Applicable measurement systems for determining the amount of electrostatic charge generated on textile materials

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Review*

Static electricity is a phenomenon that describes the instability of an electric charge inside or on the surface of an observed object. Previously, static electricity was closely related to electrical resistivity, i.e., the electrical conductivity of the observed object. More recently, electrical resistance is no longer sufficient as a reference value, especially with the increasing use of multipurpose materials such as textiles that contain active elements that are powered by electricity. E-, smart or intelligent textiles are limited by their energy storage capacity and proximity to the nearest power source. Therefore, portable energy harvesting devices such as triboelectric generators (TEG) are used to generate electrostatic charge and convert it into usable electrical energy. The need for further analysis of the electrical properties of textile materials has led to several research papers observing the voltage and capacitance values induced by contact or non-contact electrification of textile materials. From the numerous investigations, a few reference examples were selected in which the electrification of materials was performed by contact or non-contact and with different measurement setups to determine the electrostatic charge.
Keywords: *static electricity, electric charge, textile, voltage, capacity*

1. Introduction

It is common knowledge that all matter is composed of atoms, which are composed of electrons, protons, and neutrons, but only electrons and protons have an electric charge, which defines the polarity of matter itself. In electrostatics, the equilibrium state of matter is defined as the so-called neutral state, which is determined by the internal number of electrons and protons. Electrons are considered as the moving parts of an atom, and their transition from one object to another creates an energetic imbalance due to the newly created redistribution of electrons in or on the surface of an observed object. The effect described is called static electricity and can occur after direct contact between two objects or due to the influence of an electric field (ionization). The strength of the effect depends on the electrical conductivity of the object, which is defined by its electrical resistivity [1-5]. Recently, electrical resistivity is no longer sufficient as a reference value for determining the electrostatic properties of the material. Especially with the increasing use of multipurpose materials, such as textiles, which are no longer limited to their passive properties such as weight per unit area, breaking strength, elongation, air permeability, resistance to external(mechanical) conditions, water repellency, fire resistance,

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and so on. In addition, they are upgraded with active elements that are powered by electricity. Such textiles are called e-, smart- or intelligent textiles, with additional functions such as electroluminescence, thermoregulation, health care and more [6-10]. The functional life of these technologically advanced textiles and garments is limited by the capacity of their energy storage and proximity to the nearest power source. For this reason, more and more wearable energy harvesting devices are introduced, which are specially designed for textile materials and use different types of energy, such as biomechanical, thermal, solar, environmental, etc. [11-14]. One type of textile energy harvesting device is called triboelectric generator (TEG) and can convert the electrostatic charge generated by textiles into usable electrical energy. The working principle of TEG is based on human motion and the electrostatic properties of textiles defined by the triboelectric series [15-16]. But the series have been shown to be unreliable in determining the performance of TEG [17-20].

Therefore, the need for further analysis of the electrical properties of textile materials led to a series of research works observing the values such as voltage and capacitance induced by contact or non-contact electrification of textile materials [21-24]. In this research, the researchers used different methods to induce the electrostatic charge and accordingly the measurement system to determine the electrostatic charge generated. The right choice and the number of elements determined before a certain type of test directly affect the result obtained. Thus, when testing the electrostatic properties of textiles, the test method depends on the principle of electrostatic charge induction (by contact or by an electric field), but also on the capabilities of the measuring device, which will be shown by a brief overview of research in this field. induction (by contact or by an electric field), but also on the capabilities of the measuring device, which will be shown by a brief overview of selected research in this field.

2. Measurement Systems and Devices for Determining of Electrostatic Properties Textiles

2.1. Contact measurement system for determining the amount of electrostatic charge induced by linear rubbing

The presented method is proposed in a paper entitled "Frictional Electrification on Polymeric Flat Surfaces" [25] to determine the electrostatic charge generation on polymeric films: nylon (PA 6.6), polypropylene (PP) and polytetrafluoroethylene (PTFE). For a better understanding of the mechanism of electrostatic charge generation and dissipation on polymer surfaces. The method consisted of a linear friction device and a measuring device, a voltmeter. The proposed measurement system could measure electrostatic charge generation (forward motion) and dissipation (backward motion) during a friction cycle. The potential energy is detected by an electrical potential probe (Model 1017, Monroe Electronics®) located on the bushing (Fig.1). The distance between the friction head and the probe is 20 mm, and the distance of the probe from the friction plate is 3 mm (Fig.2). The bushing and thus the head of the linear friction device and the measuring probe are driven by a computer-controlled stepper motor, so that the device can achieve different contact forces and friction speeds. The surface area of the material in the grating head was 10 x 20 mm, while the surface area of the grating plate was 300 x 90 mm. Before the experiment, all the materials used were exposed to an atmosphere with a temperature of 21°C and a relative humidity of 43%. Also, at the beginning of the experiment, the samples were cleaned and deionized with ethanol, ionized water, and an ionized gas to remove impurities and the initial electrostatic charge that may have accumulated.

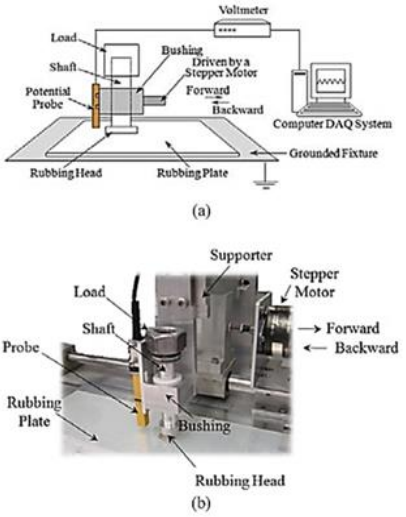

Fig.1. Schematic representation of the measuring system (a), an image of the measuring system (b). Reproduced with permission from reference 25. Copyright © 2013, © SAGE Publications. No changes were made.

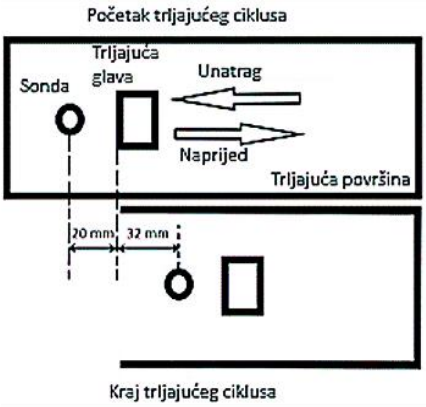

Fig.2. Schematic representation of one rubbing cycle

The authors performed three sets of experiments, to determine the influence of different:

- contact forces (0.4, 1, 1.5, 2 N), with the fixed parameters of rubbing speed (47 mm/s), rubbing stroke length (52 mm), and number of rubbing cycles (forward and backward stroke/cycle, 50),
- rubbing speeds (0, 27, 47, and 95 mm/s), with constant contact force (1 N), rubbing stroke length (52 mm), and rubbing cycles (50), and
- rubbing surfaces (stainless steel, PA 6.6, PP, PTFE) with constant parameters of rubbing speed (47 mm/s), contact force (1 N), rubbing stroke length (52 mm), and the number of rubbing cycles (50).

Chosen parameters were used because they didn't cause severe damage to the tested polymer material or any jerk motion of the linear rubbing device.

The results obtained indicate a relationship between the contact force and the polymer morphology observed in polymers with a higher content of amorphous domains, such as PTFE. Where a higher contact force allowed a larger contact area, a larger amount of electrostatic charge was also generated.

The study of the friction velocity and its influence compared to "zero velocity", i.e. contact and separation of two surfaces, showed no significant influence. Moreover, when the tested polymer materials were rubbed against each other, it was found that the greater difference within the triboelectric series (PA 6.6 and PTFE) did not lead to a greater electrostatic charge.

The charge decay was observed within 30 seconds after the last friction cycle for all three series of tests. Only PA 6.6 (60%) was found to have charge decay due to its low moisture content (2%), but still significantly higher than PP and PTFE (0%).

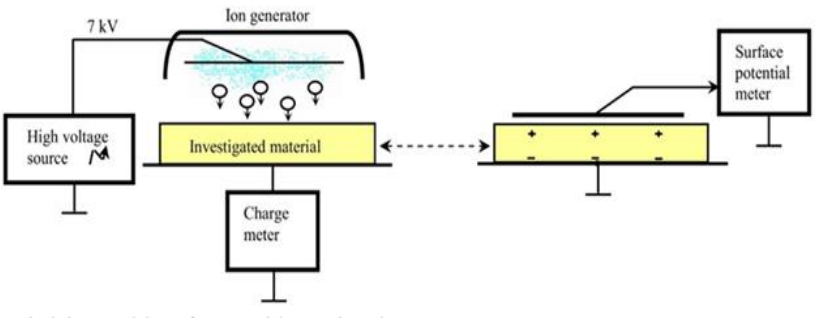

Fig.3. Deposited charge and the surface potential measuring scheme. Reproduced from reference 26, published open access under the CC-BY 4.0 license. No changes were made.

2.2. Non-contact measurement system for determining the amount of electrostatic charge induced by the high voltage ion generator

The measurement system shown in "Electrostatic Properties and Characterization of Specific Polymeric Materials for Building Purposes" [26] was intended for measuring electrical parameters and properties of insulating sheet-like materials such as plastic films and sheets. The electrification process non-contact and is achieved by a high voltage source (7kV) that periodically ionizes air molecules with positive and negative ions that impinge on the surface of the tested material (Fig. 3). The amount of charge deposited, and the surface potential are monitored in the form of voltage signals by a meter connected to a computer with an analog-to-digital converter. The computer records the measurements in real time and provides the following dependencies: the dependence of the surface potential on time (V - t); the dependence of the surface potential on the deposited charge (V - Q); the dependence of the electrical capacitance on the surface potential (C - V); the dependence of the volume resistivity on the surface potential (R - V). The measured dependences allow this measurement system to calculate values such as: the surface potential limiting value (V_{max}); the surface potential discharge rate (t_{med}); the maximum deposited charge (Q_{max}); the layer capacitance (C_l); the energy of the accumulated charge (W_Q); the volume resistance (R). The following values give significant insight into the material's electrostatic properties, without damaging it in the process.

The surface potential limiting value (V_{max}) is determined after the calculated capacitance (1) of the test material becomes double its initial value.

$$C = \varepsilon \cdot \varepsilon_0 \cdot \frac{S}{d} \qquad (1)$$

ε – permittivity of the tested material
ε_0 – permittivity of free space
S – the surface area of the tested material
d – thickness of the tested material

The surface potential discharge rate (t_{med}) is determined after the value of the surface potential (V) starts to decrease and becomes half its value.

The maximum deposited charge (Q_{max}) can be calculated when the V_{max} is reached or when the material surface potential reaches the pre-established value.

$$Q = \frac{U}{k} \qquad (2)$$

Where k in (2) is calculated as 1/C of the capacitance of the capacitor (C) used in the operational amplifier with high input impedance, connected to a computer.

The layer capacitance (C_l) is determined when the V is half of the V_{max} value.
The energy of the accumulated charge (W_Q) is calculated from C_l and V_{max} (3).

$$W_Q = \frac{C_l \cdot V_{max}^2}{2} \quad (3)$$

The volume resistance (R) is defined when the surface potential reaches V_{max} and when the V_{med}.

A series of materials meant for the same building purpose were tested with this measurement system, and the comparison of the result was confirmed, but all the calculated values depend mainly on the set V_{max} value.

2.3. Contact measurement system for quantifying the triboelectric series of electrostatic charge induced by contact and separation (liquid electrode)

The authors of the article "Quantifying the triboelectric series" [27] proposed a standardized method for quantifying the present qualitatively classified materials in triboelectric series, mainly polymeric materials. The method was carried out under defined environmental conditions, insured in a glove box that housed the entire measurement system shown in Fig.4.

Such a system was intended to determine the amount of electrostatic charge transferred during many repeated cycles of contact and separation of pre-cleaned polymer material samples. By design, the measurement system is a capacitor in which the distance (L) between two metal plates is adjustable according to the thickness of the tested material (d1). Like a classical capacitor, it contains two electrodes separated by a dielectric, i.e. the tested material. However, instead of two separate metal plates, one elec-trode was applied directly to the

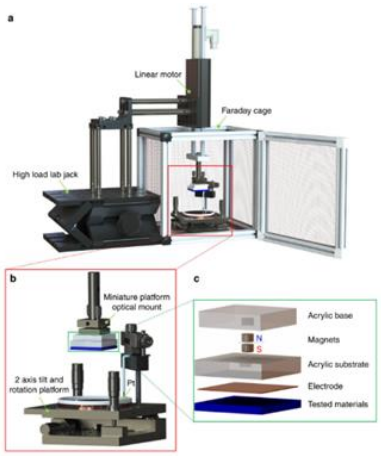

Fig.4. The whole measurement experimental set-up for the triboelectric series measurement (a); The static and the motion part of the setup (b); Sample holders (c). Reproduced from reference 27, published open access under the Creative Commons Attribution 4.0 license. No changes were made.

test material and consists of two layers: Ti (15 nm) and Copper (< 300 nm), while the other electrode was physically separated and consists of Mercury. By directly depositing a metal layer on one side of the tested material using the electron beam scattering technique (e-beam) and using mercury as the second electrode, the authors have solved the problem of the uneven contact area. Moreover, the use of an electrode in the liquid state avoided the influence of the contact pressure of two solid materials, which depends on their hardness, elasticity and stiffness. The experiment was performed under controlled conditions in a glove box filled with ultra-high purity nitrogen gas at a temperature of 20 ± 1 °C, atmospheric pressure, and humidity of 0.43%. The measuring instrument used was the Keithley 6514, which was connected via platinum wires to both electrodes (copper coating and mercury). The resolution of the measuring instrument for measuring surface charge density is from 10 fC to 20 μC, while for high voltage measurements it contains an input impedance of 200 TΩ and a measuring speed of 1200 readings/s.

The mathematical model of the proposed measurement system is shown through equations 4-7. Where it is assumed that the density of free electrons on surfaces of the electrode (σ_l) is a function of distance between the electrodes (L) and time (t), and that its value is closer to the actual surface charge density (σ_C) when the distance between the two the electrode is much larger than the thickness of the material (d_1) and the dielectric permittivity of the material itself (ε_1) and the air gap (ε_0).

The electric field strength in the media and air gap is given by:

$$E_1 = \frac{\sigma_l(L,t)}{\varepsilon_1} \quad (4)$$

The voltage between the two electrodes:

$$E_{\text{air}} = \frac{\sigma_l(L,t) - \sigma_C}{\varepsilon_0} \quad (5)$$

The charge density of free electrons on the surfaces of the electrode, in short circuit condition:

$$V = \frac{\sigma_l(L,t)}{\varepsilon_1} \cdot d_1 + \frac{\sigma_l(L,t) - \sigma_C}{\varepsilon_0} \cdot L \quad (6)$$

The electric field strength in the media and air gap is given by:

$$\sigma_l(L,t) = \frac{L \cdot \sigma_C}{\frac{d_1 \cdot \varepsilon_0}{\varepsilon_1} + L} \quad (7)$$

σ_l (L,t) - density of free electrons on surfaces of the electrode
L - the distance between the electrodes
t - time
ε_1 - dielectric permittivity of the material
σ_C - the surface charge density
ε_0 - dielectric permittivity of the air gap
d_1 - material thickness

2.4 Contact and non-contact measurement system for mathematically modeling of time-dependent electrostatic charge generation

Today a significant number of mathematical models have been derived as a tool for predicting the electrostatic charge generation in devices such as triboelectric generators (TEG).
Many of them treated electrostatic charge generation as a constant and time-independent quantity [22-23, 28], which by its nature it is not [29, 30]. Therefore, the researchers of the paper "*Modeling of triboelectric charge accumulation dynamics at the metal-insulator interface for variable capacitive structures: application to triboelectric nanogenerators*" [24], developed a measuring system, to test their *dynamic charge model* and it computer simulations, to find the right correlation of the surface charge density and the surface voltage of the tested material, generated during and after number of successive contact and separation of the upper electrode.
The proposed measurement system, in its center, has a capacitor like a device, which through vibration (oscillating) of the upper metal plate (electrode) causes contact electrification of the material under testing (Fig.5a). Samples of materials are cut into squares (3 x 3 cm) and cleaned with isopropanol, after which they are placed on bottom double-sided adhesive tape and additionally discharged with the deionized water, from any residual or newly formed electrostatic charge.
The measurement device, voltmeter (Trek 347) is placed in partially shown lumped model of measurement circuit in Fig.5b, 5c. The full mea-surement circuit consisted of a half-wave rectifier, made from two low-leakage diodes (D1, D2, type: MMBD1503A) and an additional 3.33 nF capacitor (C). The initial assumption of the dynamic charge model is: that the surface of each dielectric material will become saturated after a certain time, due to successive contact and separation of the top electrode, which is described by the equation (8).
Authors, separated the case of non-contact and contact electrification, as for the positive, so for negative charge generation, and derived the corresponding equations (11)-(14).

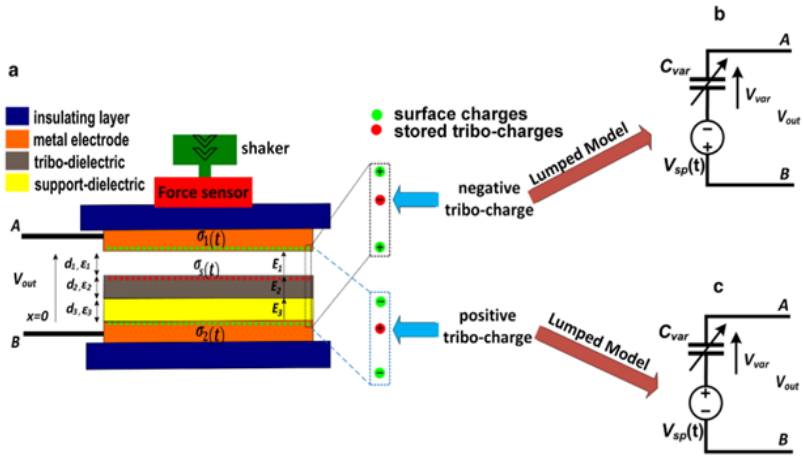

Fig.5. Simplified representation of the proposed capacitor device (a) and lumped model of the measurement device for the negative surface triboelectric charges (b) and with positive surface triboelectric charges (c). Copyright © 2019, Springer-Verlag GmbH Germany, part of Springer Nature. No changes were made.

The proposed *dynamic charge model*:

$$\sigma_s(t) = \sigma_s(0) + \Delta\sigma_s(t) = A + B\exp(\frac{-t}{\tau}) \quad (8)$$

$$A + B = \sigma_s(0) = \sigma_s(t)|_{t=0} \quad (9)$$

$$B\,(\exp(\frac{-t}{\tau}) - 1) = \Delta\sigma_s(t) = \sigma_s(t) - \sigma_s(0) \quad (10)$$

$\sigma_s(0)$ – initial (stable) charge density on the surface of the dielectric material
$\Delta\sigma_s(t)$ – Surface density of the accumulating charges in the observed time
$\sigma_s(t)$ – the total charge density at the surface of the dielectric material
τ- cumulative time of all charging and discharging events
A- the initial amount of charge on the dielectric material
B- the amount of charge generated

Contact mode:

$$\sigma_s(t) = \frac{V_{sp}(t)\cdot\varepsilon_0}{\left(\frac{d_3}{\varepsilon_3} + \frac{d_2}{\varepsilon_2}\right)} \quad (11)$$

Non-contact mode:

$$\sigma_s(0) = \frac{V_{sp}(0)\cdot\varepsilon_0}{\left(\frac{d_3}{\varepsilon_3} + \frac{d_2}{\varepsilon_2}\right)} \quad (12)$$

Negative charge surface charge density:

$$\sigma_s(t) = \frac{V_{sat}\cdot\varepsilon_0}{\left(\frac{d_3}{\varepsilon_3} + \frac{d_2}{\varepsilon_2}\right)\left(\frac{C_{max}}{C_{min}} - 1\right)} \quad (13)$$

Positive charge surface charge density:

$$\sigma_s(t) = \frac{V_{sat}\cdot\varepsilon_0}{\left(\frac{d_3}{\varepsilon_3} + \frac{d_2}{\varepsilon_2}\right)\left(1 - \frac{C_{min}}{C_{max}}\right)} \quad (14)$$

$\sigma_s(0)$ – initial (stable) charge density on the surface of the dielectric material
$\sigma_s(t)$ – dynamic charge density at the surface of the dielectric material
$V_{sp}(t)$- dynamic voltage across the tested material and bottom electrode
$V_{sp}(0)$- the initial constant surface voltage
V_{sat}- the saturation voltage
d_2 – thickness of material under testing
d_3 – thickness of double-sided adhesive tape
C_{min} – the lowest measured value of capacity
C_{max} - maximum measured capacity value
ε_0 – the relative permittivity of free space
ε_1 – the relative permittivity of the air
ε_2 – the relative permittivity of the tested material
ε_3 – the relative permittivity of double-sided adhesive tape

The measurement procedure was performed with a voltmeter (Trek 347) and consisted of one measurement in the noncontact mode and nine consecutive measurement cycles in the contact mode, for both positive and negative charge generation. The maximum compressive force in contact mode was 2.8 N, and the measured time to reach saturation voltage (Vsat) for each of the samples was 60 s. Footnote: There is no discharge of the sample between successive measurement cycles in contact mode. The initial charge of each next cycle is the final voltage of the previously measured cycle. In addition, the effectiveness of the dynamic charge model was investigated by using a charge-sensitive conditioning circuit based on the principles of Bennet's doubler circuit. During the measurement procedure, three, six, and nine discrete reference measurement points were selected to determine which number of reference points would give the least error in the simulation. That is, to see what happens to the charge evolution over time. In the end, the proposed method was applicable for detecting the initial charge on the tested material and confirmed that the charge generation increases with time.

3. Conclusion

The presented measurement systems show ways to determine the amount of electrostatic charge generated on the surface of the tested material by contact (2.1, 2.3 and 2.4) or non-contact (2.2) electrification. Since the measurement systems cannot measure the value of the surface charge directly, it is calculated indirectly from one of the directly measureable values such as capacitance or voltage. For this purpose, suitable mathematical conversion formulas were required, which the researchers provided according to the assumptions correlated with their method. In summary, all the presented measurement systems for quantifying electrostatic charge provide valuable data that can be used to predict the behavior of devices such as TEG, but are limited by their robust measurement equipment and rigid atmospheric conditions.

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