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SNOW ACCRETION ON ELECTRIC WIRES AND ITS PREVENTION

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ABSTRACT. This paper presents a study on the accretion of wet snowflakes transported by a strong cyclone on electric wires by means of wind-tunnel experiments and field observations with the aim of successfully preventing them from accreting on and causing damage to power lines and high-voltage power-transmission towers in snowy areas in such countries as Japan, Canada, and the U.S.A. Although extensive studies have been made on snow accretion in Japan since the 1930's by many workers, their studies have been restricted to the coastal regions of central Honshu facing the Sea of Japan, which are typified by heavy wet snowfalls of the monsoon type in a weak wind of less than 3 m/s at a temperature between −1° and +1.5°C continuing throughout the day. However, it has long been known that a cyclone characterized by a strong wind exceeding 10 m/s that carries heavier and wetter snowflakes can cause snow accretion on electric wires to grow to 20–30 cm in diameter. Because its detailed accretion processes and mechanism had not been clarified, studies have been made on the growth processes of snow accretion, the adhesive stress of snow to a wire, the structure and texture of the accreted snow, coefficients of collision and collection of snow on the wire, and trajectories of individual snow particles impinging on or passing by a wire at various wind speeds. It has been confirmed that wet snow can accrete on wires at any wind speed between 0 and 20 m/s. Moreover, new techniques have been developed to prevent wet snow from accreting on wires, and these have proved to be effective *in situ* for any type of snow accretion in Hokkaido.

RÉSUMÉ. *Givrage de fils electriques par la neige et sa prevention.* Ce papier présente une étude sur l'accrétion de flocons de neige humide transportés par une forte tempête sur des fils électriques. Des expériences en tunnel de soufflerie et des observations de terrain avaient pour but de réussir à prévenir les accrétions sur les fils et les dommages sur les lignes et pylônes des lignes à haute tension dans des pays comme le Japon, le Canada et les U.S.A. Bien que des études extensives avaient été faites sur les accrétions de neige au Japon depuis 1930 par un grand nombre de chercheurs, leurs études se sont limitées aux régions côtières dans le Honshu face à la mer du Japon qui sont caractérisées par des chutes abondantes de neige humide du type précipitation de mousson avec un vent faible de moins de 3 m/s de vitesse à une température allant de −1° à +1,5°C et se poursuivent tout le jour. Cependant il a été reconnu que des tempêtes comportant un vent fort de plus de 10 m/s transportant des flocons plus lourds et plus mouillées peuvent se produire des accrétions de neige sur les fils allant jusqu'à 20 à 30 cm de diamètre. Comme les processus et mécanismes de ces accrétions n'avaient pas été clarifiés, on a fait des études sur les processus de croissance des accrétions de neige la force d'adhésion de la neige sur un fil, la structure et la texture de la neige collée, les coefficients de collision et de retenue de la neige sur le fil, les trajectoires des particules individuelles de neige heurtent ou touchent un fil à des vitesses variées. Il a été confirmé que la neige humide peut s'agglomérer sur les fils à n'importe quelle vitesse entre 0 et 20 m/s. De plus de nouvelles techniques ont été mises au point pour prévenir l'accrétion de la neige humide sur les fils, techniques qui ont prouvé leur efficacité sur le terrain pour n'importe quel type d'accrétion de neige dans l'île d'Hokkaido.

ZUSAMMENFASSUNG. *Das Anwachsen von Schnee an elektrischen Leitungen und seine Verhinderung.* Diese Arbeit schildert eine Untersuchung über das Anwachsen nasser Schneeflocken, angeweht durch einen starken Sturm, an elektrischen Leitungen; sie wurde durch Versuche im Windkanal und durch Feldbeobachtungen ausgeführt, mit dem Ziel, wirksame Massnahmen gegen das Anwachsen an und die Beschädigung von Starkstromleitungen und -masten in schneereichen Ländern wie Japan, Kanada und den U.S.A. zu entwickeln. Zwar wurden extensive Studien des Schneeanwachsens von vielen japanischen Forschern bereits seit den 30er-Jahren angestellt, doch blieben diese Arbeiten auf die Küstenregionen in Zentral-Honshu an der Japan-See beschränkt, für die starke, nasse Schneefälle vom Monsuntyp mit schwachem Wind von weniger als 3 m/s Geschwindigkeit bei Temperaturen zwischen −1 und +1,5°C, die den ganzen Tag über anhalten, charakteristisch sind. Es war jedoch schon bekannt, dass ein Sturm mit Windgeschwindigkeiten über 10 m/s, der schwerere und nassere Schneeflocken mit sich bringt, das Anwachsen von Schneemänteln an elektrischen Leitungen bis zu 20 und 30 cm Durchmesser bewirken kann. Da der Anwachsprozess und -mechanismus im einzelnen nicht bekannt war, wurden Versuche zum Wachstumsprozess, zur Adhäsionskraft des Schnees am Draht, zur Struktur und Textur des haftenden Schnees, zu den Kollisions- und Kollektionskoeffizienten des Schnees am Draht und zu den Flugbahnen einzelner Schneepartikel, die in Winden verschiedener Geschwindigkeit gegen einen Draht stossen oder an ihm vorbeifliegen, angestellt. Erneut zeigte sich, dass nasser Schnee an Leitungen bei beliebigen Geschwindigkeiten zwischen 0 und 20 m/s anwachsen kann. Darüberhinaus wurden neue Techniken entwickelt, um das Anwachsen nassen Schnees an Leitungen zu verhindern; sie erwiesen sich auf Hokkaido als praktisch wirksam gegen jede Art von Schneeanwachsen.

Introduction

Wet snowflakes containing much free water easily accrete on electric wires; this often causes serious damage such as the breakage of power lines and crashing down of high-voltage power-transmission towers.

Extensive studies concerning snow accretion and sleet jump on power lines have been made by many workers in Japan since the 1930's. Among them was Shōda, the first person who studied in detail the growth processes and mechanisms of snow accretion on wires. He found that snow accretion takes place at an air temperature between −1° and +1.5°C when the wind speed is less than 3 m/s (Shōda, 1953). He emphasized that when the wind speed exceeds 3 m/s snow accumulated on a wire is easily blown from the wire by wind action. These earlier works were, however, restricted to the Hokuriku district in coastal regions in central Honshu facing the Sea of Japan. Snow accretions there derived mainly from monsoon-type heavy wet snowfalls in winter. (Snow accretions derived from monsoon-type snowfalls are referred to as "monsoon-induced snow accretion" for convenience.)

In Hokkaido, the northernmost island of Japan, incidents of serious damage to power lines and transmission towers due to heavy wet snow accretions have been frequently reported in the last 15 years; these took place when a strong cyclone passed this area in winter or early spring. (Snow accretions derived from a cyclone are referred to as "cyclone-induced snow accretion" for convenience.) The wind speed of such a cyclone was 10, 15 or 20 m/s at times, very different from the wind speed observed and reported by Shōda for the monsoon-induced snow accretion. Attention has been drawn to the fact that damage of this nature is not unique to Hokkaido but has been reported from other parts of Japan.

Summarized in Table IA are available data of such snowfalls that resulted in heavy damage to power lines and transmission towers, i.e. the date of occurrence, location, the degree of damage and certain meteorological factors. Similar information on damage reported from Canada and the U.S.A. is given in Table IB, where the cause of the damage includes mountain icing and freezing rain.

TABLE IA. SELECTED DATA FOR HEAVY SNOW ACCRETIONS, CAUSING SERIOUS DAMAGE TO POWER LINES OR TRANSMISSION TOWERS, REPORTED RECENTLY FROM JAPAN

Date	*Location*	*Damage: number of crashed towers (voltage)**	*Maximum wind speed* m/s	*Temperature* °C	*Type of snow accretion*
4 March 1954	Toyama, Honshu		16	0 to 1	Cyclone-induced
3 December 1962	N. Hokkaido		13	0.6 to 1.4	Cyclone-induced
25 February 1963	S.E. Hokkaido	18 (66 kV)	10	0.5 to 1.9	Cyclone-induced
31 January 1970	S. Hokkaido	1 (187 kV)	18	0 to 1	Cyclone-induced
16 March 1970	S.E. Hokkaido	4 (66 kV)	25	0 to 1	Cyclone-induced
15–16 January 1972	N.E. Honshu	10 (154 kV, 66 kV)	15		Cyclone-induced
10 February 1972	Hiroshima, Shikoku	1 (66 kV)			Cyclone-induced
14 February 1972	Central Hokkaido			1 to 2	Cyclone-induced
27 February 1972	S. and S.E. Hokkaido	3 (187 kV, 66 kV)	21		Cyclone-induced
1 December 1972	N. and E. Hokkaido	60 (110 kV)	38	0 to 2	Cyclone-induced
22 December 1973	S.W. Hokkaido		39	−4.5	†
20–21 March 1975	S.E. Hokkaido		2	0.2 to 0.5	Cyclone-induced, but weak wind

* No entry indicates serious damage to wires but with no towers crashed down.

† Near the sea coast; though the temperature was low, the wires were splashed with sea-water and covered with snow wetted by the splash.

Table IB. Snow or ice accretions reported from Canada and the U.S.A.
(compiled by K. Koike, Hokkaido Electric Company)

Date	*Location*	*Damage: number of crashed towers (voltage)*	*Maximum wind speed* m/s	*Temperature* °C	*Type of snow accretion*
12 November 1969	Quebec, Canada	30 (735 kV)	9	−4 to −1	Mountain icing
27 February 1970	Newfoundland, Canada	79 (230 kV, 138 kV)			Freezing rain
17 December 1970	Oregon, U.S.A.	8 (500 kV)			
28 April 1971	Saskachewan, Canada	93 (138 kV)	11	0 to 3	Cyclone-induced
19–20 January 1972	Vancouver, Canada	27 (500 kV)			Freezing rain
28–30 April 1973	Quebec, Canada	32 (735 kV)			Mountain icing

In order to clarify the detailed processes and mechanisms of snow accretion in a strong wind on wires, as often observed in Hokkaido, a series of experiments was conducted on artificial snow accretion in a wind tunnel installed in a cold laboratory. On the basis of the results obtained from the experiments and field observations, effective devices against snow accretion have been developed in the Technical Research Institute of the Hokkaido Electric Company (Nakano and others, 1974, p. 1–32; Gotō and Kuroiwa, 1975).

Wind-tunnel experiments

A wind tunnel installed with a device to produce artificial wet snow particles was used to study the growth processes and mechanisms of snow accretion on electric wires. A lump of snow collected from a natural snow-pack was crushed by three-layered vibrating metallic sieves; a supply of these disaggregated snow particles was fed continuously into the wind tunnel; they were wetted by spraying water at 0°C before they impinged on the wires stretched horizontally in the tunnel and perpendicular to the direction of the wind. The air temperature in the tunnel was controlled between +1.0° and 2.0°C. Two types of wire were used: a single wire with a circular cross-section and a stranded wire.

Time-lapse and slow-motion pictures were taken on 16 mm film to observe the growth processes of snow accretion and the trajectories of the snow particles impinging on or passing by the wire. The adhesive force of wet snow to the wire was also measured. Snow accreted on the wire was carefully removed from it, so that the structure, density, free-water content of snow and the microscopic texture, including the grain-size, shape and crystallographic orientations, could be measured and observed.

Experimental results

Growth processes of snow accretion on wires

When wet snow was continuously blown on to a single wire in the wind tunnel, it began to accrete in the windward direction (Fig. 1a). When the snow accretion reached a thickness similar to the diameter of the wire, it began to rotate slowly around the wire by its own weight, hanging down from the wire (Fig. 1b), without being blown away by the wind. A continuous accumulation of snow took place on the windward face of the wire; the whole snow mass rotated again and this process was repeated (Fig. 1c and d). The wire was soon entirely enveloped by wet snow. The snow deposit thereafter was rarely blown away by the wind and it grew to a thick cylindrical snow body.

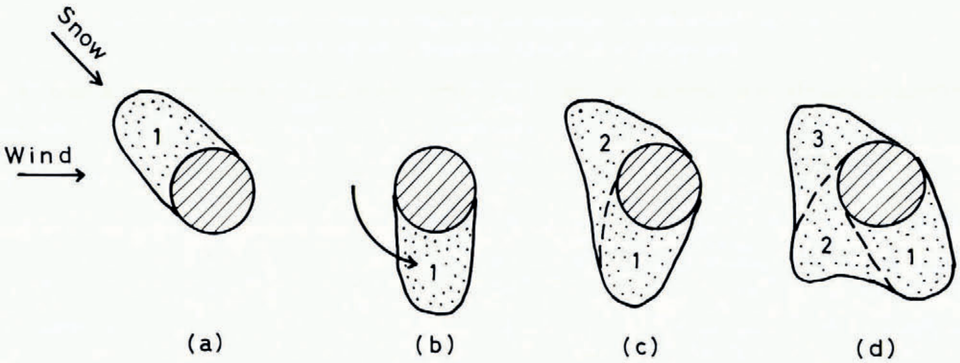

Fig. 1. Schematic representations of growth processes of snow accretion on a wire in a weak wind.

Though the free-water content (mass of water/mass of wet snow, in %) of the falling snow fed into the wind tunnel was 3–8%, that of the snow deposit on the wire increased with time due to an effective heat transfer from the moving air to the snow mass. The snow deposit gradually became semi-transparent during its growth, and the excess of free water was removed from the leeward of the snow deposit. The free-water content of the snow deposit on the wire was measured immediately after the end of each experiment by a calorimetric method; its value ranged from 18 to 37%.

There is a possibility that freezing of free water in the snow deposit may take place during its growth due to evaporation in a strong wind. In order to investigate this possibility, the temperature distribution within the snow deposit was measured by using eight thermocouples embedded in it at a wind speed of 10 m/s and a relative humidity in the wind tunnel of 70%, but no evidence indicating the freezing of water was obtained.

As for snow accretion on a stranded wire, its growth process was different from that on a single wire; namely, snow accreted slowly and slid down along the strands of the wire. Rotating around the wire, it also grew to form a cylindrical snow deposit.

Effect of wind speed on snow accretion

A series of experiments was carried out to clarify the effect of wind speeds in the tunnel from 0 to 20 m/s. In these experiments it was found that a heavy snow accretion took place at any wind speed up to 20 m/s, though the modes of snow accretion were somewhat different from one another. For instance, when the wind speed was less than 10 m/s, the snow deposit tended to rotate around the wire under gravitation but, when the wind speed exceeded 10 m/s, the rotation of snow was sometimes upwards due to aerodynamic lift. It was also found that the snow deposit fell from the wire when the wind speed was suddenly reduced from 10 to 0 m/s in the initial stage of snow accretion. These facts suggest that a high wind speed such as 10 m/s plays an important role in the development of snow accretion on wires; that is, a strong wind produces aerodynamic lift which acts on the snow deposit in equilibrium with the gravitational force, thus preventing the snow deposit from falling off the wire. This experimental fact is clearly contrary to earlier workers' results which emphasized that a strong wind easily removes a growing snow deposit from the wire.

Adhesive force of snow accretion to wires

If the snow deposit falls from the wire after the initial rotation around it in the early stage of snow accretion, it cannot develop to a thick cylindrical snow body. The adhesive force by which the snow deposit hangs down from the wire, is therefore very important in the study of practical problems. The adhesive force between the snow deposit and the wire was measured as follows.

Wet snow was deposited continuously on to the upper surface of a wire 40 and 20 mm in diameter under no wind conditions. When the weight of snow accumulated on a unit length of the wire exceeded approximately 1.2 g/mm, the mound-like deposit of snow became unstable and began to rotate around the wire by the action of gravity and then fell off the wire. If the weight of the deposit was less than 1.2 g/mm, the snow rarely began to rotate by itself. Then, a very slow rotation was given to the wire such as to allow the snow to start turning around the wire. When the deposited snow was turned over, it sometimes fell from the wire, but sometimes not, hanging down from the bottom surface of the wire. The shear stress σ_S, which prevents the snow turning around the wire, could be estimated from the critical angle at which the rotation began; the value of σ_s thus obtained was approximately 0.2×10^{-3} bar.

It may be assumed that the negative pressure induced in water existing at the interface between the wet snow and the wire allows the snow to adhere to the wire. The pressure, p, is given by the formula $p = -(\sigma/r)$, where σ is the surface tension of water and r is the radius of curvature of the concave water surface at the interface. The value of r may be of the order of the radius of the snow grains, e.g. 0.3–0.5 mm. When the negative pressure is overcome by the gravitational force, the snow should fall from the wire; when the negative pressure exceeds the gravitational force, it never falls off but hangs down from the wire. Hence the negative pressure gives us the adhesive stress. The adhesive stress thus obtained was approximately $(1.9\pm0.1)\times10^{-3}$ bar when the free-water content was greater than 20%, or when air voids among the snow grains at the interface were saturated with water. Substituting the adhesive stress thus obtained into p of the above formula, the derived radius of curvature r of the water surface at the interface is 0.4 mm, which agrees well with that estimated from the grain-size of the snow. The adhesive force becomes smaller when the free-water content of snow is lower than 20%, because the air voids are not saturated with water.

Density, structure and texture of snow accretion

The density of an artificially made snow accretion ranged from 0.7 to 0.9 Mg/m³, which agreed well with the densities observed for natural cyclone-type snow accretions. This is in remarkable contrast to the monsoon-type snow accretion with a density of approximately 0.2 Mg/m³.

Natural snow accretions of the cyclone type were sliced to a thickness of 10 mm and diluted ink was sprayed on to the sliced surface to reveal the internal structure of the snow. A continuous helical structure was found in the sections as illustrated in Figure 2a. This strongly suggests that the snow accretion had grown by turning around the wire many times, and that the wire itself was twisted in such a way that the middle part of a long span between the transmission towers rotated freely around the axis, thus allowing the helical growth of the snow accretion around the wire as shown schematically in Figure 2b. It has been actually observed *in situ* that most of the catenaries were twisted by rotation of as much as several times 2π radians by the torque induced by an irregular accumulation of snow on the windward surface of the line during the growth of a heavy snow accretion. Snow accretions were, however, easily broken down and fell from both of the end parts of a line close to the towers where only slight twisting was allowable, and where a thick cylindrical snow accretion never developed. These facts show that the torsional twist of the wires and catenaries may play an important role in the development of a snow accretion. Results similar to those obtained *in situ* were obtained in the wind-tunnel experiments; if the wire was fixed firmly to a rigid framework, the snow deposit frequently fell from the wire during its growth but, when the wire was not fixed and allowed to rotate, it readily grew into a thick cylindrical snow deposit without falling off the wire. In the unfixed condition, when the wind speed was less than

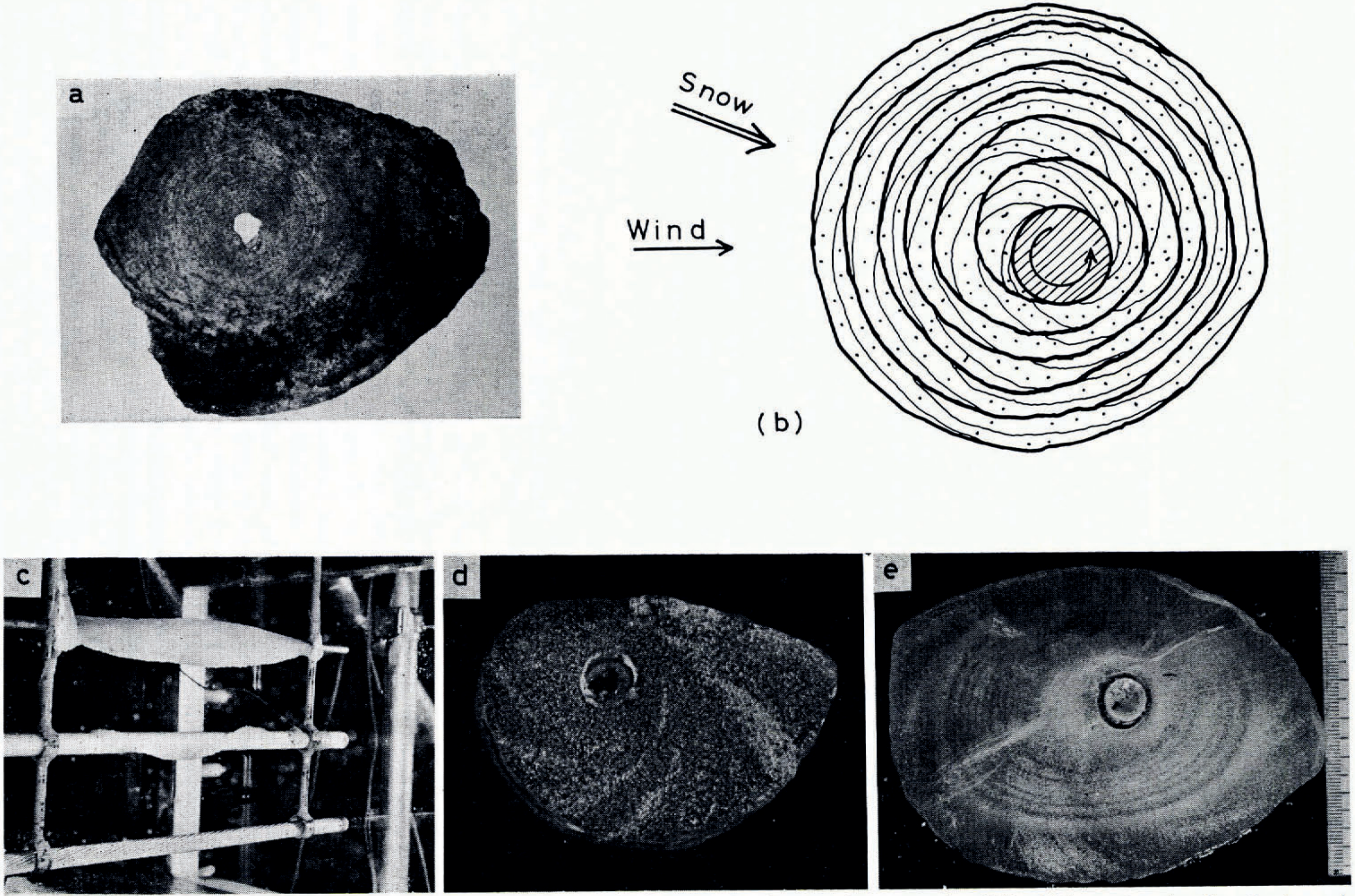

Fig. 2. *Cross-sections showing growth processes of snow accretion on wires.* (*a*) *A cross-section of a natural snow accretion. Diluted ink was sprayed on the section to reveal its internal structure. Diameter of the snow accretion was approximately 300 mm.* (*b*) *Schematic representation of a snow accretion on a long-spanned power line due to the rotations of the wire.* (*c*) *Artificial snow accretions on wires in a wind tunnel.* (*d*) *and* (*e*) *Thin sections of artificial snow accretions showing discontinuous rotational growth in a weak wind* (*d*) *and continuous rotational growth in a strong wind* (*e*).

10 m/s, the snow deposit moved downwards to some extent as it grew, causing the wire to rotate around its axis discontinuously, whereas when the wind speed exceeded 10 m/s, the snow deposit moved continuously either upwards or downwards as it grew, causing the wire to rotate around its axis continuously. This continuous rotation was frequently observed when the wind speed varied between 12 and 17 m/s. Immediately after the experiment was completed, the accumulated snow was carefully removed from the wire and cut into 10 mm thick slices to study its internal structure. Sector-shaped structures were observed in the thin sections of the snow deposit formed in a comparatively weak wind as illustrated in Figure 2d. A number of conformable circular structures were observed in the sections of the snow accumulated at a wind speed greater than 10 m/s (Fig. 2e). These structures of sector or circular patterns seen in the sections of the deposited snow are therefore a good reflection of the rotational growth of snow accretion on wires.

Coefficient of collision and coefficient of collection of snow particles on the wire

Though the coefficients of collision and collection of snow particles on a wire are very important factors in the understanding of snow accretion, they are not yet well known. In order to determine these factors, the trajectories of snow particles were studied by photographing them when they were just impinging on or rebounding from the wire (Fig. 3a). A technique of narrow-banded lighting and stroboscopic lighting was used to distinguish the traces of individual snow particles colliding with or rebounding from the wire. 16 mm slow-motion pictures were taken to observe continuously the paths of the particles just impinging on or passing by the wire.

It was found from an analysis of these photographs and films that the trajectories of snow particles just passing by a wire were very straight, as seen in Figure 3, which means that the coefficient of collision defined by Langmuir and Blodgett (1946) is 100%. Though it had been believed that wet snow particles impinging on a wire may easily adhere to its surface, these experiments showed that the number of snow particles which rebounded from the surface of the wire or the snow deposit was unexpectedly large (Fig. 3). The coefficient of rebound exceeded 80% for a wire 4 cm in diameter; hence, the coefficient of collection of snow particles was less than 20%. It was frequently observed that a snow particle which collided with the surface of the snow expelled several snow particles each time from the surface. It should be noted that, with a decrease in the radius of the wire, the coefficient of collection of snow particles increased. These facts are very important in order to estimate the growth rate of snow accretion on power lines in computer simulations.

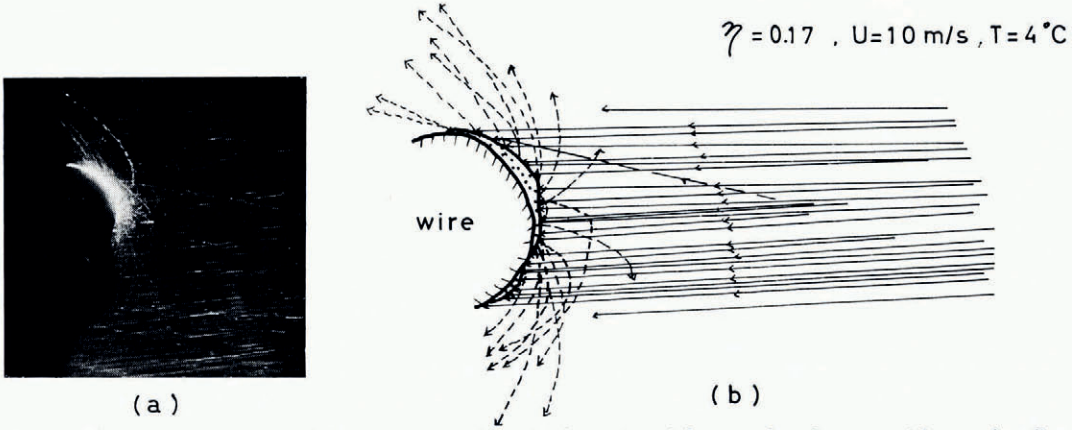

Fig. 3. Trajectories of snow particles impinging on and passing by a wire. A large number of snow particles are rebounding from the snow deposit on the wire.

New techniques for preventing lines from accreting snow

As described above, a lump of wet snow accumulated on a stranded wire slowly slides along the strands of the wire, and then develops into a large cylindrical snow accumulation. Therefore, if the sliding rotation along the strands is stopped, the cylindrical growth of snow accretion may be interrupted. When plastic rings 2–4 mm in thickness were attached to the surface of a stranded wire at an interval 1.5–2 times the length of the stranding pitch (Fig. 4a), the rotational sliding of the snow along the strands was arrested; hence, the cylindrical growth of the snow accretion could be stopped. This new technique was developed by the Snow Accretion Prevention Research Group of the Hokkaido Electric Company; it has been proved that this was very effective for a short-span catenary, less than 100 m, of the transmission lines with ACSR (Aluminum Conductor Steel Reinforced) 13.5–18 mm in diameter, but the de-icing effect of the plastic rings was reduced for long spans of transmission lines because of the twists of the wires themselves. In the latter case, 0.8 kg m anti-torsion weights were attached to the wire at intervals of less than 100 m to prevent the wires from twisting. It has been proved *in situ* that this method is also very effective for the prevention of snow accretion on a long-spanned transmission line.

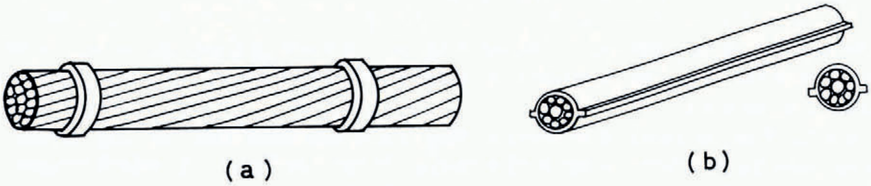

Fig. 4. New techniques for the prevention of snow accretion on a stranded wire (a) and a single vinyl wire (b).

In the case of vinyl-covered single wires with a circular cross-section, which are mainly used in towns and streets in urban areas, a lump of snow accumulated on them slides down along the cross-section, and then develops into a large cylindrical snow accretion. If the rotation is interrupted by an obstacle, the growth of the snow accretion may be stopped. A pair of tiny fins was attached to both sides of the vinyl wire as schematically shown in Figure 4b. This new technique which was also developed by the Hokkaido Electric Company Group has proved to be very effective for these kinds of wires.

Concluding remarks

It has been confirmed that there are two types of snow accretion: "monsoon-induced snow accretion", which often occurs in Honshu in the middle of winter when a heavy wet snowfall 4–5 mm/h in intensity continues all day long at an air temperature between -1 and $+1.5$°C in a wind of less than 3 m/s; "cyclone-induced snow accretion", which often occurs in Hokkaido when a heavier wet snowfall 20–30 mm/h in intensity accompanied by a strong cyclone passing by this island continues all day long at an air temperature between 0 and $+2$°C in a strong wind of more than 10 m/s. There is a great contrast between the growth conditions for these two types of snow accretion, in spite of the wind speed in which snow accretion develops. The reason why the cyclone-induced snow accretion can develop even in a strong wind may be explained as follows: the free-water content of cyclone-induced snow accretion is much larger than that of the monsoon-type accretion. The great difference between the density of snow accretions of these two types, i.e. 0.7–0.9 Mg/m^3 for the cyclone-induced type and 0.2 Mg/m^3 for the monsoon-induced type, is due to the difference in free-water content of snow between the two. In general, the adhesive force of snow to a wire increases with an increase in the free-water content. The cyclone-induced snow accretion therefore, adheres much more to a wire than the monsoon-induced one, and it can grow to a cylindrical accretion as thick as 30 cm in diameter without falling from the wire even when the wind speed exceeds 10 m/s. The monsoon-induced snow accretion is, on the contrary, easily blown off in a strong wind because of the smaller adhesive force to the wire due to a smaller free-water content.

A series of wind-tunnel experiments for cyclone-induced snow accretions was conducted at a controlled temperature ranging from +1 to +3°C, and it was confirmed that artificially wetted snow can accumulate on wires at any wind speed between 0 and 20 m/s. Studied in these experiments were the growth processes of snow accumulation, the adhesive force of snow to wires, the structure and texture of snow accumulated on wires, coefficients of both collision and collection of snow particles on wires, and the trajectories of snow particles passing near a wire.

New techniques for the prevention of snow accretion both on stranded and single wires have been developed, and these have proved to be very effective for de-icing any type of electric line or wire in snowy areas.

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DISCUSSION

A. FROLOV: Your experiments and measurements are very interesting and important. However, I should like to know whether you have any data on the qualitative dependence between thickness of ice formation per unit of time and the different thermodynamic conditions of the experiments.

G. WAKAHAMA: No. We have no quantitative relations between rate of accretion of snow and thermodynamic conditions at present. However, we are currently analysing our films and hope soon to be able to determine growth rate as a function of wind speed, air temperature, etc.