Effects of Wind Speed on the Accumulation Rate of Pollution on Outdoor Insulators under Winter Conditions

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***Abstract*—This paper describes the road salt deposition process on the high voltage line insulators. A computer model is developed which simulates the contamination deposit on the insulator surface. The rate of road salt deposit is determined as a function of wind velocity for an IEEE standard disk line insulator. This is a preliminary work which is being carried out to indicate the feasibility of assessment of pollution severity and prediction, using the proposed model. This model could be very helpful for future winter pollution modeling or simulation.**

I. Introduction

During the winter, outdoor insulators can be contaminated by pollution of various origins. Most electric power lines installed near urban roads or highways are exposed to winter pollution brought by the wind. In presence of fog, frozen rain or melting snow, the pollution layer become electrically conductive and can be at the origin of partial arcs which may lead to flashover under certain conditions [1]. This pollution comes mainly from the products used to de-ice roads. It accumulates progressively on the insulators and forms a salt layer that is characterized by a deposit density of hundreds of μg per cm^2. The rate of accumulation is a function both of wind effects and of the density of road salt particles projected by car wheels.

One example of winter flashovers, caused by salt accumulation, occurred in Toronto, Ontario, Canada on the morning of January 27, 2004 [2]. Flashovers on 115-kV bushings at a critical substation caused a ninety-minute power outage in the downtown area. For the 24 hours prior to these flashovers, the median wind speed at the nearby Toronto Island Airport was 56 km/h from the east [3]. A major overhead expressway interchange is located south and east of the station, as shown in Fig. 1. Measurements at the substation showed that the insulator contamination levels reached 90 μg/cm^2 after this exposure. This event will be used as a benchmark for the proposed modeling.

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Fig. 1. Fault Location (2004 01 27) near Gardiner Expressway in Toronto

Road salting is not the only source of pollution observed in winter: dust, domestic heating and vehicle exhaust also contribute to the deposits observed on the surface of the insulators. In addition, partial arcs produce another kind of pollutant, which is nitric acid. However, for the sake of simplification, only NaCl is considered as the contaminant in the present study.

II. Contamination Process

It was found that the wind effect is the most important factor during the contamination process [4], [5]. When the suspended particles flow towards an insulator, the insulator forces the flow to divide in two regions. Figure 2 shows a viscid free-stream flow, where the air is at rest so that large or dense particles are trapped. The other region consists of viscous flow that allows light particles to escape. The efficiency with which the insulator catches the contaminant particles depends on three principal factors: 1) the shape of the insulator, 2) the size and density of the particles and 3) the speed of the flow, which can be extremely high in winter.

The distance from the pollution source (expressway or urban roads) to the electrical installation is also a dominant variable in the exposure for any kinds of insulator. But in this study, the particles are already considered as near enough the insulator, so the effect of distance is not taken in account.

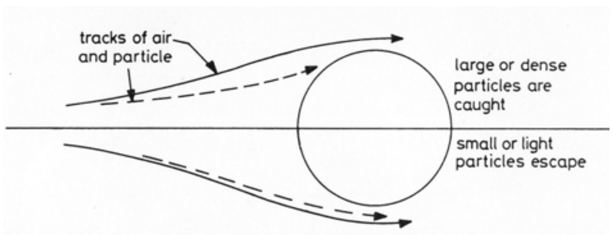

Fig. 2. The air flow field about an object

III. Model Description

I. Flow calculation

It has been mentioned that the insulator divides the flow in two regions. Then, the computation for airflow is divided in two independent calculations, which are carried out iteratively (Fig. 3).

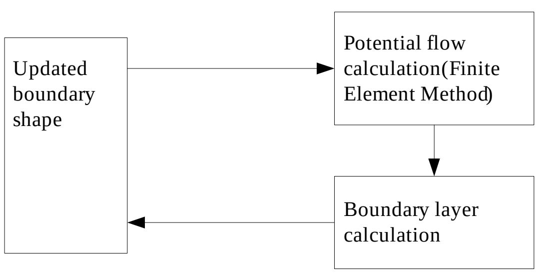

Fig. 3. Airflow computation

As the potential flow is ideal, irrotational and incompressible, the boundary element method is the best way to solved it numerically [6]. The combination of initial stream φ_1 and disturbance flow φ_2 could be considered as the stream function φ at any position in the flow field (1).

$$\varphi = \varphi_1 + \varphi_2 \qquad (1)$$

where $\partial\varphi / \partial x = v_y$ and $\partial\varphi / \partial y = v_x$.

v_x and v_y are the components of the wind velocity.

The steady onset flow is defined by the equation $\varphi_1 = V_0 y$ (V_0 is the onset airflow speed), whereas the disturbance flow may be expressed in the form of Laplace's equation:

$$\nabla^2 \varphi_2 = 0 \qquad (2)$$

Thus, knowing the uniform stream φ_1, it is possible to solve the variable φ_1 in terms of the disturbance stream φ_2.

II. Local collision efficiency evaluation

Since it is extremely time-consuming to track the movement for each particle, a method frequently used in the icing research [7] may be applied in this problem. According to this method, the amount of particles collected at any given position on an object is represented by the Local Collision Efficiency (LCE) which is defined by (3), which can be illustrated as shown in Fig. 4.

$$\beta(\theta) = \frac{dY}{dL} \qquad (3)$$

where Y represents the vertical distance between two trajectories in the onset flow, and L is the distance between the impact points on the object surface.

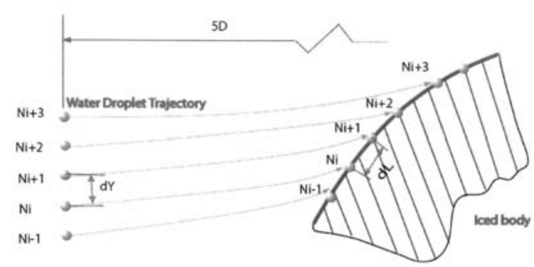

Fig. 4. Definition of the LCE [4]

For a cylindrical object, the LCE may be determined by the equations and tabulated results of Langmuir and Blodgett (1946) [7], which were obtained using a differential analyzer. The validity of this approach was verified by recent studies (e.g., McComber, 1983), though, using different methods.

Notwithstanding, it is necessary to examine the validity of such practice, i.e. the conditions applied in Langmuir's method should also be satisfied by the current problem. These conditions include: the object exposed to the air-borne particles should be cylindrical or approximately cylindrical; the particles under simulation may possibly be regarded as rigid spheres; and the particles are so small that the celebrated Stokes' law may safely be applied ($Re_d << 1$). Since the salt is carried as an aerosol, the conditions for the particles may be applied. However, an insulator cannot be considered as a real cylindrical object. In order to apply Langmuir's method, the insulator surface should be subdivided in several cylinders (Fig. 5) and the total mass of particles on the insulator will be the sum of the mass of the particles deposited on the surface of each cylinder.

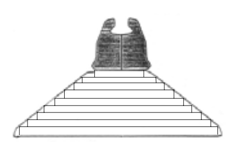

Fig. 5. Subdivision of the disc insulator surface in small cylinders

IV. Simulation Results

To implement the simulation, we used a disk of a standard IEEE porcelain suspension insulator (Fig. 6). The insulator disk was subdivided as shown in Fig. 5, in ten cylinders. The duration of the contamination event is 24 hours, i.e. one day. The exposed area of the top surface is approximately 600 cm^2. During the simulation period, we assumed that the mean value of the air temperature is equal to -15^{o}C and that there is no natural washing.

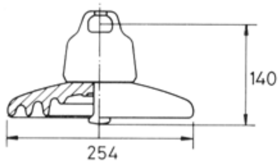

Fig. 6. Sample disk of porcelain suspension insulator

I. Parameters

As listed in Table I, two types of input parameters were used to run the simulation.

TABLE I
MODEL INPUT PARAMETERS

Type	Simulation Conditions
Contamination Conditions	Wind Speed, Air Temperature, Particle Size, Total Suspended Particles (TSP)
Simulation Parameters	Contamination Event Duration, Simulation Time, Insulator Dimensions

Total Suspended Particles (TSP) represents the mass of particles of road salt contained in one unity of volume of air sample. The size of these particles, in term of median volume diameter (MVD), is ranged between 0.1 and 100 microns [8]. The top and bottom diameters as well as the height are the necessary dimensions for the insulator. Certain parameters among others may be evaluated on the basis of the simulation conditions mentioned above.

II. Obtained results

The sole output of the model is the mass of particles accumulated on the surface of the insulator. By dividing this mass by one day of contamination event duration, we obtained the rate of accumulation expressed in mg/day. We divide this rate by the top surface area to finally obtain a rate of increase of salt deposit density. Four simulations have been run, varying some parameters, in order to better analyze the wind speed effect.

In the first simulation, the wind speed is the independent variable, the other parameters are considered like constant. The obtained result is as shown in Fig. 7.

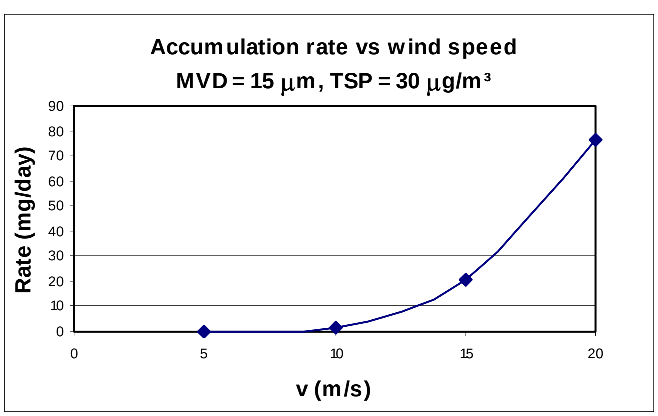

Fig. 7. Accumulation rate versus wind speed

From this figure, we can already observe the effect of the wind speed on the variation of the accumulation rate. A strong wind of 15.5 m/s (56 km/h) involves a high accumulation rate of 20 mg per day or 33 μg/cm^2/day and the variation is not linear. However, if the mean size of particles is about 15 μm and the TSP is 30 μg/m³, the simulation result shows that the risk of accumulation in one day is low at wind speed less than 10 m/s.

The objective of the second simulation is now to observe what happens if the median volume diameter of the particles is varying.

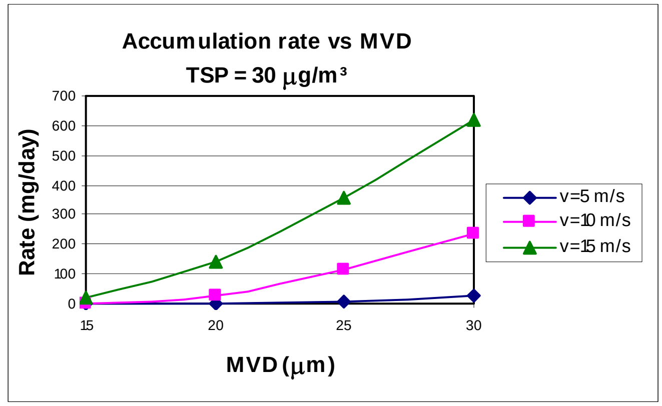

Fig. 8. Accumulation rate versus MVD at different wind speed

Fig. 8 shows that the combination of relatively large size particles and strong wind contribute towards a high accumulation rate of pollution. For example, at wind speed of 15 m/s, if the median volume diameter of particles is 30 μm, the rate is about 600 mg per day (1 mg/cm^2/day) for a TSP equal to 30 μg/m³. This is already well above the salt deposit levels that are considered "High" in electrical testing. From this second simulation result, we can also observe the non-linearity of the variation of the accumulation rate in relation to the wind speed.

During the third simulation, the pollution accumulation rate was compiled varying the TSP. According to the obtained result shown in Fig. 9, the variation is linear. And a combination of high particles content and a high wind speed increases the risk of pollution accumulation. It means that typical road salting, combined with a gale force wind during winter season may have disastrous consequences for the electrical performance of insulators near the road.

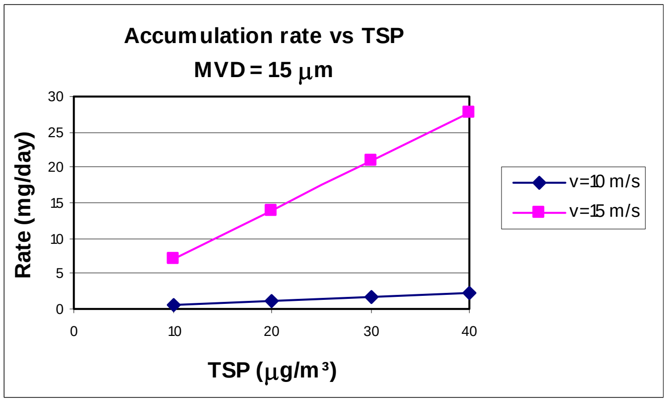

Fig. 9. Accumulation rate versus TSP at different wind speed

The effect of exposure duration was explored in the fourth simulation. The result plotted in Fig. 10 shows that the mass of the pollution accumulation increases linearly with time.

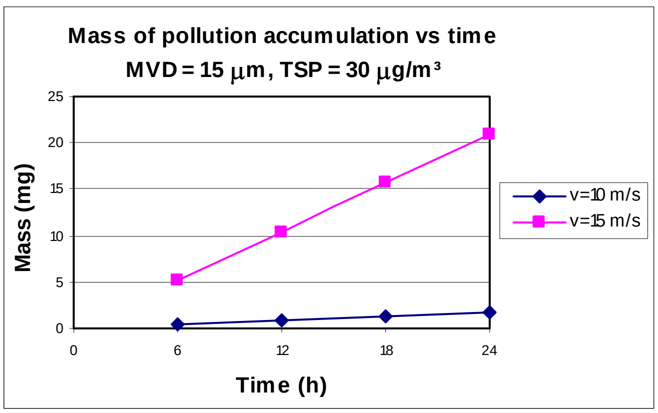

Fig. 10. Mass of pollution accumulation versus contamination event duration at different wind speed

From this figure, we can also observe the important change of slope of the curve when the wind speed increases. It means that the pollution accumulation rate becomes very threatening when the wind speed is so high.

V. Comparison with Flashover Event of 2004 01 27

In the Introduction, we described an exposure event that led to insulator contamination levels of 90 µg/cm² after 24 h of exposure at a median wind speed of 56 km/h. This contamination level corresponds to an accumulation weight of 54 mg on the 600 cm^2 top surface of the disc insulator. The simulations show that this exposure is well within the practical range of parameters. A TSP value of 80 µg/m^3 at a Mean Volume Diameter of 15 µm fits this observation, as does a TSP value of 30 µg per m^3 coupled with a MVD of 17 µm. The high sensitivity of accumulation rate to MVD is interesting and remains to be validated in future work.

VI. Conclusions

The numerical model used in this study showed that the wind speed has an important effect on the pollution accumulation rate on outdoor insulator surface, which is non linear. And, even if the mass of accumulation is in the order of some milligrams, the consequence may be disastrous for the insulator because this accumulation can have an important equivalent salt deposit density. Thus, under winter conditions, characterized by a gale force wind, road salting constitutes both a potential and a practical threat for high voltage line insulators.

This preliminary work in the modeling of the effect of wind speed is encouraging, but has also raised questions about the correct volume mean diameter of salt aerosol in winter conditions. Further theoretical studies are necessary and some experiments in laboratory must be carried out. Indeed, the actual numerical model was developed to be applicable with water droplets and a cylinder object, in two dimensions. In this way, some assumptions have been used and the insulator surface has been subdivided in ten stacked cylinders.

More advanced numerical models should be extended to better simulate the road salt accumulation on top and bottom insulator surfaces.

VI. Acknowledgment

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