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Performance Investigation of Textile Triboelectric Generators

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ABSTRACT

With respect to the theory of the four Triboelectric Generators (TEGs) operational modes, a testing method is proposed. It describes and imitates more precisely the real conditions of the motion of the materials in a wearable clothing-based TEG. The phenomenon of triboelectricity is investigated from a clearly textile approach, using typical textile fabrics made by ordinary textile production methods and environmentally friendly materials. The performance investigation is based on the comparison of their triboelectric outcomes. It is of special interest that cotton fabrics showed an adequate electrical response, and among them, the twill 2/2 weave pattern offered the highest voltage outputs.

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1. INTRODUCTION

During the last decade, more and more research is applied in the area of Triboelectric Generators (TEGs). The potential energy sustainability which they can offer to wearable electronic devices has been of high importance [1]. Triboelectricity can be briefly defined as the natural phenomenon in which electric charges of opposite signs are induced by the frictional contact and separation of the surfaces of two materials [2,3]. It remains a complicated physical phenomenon, very difficult to investigate without approaching it from a multidisciplinary aspect. But in the meanwhile, beyond the questions about the phenomenon itself, a lot of interest is applied in developing new TEGs which might be used in new application areas and which can provide considerable electrical power outputs [4].

Following the principle of triboelectricity, TEGs are miniaturised devices which exploit the triboelectricity phenomenon in order to collect energy from our daily life movements or our ambient environment which would be otherwise wasted [5]. Until today, TEGs have gained a significant interest to combine them with human daily motion (e.g walking or running). TEGs constitute by definition a sustainable form of energy, contrary to batteries which are bulkier, stiffer, heavier, need often replacement and cause environmental pollution [6–9]. This advantage and eco-friendly character drive a lot of effort to develop TEGs and apply them in low-consumption wearable electronics, or even to further applications areas independent of the need of a wearer.

The two main functions of TEGs lay between two areas: the one of providing sustainable electrical power by harvesting all kinds of mechanical energy, and that of providing sensoring which would be self-powered without the need for an external power supply or batteries [10]. Many studies and trials have been applied over the last decade in order to attach TEGs onto human wearable garments, shoes or accessories (e.g. bags), bringing to the surface a wide range of medical, sportive and other daily life human applications. The power supply of low-consumption wearable devices like a wearable watch, the use as a self-

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powered breathing or heart rate sensor, the use as a garment-embedded keyboard or button, and the use for self-powered wearable temperature or humidity sensors are only a few examples to mention [11].

The intensity of the triboelectric process of a TEG depends on various parameters like the contact force between the two surfaces, the ambient humidity and temperature, the surface structure, the area size of the contact surfaces, the thickness of the contacting materials etc [11,12]. Among these parameters, the pairs of the contacting surfaces play a major role in the produced energy [2, 13–16]. This means that the materials' chemical or mechanical properties also affect the resulting electrical outputs. So for example, many polymer materials like fluorinated ethylene propylene (FEP), polyvinylidene fluoride (PVDF), polydimethylsiloxane (PDMS), polytetrafluoroethylene (PTFE), and polyvinyl chloride (PVC) have been proved to be good for building efficient TEGs, keeping also the cost low [17]. Additionally, the surface structure is important, as it directly relates to the increase of the contacting area. Considering this, significant improvements have been done to develop the surface structures by using nanoparticles, chemical treatments, block copolymer patterning, nature patterns replication and another forms of nanoprocessing. For example, state-of-the-art technologies for particular material structures like aerogels have been introduced in TEGs building in order to achieve high efficiency. Indeed aerogels are particularly interesting in TEGs applications area because of their high porosity, flexibility, light weight and large surface areas, while they can also be combined with another energy harvesting family, called Piezoelectric Generators to build improved hybrid generators [17,18].

The fundamental mechanism of triboelectricity has not been fully and exhaustively clear yet and this is out of the scope of this current work. The fact that triboelectricity can appear between different or identical materials, between conductive or insulative ones, between solid and liquid, solid and solid, gas and solid etc, makes it very complicated to study it under various external conditions and to build an overall mechanism theory which would cover all the cases happening. Among them, the dominant mechanism is the electron transfer (others are ion transfer, material transfer, H^+ and OH^- transfer) which happens when the interatomic distances between the surfaces of two contacting materials become shorter upon contact, driving consequently to electron clouds overlap, a lowering of the energy barrier between the participating atoms of the two surfaces, and the final result of allowing electrons to move from one atom to another [10]. At this point, we must mention that the application of force and rubbing enlarges the participating area of this pre-described mechanism.

In the case of textile-based TEGs, the chosen contacting surfaces are textile structures, so they may have the form of woven, knitted, non-woven or yarns. These textile structures donate to the TEG their mechanical or physical advantages of flexibility, elasticity, breathability, skin-friendliness, eco-friendliness, tailorability etc. This means for example that the textile-based TEGs may be friendlier to the wearer and the human skin. Additionally, they offer the possibility of getting directly embedded as part of the clothing or textile-based wearable device.

Four operational modes of TEGs exist to step on, develop and construct test mechanisms to harvest electrical energy [1,19]. The most simple and common operational mode used is the vertical contact-separation mode (also known as contact-separation mode). In that, the contacting materials face each other and execute a motion which is perpendicular to their contacting surfaces, resulting in a tapping action. Similar is the single electrode mode, which differs in the fact that one of the two surfaces is simultaneously also the electrode. In the rest two modes, the in-plane (also known as linear sliding) and the free-standing, the contacting materials execute a motion which is longwise to their contacting surfaces, resulting in a sliding action.

In this research work, with respect to the theory of the four operational modes, a testing device has been designed, analysed and constructed. It executes a realistic motion of the contacting surfaces approaching the motions of the human body in real life. It applies on the samples' surfaces a combination of a perpendicular (tapping) and a longwise (sliding) motion. Thus it combines the vertical contact-separation mode and the linear sliding mode. This may imitate more realistically the motion of the materials in a wearable TEG of clothing, as it might take into consideration both the contact-separation state plus the intermediate friction under regular force loads.

2. MATERIAL AND METHOD

2.1 Material

In this study, the phenomenon of triboelectricity was examined from a clearly textile point of view. Thus the tested textile fabrics were made by ordinary textile production methods and without applying any additional chemical or mechanical treatments to affect the properties of their surface. As can be seen in Figure 1, the testing samples were made of three different weaving patterns: plain, twill 2/2 2/2 and honeycomb [20]. Warp and weft density was equal to 20.4 yarns/cm, and they were kept constant during the production of all samples.

All of the patterns were produced using the same two-ply yarn. It came from a 100% cotton carded blend, it had a linear density of 20x2 Tex (30/2Ne) and 620 twists per meter (15.75 twists per inch). Its mass evenness and surface quality characteristics were also measured: Uster evenness value was 8.1U% (CV_m=10.1) and hairiness value 6.0.Moreover, the single-ply yarns which were used for the production of the two-ply yarn, had 917 twists per meter (23.3 twists per inch), 12.5U% (CV_m=15.6) and 5.1 hairiness.

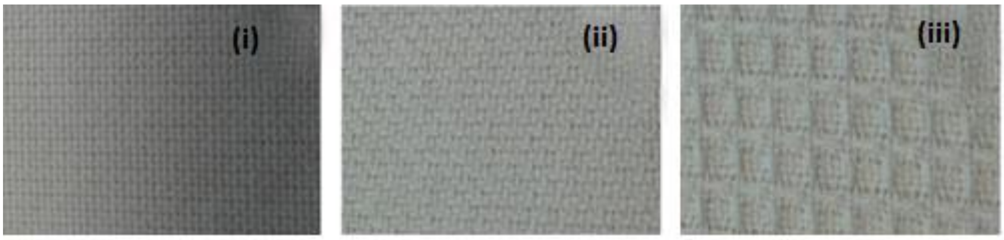

Figure 1. Images showing the used (i) plain, (ii) twill 2/2 and (iii) honeycomb textile patterns [20]

The cotton material was selected because of the high interest it has as it is an environmentally friendly material and also very friendly to human skin. Additionally, it was selected in a frame of investigating the possibilities that natural textile materials may provide to us as contacting parts of a TEG. Each testing specimen had a dimension of 5x5cm. In each measurement series, newly cut specimens were used to compare, avoiding any previous possible wear on the surfaces.

To compare the triboelectric outputs of the three different cotton samples, a second material was selected to combine and pair with each of the samples. For this need, in the currently presented experiments, a 5x5cm PE film was chosen which would provide a clear and flat surface. This was used as the reference material sample. Keeping it constant in all the measurements, we preserved the same conditions for the comparison of the before-mentioned various textile samples.

2.2 Method

This research focused on approaching the triboelectricity phenomenon in a more realistic way from a textile clothing point of view, applying normal weight loads of a few grams (e.g. 10grams) as if the load was caused by the slight motion of a clothing part. The application of significantly high forces usually met in the literature (several Newtons like the ones applied by big linear motors) between the TEGs' contacting surfaces has been avoided, as such conditions might not be met in wearable clothing except for shoes which gather the body's weight during running or walking.

Moreover, friction was taken into account to simulate the TEG's performance under more realistic conditions. As already mentioned, most of the contact-separation testing devices can describe the performance of a TEG taking into account only the movement of the triboelectric surfaces on a perpendicular axis (tapping). Hereby, to keep it more realistic, the appearing friction from the horizontal displacement of the surfaces on the horizontal axis has been considered too.

The proposed method combines the contact, friction and separation of two contacting surfaces, to simulate accurately the real operating conditions on a human body, especially if the two triboelectric surfaces are placed on the inner side of the sleeve and aside from the body as shown in Figure 2 (black and yellow strips).

Figure 2. Example of the contact, friction and separation motion executed by two triboelectric surfaces on the inner side of the sleeve (black strip) and aside from the body (yellow strip) while walking

This motion of one sample over the other is thoroughly presented in Figure 3C. Starting from the initial position of phase (i), the upper sample (black color) moves toward the lower sample (yellow color) during phase (ii). At some point it contacts the lower sample at phase (iii) and keeps moving over the surface of the lower sample. During phase (iv) the two samples are positioned and stopped exactly one over the other and they are under a certain weight load. The inverse motion is applied afterwards, moving away the upper sample at phase (v), separating it at phase (vi) and finally stopping it at its initial position in phase (vii).

We may consider that the hereby proposed TEG testing device combines both the two motions which are used individually by more traditional TEGs, as presented in Figure 3 A and B. Firstly, in Figure 3A is represented the vertical motion of the two participating triboelectric surfaces of a vertical contact-separation TEG. In that, the surfaces are coming in contact and separate on a straight vertical axis of motion. During the contact, a load is applied between the two surfaces. Secondly, in Figure 3B, is represented the horizontal motion of the two participating triboelectric surfaces of a in-plane mode TEG. In that, the surfaces are sliding until they cover each other, and then they separate again. During their overlap, a load is applied between the two surfaces resulting in appearence of friction phenomena between them. In this way, friction is introduced into our measurements.

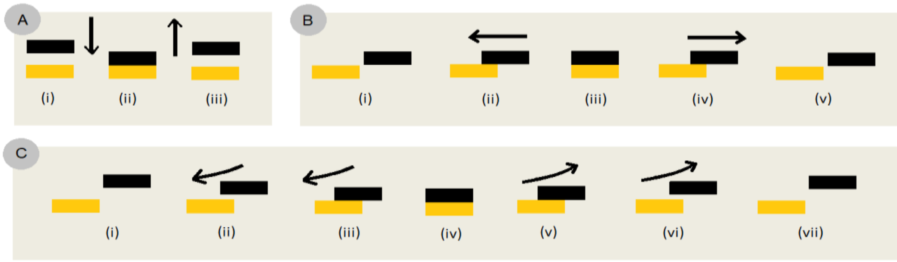

Figure 3. Representation of the relative motion executed by the upper sample over the lower sample

The proposed testing device might be used to test woven, knitted or more complicated textile structures of various densities, thicknesses, materials etc. The compression load applied during phase (iv) can be respectively adjusted. It achieves the desired motion between the two tested samples thanks to the use of a mechanical actuator and a connected pair of arms building a cradle, whose swinging motion brings in contact, rubs and separates the two samples, at the back side of which are attached the electrodes (Figure 4).

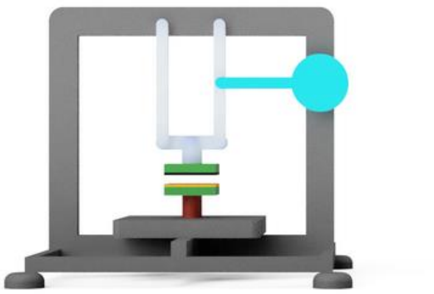

Figure 4. Sketch of the testing device which was designed and constructed, presenting the mechanical actuator (turquoise), the pair of arms (white), the two samples (black and yellow)and the two electrodes (green)

The proposed testing device contains two specially designed specimen holders, with a conductive surface on their exposed side. Each specimen is attached to the conductive surface of the holder, which serves as the output electrode of the TEG. A load sensor is attached to one of the specimen holders to measure the applied load upon sliding. The motion of one sample over the other is executed with high accuracy in what concerns their position and timing (e.g. operating frequency).

Additionally, an oscilloscope was connected with the device's electrodes to measure the electric outcomes. During the test measurements, the peak-to-peak voltage (V_{pp}) was measured.

3. RESULTS AND DISCUSSION

The proposed method is a tool for precise measurements allowing the study of the triboelectric properties of many textile materials, with the cotton included. This is due to the intervention of the friction between the contact and separation phases which increases the electrical outcomes. An example of the electrical response is presented in Figure 5, as it can be seen on the oscilloscope's display screen.

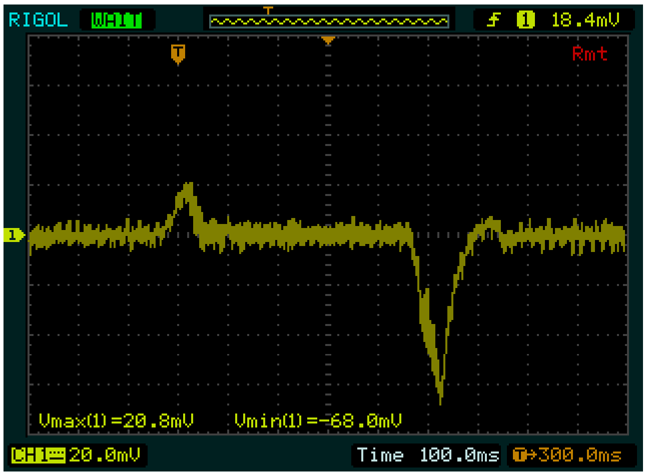

Figure 5. Generated voltage waveform.

Two peaks were appearing upon each test cycle which included one contact, sliding and separation of the two TEG's surfaces. The first peak appears at the moment of the contact phase, which is represented in stage (iii) of Figure 3C. The second peak corresponds to the moment of the separation phase which is represented in stage (v) of Figure 3C. Finally as seen on the oscilloscope, there is no electric output between stages (iii) and (v) of Figure 3C, where friction contact occurs between the two surfaces.

Concerning the comparison of the samples of different weaving patterns, it was found that the twill 2/2 patterned fabric gave the highest peak-to-peak voltage output, followed by the plain, and finally the honeycomb (Figure 6). This result agrees with previous studies which have set the twill 2/2 patterns as more effective than others [13,15,21].

More precisely, when the cotton plain sample was combined with the PE film sample as the two contacting surfaces of the TEG, they gave V_{pp} ranging from 112 to 120mV, with a mean V_{pp} value of 116mV. On the other hand, the cotton twill 2/2 sample combined with the PE film sample as the two contacting surfaces, gave much higher voltage outputs. The V_{pp} was ranging from 142 to 149mV, with a mean V_{pp} value of 145mV. Finally, the cotton honeycomb pattern sample combined with the PE film sample gave the lowest voltage outputs. The V_{pp} was ranging from 100 to 108mV, with a mean V_{pp} value of 104mV.

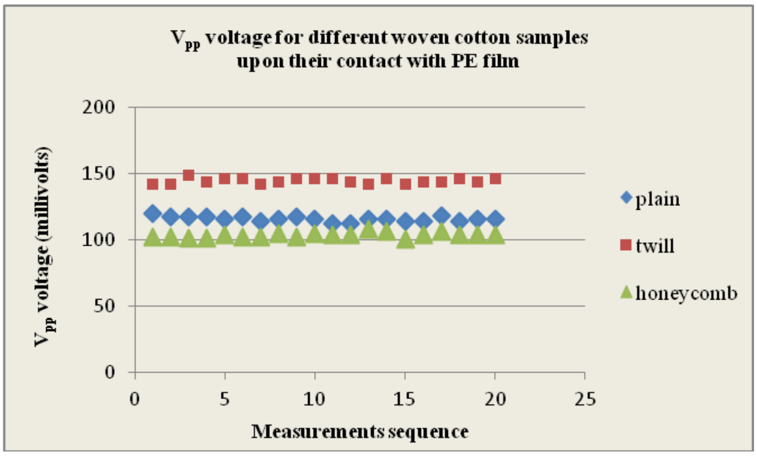

Figure 6. Repeated peak to peak voltage measurements during the contact and separation of the two contacting surfaces.

Traditionally, it has been known that a weaving pattern plays a major role in the regular textile properties like for example the surface roughness [22], the shear behaviour [20] etc. Hereby, it is also proved that as a weaving pattern primarily affects the surfaces of textile-based TEGs, it also secondarily affects its triboelectric outcomes.

It is worth mentioning the high repeatability level of the measurements as it comes from the above graph. The stability and repeatability properties are mainly because of the precise design and construction of the testing device.

In the majority of the related sources, research refers to the development of TEGs whose contacting materials are polymer-based, in the form of film or complicated multi-layered structures [11]. However, this research work has focused on the possibilities of a broadly used natural material like cotton, staying close to traditional and widely used textile structures.

Moreover, each of the four TEGs operational modes is limited to offering only a perpendicular or longwise motion, and cannot provide simultaneously both tapping and sliding action. This can be practical from a laboratory reference point, but not representative of the real usage conditions. Herein a more representative simulation of the motion of the contacting surfaces in a textile-based TEG has been achieved.

4. CONCLUSION

Providing the necessary precision and flexibility, the proposed method will allow a better study of the textile-based TEGs. We have hereby seen a comparison of the electric outputs of three well-known weaving patterns (plain, twill 2/2 and honeycomb), of which the samples were made out of the same material (carded cotton) and production settings (yarn density, weaving density etc).

During the tests, the executed contact, rubbing and separation of each sample with a PE film under a low load of 10 grams, showed that the twill 2/2 pattern provided a mean Vpp value of 145mV. That was the highest in comparison with the plain pattern which gave 116mV and the honeycomb pattern with 104mV.

The patterns of the contacting surfaces of the materials participating in the triboelectric effect of a TEG are of major importance, as from a textile point of view, they correlate to the various textile properties of surface roughness, density, porosity, breathability etc, from which in turn the triboelectric performance depends.

For future study, interest has risen to extend the tests by substituting the hereby used reference sample (PE film) with a reference sample of a textile fabric. In this way, the triboelectric effect of two textile surfaces would be tested, exactly as they might be used under real conditions in a garment.

This proposed method permits a realistic testing motion of the contacting surfaces which approaches the kinetics of the human body in real life. Thus, the use of the specific device it is expected to serve a more realistic loading simulation. Consequently, a precise performance examination is expected, supporting the comparison of the countless textile patterns and materials, which might be used for the design and development of textile-based TEGs.. In this way, the optimum weaving, knitting or nonwoven pattern and material might be chosen according to the needs of the desired textile-based TEG and the clothing item or accessory to get attached on.

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