EFFECTS OF ACID RAIN ON OUTDOOR INSULATORS

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This paper gives an overview of the acid rain problem in Europe, Poland and the Polish province of Silesia. The relationship between pH and water conductivity is shown. Different reactions between acid rain and particles are presented. Effects of temperature on the conductivity of H_2SO_4 solutions were studied. Finally, pollution flashover voltages and leakage currents on a model insulator that was contaminated with H_2SO_4 and other solutions were measured.

1. INTRODUCTION

The influence of rain precipitation on transmission line insulation was studied in the 1920's and 1930's [1]. It was found that the rain conductivity can attain a value of 100 µs/cm, while the rain intensity can be as high as 3 mm/min. These results were the basis for preparing the IEC standard - wet test for outdoor insulators. In the 1960s, the environmental contamination increased to a point that the rain conductivity had reach a value of 4000 µS/cm [2, 3, 4]. In Upper Silesia (Poland) the rain conductivity was at a level of 1000 µS/cm, while drizzle was up to 2000 µS/cm. Conductivities in the vicinity of chimney cold storage were at a higher level of 3000 µS/cm [5]. The flashover voltage (F.O.V.) during a rain with such a high conductivity can be two times lower than the F.O.V. under the wet test (according to IEC standard).

In the 1960s it was found that rain precipitation had not only a high conductivity but also a low pH value (smaller than 5.6). The negative influence of acid rains on soil, forest, buildings, steel constructions was recognised a long time ago. To limit environmental impact, SO_2 and NO_x emissions were gradually decreased in many countries. This effort produced measurable effects. In spite of this, in some regions the pH value of rain water still remains lower than 5.6.

Acid rain causes the ageing of polymer insulators. The chemical interaction between the acids and the polymer can contribute to hydrophobicity loss and material erosion. The most dangerous is the brittle fracture phenomenon that leads to insulator breaking [8]. In this paper the influence of acid rain on the pollution flashover voltage is presented. The work is concentrated on porcelain insulators but some results are valid for polymer insulators as well.

2. ACID RAIN FORMATION

The emission gases: sulphur dioxide SO_2 and NOx (a combination of NO_2 and NO) are most responsible for the acidification of rain. A considerable emission increase of SO_2 in Europe was observed initially at the beginning of the twentieth century, then thaw in the 1950's to 1970's. Sulphur dioxide and nitric oxides are transported for long distances, e.g. from West or Middle Europe to

Scandinavia. During transport, SO_2 and NO_x oxidise to form sulphuric and nitric acids. These acids are absorbed up by precipitation (rain and snow), and settle out of the atmosphere due to the size of the resulting drops. This process is referred to as wet deposition. Other materials contained in particles settle to the ground without interaction with rain or snow. This process, referred to as dry deposition, is most significant in the vicinity of the emission source. Thus, the rain acidity can be very similar near the emitter and far from it (e.g. Middle Europe and South Scandinavia).
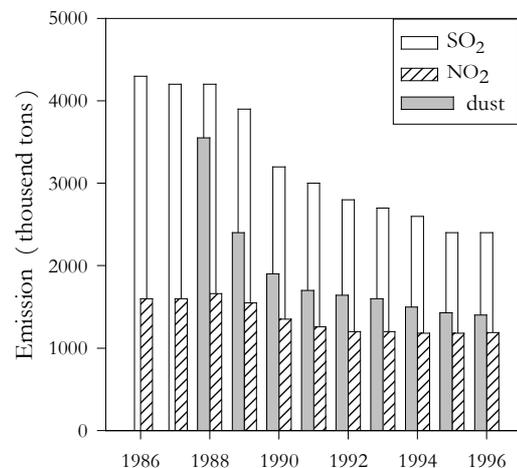

Fig. 1. Emission of gases and particles in Poland in the years 1986–1996 [9]

The emissions of gases and particles in Poland decreased since 1986 (fig. 1). This decrease in emission was initially caused by a decrease in industrial production. However, after 1992 the decrease was a result of ecological investments (building of desulphurizing plants, installation of new, more efficient filters taken by large etc.). This success was accomplished through positive steps the activities of big plants that in the past were huge environmental polluters. The copper smelter plant in Głogów and the electric generation in power station Turów are the examples of large plants. These plants limited SO_2 and particle emission by 20 and 7 times, respectively.

Therefore, it is interesting and important to once again evaluate the pollution stress on outdoor insulation taking into account this new, advantageous situation circumstances.

3. CONDUCTIVITY AND pH FACTOR OF RAIN

Clean rain water is slightly acidic (pH = 5.6) due to the presence of CO_2 in the atmosphere. The lowest pH value of 1,5 was detected in 1979 in Wheeling (West Virginia, USA). In Europe, the lowest pH value was 2,4, and occurred in Pitlorchy (Scotland, 1974) [10]. There are regions (e.g. Upper Silesia, Poland) where the pH decreased (became more acidic) in spite of decreasing particle and gas emissions. In Katowice in 1989 the majority of rain samples had pH values ranging from 6,1 to 7,0. Nine years later about 70% of the rain samples were characterised by a pH value from 4,1 to 5,0, and about 11% by a value from 3,1 to 4,0 [11]. It is believed that the primary cause of the decrease in rain acidity is the limitation of particle emissions. These particles have neutralisation properties because of their alkaline character. However, in regions where the lowest pH value was recorded in 1989 e.g. in the "black triangle" in the Sudety Mountains, the rain acidity became smaller over time (fig. 2).
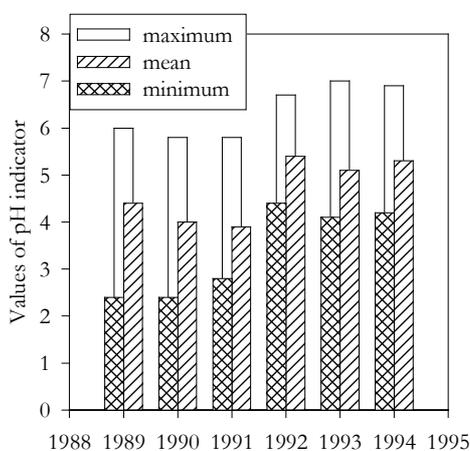
Fig. 2. The changes of pH values in Sudety Mountains, Rozdroże Izerskie between 1989 and 1994 [12]

The conductivity of rain water is initially greater and usually decreases with time [1]. On the other hand the pH value can initially decrease and then increase. Both processes are caused by contaminant washing and neutralising reactions of rain water and alkaline particles. The mean conductivity of rain water measured after the end of rainfall can sometimes be lower than its maximum (fig. 3). Additionally, the conductivity of a sample collected during rainfall and subsequently measured can be smaller than the weighted mean value from continuous measurements (as seen in fig. 3). This effect can be explained by neutralisation reactions.
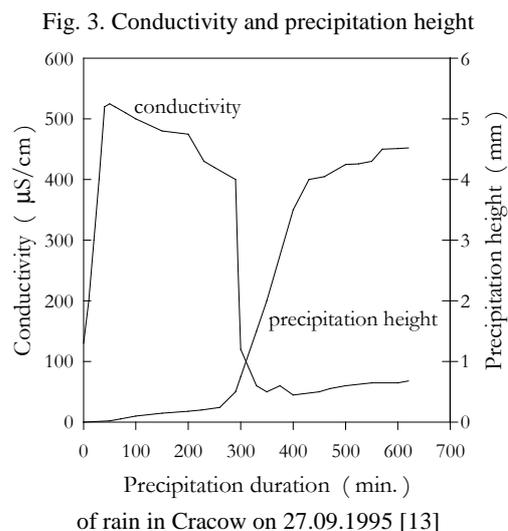
Fig. 3. Conductivity and precipitation height

of rain in Cracow on 27.09.1995 [13]

The conductivity of rain water (κ) depends on its acidity (H^+ ions concentration) and on the amount of dissolved salts. Conductivity can be expressed as the following sum:

$$\kappa = \sum_{i=1}^{m} n_i \cdot \mu_i \cdot e_i \qquad (1)$$

where: n_i, μ_i, e_i – represent concentration, mobility, and charge of carriers, respectively, and m represents the carrier number.

A measure of acidity of a solution is the hydrogen ion concentration $[H^+]$ (measured in mol/dm^3). For simplification, the logarithm the concentration of hydrogen ions is used (pH = $-\log [H_3O^+]$). The conductivity can be re-expressed using the following equation:

$$\kappa = [H_3O^+] \cdot \mu_{H_3O} e + \sum_{i=1}^{m-1} n_i \cdot \mu_i \cdot e_i \qquad (2)$$

where: e – is the elementary charge.

Therefore:

$$\log \kappa = -pH + B \qquad (3)$$

where: B is a constant that depends on the chemical composition of rain.

Figure 4 shows the dependence of conductivity of sulphuric acid on pH. In the pH region 1,5 ÷ 5, the dependence is a line that can be described by the equation:

$$\log \kappa = -pH + 5,5 \qquad (4)$$

where the units of conductivity, κ, are µS/cm. The constant B, for rain water changes. However, B is generally greater than 5,5.

The dashed region in fig. 4. represents the possible pH and κ values of acid rain water. There is not a strong correlation between conductivity and acidity of rain.

There simply exists a greater probability that rain with a maller pH will have a higher conductivity. From fig. 4 it can be seen that record rain from Wheeling (pH = 1,5) was characterised by a conductivity of about 10000 μS/cm.

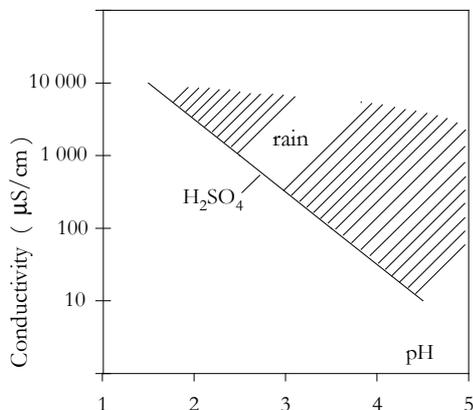
Fig. 4. Dependence of conductivity on pH factor for sulphur acid and acid rain [14]

4. ACID RAIN – PARTICLE INTERACTIONS

Pollution flashover voltage depends not only on the conductivity of rain but on the conductivity of the mixture consisting of particulate matter pollution and rain water on the insulator surface. Industrial particles often contain a great deal of alkaline metals such as Ca, Na, K. Therefore, in a mixture of acid rain and particles, a typical neutralisation reaction may occur. This reaction: $H^+ + OH^- = H_2O$ results in the replacement of very mobile hydrogen ions by less mobile molecules of water. Figure 5 shows the titration results of a 0.1% H_2SO_4 solution using particles from a copper power plant. Due to neutralisation the solution's acidity continually decreases. The conductivity decreases only to the balance point and then increases because of the higher ion concentration caused by soluble particle components.
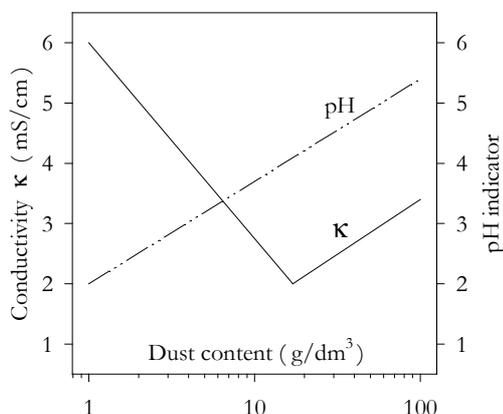

Fig. 5. Titration results of 0,1% H_2SO_4 solution by particles from a copper power plant [14]

The rate of the previously mentioned reactions could also affect the pollution flashover voltage of insulators. These reactions are bimolecular (of second order). Therefore the time needed for half of the substratum to react is dependent on the initial substratum concentration. Therefore the surface conductivity on more polluted insulators that are sprayed by acid rain decreases more rapidly than on less polluted insulators.

5. TEMPERATURE DEPENDENCE OF CONDUCTIVITY

Intensive discharges that can lead to pollution flashover warm up the electrolyte on the insulator. The conductivities, κ, of diluted solutions in the temperature range 0 °C – 30 °C are given by the following equation:

$$\kappa = \kappa_o [\, 1 + a\,(\,\vartheta - 18\,) + b\,(\,\vartheta - 18\,)^2\,] \quad (5)$$

where: κ_o − is the conductivity at 0 °C, ϑ − is the temperature in degrees Celsius, and a and b − are parameters that depend on the type of electrolyte. Values for the parameters a and b are given in table. 1.

The conductivity of acid solutions increases slower than NaCl. Additionally, at higher temperatures the conductivity of some solutions can be a nonlinear function of temperature (fig. 6).

Table. 1. Values of parameters a and b

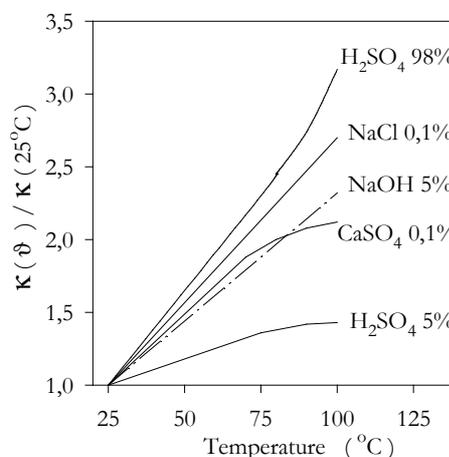| electrolyte	a 10^{-4} (°C)$^{-1}$	b 10^{-6} (°C)$^{-2}$
$^1/_2$ H_2SO_4	165	-16
HNO_3	163	- 16
NaCl	226	84

Fig. 6. Conductivity increase of non-saturated solutions with temperature

6. FLASHOVER VOLTAGE AND LEAKAGE CURRENT

The flashover voltage and leakage current were measured on a flat model insulator. A constant volume of electrolyte was spilled giving a uniform surface layer with dimension 65 cm × 8 cm and a thickness of 0,23 mm. The flashover voltage was measured according to the up and down method using two diluted solutions: NaCl, H_2SO_4 and a saturated solution of $CaSO_4 \cdot 2H_2O$. During the test the leakage currents were also measured.

The results (fig. 7) show the currents obtained after switching on the voltage (25 kV) to the model insulator that was polluted by solutions of NaCl, H_2SO_4, and $CaSO_4 \cdot 2H_2O$ with the same initial conductivity of 2 mS/cm. The leakage current caused a temperature increase of the electrolyte. As a result the electrolyte conductivity and leakage current also increased. Due to intensive damping, the pollution layer thickness decreased, and dry zones appeared after 1 - 2 seconds. When the discharges ignited, the current became a non-continuous function of time.
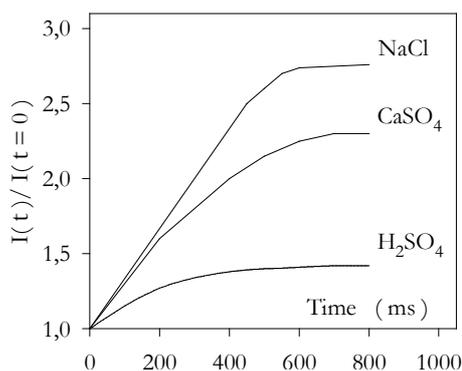

Fig. 7. Current changes after applying on the voltage of 25 kV to the flat model insulator [14]
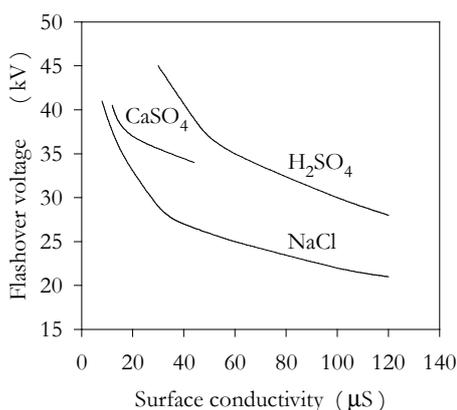

Fig. 8. F.O.V. as a function of surface layer with conductivity. Flat model insulator sprayed different solutions [14]

Figure 8 shows the measured flashover voltage of the model insulator as a function of surface conductivity before voltage application. As expected, the F.O.V. in the presence of the NaCl solution is the lowest. The highest F.O.V. was measured in the presence of the sulphuric acid solution. These results show the importance of the chemical composition of the pollution layer and the temperature dependence of solution conductivity for flashover voltage of insulators.

7. DISCUSSION

Our results show that a diluted solution of sulphuric acid is less dangerous for porcelain insulators than NaCl solution. However, this does not mean that acid rain does not lead to pollution flashovers on outdoor insulators and thus power ortages. In fact, such incidents were noticed in Norway during the winter months of the 1980's [16]. Many unexplained outages were also observed in Poland in the vicinity of Wałbrzych [17]. It is probable that those flashovers were also caused by acid rain. In our experiments acid rain was modelled using H_2SO_4. The F.O.V. of insulators sprayed with nitric acid solution is lower than that of insulators sprayed with sulphuric acid (fig. 9). The lower F.O.V. for HNO_3 cannot be explained by the temperature dependence of conductivity since this property is identical for both acids (see Table. 1).
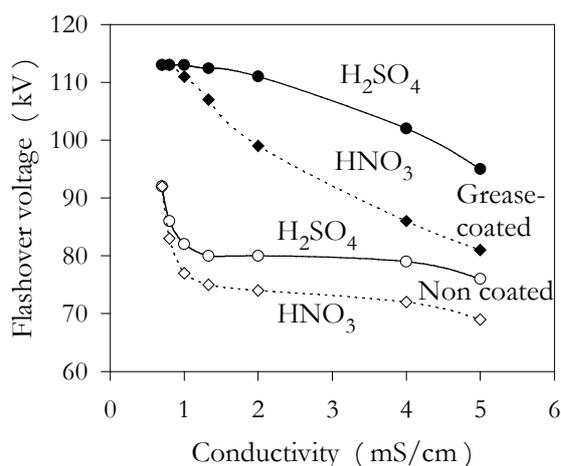

Fig. 9. Flashover voltage as a function of acid rain water conductivity [18]

CONCLUSIONS

1. In spite of the decrease in the emissions of particles and SO_2 in Poland, the acidity of train is still high. In the Upper Silesia province, the pH of rain is now lower than it was in the 1980's.
2. At the beginning of light rainfall, high conductivities (a few hundred μS/cm) and low pH values (≈ 3) can be observed.
3. Acid rains are known to cause outages in Norway in winter. It is possible that acid rain may have contributed to flashovers experienced in Poland during the summer months in the vicinity of Wałbrzych, in south-west Poland.

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