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The Effect of Flat Panel Reflectors on Photovoltaic Energy Harvesting in Wireless Sensor Nodes under Low Illumination Levels

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ABSTRACT:

The electric double layer is known to affect thin-film lubrication. Other researchers have shown that tribocharging affects the breaking torque in a metal shaft-oil-lip seal system and that an external electric field may be employed to control this phenomenon. One main issue in all these studies is the characterization of the charging state of the bodies in contact. This is quite a difficult challenge when the contact occurs between two insulating materials. The ultimate aim of this paper is to validate an experimental procedure appropriate for ensuring the reproducibility of the tribocharging conditions in sliding contacts between polymeric materials. The experiments were performed with samples of polystyrene and polyvinyl chloride. Surface potential measurements were done to evaluate the tribocharging effects. The experiments pointed out that the amount of charge accumulated on the sliding bodies depends on the external force applied to the contact and the number of tribocharging cycles (i.e., back-and-forth relative motions). However, this charge is nonuniformly distributed on the surface of the samples. This means that it will be difficult to use the tribocharging effect for controlling the charging state and, hence, the lubrication of the contact between two insulating bodies

INTRODUCTION Polymers are more and more used as materials for sliding machine components, due to their low cost, ease of manufacturing, as well as good mechanical and thermal properties [1]. Understanding of tribological processes in both lubricated and dry polymers-on-polymer contacts is crucial in the design of such components [2]. Thin film lubrication is known to be affected by the electric double layer [3]. On the other hand, experiments made on a rotating shaftoil-seal system demonstrated that an auxiliary external DC electric may cause a reduction in the

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braking torque [4]. The reported experimental data reveal the influence of tribocharging of synthetic motor base oils blended with different additives friction modifiers (FM) and antiwear agents (AW). The DC electric field is used to compensate for the natural electric field generated by the net charge of mobile ions and molecules in the zone between rotating metal shaft and the lip of the seal [5]. Electrical charges generation occurring during contact and friction of insulating materials has been studied for a long time [6], [7]. Various test methodologies have been proposed for this so-called "triboelectrification" effect [8], [9], which strongly depends on load, on sliding speed and on ambient conditions [10]-[13], and affects friction and wear [14]-[19]. It is possible to control the triboelectrification of rubbing elements by using appropriate materials, according to their position in a triboelectric series [20]. Most of these triboelectrification studies were performed with devices characterized by non-conformal contacts. In such devices, the area of contact between the surfaces is very small; as a result, the contact pressure is high and the wear of the surfaces is significant even under low load. The respective experimental benches typically provide uni-directional relative movement of the bodies in contact: a pin and a rotating disk or two rolling rings. The rotational movement is accompanied by charge generation due to the continuous friction between the two bodies. Fewer studies were made on the tribocharging phenomena associated to conformal contacts, where the surface of the contact area is comparable with the size of the bodies involved [21]. The benches described in the literature were typically making use of crank – shaft mechanisms to provide back-and-forth motion between the bodies in contact [22], [23]. In the present paper, the sliding contact occurs between two plate-type samples, one fixed and the other attached to a bi-directional belt conveyor. Triboelectrification has been investigated as a source of hazards in pneumatic transportation systems [24], [25]. The same phenomenon has been extensively studied in relation with the selective charging and electrostatic separation of granular plastics mixtures [26]-[30]. The triboelectric effect in oil-lubricated contacts has been the object of only few studies [31]-[33]. One main issue in all these studies is the characterization of the charging state of the surfaces in contact. This is a difficult challenge when the contact occurs between two insulating materials. Therefore, the aim of the present work is to validate an experimental procedure appropriate for ensuring the reproducibility of the tribocharging

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conditions in sliding contacts between polymeric materials.

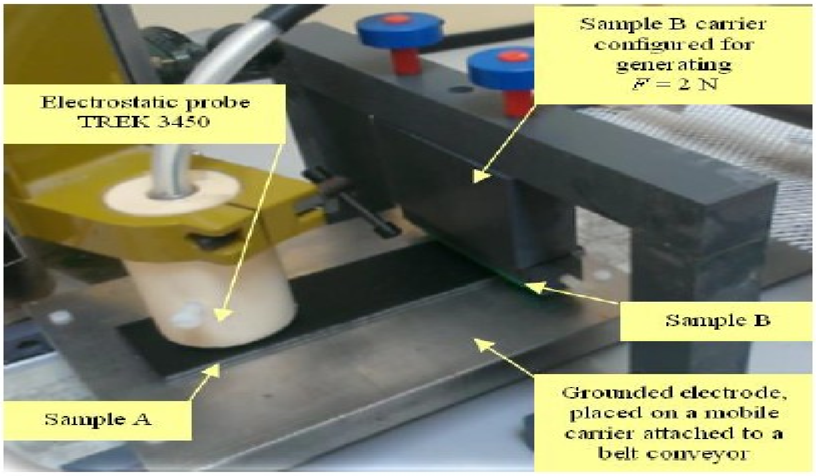

Fig. 1. Photograph of the tribocharging system.

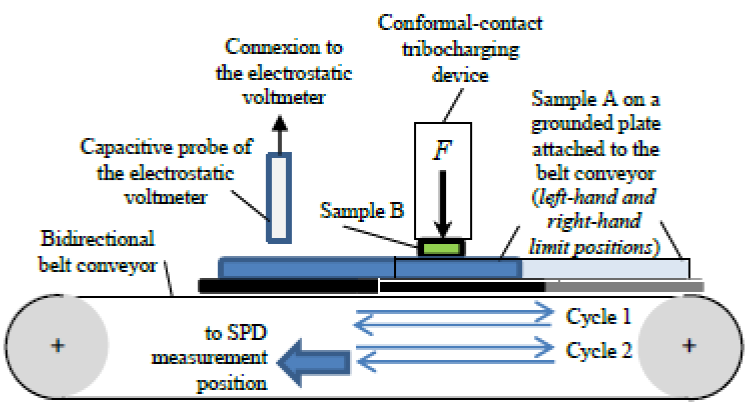

Fig. 2. Schematic representation of the experimental procedure: the bidirectional belt conveyor moves the sample A back-and-forth with respect with the central axis of sample B (two tribocharging cycles), then carries it under the capacitive probe of the electrostatic voltmeter (the axis of the probe is located in the vertical plane defined by the central transversal axis of the sample A) .

II. MATERIALS AND METHOD

The experiments were performed with 4-mm-thick samples of polystyrene (PS) and polyvinyl-chloride (PVC). The samples were cut in two sizes: *A* (50 mm x 183 mm) and *B* (100 mm x 15 mm). The samples *A*are fixed on a grounded metallic electrode (200 mm x 200 mm), placed on a carrier attached to a conveyor belt (Fig. 1). A reversible DC motor entrains the conveyor and the carrier at a fixed speed of 100 mm/s. The samples *B* are attached to a tribocharging device that can impose a load of 1 N or 2 N on the surface of contact between the two samples (size: 50 mm x 15 mm; the long axis of sample *B* is parallel to the short axis of sample *A*). The device is carried by an arch-type support, as shown in Fig. 1. In this way, the sample *B* has a fixed position in horizontal plane, and can move only in vertical direction, so that to be in free contact with the sample *A*. The latter can move back-and-forth for a distance of 150 mm, symmetrical with respect to the central axis of the sample *B* (Fig. 2).

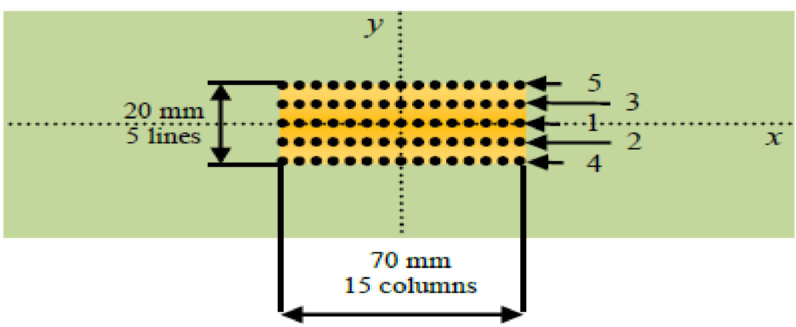

Fig. 3. Schematic representation of the 2D zone scanned by the probe of the electrostatic voltmeter at the surface of the *A*-type sample

A tribo-charging cycle typically consisted in such a back-and-forth motion. Two cycles were found to be enough for the accumulated charge to be detected by the measurement of the electrical potential at the surface of sample *A*. In a first series of experiments, the type *A* and *B* samples were made respectively of PVC and PS. They were subjected five sets of two tribo-charging cycles. The electric potential at the center of the sample *A* was measured with the probe (Trek, model 3450) of an electrostatic voltmeter (Trek, model 341B), for about 20 s, after each of the five sets of two cycles. The measured values were displayed on a virtual instrument, using LabView software. During the experiment designated as #1.1, a normal force of 1 N was imposed to the contact between the two bodies. Then, for the experiment #1.2, the

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normal force was increased to 2 N, and five additional sets of two tribo-charging cycles were performed, each followed by a 20-s surface potential decay measurement. Finally, five similar sets of two tribo-charging cycles and surface potential measurement were performed for two virgin samples *A* and *B*, with the 2 N load (experiment #1.3). The second series of experiments, which are designated as #2.1 and #2.3, were in all respects similar to respectively #1.1 and #1.3, described above, except for the fact that PS was employed as sample *A* and PVC as sample *B*. The experiments #2.4 and #2.5 were similar to #2.1, but the normal force was increased to 3 N. The difference between the experiments #2.4 and #2.5, consisted in the roughness of the PS sample *A*: 0.02 µm for the former, 8.5 µm for the latter. A distinct experiment, designated as #3, was performed right after the end of an experiment #1.3. Thus, the already-charged sample *A* in PVC, was subjected to an additional set of two tribo-charging cycles, then the surface potential decay in its central point was recorded for 3 hours. In the end, the repartition of the potential along the central longitudinal axis at the surface of an *A*-type sample in PVC was measured after six tribo-charging cycles with a *B*-type sample in PS and a load of 2 N (experiment #4.1). The measurement of the surface potential distribution was repeated after a second set of six tribo-charging cycles (experiment #4.2). In order to better characterize the surface distribution of the charge, an *A*-type PVC sample subjected to 10 tribocharging cycles at a load of 3 N was moved to a PC-controlled positioning platform that enabled the 2D scanning of the electric potential (experiment #4.3, figure 3).

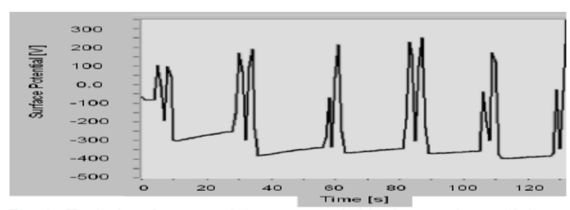

Fig. 4. Typical surface potential curve recorded in the experiment #1.1 (sample *A* in PVC; sample *B* in PS; load 1 N).

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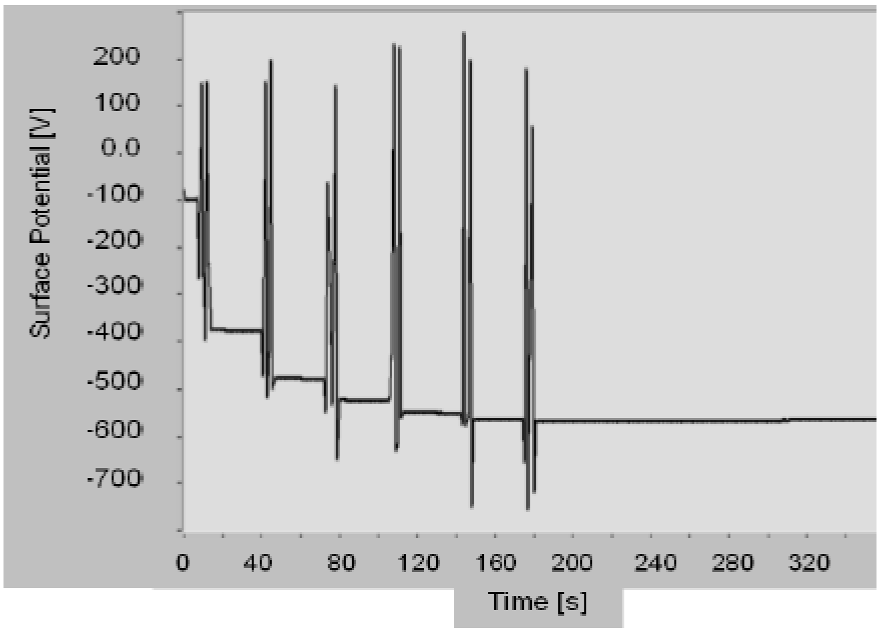

Fig. 6. Typical surface potential curve recorded in the experiments #1.3 and #3 (sample *A* in PVC; sample *B* in PS; load 2 N).

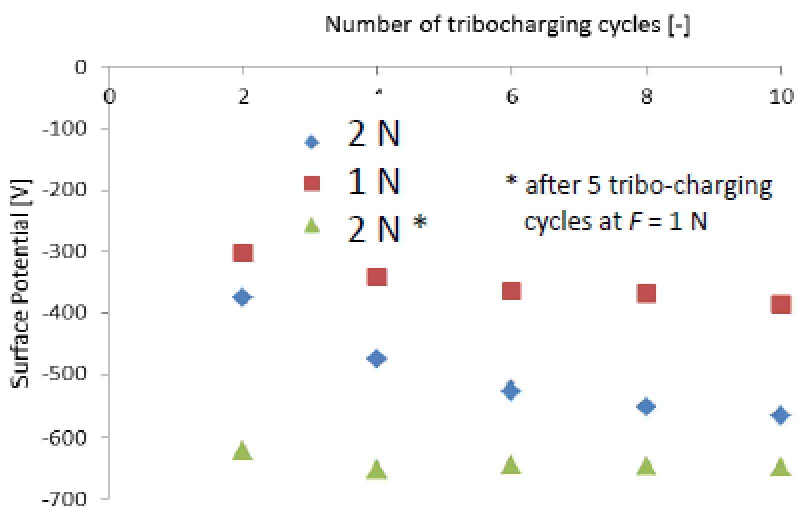

Fig. 5. Comparison between the values of the surface potential at the center of sample *A* (in PVC) recorded after each set of two tribocharging cycles in the experiments #1.1, #1.2 and #1.3 (sample *B* in PS). The data are averages of five measurements; the standard deviation represents 5 to 10% of the plotted values.

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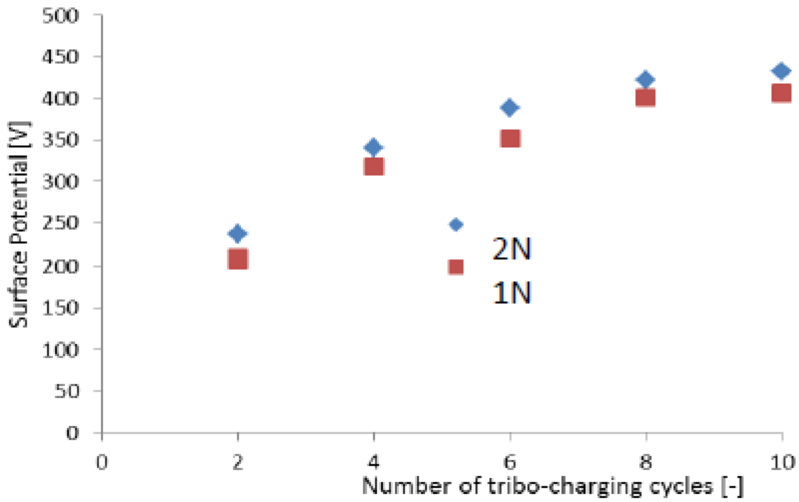

Fig. 7. Comparison between the values of the surface potential at the center of sample *A* (in PS) recorded after each set of two tribocharging cycles in the experiments #2.1 and #2.3 (sample *B* in PVC; load 1 N or 2 N). The data are averages of five measurements; the standard deviation represents 5 to 10% of the plotted values.

III. RESULTS AND DISCUSSION

The curve in Fig. 4 represents the surface potential continuously recorded at the center of the sample *A* (in PVC) for the five tribo-charging cycles of the experiment #1.1 (sample *B* in PS; load 1 N). During the back-and-forth motion of each tribocharging cycle, the capacitive probe of the electrostatic voltmeter faced also the surface of the insulating belt conveyor (the right-hand limit position of the sample A, in Fig. 2). The positive peaks on the curves correspond to the potential “seen” at the surface of the belt, which is not related to the tribocharging process and are not discussed here. The differences between the positive peak heights are due to the fact that the back-and-forth motion was manually controlled. Therefore, the stroke was not rigorously the same and the points at the surface of the belt examined by the electrostatic probe were slightly different. At first, the electric potential measured at the center of the sample A progressively increases (in absolute values) with the number of tribo-charging cycles, then saturates at about – 375 V. The increase of the load to 2 N (experiment #1.2) has quite a significant effect on the surface potential (Fig. 5). The imperfections of the mechanical device and the non-homogeneous characteristics of the samples are most likely at the origin of standard deviations as high as 10% of these averages. The experimental bench should be modified, to better control the applied load and the position of sample B. The experiment #1.3 confirmed the fact that the sample attains quite easily a saturation potential (Fig. 6), which seem to be correlated to the force applied to the bodies in sliding contact. However, the derivation of a statistically significant correlation between this force and the value of the maximum measured potential would require more experiments carried out with an experimental bench provided with means to control the ambient conditions (temperature and relative humidity), to adjust the load and to guarantee its uniform distribution on the contact area between the two surfaces. The observations made in the second series of experiments (sample *A*in PS and sample *B* in PVC) are similar to those described above. The progressive increase of the potential with the number of tribo-charging cycles for two loads (1 N and 2 N) is displayed in Fig. 7, for two typical experiments #2.1 and #2.3. The saturation occurred after eight tribo-charging cycles, at values that are not statistically significant different than those in experiments #1. The load change from 1 to 2 N has less effect on the PS samples in Fig. 7, than on the PVC samples in Fig. 5, as they get more easily close to saturation.

The effect of surface roughness on the tribocharging process can be examined in Fig. 8, which compares the results of experiments #2.4 and #2.5. As expected, the maximum surface potential of the "lean" sample was significantly lower than the one obtained for the "rough" sample. The surface potential decay recorded after the complex set of tribo-charging cycles of experiment #3 can be examined in Fig. 6. This measurement, confirmed by several other tests, not displayed here, point out the fact that the PVC preserves for a long time the charging state acquired by triboelectric effect. The PS samples display a similar behavior (Fig. 8). This observation validates the possibility of using the electrostatic probe for scanning the distribution of the electric potential at the surface of the sample (experiment #4). Indeed, during the less than 90 s of the scanning process, the potential in any point of the sample decreases by less than 0.5%. However, the interpretation of the data recorded by the electrostatic voltmeter is not straightforward. The probe "sees" at each instant an area of roughly 2 cm2, and that the measurements are made at different time instants, with the sample in motion. The position of the probe at any given time can be calculated by taking into account the speed of the belt conveyor that carried the sample A, but the value indicated by the electrostatic voltmeter does not rigorously represent the electric potential in that point; it characterizes the distribution of the electric charges in an area defined by that point. Represented in Fig. 9 are two typical curves obtained in experiment #4, after respectively 6 and 12 tribo-charging cycles. Quite surprisingly, the potential recorded in the latter case is not higher in every point of the samples. The pattern of surface potential distribution varies from one experiment to the other, which may be explained by the differences in the intrinsic structure of the polymers, and the mechanical imperfections of the experimental device. However, in all cases, the potential recorded in the peripheral zones of the samples was higher (in absolute values) that that measured in the central zone.

The 2D plot obtained for the 3 N loaded *A*-type PVC sample in experiment #4.3 can be examined in Fig. 10. It confirms the above observations. The increased potential measured in the peripheral zones of the samples is most probably due to the slight machining imperfections of the edges of sample B, which imply increased local roughness and pressure, and hence higher local values of the friction coefficient between the two samples in those peripheral zones, where rubbing changes the direction.

IV. CONCLUSIONS

The experiments described in this paper concern the tribocharging of only one pair of polymers: PS and PVC. Therefore, further studies, with other materials (polycarbonate, polyacetate, …), should be performed in order to confirm the following conclusions:

(1) The surface potential attains a saturation value after a limited number of tribo-charging cycles. This value is higher when the force exerted on the surface of contact between the two polymers is higher, most probably due to the thermal activation related to the energy dissipated in the friction process, but also to the possible transfer of material between the bodies in contact.

(2) The charges transferred in the tribo-charging process at higher load are quite stable, the surface potential decay being very slow.

(3) The distribution of the charges at the surface of the samples is non-uniform, with higher values recorder closer to the edges of the samples. The roughness of the edges of sample B may explain the higher local values of the friction coefficient and of the contact pressure between the two samples in that zones, where rubbing changes the direction. This non-uniformity is likely to affect the lubrication conditions of sliding contacts.

(4) The ultimate goal of the present work has not yet been attained: the proposed experimental procedure is not appropriate for ensuring the reproducibility of the tribocharging condition in

sliding conformal contacts between polymeric materials. The experimental bench should be provided with more accurate means to control the position of the sample and the environmental conditions (temperature and relative humidity of ambient air), as well as with auxiliary devices to adjust the load and to guarantee its uniform distribution on the contact area between the two surfaces.

(5) A larger number of experiments should be performed, using such an improved experimental bench, in order to make possible the statistical evaluation of the effects of the various factors that might affect the charging state of the polymers. Of particular interest would be the investigation of the effects of ambient temperature and relative humidity on the distribution and on the decay of the potential at the surface of the samples.

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