Triboelectrification of Wood with PTFE

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***Abstract*-Triboelectrification for a rolling contact between hardwood and softwood spheres and a polytetrafluoroethylene (PTFE) plane is studied. For a variety of experimental parameters, the saturation charge developed on the spheres was measured. The results are compared with those reported previously where PTFE spheres were rolled on wood planes. The observations suggest that different principles are involved in the two experimental situations; however, in both cases the saturation charge developed depends on the apparent area of contact.**

***Index Terms*- triboelectrification, hardwood, softwood, PTFE**

I. INTRODUCTION

Triboelectrification is a charging process which results from the contact and separation between two dissimilar materials [1]; studies have been done for dielectric/metal [2,3] and dielectric/dielectric [4] interfaces. Equal and opposite charges result on the two charging partners; the polarities depend on the effective work functions of the two materials. The amount of charge developed depends on many factors which include the area of contact. Manufacturing operations involving the cutting and sanding of wood generate sawdust; the transport of this material through pneumatic collection systems has been observed by the author to generate charge by triboelectrification. Commercially available grounding systems are often used to dissipate the charge [5]. Typical triboelectric series usually show wood located around the middle of the table [6]; materials with a higher effective work function than wood should charge negatively. However, little information is available on the triboelectrification of different wood species.

In previous work [7], the triboelectrification between a PTFE sphere and eleven different planar wood substrates was studied. All woods charged positively; slightly different negative saturation charge levels were measured on the PTFE sphere. It was suggested that the observed results are due to difference in the apparent areas of contact between the charging partners.

II. OBJECTIVE

The objective of this experimental work was to study the triboelectrification of commercially available hardwood and softwood spheres in a rolling contact with a polytetrafluoroethylene (PTFE) plane.

III. SPHERE-PLANE TRIBOELECTRIFICATION

A simple model can be developed for the charging of a sphere rolling on a plane surface [8,9]. It is assumed that for a given speed of rolling, the rate of acquiring charge by the sphere by triboelectrification is proportional to the uncharged area remaining on the surface of the sphere and the rate of discharge is proportional to the total charge on the sphere. Then, the equation for the net rate of charging is

$$\frac{dq}{dt} = \alpha(q_S - q) - \beta q \tag{1}$$

where

q	charge at time t;
q_S	saturation charge in the absence of leakage;
$\alpha(q_S - q)$	charging current proportional to the uncharged surface area on the sphere at time t;
βq	discharge current due to leakage with β being proportional to the conductivity of the discharge path.

Let the initial rate of exposure of area A to contact be $(dA/dt)|_0$. Let the area of the sphere which ultimately undergoes contact be A_S and the charge density separated due to triboelectrification be σ. As an initial condition, q = 0.

$$\left.\frac{dq}{dt}\right|_0 = \sigma \left.\frac{dA}{dt}\right|_0 \tag{2}$$

$$q_S = \sigma A_S \tag{3}$$

$$\therefore \quad \alpha = \frac{1}{q_S}\left.\frac{dq}{dt}\right|_0 = \frac{1}{A_S}\left.\frac{dA}{dt}\right|_0 \tag{4}$$

The units of α are s^{-1}; $1/\alpha$ is the time constant τ for the charging process.

$$\tau = 1/\alpha = A_S \Big/ \left.\frac{dA}{dt}\right|_0 \tag{5}$$

It can be seen that the time constant is directly proportional to the contact area of the sphere and inversely proportional to the velocity. In the absence of charging,

$$\frac{dq}{dt} = -\beta q \tag{6}$$

For this situation, let the potential of the sphere be V, the effective resistance of the discharge path be R and the capacitance of the sphere be C. Then,

$$V = -\frac{dq}{dt} R = \frac{q}{C} \quad (7)$$

$$\frac{dq}{dt} = -\frac{q}{RC} \quad (8)$$

$$\therefore \quad \beta = \frac{1}{RC} \quad (9)$$

Integration of (1) yields:

$$q = q_S \frac{1}{1+\beta/\alpha}[1-e^{-(\alpha+\beta)t}] \quad (10)$$

For

$$t \to \infty \quad q = q_M = q_S \quad /[1+\beta/\alpha] \quad (11)$$

where q_M is the maximum or apparent saturation charge. Some observations can be made.

1) For $t \gg 0$,

$$q = q_S \frac{1}{1+\beta/\alpha} \quad \text{if} \quad \alpha \ll \beta, \quad q \to 0$$

$$\text{if} \quad \alpha \gg \beta, \quad q \to q_S \quad (12)$$

2) For $\beta = 0$,

$$q = q_S \quad [1-e^{-\alpha t}] \quad (13)$$

3) If the sphere has an initial charge q_0 at $t = 0$ and $\alpha = 0$,

$$q = q_0 e^{-\beta t} \quad (14)$$

For the basic sphere/plane contact, an estimate of the apparent area of contact in cm^2 is given by [10]:

$$A_C = 3.8 \left[\frac{Wr_1}{2}\left(\frac{1}{E_1}+\frac{1}{E_2}\right)\right]^{2/3} \quad (15)$$

where W is the force of contact (Kg), r_1 is the radius of the sphere and E_1 and E_2 are Young's Modulii for the sphere material and the plane material respectively (Kg/cm^2). This basic equation shows that for a sphere/plane contact, the area of contact depends on the mass of the sphere, its radius and the Young's Modulii for the sphere and plane materials respectively.

An examination of (15) yields the following observation.

$$\text{Let} \quad f = \frac{1}{E_1}+\frac{1}{E_2} = \frac{E_1+E_2}{E_1E_2} \quad (16)$$

$$\text{If} \quad E_1 \gg E_2, \quad f \approx \frac{1}{E_2} \quad (17)$$

If this condition can be imposed in the design of experiments, a simplification of (15) results.

An experiment was designed using a rolling contact between hardwood and softwood spheres and a PTFE plane. The inclination of the plane was adjusted to allow saturation charge levels to be developed on the sphere. Consider a wood sphere in contact with a PTFE plane. The Young's modulus for wood E_1 is of the order of 10 GPa [11]; for PTFE, the value of the Young's modulus E_2 is about 0.5 GPA [12].

Equation (15) can be rewritten:

$$A_C \quad = \quad k_1 \quad [Wr]^{2/3} \tag{18}$$

k_1 is a constant in experiments conducted with different wood spheres in contact with a PTFE plane since $E_1 >> E_2$.

IV. EXPERIMENTAL PART

A. Charge Measurement

The experimental setup modelled after the design used in xerography experiments [13] is shown in Figure 1. A sketch of the charging platform constructed from PTFE is shown in Figure 2. Commercially available hardwood and softwood spheres were used as the charging partner; the sphere was manually rolled from one end of the platform to a temporary stop located at the other end and back to the start position in what was defined as a charging cycle. The effective charging length of the PTFE platform was 42.4 cm; the rolling distance traversed by the sphere in one cycle was then 84.8 cm. An end to end traverse of the sphere took approximately one second; an estimate of the rolling velocity is then 42.4 cm/s. After a given number of charging cycles, the stop was removed to allow the sphere to drop into a Faraday cup; the charge acquired by the ball was measured using a Keithley Instruments model 602 electrometer. The number of charging cycles which were done before a charge measurement was made was referred to as a run.

Preliminary experiments were done in which the platform was not cleaned between consecutive runs; however, each run always used a new clean sphere. The total number of runs in a given experiment constituted a session. The PTFE platform was cleaned and discharged by rinsing in iso-propyl alcohol followed by an air dry; the wood spheres were discharged using a NRD model P-2021-Z703 neutralizer gun (Polonium 210 source).

The commercially available wooden spheres used in the experiments were fabricated from a softwood (cedar) and a hardwood (birch). A single size of cedar sphere of nominal diameter 22.3 mm (0.875") was available; two sizes of birch spheres of nominal diameters 19.1 mm (0.75") and 25.4 mm (1") were available.

B. Other Measurements

For each experimental session, the laboratory temperature and relative humidity were measured and recorded. The laboratory environmental conditions for all tests were in the range of 23-25 ˚ C and 18-24 % relative humidity. An additional experiment included the measurement of the effective resistance of the wood spheres using a methodology suggested in standards related to resistive characterization of planar materials [14]. The measurement set up is shown in Figure 3. An Agilent model E3630A power supply was connected to a 2.27 kg metal electrode of 63.5 mm diameter which rested on top of the wood sphere which was mounted on a stainless steel plate insulated from ground. The current to ground was measured using a Keithley model 602 electrometer. Resistance was calculated for an applied voltage of 20 V.

The weights of the wood spheres were measured using an Ohaus model CD200 digital scales. The diameters of the spheres were measured using Tajima dial calipers.

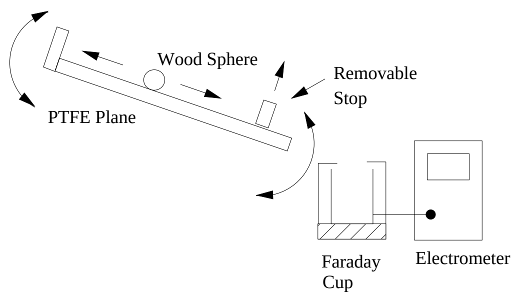

Fig. 1. Experimental setup for charging of wood sphere on PTFE platform

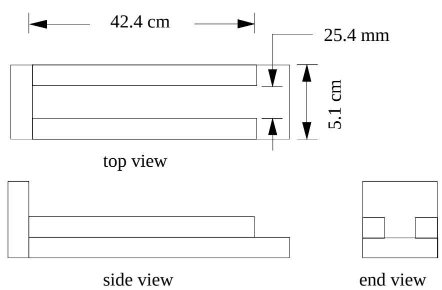

Fig. 2. Detail of PTFE platform

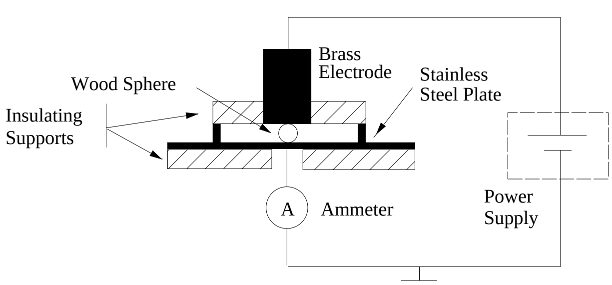

Fig. 3. Measurement of resistance of wood sample

V. RESULTS

Typical results for a 19.1 mm diameter hardwood sphere are presented in Figure 4. In this session of 40 cycles, a new sphere was used for each run which comprised of 4 cycles; the PTFE platform was not cleaned after each run. It was decided that the experimental procedure would be altered such that after each run; not only would a new sphere be used but the PTFE platform would be cleaned and discharged. For this session, the data was curve fitted; the results are presented in Figure 4. The saturation effect is evident. The general scatter in data associated with triboelectrification experiments is well known; to show the typical variation in the results, no curve fitting was done for the other graphs in this study. The results for this experimental session with no curve fitting are presented again in Figure 5.

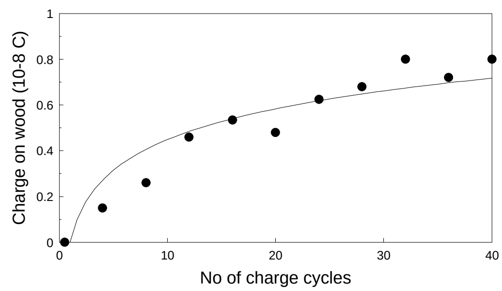

Fig. 4. Charge acquired by hardwood sphere vs number of charging cycles; data curve fitted

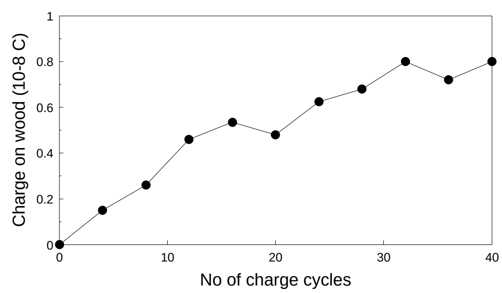

Fig. 5. Charge acquired by hardwood sphere vs number of charging cycles; no curve fitting

The results for a 19.1 mm diameter hardwood sphere and a 22.3 mm diameter cedar sphere are presented in Figure 6. In these sessions of 40 cycles, each run comprised of 5 cycles; the PTFE platform was cleaned and a new sphere introduced after each run. The saturation effect is evident and the charge developed on the cedar is slightly greater compared to the birch sphere.

The results for 19.1 mm diameter and 25.4 mm diameter hardwood spheres are presented in Figure 7. In these sessions of 50 cycles, each run comprised of 5 cycles; the PTFE platform was cleaned and a new sphere introduced after each run. Again, the saturation effect is evident and the charge developed on the larger sphere (25.4 mm diameter) is slightly greater compared to the smaller sphere (19.1 mm diameter).

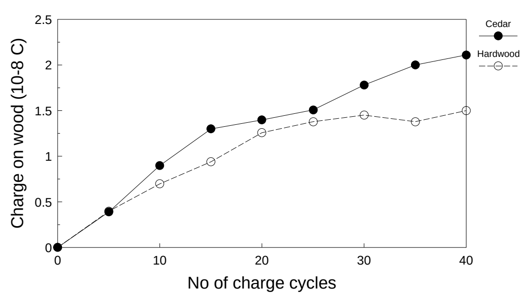

Fig. 6. Charge acquired by hardwood and softwood spheres vs number of charging cycles

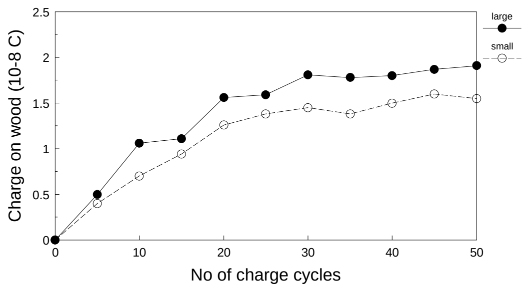

Fig. 7. Charge acquired by different sizes of hardwood spheres vs number of charging cycles

The resistances of the wood spheres measured with the electrode method were of the order of 10^{12} ohms. In order to estimate the relaxation time of wood, the capacitance of an isolated sphere of diameter 25.4 mm was employed; the calculated capacitance is approximately 1 pF. The relaxation time τ given by RC is very small, of the order of 1 second. The experimental conditions are then essentially the same as a metal sphere rolling on a insulating plane. The saturation charge developed on the wood sphere is then proportional to the uncharged contact area of the PTFE platform.

It was of interest to conduct some experiments in which a metal sphere was rolled on the PTFE platform. Typical results for a 14.3 mm (0.563") diameter chrome plated steel sphere are presented in Figure 8. In this session of 50 cycles, a new sphere was used for each run which was comprised of 5 cycles; the PTFE platform was not cleaned after each run. As with the experiments done with the wood spheres, it was decided that the experimental procedure would be altered such that after each run , not only would a new sphere be used but the PTFE platform would be cleaned and discharged.

The results for 14.3 mm diameter chrome plated and 19.1 mm diameter stainless steel spheres are presented in Figure 9. In these sessions of 50 cycles, each run comprised of 5 cycles; the PTFE platform was cleaned and a new sphere introduced after each run. Again, the saturation effect is evident and the charge developed on the larger sphere (19.1 mm diameter) is slightly greater compared to the smaller sphere (14.3 mm diameter).

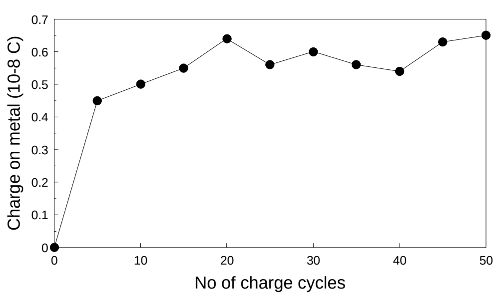

Fig. 8. Charge acquired by chrome plated steel sphere vs number of charging cycles

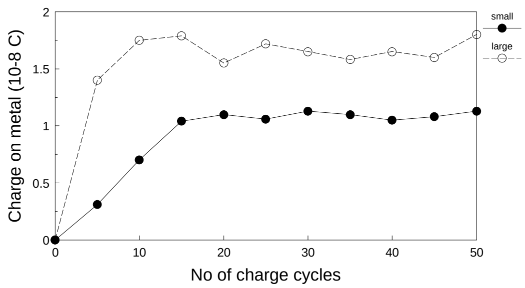

Fig. 9. Charge acquired by chrome plated steel and stainless steel spheres vs number of charging cycles

VI. DISCUSSION

In all of the experiments conducted, the charge acquired by the wood and metal spheres in contact with a PTFE planes was positive in polarity; the effective work functions of these materials are then considered to be less than that of PTFE. For triboelectrification between wood spheres and a PTFE substrate, the experimental conditions appear to be similar to those of a metal sphere in contact with a dielectric plane. Since PTFE was used as the substrate material, the charge acquired by the sphere was proportional to the apparent area of contact which is proportional to $(Wr)^{2/3}$. Smaller magnitudes of the saturation charge acquired by the sphere were observed when the PTFE platform was not cleaned after consecutive runs. This supports the belief that charge exchange takes place with the uncharged area on the PTFE plane until no uncharged area remains.

Consider a wood sphere in contact with a PTFE plane. The Young's modulus for wood E_1 is of the order of 10 GPa; for PTFE, the value of the Young's modulus E_2 is about 0.5 GPA.

The equation for the apparent area of contact for a wood sphere of radius r and weight W in contact with a PTFE plane simplifies to:

$$A_C \quad = \quad k_1 \quad [Wr]^{2/3} \tag{19}$$

k_1 is a constant in experiments conducted with different wood spheres in contact with a PTFE plane.

A measurement of the weights and diameters of samples of ten of each of the different spheres was done. For the cedar spheres, the average weight was 2.7 g; the average diameter was 22.1 mm. For the small hardwood spheres with a nominal diameter 19.1 mm, the average weight was 2.5 g; the average diameter was 19.2 mm. For the larger hardwood spheres with a nominal diameter of 25.4 mm, the average weight was 5.36 g; the average diameter was 24.9 mm.

To test the hypothesis that the saturation charge levels are proportional to the apparent areas of contact, the following ratio was calculated for cedar spheres of an average diameter of 22.1 mm compared to hardwood spheres of an average diameter 19.2 mm..

$$\frac{A_{cedar}}{A_{hardwood}} = \left[\frac{2.7}{2.5} \quad x \quad \frac{22.1}{19.2}\right]^{\frac{2}{3}} = 1.16 \tag{20}$$

To test the hypothesis that the saturation charge levels are proportional to the apparent areas of contact, the following ratio was calculated for large hardwood spheres of an average diameter of 24.9 mm compared to small hardwood spheres of an average diameter 19.2 mm..

$$\frac{A_{\text{large hardwood}}}{A_{\text{small hardwood}}} = \left[\frac{5.3}{2.5} \quad x \quad \frac{24.9}{19.2}\right]^{\frac{2}{3}} = 1.96 \tag{21}$$

The results presented in Figure 6 and Figure 7 support this general hypothesis. For cedar spheres compared to hardwood spheres, the trend is in the correct direction and the difference in magnitudes is in fair agreement with (20). For large hardwood spheres compared to small hardwood spheres, the trend is in the correct direction; the difference in magnitudes is some what less than that predicted by (21).

Consider a metal sphere in contact with a PTFE plane. The Young's modulus for metal E_1 is of the order of 200 GPa [15]; for PTFE, the value of the Young's modulus E_2 is about 0.5 GPA.

The equation for the apparent area of contact for a metal sphere of radius r and weight W in contact with a PTFE plane simplifies to:

$$A_C = k_2 \quad [Wr]^{2/3} \tag{22}$$

k_2 is a constant in experiments conducted with different metal spheres in contact with a PTFE plane.

A measurement of the weights and diameters of samples of ten of each of the different metal spheres was done. For the chrome plated steel spheres, the average weight was 11.84 g; the average diameter was 14.3 mm. For the stainless steel spheres, the average weight was 28.8 g; the average diameter was 19.0 mm.

To test the hypothesis that the saturation charge levels are proportional to the apparent areas of contact, the following ratio was calculated.

$$\frac{A_{\text{stainless steel}}}{A_{\text{chrome plated steel}}} = \left[\frac{28.8}{11.84} \quad x \quad \frac{19.0}{14.3}\right]^{\frac{2}{3}} = 2.19 \tag{23}$$

The results presented in Figure 9 support this general hypothesis. For stainless steel spheres compared to chrome plated steel spheres, the trend is in the correct direction; the difference in magnitudes is in fair agreement with that predicted by (23).

A final calculation was done to determine how the charge levels measured on the spheres compared to those which might cause air breakdown. For a conducting sphere of radius r and total charge Q, the electric field E at its surface can be calculated from Gauss's law.

$$4\pi\varepsilon_0 r^2 \quad E = Q \tag{24}$$

If one assumes a nominal breakdown strength of 30 kV/cm for air, the maximum charge can be calculated a function of the sphere radius. This information is shown in Figure 10 for the range of sphere sizes used in the experiments. It is to be noted that the charge levels measured are of the same order of magnitude as those shown in Figure 10; however, the increase in charge as a function of sphere radius is not a large as predicted from the calculations. It was concluded that the observed results are due to the difference in the apparent areas of contact.

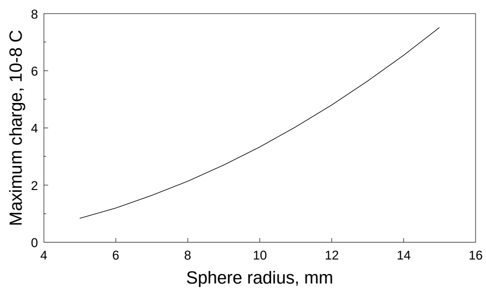

Fig. 10. Maximum charge on a conducting sphere vs sphere radius

VII. SUMMARY

The triboelectrification between hardwood and softwood spheres and a PTFE substrate has been studied. It is suggested that the observed results are due to difference in the apparent areas of contact between the charging partners. Future work will include triboelectrification experiments involving PTFE spheres and PTFE planes and wood spheres in contact with wood planes. Experiments involving smaller diameter wood and metal spheres will also be done to further study saturation charge levels due to air breakdown.

ACKNOWLEDGMENT

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