3.6	3.1	(0.87)	0.8	0.6	0.4	0.21	1.7	2.0	3.18	0.878
33	2	100	14/3/83	18.2	0.7	5.0	4.0	0.49	4.5	4.5	−0.1	−0.05	1.5	7.1	7.83	0.302
34	2	100	14/3/83	18.2	0.7	5.0	3.5	0.56	4.5	4.5	−0.1	−0.05	1.5	7.1	7.83	0.316
35	2	100	14/3/83	18.2	0.5	4.0	3.0	0.63	5.5	5.1	−0.2	−0.11	1.6	9.5	9.35	0.218
36	3	16	21/2/83	22.4	4.7	15.0	13.0	0.31	2.8	2.7	−0.8	−0.39	1.3	4.3	17.18	0.347
37	3	10	21/2/83	22.4	1.3	8.0	8.0	0.29	2.7	2.5	−0.8	−0.39	1.3	4.1	16.54	0.165

Table 1. (*Cont.*)

no.	ID	alt. (m)	date (dd/mm/yy)	diam. of wire (mm)	wt of AS (kg m^{-1})	size of AS (cm)	density of AS (g cm^{-3})	V (m s^{-1})	V_N	T	T/T_D	P	P_n	$P_n t$	α
										meteorological parameters					
38	3	10	21/2/83	18.35	(11.8)	(20.0 18.0)	(0.42)	2.7	2.3	−0.7	−0.34	1.3	3.7	15.47	0.746
39	3	20	21/2/83	18.35	(8.9)	(18.0 15.0)	(0.42)	2.7	2.3	−0.7	−0.34	1.3	3.7	15.47	0.641
40	3	10	21/2/83	13.0	1.7	10.0 7.0	0.30	2.6	2.5	−0.7	−0.34	1.3	3.8	15.90	0.221
41	3	12	21/2/83	13.0	7.2	20.0 15.0	0.30	2.6	2.5	−0.7	−0.34	1.3	3.8	15.90	0.486
42	1	5	2/1/62	18.2	5.5	13.5 11.5	0.45		5.7	0.67	0.312			9.64	0.805
43	1	9	25/2/63	18.2	5.5	10	0.67		4.9	0.95	0.455			22.11	0.417
44	1	110	1/2/70	22.4	5.8	10	0.78		6.6	1.11	0.605			43.8	0.228
45	1	2	16/3/70	18.2	7	8 10	0.7		5.5	0.88	0.393			22.94	0.470
46	1	70	27/2/72	18.2	5.6	>15	0.32		2.3	0.19	0.101			13.99	0.487
47	1	40	28/2/72	18.2	5	10	0.66		8.3	0.37	0.191			20.15	0.430
48	1	70	28/2/72	13.0	7.8	15	0.44		2.6	0.34	0.181			14.8	0.615
49	1	60	28/2/72	17.5	4.47	>11	0.47		1.1	0.25	0.103			9.36	0.815
50	1	20	7/4/76	22.4	6	19 15	0.3 0.7		1.8	0.63	0.314			8.33	1.012
51	2	430	16/1/72	25.3	4.9	>12	>0.45		1.81	1.00	0.589			22.79	0.307
52	2	120	5/2/75	18.2	5.7	11	0.62		4.55	0.54	0.296			9.54	0.978
53	3	20	16/2/68	9.6	3.8	10	0.43		5.01	0.59	0.294			10.46	0.633
54	3	30	15/2/68	9.6	2.0	8	0.4		4.06	0.63	0.320			5.92	0.763
55	3	15	12/3/69	10.5	1.9	6	0.7		9.02	0.97	0.476			8.63	0.647

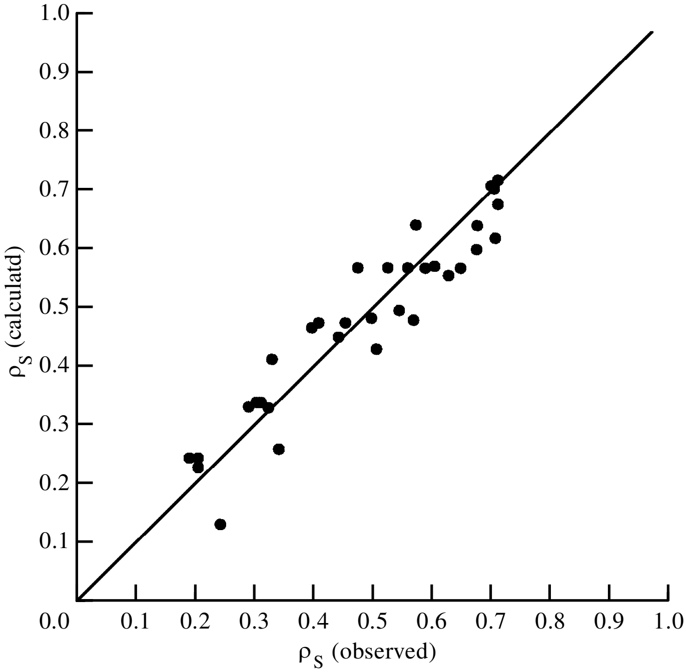

Figure 12. Comparison between measured and calculated densities of accreted snow (natural accretion).

In table 1 it is seen that some reported air temperatures are sub-freezing and indicates some of the errors included. However, such data have been used for the following analysis without any corrections.

Using the same procedure as in the wind-tunnel experiments, a multiple regression analysis gave the following empirical equation expressing density as a function of basic parameters:

$$\rho_{\mathrm{SN}} = 0.220\,69 + 0.294\,02V_{\mathrm{N}} - 0.200\,72^{1.1}_{\mathrm{N}} + 0.099\,61. \qquad (3.13)$$

The number of data used for deriving the equation was $n = 34$ (selected from table 1, taking reliability into account), and the multiple correlation coefficient was $r = 0.942$. In figure 12, the measured density is compared with the calculated value using (3.13). In (3.13), the term $V^{1.1}$ is included to avoid excessive densities over 1.0 and also for avoiding density decreases with increases in V_{N}.

The empirical equation derived from natural data predicts similar trends to wind-tunnel experiments; that is, the density increases with wind speed and temperature. Moreover, a term dependent on precipitation intensity is not included, since the range of precipitation intensity included in observations was too narrow and its effect could not be clearly identified.

The author suspects that the density of snow just accreted will be lower than that calculated using (3.13). Modifying (3.13) is an important task for future research.

Following the same procedure as in the wind-tunnel experiments, the empirical equation expressing the accretion efficiency as a function of basic parameters was

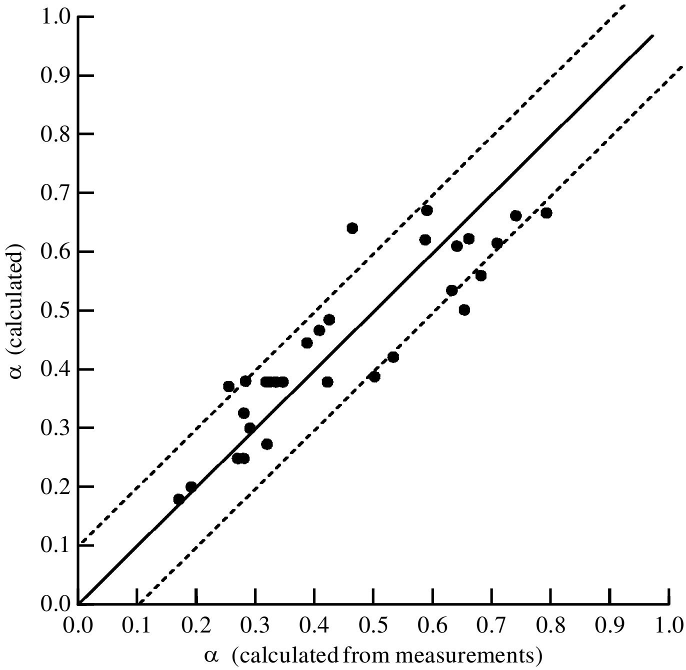

Figure 13. Comparison between α measured and calculated by equation (3.14) (natural accretion).

derived as follows:

$$\alpha_{\mathrm{N}} = \exp\{-1.01 + 4.37T_{\mathrm{R}} - 6.89T_{\mathrm{R}}^2 - 0.0169P_n t\}. \tag{3.14}$$

Here, the number of data points used was $n = 24$, with the multiple correlation coefficient $r = 0.938$. In figure 13, calculated accretion efficiencies based on observations given in table 1 are compared with those calculated from (3.14). Equation (3.14) is applicable for $P_n t$ less than 40. Beyond this limit, the calculated mass of snow decreases with increasing values of $P_n t$. This is clearly in contradiction of real situations.

On inspection of (3.9), it is clear that if the higher density of accreted snow is used then, keeping all other parameters the same, a higher accretion efficiency is predicted.

In conclusion, equation (3.14) may predict accretion efficiency higher than in real situations.

(*e*) *Investigations to modify the empirical model*

Because of the above conclusion, efforts in modifying the model in order to give estimates for more reliable density and accretion efficiency have been continued.

In parallel with collecting more reliable data on natural accretion, a worldwide survey of models proposed by other researchers and engineers has been made (see also the suggestions given in papers presented at IWAIS, reviewed and summarized in Admirat *et al*. (1990) and Sakamoto & Miura (1993)). Amongst these, Admirat *et al*. (1988*b*) proposed models estimating density based on observations in France for relatively low wind speed and also proposed that the accretion efficiency is inversely proportional to the wind speed. Use of their simple form of accretion efficiency has considerable advantages (see also Makkonen & Ahti 1993). On the other hand, Finstead *et al.* (1988) proposed a model in which the accretion efficiency was inversely proportional to the product of wind speed and diameter of the body exposed to the action of wind as follows:

$$\alpha = 0.038T_{\mathrm{A}}/(V_{\mathrm{N}}D). \tag{3.15}$$

In this model, it is also assumed that the accretion efficiency is proportional to the air temperature. This tendency is qualitatively consistent with the author's model at lower ranges in temperature but is, however, clearly in contradiction at higher temperature. Thus the Ervik model has obvious limitations.

The author has attempted to combine his empirical model with that of Ervik. Employing (3.15) in the standard cylindrical snow-sleeve model (see (3.3)), yields the following:

$$2\pi R\rho_{\mathrm{S}}\,\mathrm{d}R = -\frac{38T_{\mathrm{A}}}{V_{\mathrm{N}}}P_n\,\mathrm{d}t. \tag{3.16}$$

In this equation, it is pointed out that the $2R$ in the right-hand side of (3.3) was eliminated as it was assumed that accretion efficiency is inversely proportional to the diameter of accreted snow. Integrating (3.16) yields

$$\pi\rho_{\mathrm{S}}(R^2 - R_0^2) = \frac{38T_{\mathrm{A}}}{V_{\mathrm{N}}}P_n t. \tag{3.17}$$

Since the mass of accreted snow per unit length of wire is

$$W = \pi\rho_{\mathrm{S}}(R^2 - R_0^2), \tag{3.18}$$

there results a simple equation for the mass of accreted snow, namely

$$W = \frac{38T_{\mathrm{A}}}{V_{\mathrm{N}}}P_n t. \tag{3.19}$$

For cases in which the wind speed is high, P_n is approximately equal to the precipitation rate water equivalent multiplied by the wind speed. This implies that the mass of accreted snow is then approximately equal to the precipitation rate multiplied by the air temperature during accretion. Here it is especially noted that the density does not appear in the equation for calculating the mass of accreted snow. This is because, in (3.17), an increment of sectional area of accreted snow $\pi(R^2-R_0^2)$ is inversely proportional to the amount of snow contributing to accretion (the right-hand side of (3.17)) and it was assumed that this increment in mass was independent of the diameter of the accreted snow.

The above equation is very simple and convenient for practical applications. On calibrating the equation for the data given in table 1, it was found not to be applicable for wet-snow incidents in Japan. As mentioned previously, there is an air temperature at which the accretion efficiency is a maximum. Therefore, combining the idea of Ervik that the accretion efficiency is inversely proportional to the diameter of accreted bodies, and incorporating the fact that accretion efficiency attains a maximum at some temperature, the following equation is proposed for determining the accretion efficiency:

$$\alpha = a\frac{\exp\{b(T/T_{\mathrm{D}} - c)^2\}}{V_{\mathrm{N}}^{G} D}, \tag{3.20}$$

where a, b, c and G are unknown constants. Attempts were made to find values of these constants by best-fitting data by trial and error and this yielded the following equation for determining the mass of accreted snow per unit length of wire:

$$W = 4.5\frac{\exp\{-6(T/T_{\mathrm{D}} - 0.32)^2\}}{V_{\mathrm{N}}^{0.2}} P_n t. \tag{3.21}$$

While this equation includes uncertainty included in the data of table 1, for the present it is recommended to estimate snow load design of projected power lines in conjunction with (3.12) and (3.13).

4. Statistical distribution used for establishing design snow load

In establishing the design snow load for any power line, it is necessary to select an appropriate statistical distribution. In the Technical Report 826 (IEC 1991), it is recommended that a type-I extreme value distribution (Gumbel distribution) is applied for the snow load, but this may present problems in some regions. Pezard (1993) pointed out that there are regions where snow accretion is not normally experienced but which may have extremely high snow load with very low probability; Pezard suggests that in these rare cases a Poisson-type distribution would be more appropriate for expressing real situations. This suggestion implies the possibility that severe damage to lines may be encountered for certain regions where normally no line damages due to snow have been experienced. In fact, for some areas in Japan, it has been found that, when estimating snow load based on climatological records, data samples may indicate larger values of sample standard deviations than the mean values and this throws doubt on the application of the type-I distribution. Occurrence of heavy wet-snow load is a phenomenon which happens only when several conditions are satisfied, such as a high intensity of precipitation, an air temperature suitable for accretion, suitable wind speed and direction, together with sufficient time for accretion. Note that such conditions do not promote the shedding of snow from wire. If the occurrence probability of such snow events is low enough the application of a type-I extreme value distribution may not be acceptable and the author is in agreement with Pezard's suggestion. Consequently, attempts are made to find limitations for the application of certain types of distribution, taking into account the occurrence frequency of each event leading to the severe wet-snow accretion.

5. Concluding remarks

This paper deals first with the fundamentals of snow accretion on overhead wires, namely the meteorological conditions. There follows a discussion of the suspected mechanisms whereby a snow sleeve can form around wires, including the use of heat balance on the surface of the wire, to deduce the thermodynamic state of the accreted snow. Finally, an account is given of progress directed towards estimating an acceptable snow load on power lines from a practical viewpoint.

The reason why these aspects have been selected is because there is less consensus in our understanding of snow accretion than of ice accretion (glaze and rime ice). So as to avoid repeating research and to accelerate further progress it is thought that a summary of past experiences would prove useful.

As previously described, severe damage to power lines has been experienced due to heavy overload caused by wet-snow accretion superposed with wind load. In addition, shedding of accreted snow promotes unbalanced tension in wires, leading to further damage to power lines.

Fortunately, through meetings such as IWAIS, IEC and the CIGRE task force for icing (see IEC 1997), opportunities for the exchange of recent information has increased significantly. It is expected that research work on wet-snow accretion fields will progress rapidly in the near future.

The problems that remain are listed as follows.

(a) A method for estimating the density of accreted snow on wires more accurately based on meteorological parameters.

(b) A method for estimating the accretion efficiency more accurately based on meteorological parameters.

(c) The effect of torsional rigidity of a wire span on the mass of accreted snow.

(d) Conditions under which snow shedding occurs (the effect of the current carried by the wire, solar radiation, temperature, wind, etc.).

(e) Statistical distributions applicable to certain regions.

(f) The type of snow shedding (shed simultaneously over the entire span or shed partly) and conditions under which snow sheds. Such phenomena affect the torsional and bending loads on supporting structures due to unequal tension in wires.

(g) Change in characteristics of snow after accretion (freezing due to the decrease of temperature, increase in density and mass due to light rain, etc.).

(h) Methods for treating incidents of wet-snow accretion combined with other types of icing in a single icing event.

The author is deeply indebted to a number of experts worldwide who have had discussions with him and exchanged invaluable ideas and suggestions regarding icing problems; in particular, those delegates of IWAIS and related meetings. Also my thanks go to the staff of Electricité de France, CRIEPI and the utilities of Japan that have participated in the wet-snow research project.

I greatly appreciate this opportunity to review the present state of wet snow research.

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