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Full paper

Water tank triboelectric nanogenerator for efficient harvesting of water wave energy over a broad frequency range

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ABSTRACT

A water tank triboelectric nanogenerator based on polytetrafluoroethylene (PTFE) is fabricated for harvesting water wave energy. The impacts of contact frequency over a broad frequency range including the frequency range of ocean waves and output characteristics under resistive and capacitive loads for different liquid types are investigated in order to identify the optimal contact frequency and load conditions for maximizing the power density and energy conversion efficiency. In addition, surface modification of PTFE with different patterns for enhancing its hydrophobicity is implemented in order to reduce charge screening. Furthermore, the impact of contact frequency on the output characteristics for the surface modified PTFE is also studied. It is observed that the open-circuit voltage and short-circuit current exhibited opposite trends with increasing contact frequency. The highest power density of 9.62 W/m^2 and energy conversion efficiency of 63.2% are achieved using saline water and rhombic pattern surface modified PTFE at contact frequency of 0.1 Hz, representing 8 fold improvement compared to the reported water tank based triboelectric nanogenerator based on fluorinated ethylene propylene. The results demonstrate that the nanogenerator has promising potential in scavenging water kinetic energy.

1. Introduction

With the inadequate supply of conventional fossil fuels in the future and the associated environmental problems, scientists have devoted to search for alternative renewable energies, such as solar and wind energy. Nevertheless, this type of energies is mainly to cater for large-scale power grids and the concern in intermittency remained a major obstacle [1,2]. With technological advancement, small-scale electronic devices [3,4] have been permeated into every aspect of our lives and the use of sustainable sources to power them has risen to public attention. Among renewable energy sources, water energy [5], being one of the most abundant source covering 70% of the earth's area, is sustainable and independent of season, climate and weather condition. Thus, conversion of water kinetic energy to electrical energy has great potential and significance toward sustainable development.

Triboelectric nanogenerator (TEG), as a mechanical energy convertor, can harvest the kinetic energy from the ambient environment based on the coupling of contact electrification and electrostatic induction effect [6]. TEG has attracted increasing attentions due to its simple working mechanism and fabrication process, high power output, and efficient energy conversion. On the other hand, since the first TEG was reported in 2012 [7], advancement of TEG has mainly focused on the following aspects, structure design [8,9], multi-energy harvesting [10,11], power output enhancement with high conversion efficiency [12,13] and integration in self-powered small electronics [14,15]. On of the key factors that impact on the performance of TEG is surface charge density [16], which can be taken as a standard to characterize the triboelectric charging behavior and the performance of the constituting triboelectric material. The surface charge density can be improved by selecting appropriate materials and by increasing the effective contact area. While material selection can intuitively be addressed by combining a highly electron donating material with a highly electron accepting material according to the triboelectric series [17], to enhance the charge separation, surface roughness increases the effective contact area. On the other hand, enhanced surface hydrophobicity [18] is beneficial at the interface of liquid and solid materials.

While solid-solid based TEG have proved to produce higher voltage in dry conditions [19], contact electrification charges are also generated at liquid-solid interfaces [20–22]. Thus, herein we explore the use of water as one side of the nanogenerator in order to investigate the contact electrification between liquid and dielectric material for harvesting water wave energy. A water tank TEG is fabricated using polytetrafluoroethylene (PTFE) as the negative triboelectric material. To investigate the triboelectric effect at the liquid-solid interfaces,

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deionized water (DI-water), tap water, and sodium chloride (NaCl) with a concentration of 0.6 M were compared. Subsequently, the impacts of contact frequency and output characteristics under both resistive and capacitive conditions were studied in order to identify the optimal contact frequency as well as load conditions for maximum power output. In addition, surface modification of PTFE with three different patterns for enhancing its hydrophobicity was carried out to reduce charge screening for enhancing the energy conversion efficiency.

2. Experimental methodology

2.1. Materials selection

The liquid used for the water tank TEG is water based, that is positively charged according to the triboelectric series, easily accessible, non-toxic and non-corrosive. Compared to liquid metals, such as gallium and mercury, though with high conversion efficiency, liquid mercury is extremely toxic and both mercury and gallium must be handled with care, thus making the application of liquid metal TEG of low practicality. In addition, two other types of liquids, tap water and 0.6 M saline water solution (termed 0.6 M NaCl) were also applied for comparison with DI-water. PTFE was selected for the solid side due to its hydrophobicity, high negativity in the triboelectric series, and chemical and thermal stability [23]. It is noted that the influence of hydrophobicity of the solid film is significant since there would be charge equilibrium [20] with water droplets remaining on the surface affecting the output performance. The hydrophobic property as well as the low friction coefficient of PTFE make it an ideal dielectric material for fabricating a liquid-solid based TEG (LSTEG).

2.2. Structure design and fabrication

The water tank triboelectric nanogenerator is composed of a polypropylene (PP) tank with a dimension of 7.5 × 7.5 × 4 cm (L × W × H) and copper electrode partially covering the bottom and the sides of the tank for maximizing the contact electrification charge generation. Since there still exist gaps at the connecting edges between the tank walls and Cu electrode, 3 mL of polydimethylsiloxane (PDMS) solution was applied to seal the gaps and the tank was then placed in an oven for 60 min at 65 °C to thoroughly the PDMS seal. For the solid triboelectric material, commercial PTFE with a thickness of 2 mm was cut to a size of 6 × 5 cm (L × W) with a Cu electrode of the same size was pasted on one-side of the PTFE film as the top electrode. A linear motor (LinMot®, Force range 1–44 N) was utilized to control the position and movement of the solid PTFE fixed on the motion probe in perpendicular to the movement direction. The volume of liquid during the output measurement was set at 100 mL equating to 44.5% of the total volume of the tank, which is equivalent to the total volume the Cu electrode. Under periodical movement of the probe, the gap distance between PTFE and liquid was set as 6 cm at a temperature of 21 °C.

2.3. Surface modification and characterization

Hydrophobicity of the solid material plays a key role on the output performance of LSTEG because of the retention of liquid droplets, which could screen the charges on the solid surface thus reducing the power output. Since commercial PTFE is not of high hydrophobicity, surface modification is necessary to enhance its hydrophobicity. Here, sandpaper with 180 granularity was applied to modify the PTFE surface with different patterns of line, checkered and rhombic for improving the surface roughness. A high pressure sanding process by controlling the compression magnitude (3 N) and pressure (1 kPa) was adopted to modify the PTFE surface. The line and checkered pattern modification were obtained by sanding the PTFE surface under controlled pressure for 5 cycles. The rhombic pattern was obtained using a belt grinder with controlled pressure and rotating speed. A FlexiForce pressure sensor was placed beneath the PTFE film to monitor the applied pressure. A detailed surface modification diagram can be found in Supporting information, Fig. S1.

To evaluate the load characteristics and output performance of the LSTEG, a simple circuit include a full bridge rectifier and a capacitor for energy storage was designed to rectify the cycled positive and negative signals and store the converted electricity. Keithley SourceMeter (Keithley 2400) was used to analyze the generated open-circuit voltage (V_{oc}) and short-circuit current density (J_{sc}). The surface water contact angle of PTFE before and after surface modification was measured using drop analyzer (DSA100, KRÜSS). The surface morphology and topology of PTFE before and after surface modification were observed by scanning electron microscopy (SEM, Quanta 450) and atomic force microscopy (AFM, Dimension Icon, Bruker), respectively.

3. Results and discussions

3.1. Working mechanism of LSTEG

The water tank based TEG system mainly consists of three parts, external mechanical input (linear motor), energy conversion from mechanical energy to electricity (water tank and LSTEG) and power measurement (source meter). A typical structure of the water tank TEG is shown in Fig. 1**a** with two Cu electrodes (top and bottom) and the triboelectric pair (PTFE film and liquid).

The working mechanism of pristine PTFE and DI-water triboelectric pair can be described in the following four steps. At the initial position ($d = d_0$), we assume there is no charges induced on PTFE or the liquid until they come in full contact with each other. Since PTFE is easily to capture electrons while DI-water is easily to lose electrons, the contact electrification charges (triboelectric charges) generated on the surfaces of each side are in opposite polarities with same magnitude as shown in Fig. 1-b1. As PTFE starts to separate from DI-water surface, the negative electrons on PTFE starts to induce positive charges on top electrode while the positive charges in DI-water starts to induce negative charges on bottom electrode due to the electrostatic induction effect. A negative potential difference is established between the two electrodes and electrons flow from top electrode to bottom electrode through the external circuit producing a positive short-circuit current ($+I_{sc}$, defined) as demonstrated in Fig. 1-b2. When PTFE reaches its initial position ($d = d_0$), the contact electrification charges on the triboelectric pair are in equilibrium with the electrostatic induction charges on the electrodes and a positive potential difference is achieved at the same time as shown in Fig. 1-b3. When PTFE starts to contact with the DI-water's surface again, electrons travel in reverse direction due to a break of the previous equilibrium and hence negative $-I_{sc}$ and alternating current (AC) are observed produced as shown in Fig. 1-b4. One press-release cycle of J_{sc} and V_{oc} of pristine PTFE for DI-water at contact frequency of 0.1 Hz is shown in Fig. 1c and d, respectively. Two points are worth noting here, (1) both J_{sc} and V_{oc} showed an instantaneous negative press peak when PTFE surface began to contact with DI-water, indicating that the charges (Q) on top and bottom Cu electrodes are not in equilibrium, $Q_{Cu\text{-}2} > Q_{Cu\text{-}1}$ (Fig. 1c). During the “fully contacted” stage, the negative charges on bottom Cu electrode are neutralized by the positive charges on top Cu electrode, thus making J_{sc} and V_{oc} approaching zero and (2) when PTFE separated from water, a positive V_{oc} was generated and gradually decreased during the “fully released” period. This is due to water drops remained on PTFE surface, resulting in charge screening, thus the potential difference between PTFE and DI-water decreased. At low frequency (0.1 Hz), J_{sc} showed a direct current (DC) while V_{oc} showed an AC signal, however, both J_{sc} and V_{oc} presented AC-type signals at higher frequency. This is mainly due to the negative charges on bottom Cu electrode unable to be fully neutralized by the positive charges on top electrode within the “fully contacted” stage, which will be discussed in the section of frequency impact on PTFE.