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Silicone Rubber Treatment with a Sodium Chloride Solution in the Presence of an Electric Field

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Abstract—High voltage silicone insulators that are placed close to coastal marine areas have the problem of salt fog depositing on their surfaces in the form of conductive droplets. Under the influence of an electric field, those droplets initiate partial discharges, which leads to the degradation of the hydrophobic properties of silicone rubber. This phenomenon, in which droplets serve as the cause of partial discharges, has been studied in considerable detail elsewhere. However, it remains unclear whether the droplets themselves, as moisture-laden areas, affect the properties of silicone rubber. The current work is focused on studying the combined effect of an AC electric field (E = 17 kV/cm) and a 4% solution of sodium chloride on the water-repellent properties of silicone rubber in the absence of electrical discharges. The results of the study show that the influence of moisture and an electric field leads to slowing down the droplet runoff from the inclined sample of Powersil 310 rubber. An AC electric field did not have a noticeable effect on the rate of water runoff; the slowdown was due to the pre-treatment of the sample with the solution.

Keywords: high-voltage silicone insulation, dynamic hydrophobicity, static contact angle, saline solution, water immersion

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INTRODUCTION

In aerial power transmission systems, insulators serve a dual purpose: they provide mechanical support to power lines and an electrical insulation between the conductors and the power line pylons to prevent current leakage to the ground. Consequently, insulators must possess high electrical and mechanical strength. In recent decades, silicone rubber has been widely employed in the high-voltage insulation. The key advantages of silicone insulators compared to those of the ceramic ones include resistance to contamination, mechanical strength, and hydrophobicity [1].

Despite its benefits, silicone insulation is subject to aging and degradation. The service life of silicone rubber insulators depends on external factors such as surface contamination, partial discharges, ultraviolet radiation, rain, fog, and some others [2]. To extend the service life of insulators, it is essential to understand the processes occurring under the influence of each environmental factor or their combinations. The present paper deals with the role of moisture in the degradation of silicone insulation in the presence and the absence of an electric field.

Several studies were focused on the impact of moisture on the properties of silicone rubber. Typically, rubber samples were subjected to prolonged immersion in water or solutions, and changes in the static contact angle were recorded [3–10]. Water immersion involves submerging a sample in a container filled with water or a solution. The static contact angle is a common parameter characterizing the hydrophobicity of the tested surface. Measurement of the static contact angle is performed by placing a water droplet on the horizontal surface of the sample [11]. The static contact angle is geometrically defined as the angle between the solid body and the tangent to the interface between the liquid and gas phases. A surface is considered to be hydrophobic if the static contact angle exceeds 90°. In most of the aforementioned studies, in addition to measuring the static contact angle, the weight of the sample before and after immersion was measured, which correlates with changes in hydrophobicity.

It is worth noting that the publications mentioned above often involved extended immersion periods, ranging from hundreds to even thousands of hours. Only a few studies investigated durations on the order of a few days when the effect of immersion becomes noticeable. However, in reality, moisture, such as morning dew, for instance, can be present on insulators for just a few hours, and it remains unknown whether the surface properties of rubber can change significantly during such a short period.

Several mechanisms of hydrophobicity loss due to moisture exposure have been identified [3, 12, 13]:

• transfer of low-molecular-weight structures from rubber to water;

• reorientation of methyl groups into the bulk of the rubber;

• penetration of hydrated ions and water molecules into the surface and bulk of the rubber;

• dissolution of rubber fillers in the solution or water.

The results of water immersion can depend on the duration of the test, temperature, the solution concentration, and fillers in silicone rubber. Those mechanisms may occur simultaneously; for example, low-molecular-weight structures may come out of rubber while water may be absorbed into the rubber. This complexity makes it challenging to analyze the overall process because the final sample weight and the static contact angle may not change. According to [14, 15], dynamic methods of measuring hydrophobicity are more sensitive than static ones, but they are rarely used in the studies on the impact of moisture on silicone rubber. Therefore, to assess changes in the sample surface the present investigation employs measurements of the static angle and two dynamic methods: visually observing water runoff from the vertical sample and measuring the speed of the droplet runoff on the inclined sample surface.

It is worth highlighting the works devoted to the study of the influence of an electric field on the process of water immersion. It has been shown that a DC electric field increases liquid diffusion into the rubber depending on polarity [8, 10]. Some authors reported that there was no increase in water immersion effects due to an AC electric field [6–8, 10]. All those studies investigated the effect of the electric fields strength not higher than 6 kV/cm, which is far below the critical electric field strength (25 kV/cm) for the appearance of the discharges in air. But this is exactly the electric field strength that occurs on real insulators near the edges of water droplets. And such an electric field of 25 kV/cm can hypothetically enhance the effect of interaction between rubber and moisture compared to that at 6 kV/cm. Moreover, there are grounds to believe that dynamic methods for measuring hydrophobicity are more sensitive to changes in rubber surface, and the water-aged effect is not noticeable when measuring the static angles.

Based on the aforementioned analysis, the present study aims to examine the impact of moisture on silicone rubber in the presence and the absence of an AC voltage with an electric field strength close to the critical electric field. An AC voltage was used because power lines were considered. The duration of water exposure was only a few hours, which approximates the real-world exposure to moisture in coastal marine areas. The present study used a 4% solution of sodium chloride whose salinity corresponds to the salinity of fog in coastal areas.

EXPERIMENTAL

Experimental System

Figure 1 shows the experimental setup. The idea of the experiment was as follows: to fill a part of the surface of a silicone sample with a sodium chloride solution and at the same time to apply an AC voltage. The unique feature of the setup is that it can eliminate the influence of partial discharges on the silicone samples in order to separate the influence of moisture from the influence of discharges, the latter having been extensively studied elsewhere. The test sample was positioned on a grounded electrode. Two silicone layers with a hole into which the saline solution was poured were placed on top of the sample. The rubber surfaces adhered well to each other, preventing the solution from leaking. A high-voltage electrode compressed all layers of rubber and was immersed into the solution. Due to electrochemical reactions, the electrode began to dissolve. To prevent the reaction products from depositing onto the test sample, a thin polyethylene film was always placed between the two layers of the solution. An AC voltage generator AID-70M with 50 Hz frequency was used. A capacitor of 80 pF was used as a current limiter. The voltage amplitude measurements were carried out using an analog-to-digital converter L-Card-761, through a resistive divider. In the experiments without an electric field, the setup was similar, but no voltage was applied.

The voltage V_{rms} = 5.2 kV was chosen in the present case; the root mean square (rms) electric field strength was approximately 17 kV/cm in the rubber sample and on its surface that was in contact with the solution. That voltage was selected in order to approximate the electric field strength to the critical electric field value for air—25 kV/cm. This is because during the operation of insulators, due to a water droplet on the surface of the rubber, a triple point is formed at the junction of air, dielectric, and water, near which the electric field strength can be sufficiently high to cause a discharge activity.

The ambient air temperature was in a range from 19 to 21°C and pressure—from 737 to 770 mm Hg.

The exposure to the electric field and moisture lasted for 2 h. Such a short duration was chosen because it is essential to investigate whether the impact of moisture can manifest itself under real operating conditions of insulators, for example, during morning fog.

Preliminary treatment of silicone samples was carried out according to [16]. Before testing, samples were first cleaned with isopropyl alcohol using a lint-free wipe and then rinsed in distilled water. After this, they were stored at the temperature at which the experiment would be carried out for at least 24 h.

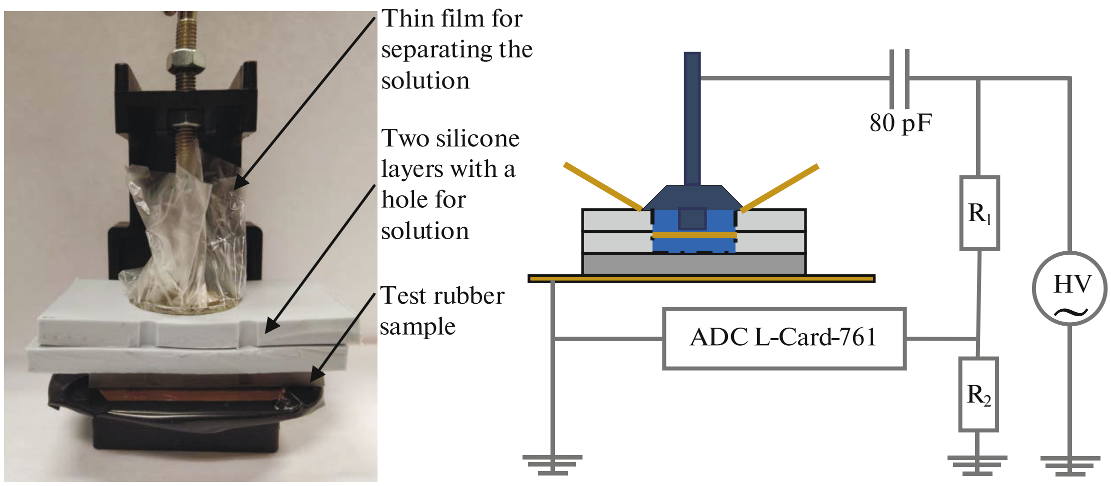

Fig. 1. Photograph and scheme of the setup for the experiment with a water layer and an electric field.

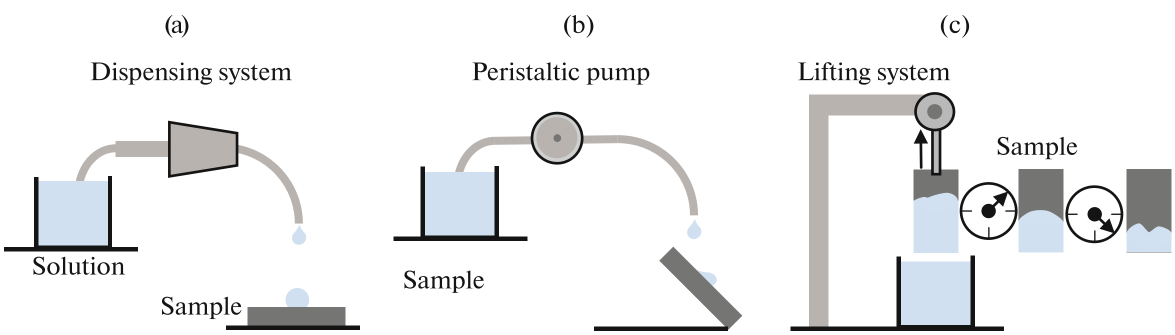

Fig. 2. Illustrations for measurements of quantitative parameters of hydrophobicity changes: (a) measurement of the static contact angle using the sessile drop method; (b) measurement of the speed of dripping droplets from an inclined sample, and (c) measurement of the flow of the water film from a vertically positioned sample.

Measurement Systems

To check the change in the surface condition of the samples before and after exposure to moisture and an electric field, three parameters were measured:

(1) the static contact angle (Fig. 2a): droplets were placed within the area of influence on the setup for measuring the contact angle, and the contact angle was measured;

(2) the speed of flowing droplets (Fig. 2b): a sodium chloride solution was supplied to the surface of the sample using a peristaltic pump at a rate of 75 ± 5 droplets per minute. The droplets flowed down the sample inclined at a 40° angle to the horizon, and their speed was measured along the entire path using software. The measurements of the droplet speed were conducted in the absence of an electric field. The volume of the dripping droplets depends on the condition of the silicone rubber surface. The process was being recorded on a camera for 5 min. To determine the dripping speed of the droplets along the sample surface, a detection and tracking problem was solved using computer post-processing. First, the boundaries of the droplet were identified on each frame using filters, and the coordinates of the center of the circumscribed circle were recorded. On subsequent frames, the new position of the same droplet was determined. By knowing the change in the center coordinates of each droplet over the dripping time, the average dripping speed could be calculated. As a result, a graph of the distribution of the average dripping speed along the sample surface was constructed.

(3) the flow of the water layer (Fig. 2c): the sample was raised vertically from a container of the ink-tinted water. The process of the flowing down of the water was recorded on a camera.

RESULTS AND DISCUSSION

First, the results for the combined effect of an electric field and a solution are presented, followed by the effects of water immersion without an electric field.

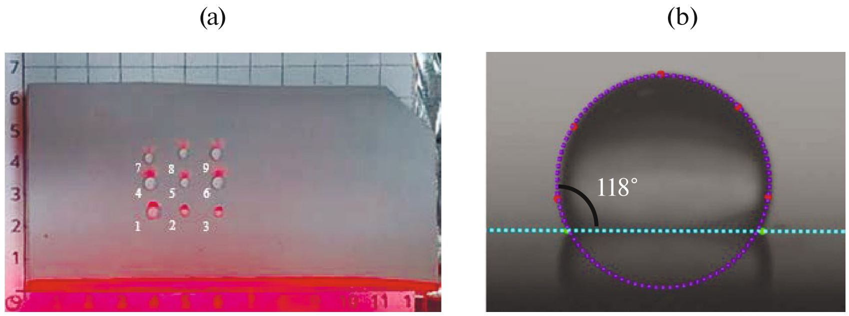

Fig. 3. (a) photograph of the silicone sample and location of the measurement droplets in the area affected by the solution layer and electric field, and (b) example of the characteristic static contact angle obtained through post-processing.

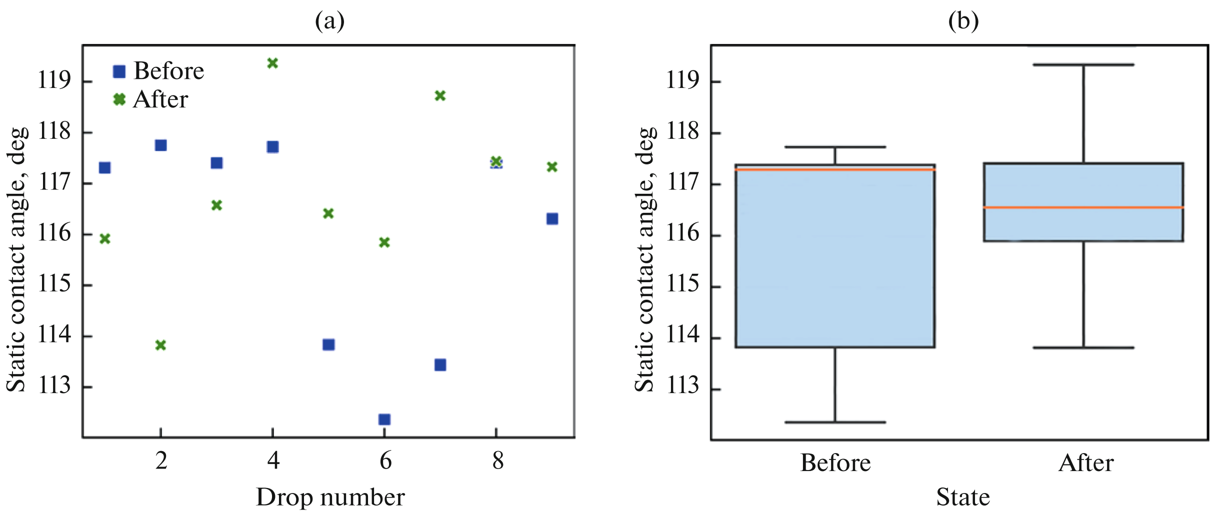

Fig. 4. Data on measurements of the static contact angle before and after exposure of the electric field and moisture for each droplet from Fig. 3a (a); quartile diagrams of the contact angle before and after exposure (b).

Solution Immersing in the Presence of an Electric Field

To measure the static contact angle on the sample surface in the presence of moisture, nine droplets were placed in the area of interest (Fig. 3a). The droplets were illuminated with red light due to the lighting used in the experiment. Figure 3b illustrates an example of measuring the contact angle through post-processing.

Figure 4 shows the dependence of static angles before and after the combined exposure to an electric field and a layer of the solution. It can be seen that there is a variation in the angle measurement results on the order of a few degrees. Moreover, for each droplet position, the static angle could either increase or decrease after exposure. Thus, it can be concluded that the effect of the combined exposure of an AC electric field and a saline solution is not noticeable in terms of measuring the static contact angle.

Figure 5 shows frames from a video capturing of water flowing down from a vertical sample as the sample was lifted out of a container filled with inked water. Frames show moments before and after combined exposure to an electric field and a layer of the solution. The region of influence is marked by a circle. It can be observed that the flowing down process after exposure to the electric field and moisture was slower compared to that before exposure. However, conducting a more detailed analysis of the process using this method is challenging, so a method involving the measurement of the droplet speed on samples was further employed.

Figure 6a shows the droplet speed dependence on the position along the sample before and after exposure to an electric field and moisture. Several features of that graph should be noted. The peak velocity in the upper part of the sample (10–15 mm along the y-coordinate) is associated with the fact that the droplets of a double volume flowed from the surface of rubber. The first droplet fell onto the surface at a distance of 10 mm from the upper boundary of the sample (see Fig. 6b). The second droplet, falling into the same area, merged with the first one. The resulting droplet of a double volume rapidly moved 5 mm lower and then began to flow downward along the sample. Therefore, the first

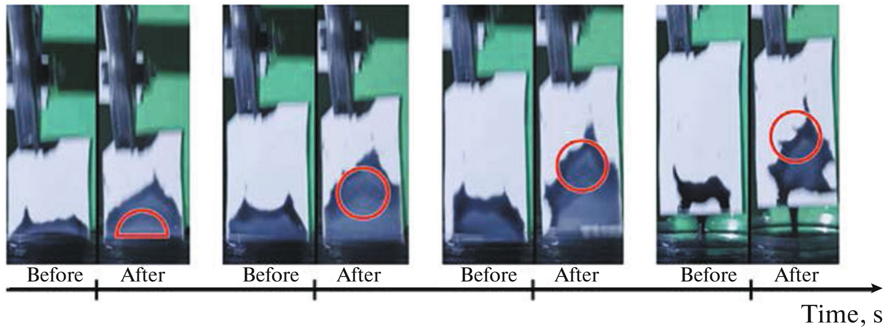

Fig. 5. Frames from video capturing of water flowing down before and after exposure to an electric field and a layer of NaCl solution. The area of the exposure is highlighted with a circle.

peak in the graphs should not be considered when comparing droplet flow velocities before and after exposure.

Another characteristic is the inability to accurately determine the boundaries of a droplet at a distance equal to its radius from the bottom of the sample. Hence, the path along which changes in the droplet flow velocity can be examined was from 15 to 57 mm along the y-coordinate.

Consequently, from the graph in Fig. 6a, it can be seen that the droplet velocity decreased by an average of 20 mm/s both in the immersion region (between the dash-dotted lines) and in the region in the contact with another rubber. To separate the wetting effect from the rubber compression effect, an additional experiment was conducted without an electric field and saline solution, and the results are presented in the following section.

Effect of Contact with Rubber

The compression of the contact between the test sample and the rubber layer can alter the surface condition. To investigate this, additional experiments were conducted by pressing a silicone rubber layer with a cut-out circle onto the test sample.

The distribution of the average droplet flow velocity along the sample surface is more informative in this case (Fig. 7). It can be observed that the droplet velocity decreased only in the region where it contacted the rubber. In the clean area, where the sample contacted air, the confidence intervals for the average droplet velocity overlap. This implies that in this region, there is no statistically significant difference in the droplet flow velocity.

Therefore, it can be confirmed that pressing one silicone rubber against another can influence the surface condition, leading to a reduction in the water drainage speed. This effect may potentially be caused by the diffusion of low-molecular-weight components. Hence, it is necessary to consider the effect of

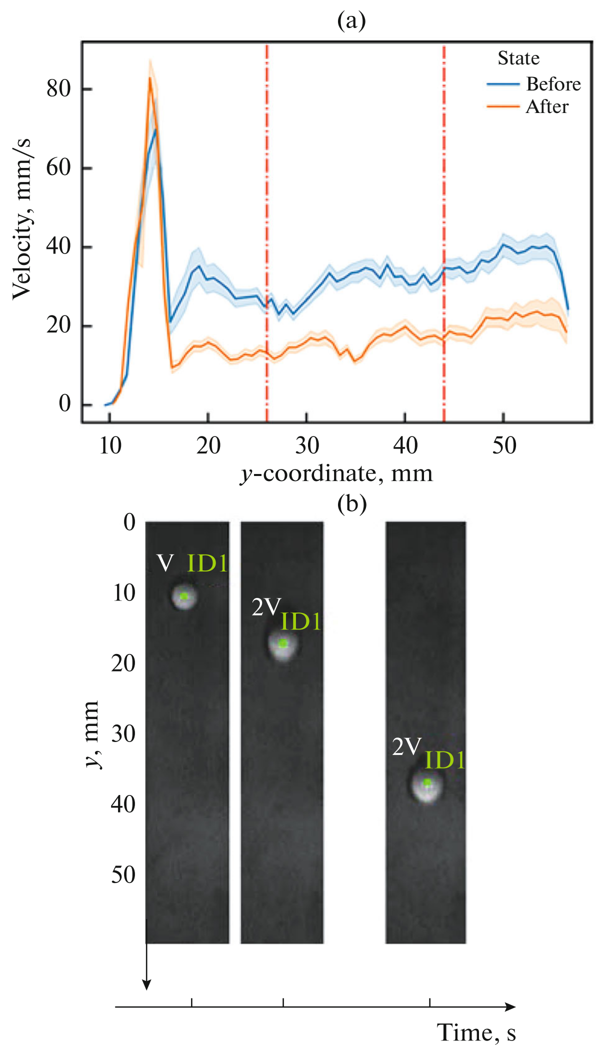

Fig. 6. (a) Dependence of the droplet velocity on its position along the sample before and after exposure to an electric field and a layer of NaCl solution, with a 95% confidence interval; the area of the exposure is highlighted with the dash-dotted lines, and (b) an example of droplets flowing from an inclined surface of the sample. “ID 1” indicates that the frames depict the same droplet. “V” and “2V” represent the volume of the droplet: first it increased and then it fell down.

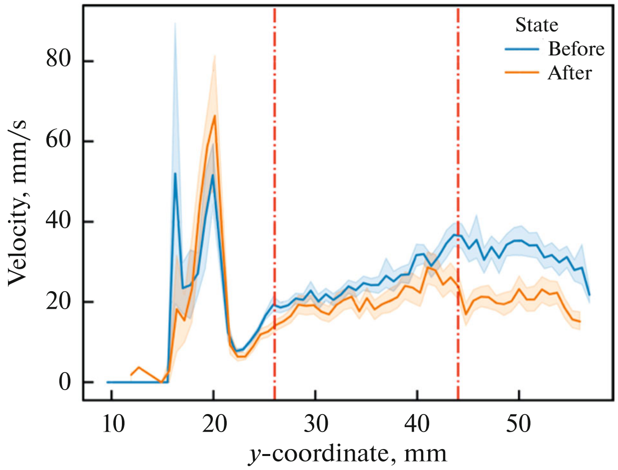

Fig. 7. Dependence of the droplet velocity on its position along the sample before and after pressing the silicone rubber layer, with a 95% confidence interval; the clean area, where the sample contacted air, is located between the dash-dotted lines.

the contact of rubbers when interpreting immersion results.

Solution Immersing in the Absence of an Electric Field

As the wetting effect was observed in the presence of an AC electric field, an additional experiment was conducted with an exposure to a saline solution without the electric field. Figure 8 shows the dependence of static contact angles before and after the exposure. The measurement results of the contact angle did not indicate that hydro-phobicity decreased after 2 h of immersion in the NaCl solution.

The dependency of the droplet drainage velocity on the sample coordinates revealed that the downward drainage velocity of droplets decreased on average by 20 mm/s due to the sample immersion in the absence of an electric field (Fig. 9). To check the influence of the electric field on the soaking process of the sample, the results of experiments in the presence and the absence of an electric field are compared further.

Comparison of Results of Solution Immersion in the Absence and Presence of an Electric Field

Figure 10 presents a graph of the droplet drainage velocity distribution before and after exposure to a saline solution in the presence and the absence of an electric field. It can be noted that after 30 mm along the *y*-coordinate, there was no significant difference in the droplet drainage velocity on the initial samples (solid curves). Since there was no difference in the initial surface condition of the two samples, it is valid to compare the drainage velocities after exposure to each other (dashed curves). It is evident that the curves on the graph intersect in the immersion region (between the dash-dotted lines). Therefore, it can be concluded that there was no significant enhancement of the immersion effect due to the influence of an electric field.

Replacement of the Layer of Solution with Downward-Flowing Droplets

In reality, droplets from insulators do indeed flow and constantly renew, so it was confirmed that there was the influence even when droplets were flowing. For this purpose, the setup in Fig. 2b was used. Instead of the immersion of the sample under a layer of solu-

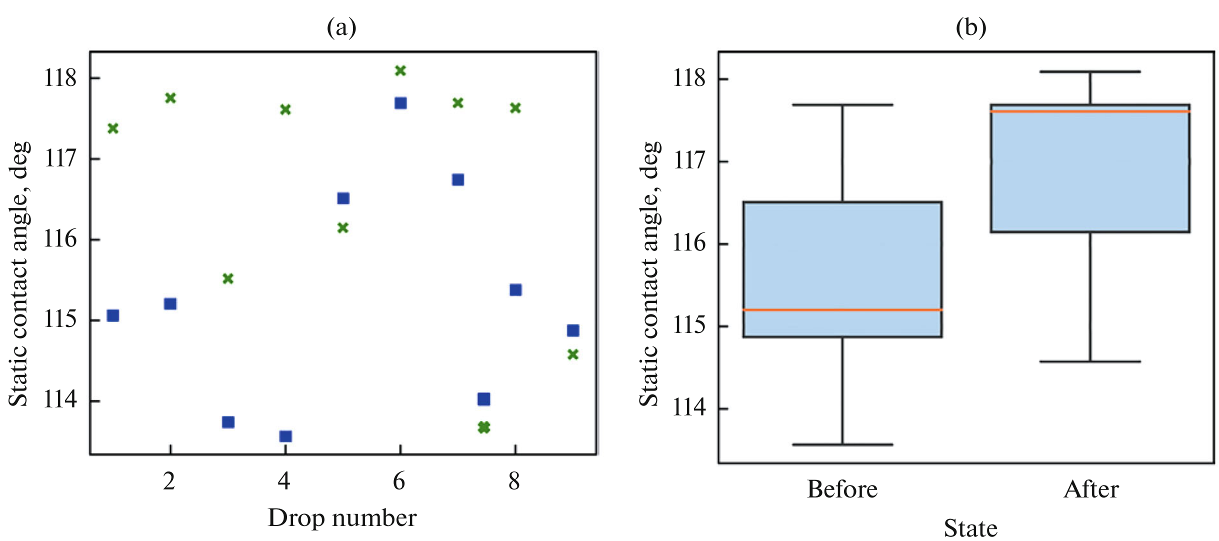

Fig. 8. Measurement results of the static contact angle before and after exposure of moisture without electric field for each droplet from Fig. 3a (a); quartile diagrams of the contact angle before and after exposure (b).

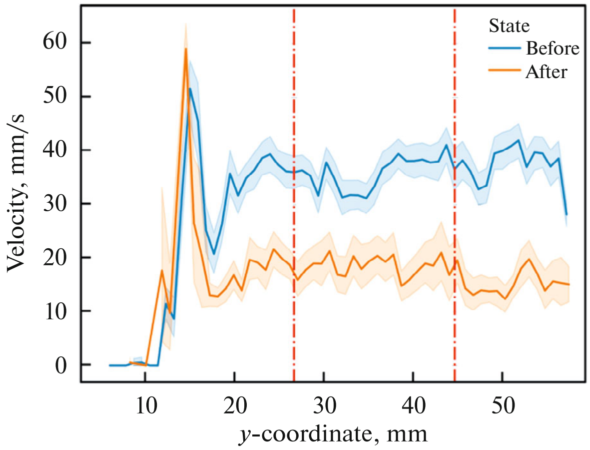

Fig. 9. Dependence of the droplet velocity on its position along the sample before and after exposure to a layer of NaCl solution without an electric field, with a 95% confidence interval; the area of the exposure is highlighted with the dash-dotted lines.

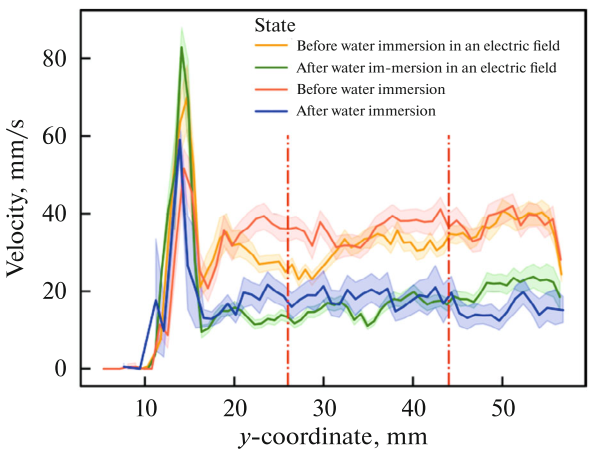

Fig. 10. Dependence of the droplet velocity on its position along the sample before and after exposure to a layer of NaCl solution with and without an electric field, with a 95% confidence interval; the area of the exposure is highlighted with the vertical dash-dotted lines.

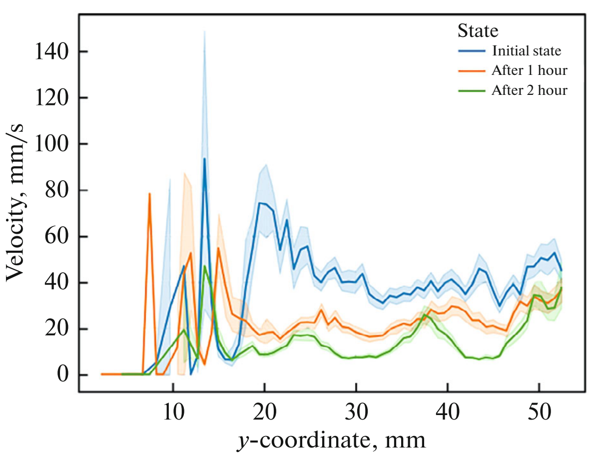

Fig. 11. Distribution of the average droplet drainage velocity along the sample surface at the beginning of the test, after 1 and after 2 h.

tion for 2 h, the droplets flowed from the sample in the performed test, with no applied voltage.

Figure 11 shows the distribution of the average droplet velocity along the sample surface at the beginning of the test, after 1 h, and after 2 h. It is evident that the droplet velocity decreased over time. It can be noted that the surface condition changed non-uniformly: on some areas, the droplet moved faster, while on others, it moves slower. This is noticeable in the distribution of the droplet drainage velocity after 2 h of testing. Therefore, it can be concluded that Powersil 310 rubber is susceptible to an immersing process.

CONCLUSIONS

An experimental set-up is presented in the paper that allows for the investigation of the combined effect of an electric field and moisture without the presence of partial discharges on silicone rubber. It was demonstrated that the immersion effect in a 4% NaCl solution on Powersil 310 rubber became noticeable even after 2 h exposure, and it was manifested as a slowdown in the droplet drainage velocity from an inclined sample. The influence of an electric field of 50 Hz on the process of immersing rubber was not observed.

A study of that effect is of interest because it can occur during the real-world operation of insulators under humid climatic conditions. Slower droplet drainage can result in prolonged exposure time of partial discharges from those droplets, leading to a reduction in the hydrophobicity loss time.

The carried out study demonstrated that the most straightforward method for measuring the combined effect of an electric field and moisture is the drainage of droplets from an inclined sample, as the static contact angle remains unchanged after exposure.

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CONFLICT OF INTEREST

The authors of this work declare that they have no conflicts of interest.

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