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The problem of ozone generation in electroadhesion devices

***Abstract**. This paper describes the problem of ozone generation during electroadhesive pad tests. For this purpose a test stand was built to supply the pad with high voltage in order to generate partial discharges on the pad surface accompanied by ozone generation. The measurement was carried out by using an ozone sensor placed together with the electroadhesive pad in a closed chamber.*

Streszczenie.** W tym artykule opisano problem generowania się ozonu podczas badań z wykorzystaniem padów elektroadhezyjnych. W tym celu zbudowano stanowisko pomiarowe do zasilenia pada wysokim napięciem, tak aby wytworzyły się wyładowania niezupełne na powierzchni pada, którym towarzyszy wytwarzanie się ozonu. Pomiar przeprowadzono za pomocą czujnika ozonu umieszczonego wraz z padem elektroadhezyjnym w zamkniętym naczyniu.**(Problem generowania ozonu w urządzeniach elektroadhezyjnych)

Słowa kluczowe: elektroadhezja, pad elektroadhezyjny, ozon, wyładowania niezupełne
Keywords: electroadhesion, electroadhesive pads, ozone, partial discharges.

Introduction

Electroadhesion is the intermolecular attraction between two different solids through the generation of an electrostatic field [1]. A device called an electroadhesive pad is used to generate an electroadhesive force. By supplying the pad with a high DC voltage, the forces generated are characterized by properties that attract different objects [1]. Electrodhesive pads are plates or tapes made of dielectric material on which two electrodes are placed [2]. Most of the cases encountered in the literature [3] [4] use copper electrodes with different electrode arrangements such as spiral or comb and others. Depending on the type of materials and the parameters of the electroadhesive pad, objects of different shapes can be attracted, caught and gripped. Electrodhesive pads made of flexible tape are then used to better adhere to complex shaped objects. Such solutions are used as grippers in aerospace [5], in industry for textile handling [6] or as an attachment element of expeditionary robots used in machine diagnostics [7] [8] [9].

Electrodhesion uses high voltages, which must be adjusted to the parameters of the electrodes so that no electrical breakdowns occur between the electrodes and no partial discharges are produced on the surface of the pad. If an electrical breakdown occurs, the pad or the material to be gripped can be damaged. Therefore, it is important to avoid such failures when using electrodes.

Research problem

Discharge on the surface of dielectric is usually an unhelpful side effect, which is produced under the action of high electrical potential difference [10]. During the generation of electrical discharges, some phenomena accompany it. In addition to the observable breakdowns between two points, which appear in the form of an electric arc, the discharges are also accompanied by audible crackling during the breakdowns and a characteristic ozone odor floating in the area of the discharge. Too high a concentration of ozone can cause side effects when inhaled by humans [11]. The average limiting concentration of ozone in air that is detectable to humans is 40 μg/m^3 (0.03 ppm). The maximum permitted concentration of ozone in the workplace is 0.1 mg/m^3. The first symptoms of ozone irritation (observed at concentrations of 0.2 mg/m^3) are coughing, scratchy throat, drowsiness, and headaches. At higher concentrations, it can lead to increased blood pressure, accelerated heart rate, and pulmonary edema leading to death (at concentrations of 9-20 mg/m^3). Ozone occurs naturally in the air and concentrations are not dangerous to humans. In small doses, ozone can have disinfectant properties. However, the estimated lifetime of ozone decreases with increasing ozone concentration in the gas mixture and with increasing temperature [12]. At room temperature, the half-life of ozone in an oxygen mixture should be estimated between 20 and 100 hours depending on the concentration [13].

During the study of the electroadhesion phenomenon it was noticed that there is a characteristic ozone smell when a partial discharge is present. It was decided to investigate what the ozone concentration will be when the electroadhesive pad is energized with high voltage and the resulting concentration will not score in ozone inhalation side effects for the duration of the measurements

Measurement system

In order to study the ozone concentration, a measuring station communicating with a computer through Matlab software was built. The electroadhesive pad was powered from a regulated low voltage power supply through a high voltage inverter and a voltage multiplier with a rectifier. Figure 1 shows the measurement setup.

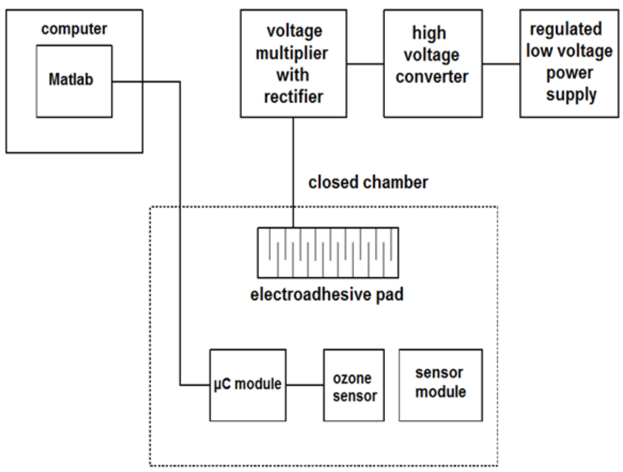

Fig.1. Electrodadhesive pad power supply system

A Gravity DFRobot SEN0321 sensor module [14] was used to investigate the ozone concentration, which was placed together with a pad in a closed chamber. The main features of this sensor are a measurement range of 0 to 10 ppm, a measurement resolution of 0.01 ppm (10 ppb), a response time of up to 90 seconds, and communication via I^2C. In addition, the environmental parameters in the laboratory were measured using the Silicon Labs module [15], which were: temperature 23.4°C, 37% humidity, and pressure 1001 hPa. Figure 2 shows the electroadhesive pad with comb-shaped electrodes that was used in the measurements.

Fig. 2. Electroadhesive pad with comb-shaped electrodes

To produce the partial discharge, an electroadhesive pad made of dielectric material was used. The height of the pad was 10 cm, the width was 5 cm, and the thickness of the pad was 0.1 mm. The electrodes were spaced 2 mm apart, the width of one electrode is 0.2 mm.

Research and results

The study, which was designed to check the ozone concentration during partial discharges on the surface of an electroadhesive pad, was conducted in three stage. The first stage consisted in placing the ozone sensor next to the electroadhesive pad and making measurements for 13 kV and 15 kV DC voltage supplying the pad. In the second stage the sensor was placed 10 cm below the pad and in the third stage the sensor was placed at the bottom of the chamber at a distance of 30 cm from the electrocohesive pad.

The test was started by turning on the microprocessor module with the ozone sensor and the concentration was measured for 15 min under container conditions. After the sensor stabilized, the power supply to the electroadhesive pad was turned on with high voltage so that a partial discharge occurred. After 15 min, the power was turned off and the ozone concentration was measured for another 15 min. The whole measurement lasted 45 min. The measurements were carried out for three stages of setting up the ozone sensor with 13 kV and 15 kV power supply for the electrodes.

The figure shows step one of the ozone concentration test, where the sensor was placed next to the electroadhesive pad. The graph does not show the initial increase in ozone concentration that the sensor needs to calibrate (90 seconds). This may be because of the electromagnetic field persisting in the area of the electroadhesive pad that is affecting the sensor. From the beginning of the measurement, the ozone concentration was rising, but after the power was turned off, the concentration suddenly increased to a value of about 470 ppb. This sudden spike was caused by the response time it takes for the sensor to return a value.

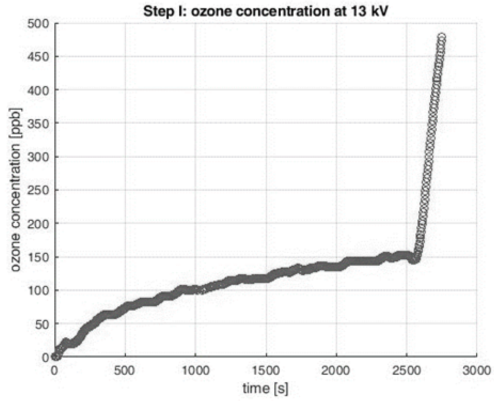

Fig.3. Step 1: Ozone concentration test at 13 kV with ozone sensor placed next to electroadhesive pad

This sudden increase was explained by the response time it takes for the sensor to return a value. Figure 4 shows step 2 in which the sensor was placed 10 cm under an electroadhesive pad. The pad was powered at 13 kV. As in step 1, an increase in ozone concentration was recorded when the power supply to the pad was disconnected.

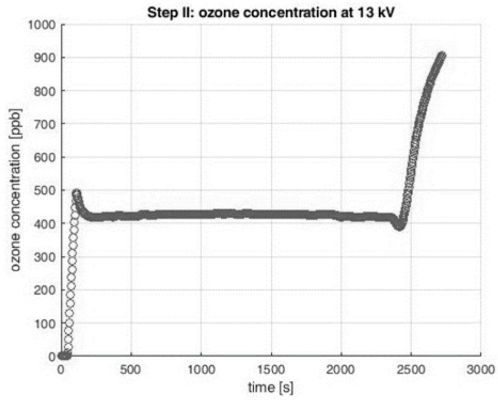

Fig.4. Step 2: Ozone concentration test at 13 kV with ozone sensor placed 10 cm below the electrodesiccation pad

In step 3 shown in Figure 5, the ozone sensor was placed at the bottom of the chamber at a distance of 30 cm from the electroadhesive pad. The voltage supplying the pad was also 13 kV. It was presumed that the ozone, because it is heavier than air, would settle to the bottom of the chamber. After powering on and leaching for 10 min the ozone concentration increased to a maximum of about 750 ppb.

The graphs show a sudden increase of ozone concentration in the initial phase of the measurement. This is the calibration time of the sensor (lasting 90 seconds) and the stabilization time of the measurements. The ozone concentration did not increase suddenly until the power of the electroadhesive pad was turned off. For all stages, the sensor response time was the same and was about 10 min. Ozone concentration results were returned in ppb (parts per billion) values. For measurements with the 13 kV pad energized, the maximum ozone concentration was between 500 and 900 ppb or about 0.9 ppm. These are relatively small ozone values and are not dangerous for humans.

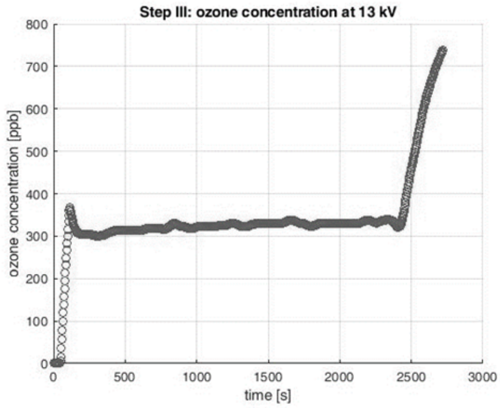

Fig. 5. Step 3: ozone concentration test at 13 kV with the sensor placed 30 cm from the electrodesiccation pad

Another test was conducted with the pad energized at 15 kV. Also three configurations of sensor placement from the electroadhesive pad were included. Figure 6 shows step 1 of the ozone concentration test, which was generated by partial discharges using a 15 kV supply voltage. The sensor was placed next to the electroadhesive pad.

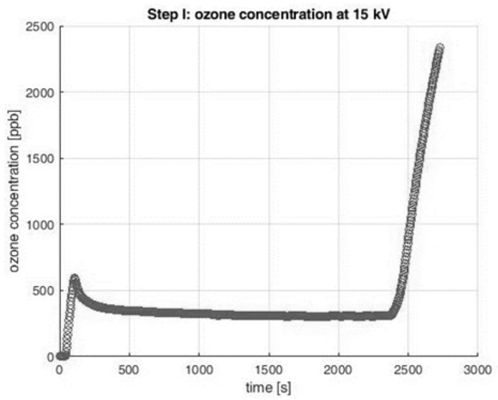

Fig.6. Step 1: Ozone concentration test at 15 kV with ozone sensor placed next to electroadhesive pad

It can be seen in the graph that the early results are similar to those obtained with the 13 kV supply voltage. However, after disconnecting the power supply, the ozone concentration is higher than in previous tests.

The next step 2 (Figure 7) was conducted for a 15 kV power supply and placing the ozone sensor 10 cm under the electroadhesive pad. In this case the non-linear behavior of the obtained measurements was noted. The reduction and increase of ozone concentration can be caused by the electromagnetic field interfering with the ozone sensor.

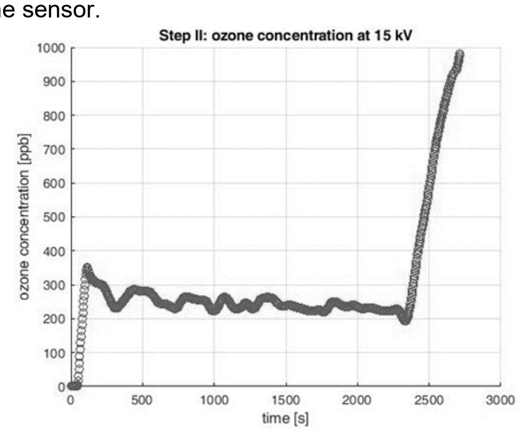

Fig.7. Step 2: Ozone concentration test at 15 kV with ozone sensor placed 10 cm below the electrodesiccation pad

The last measurement that was performed in the partial discharge ozone study was step 3. Figure 8 shows a plot of ozone concentration at 15 kV supply. The sensor was placed at the bottom of the chamber at a distance of 30 cm from the electroadhesive pad. The results that were obtained were similar to previous results using a 15 kV supply voltage.

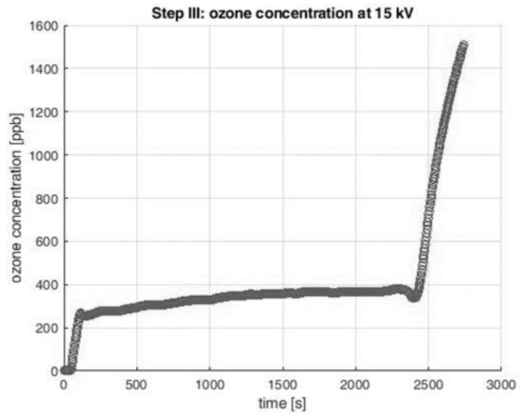

Fig. 8. Step 3: ozone concentration test at 15 kV with the sensor placed 30 cm from the electrodesiccation pad

The measurement results for the 15 kV voltage supplying the pad were slightly higher than for the 13 kV voltage. The maximum measurement results were in the range of about 1000 ppb to 2300 ppb or maximum 2.3 ppm. Although higher values of ozone concentration were obtained, it was not toxic to humans. As mentioned earlier, the dose that can irritate the upper respiratory tract starts at 2 ppm depending on the time spent in the ozone environment and the temperature.

The ozone test was also performed at 11 kV supplying the electroadhesive pad. The voltage was too low for a partial discharge to occur on the surface of the pad. The consequence of no partial discharges was the lack of ozone generation.

Conclusion

When testing with electroadhesive devices, there is a possibility of a partial discharge on the pad surface, which generates ozone. Discharges are not advisable when using electroadhesive devices as grippers because damage can result to the pad or the material being picked up.

Tests have been conducted using a high voltage of 13 kV and 15 kV supplying the electroadhesive pad so that partial discharges and ozone generation occur. Ozone concentrations were measured for 45 min including calibration of the sensor, powering up the pad, and testing ozone after powering down the pad. The sensor was placed in three configurations i.e. next to the electroadhesive pad, 10 cm under the pad, and at the bottom of the chamber at a distance of 30 cm from the pad. The distance of the sensor from the electroadhesive pad was not very important because the concentration that was measured in the chamber was very small and did not indicate toxic doses. The initial increase in ozone concentration was a calibration of the sensor (about 90 seconds) until stabilization. The measurements that were obtained fluctuated a little with the time of the study. This may have been due to the presence of electrostatic and electromagnetic fields generated by the electroadhesive pad. Ozone charges may have been induced on or near the surface of the electroadhesive pad and thus were not detected by the ozone sensor. When the pad was powered off after 10 min there was an increase in ozone concentration in each case. This was due to the response time of the sensor to give back the measured values. This was investigated while working with other tests of ozone generation by the electroadhesive pad.

Tests conducted at various distances of the sensor from the pad showed ozone concentrations ranging from 0.5 ppm to 2.3 ppm. However, the results differed and recorded lower ozone concentrations for the test at 13 kV versus 15 kV supply. In the case of the 15 kV power supply, the ozone concentration was higher because there was more intense patrial discharges and therefore a higher ozone dose was generated. However, in both cases the ozone dose is too low to take into account a possible poisoning danger.

If the measurement had been carried out without a chamber and the measurement had been carried out longer, the ozone concentration would probably have increased there is a risk of ozone poisoning, which could lead to damage to the upper respiratory tract and breathing problems. In critical cases very high ozone concentrations (9 ppm and above) could lead to death. Therefore, it is important to be in a well ventilated room and to have a secure working area to avoid electrocution when testing with electroadhesive devices that generate a partial discharge and ozone. As a future work it is planned to repeat the tests of ozone concentration measurement at different voltage and using electrodes with different width and distance between electrodes.

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