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Electro-blown spinning driven by cylindrical rotating triboelectric nanogenerator and its applications for fabricating nanofibers

Yuntao Liu^{a,b,1}, Jing Wen^{a,b,1}, Baodong Chen^{b,c,1}, Mingli Zheng^{b,c}, Di Liu^{b,c}, Yuan Liu^{b,c}, Wei Tang^{b,c}, Jun Liu^a, Ding Nan^{a,*}, Zhong Lin Wang^{b,c,d,*}

^a School of Materials Science and Engineering, Inner Mongolia University of Technology, Inner Mongolia Key Laboratory of Graphite and Graphene for Energy Storage and Coating Hohhot, 010051, PR China

^b CAS Center for Excellence in Nanoscience, Beijing Key Laboratory of Micro-nano Energy and Sensor, Beijing Institute of Nanoenergy and Nanosystems, Chinese Academy of Sciences, Beijing 100083, PR China

^c School of Nanoscience and Technology, University of Chinese Academy of Sciences, Beijing, 100049, PR China

^d School of Material Science and Engineering, Georgia Institute of Technology, Atlanta, Georgia 30332, United States

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ABSTRACT

The newly developed electro-spinning based on triboelectric nanogenerator (TENG) is one of the most convenient ways to produce nanofibers, however, it's required to have a high-voltage of no lower than 8000 V, meanwhile, it remains challenging to enhance productivity on push forward the commercialization and with low cost. Herein, we report an innovative electro-blown spinning (EBS) methodology based on a cylindrical rotating (CR) TENG that is fast, efficient, lower high-voltage and cost-effective for the fabrication of polymer nanofiber membranes. The CR-TENG serves both as a high-voltage source and as a receiver, it gave a stabilized elecric output that the short-circuit current (I_{sc}) and transferred charge (ΔQ_{sc}) are ~75 μ A, ~0.78 μ C, and the peak power density (σ) reaches a maximum of ~ 2.23 W/m². Combined with assisted blowing technology, we have successfully achieved in driven the EBS system by a voltage 6250 V, which has saved more than 21% of high-voltage consumption. In addition, the thickness of produced nanofiber membranes had reached several microns level at manufacturing time within 5 s, then productivity is obviously increased compared with the electro-spinning, and the diameter size of nanofibers has significantly decreased compared to the solution blowing spinning. Moreover, the produced membranes had reached a new level in just a case of a few microns thickness, take the polyethylene oxide (PEO) nanofiber membrane for example, the output V_{oc} , I_{sc} and ΔQ_{sc} are nearly 1.6, 1.5, and 1.7 times higher than commercial films.

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1. Introduction

Exploring new fabrication methods for nanocomposite and nanofiber materials has never ceased for the past decades [1–3]. Solution-spinning and melt-blowing are most widely adopted technologies for the production of superfine fibers in industry [4,5], however, each of these has its own disadvantages. Electro-spinning is one of the methods to produce effectively ultrafine or nanofibers possesses unique advantage in a lab environment [6–8], meanwhile is thought to have the most potential technique of commercial nanofibers fabrication. However, hazard of high-voltages, long running period, low mass production, complicated operating con-

* Corresponding authors.

https://doi.org/10.1016/j.apmt.2020.100631 2352-9407/© 2020 Elsevier Ltd. All rights reserved. ditions and energy-intensive are its serious hurdles for large-scale applications in the textile industry. Then, the method of solution blowing spinning was invented which uses high-speed air flow to replace the high-voltage electrostatic field [9]. But it is difficult directed to collect the fibers and very difficult to control without the effect of electrostatic field, generally they are from a few microns to a dozen of micron range in diameter.

The first TENG was invented by Z. L. Wang's group since 2012 [10], aiming at harnessing much underutilized the ambient energy, it's not only a innovative, high conversion efficiency energy harvesting technology [11–16], but also has novel ultrasensitive sensing characteristic [17–22]. The intrinsic output advantages of TENG is high-voltage and lower current in larger load resistance [23,24]. The potential applications of TENGs in high-voltage electrostatic fields have been developed with various types on recently, such as making it feasible for indoor air purification, low-temperature triboelectric micro-plasma, catalysis, electrochemistry

E-mail addresses: nd@imut.edu.cn (D. Nan), zhong.wang@mse.gatech.edu (Z.L. Wang).

¹ Y. L., J. W., B. C., these authors contributed equally to this work.

and other fields [25–29]. A self-powered electrospinning system driven by rotating disk type TENG was designed by Z. L. Wang's group in 2017, which a combination of TENG and electrospinning was realized that it can supplying a high-voltage of 8000 V for powering electro-spinning easy to fabricate nanofibers [30]. But, because of its inherent defect, that is unable to avoid the inefficiency problem of system due to the limited feed rate of micro-syringe. Self-powered system is not only demonstrating the potential applications of the TENGs in high-voltage manufacturing but also broadens the application to scenarios of electro-spinning. We hope technology advantages of TENGs and its characteristics of high-voltage can be fully exerted and can be widely applied to the preparation of functional nanofibers.

Here, we developed a simple, new EBS methodology for the production of polymer nanofiber membranes, it has been realized so that the blowing technique and the CR-TENG can be effectively combined for the first time. This methodologoy is not only could overcome the inherent defect of a single electro-spinning technology, but also lower voltages, quick, and easy to operate. Meanwhile, the CR-TENG can not only provide electric field of 6250 V, but also serve as a cylindrical receiver for nanofibers. In addition, we have successfully fabricated three polymer nanofiber membranes, i.e. polyethylene oxide (PEO), polyacrylonitrile (PAN) and polyvinyl alcohol (PVA). Moreover, in triboelectric properties test, these polymer membranes reached a new output level in just a few microns thickness, the results shows that the electric output is higher than commercial films, which can easily be used to powersupplying for powering dozens of green light-emitting diode (LED) bulbs.

2. Results and discussion

2.1. The structure and fabrication process of CR-TENG

One of the prime objective of our work was the production of the polymer nanofiber membranes in a quick and easy way, for this reason, the key advantages of our designed new EBS system are lower of voltages and high-speed spinning as compared to electro-spinning, the schematic and structure is shown in Fig. 1. It was composed of a freestanding mode CR-TENG device, a matched boosting circuit and pneumatic unit and protective covers, a schematic diagram of the EBS system is shown in Fig. 1a. The structure detail of the CR-TENG is show in Fig. 1b, that is consists of a inside stator, a outside rotor and supporting frames, which acrylic was selected as the structural material. For the stator part, in accordance with the order from the outside-in that is consists of polyamide (PI) triboelectic-layer, copper (Cu) foil and a acrylic hollow tube fixed on a frame, which Cu foil serves as the back electrode of the CR-TENG. For the rotor part, two Cu foils are equi-spaced fixed on the inner surface of acrylic hollow tube, play dual roles as a sliding triboelectic-layer and as a electrode. Detailed description and digital images of the components, as shown in Fig. 1c and d and Supporting Information Fig. S1a. The stator and rotor were set to be coaxial to thoroughly contact during assembled into a CR-TENG unit, as shown in Fig. 1e and Fig. S1b. Further details of the fabrication process will be discussed in the Experimental Section.

2.2. The working principle of CR-TENG

The working principle of the CR-TENG can be described by the coupling of contact electrification and electrostatic induction. The design of the CR-TENG is based on the freestanding mode. The process of electricity generation and the characteristics of electrical potentials, as schemed in Fig. 2. The running state of the CR-TENG is show in Fig. 2a, an actual three-dimensional working principle of

the CR-TENG and the electricity generation process including four typical steps (i-iv) were shown in Fig. 2b. At the initial step i, the Cu electrode of the rotor is completely aligned with the Cu electrode of the stator that it's not relatively sliding, there is no current flow or charge transfer at this point. Due to the difference on triboelectric polarities, the surface of the PI film is uniformly negative charges, the surface of the Cu foil is uniformly positive charges [31]. At the step ii, charge transfer takes place when the rotor is start to turning in the clockwise direction that the relatively sliding began to appear, that a lot of triboelectric charges will generate on their surfaces. At the intermediate step iii, the charge transfer reach the maximum when the mismatch between the two sliding surfaces reaches the maximum. At the step iv, when the rotor continues to turning, the flow of charge will is opposite direction to the beginning on the same principle, until the fully aligned position is restored (Fig. 2b step i). During this period, the density of positive charges on Cu foil is equivalent as much as the negative charges on the PI film according to the law of charge conservation [32–34]. So that, in a cycle of electric generation process, one set Cu electrode has negative charges and the adjacent another Cu electrode has the same quantity of positive charges to keep the electrostatic equilibrium, AC electric output is generated [35–37].

To theoretically predict distribution of the electrical potential between the Cu electrodes of rotor and Cu electrodes of stator, the two-dimensional cross-sections electrical potential was numerically calculated by the finite element method. At the initial point, the calculated electrical potential difference between the two electrodes is zero (Fig. 2c). Then, a potential is generated to keep the charge balance according to the simulation (Fig. 2d and f). Based on the converting process, the generated current can essentially be described by the corresponding displacement current of second terms in the Maxwell's equation as proposed by *Z. L. Wang* (Equation S1-4 in the Supporting Information).

2.3. The electric output performances of the CR-TENG

To quantitatively measure the electric output, a rotary motor was used to drive the CR-TENG for all following tests, with the operating frequency of ~13 Hz. We fabricated CR-TENG is a size of 70 mm (outside diameter) × 245 (length) mm in experiments, it gave a stabilized open-circuit voltage (V_{oc}) of up to ~1300 V, a short-circuit current (I_{sc}) of ~75 μ A and a corresponding transferred charge (ΔQ_{sc}) of ~0.78 μ C, as shown in Fig. 3a and c. The characteristics of peak power (P) and output current (I) with different load resistance, the testing results is schemed in Fig. 3d. The results shown that the **P** increases and the **I** decreases with the increases of load resistance, when the external load resistance is up to nearly ~100 M Ω , the instantaneous **P** reaches a maximum of ~0.012 W. The **P** will decrease rapidly with the continuing increase of load resistance. Fig. 3e shows the peak power density (σ) and output current density (Jsc) for the CR-TENG operated at load resistance from 1 k to 100G (Ω). The σ increases and the J_{sc} decreases with the increases of load resistance, when the matching load resistance is up to nearly ~100 M Ω , the σ reaches a maximum of ~ 2.23 W/m². The charging ability of the CR-TENG was measured for different capacitance (4.7 nF, 10 nF, 47 nF and 100 nF) by a bridge rectifier (inset: the circuit diagram of charging), as schemed in Fig. 3f. It was found that the characteristic of charging tends to become nonlinear saturation, the saturated time is very fast, and it could be seen that the charging time increases with the increase capacitance of capacitor, but all capacitors can be charged to nearlly ~1300 V in a few seconds. Moreover, the results revealed that the charging voltages of capacitors were appear even slightly fluctuated in the saturation stage. This is because of the capacitor leakage, especially when the capacity of capacitor is lower, this is much more obviously. On the contrary, with the increase capacitance of



Fig. 1. Schematic illustration and digital images of the EBS system based on the CR-TENG. (a) The schematic illustration of the EBS system. (b) The structure detail of the CR-TENG. (c) The assembling drawing of the CR-TENG as a high voltage source. (d) Digital image of the CR-TENG's parts. (e) Digital image of the CR-TENG.

capacitor the fluctuation is reduced progressively. However, when the capacitance value is too large, the charging process will take a long time to achieve the required high-voltage. For this reason, we considered capacitance of capacitor, charging time, leak current and so on, so that, a optimum capacitance of 47 nF is adopted in the following experiment.

2.4. The EBS system based on CR-TENG and its application

According to the above researchs and analysis, the electric output of the CR-TENG is demonstrated, but it is still insufficient to as a high-voltage power of the EBS system for the fabrication of polymer nanofiber membranes. To solve this problem, at present the most common approach of improve voltage, that is constructed a matched boosting circuit by configuring multiple capacitors and diodes for this system to get enough operating voltages [30,38–39]. Take many factors into comprehensive consideration when a boosting circuit was designed, in which included lowest operating voltage, running time and efficient of the EBS system, and the electric output of the CR-TENG. Schematic diagram of the CR-TENG is connected to the boosting circuit, as shown in Fig. 4a, the circuit principle and digital images of the boosting circuit are schemed in Fig. 4b and c. A test on a trial-production of nanofiber membranes for different amplifying multiples has proven that the

EBS system is capable of successful operation when the boosting circuit was reached the amplifying of 16 times (including 16 capacitors and 16 diodes) under a constant capacitance of 47 nF, and it has also been demonstrated that the nanofiber membranes were easier prepared under the assisted blowing. Therefore, the boosting circuit was built by multiple experimental test, the relationship between the output voltages of the boosting circuit and amplifying multiples is schemed in Fig. 4d, it was obvious that the output voltage linear increases with the increase of amplifying multiples. All in all, the output voltage of the CR-TENG is reached about ~6250 V by builted boosting circuit of 16 times, which it can enough to provide stability and high-voltage electric field for the EBS system. Based on the above analysis, it could be concluded that the optimum configuration is obtained under the amplifying of 16 times and a constant capacitance of 47 nF. Further details of the testing process and the devices's information will be discussed in the Experimental Section.

Next, we investigated the running performance of the EBS system based on a CR-TENG as high-voltage source for the production of polymer nanofiber membranes, its digital photographs and the name of parts are shown in Supporting Information **Fig. S2**. The operating process of the EBS system was recorded by a digital camera, as shown in **Movie S1**. Before the spinning process, a piece of aluminum (Al) foil was covered in the outside wall of the



Fig. 2. The working principles and numerically calculated electrical potentials distribution of the CR-TENG. (a) Working scenario and structure of the CR-TENG. (b) The structure of the CR-TENG as a high voltage source. (b) Three-dimensional working principle of the CR-TENG and the electricity generation process including four typical steps. (c), (d), (e) and (f) Two-dimensional cross-sections electrical potential was numerically calculated by COMSOL software.

CR-TENG's rotor as a receiver to collect polymer nanofibers, and it can rotate with the rotor. Firstly, polymer solution was loaded in a syringe connected with a coaxial spinneret, which the driven by a microinjection pump. Secondly, the CR-TENG is connected to boosting circuit of 16 times, which the negative electrode of the high-voltage was connected to Al receiver, and the positive electrode was connected to the coaxial spinneret as well, then connect all pneumatic parts. Finally, the CR-TENG was operated by a rotary motor at a rotation rate of 400 rpm, the process of charging and boost usually finishes in a few seconds, a uniform layer of nanofibers membranes have been successfully prepared within 5 s after the run formally of spinning. The focus is on the CR-TENG, the results confirmed that the nanofibers can be collected directional on Al receiver under the function of the CR-TENG's high-voltage electric field. It overcame the disadvantages of solution blowing spinning, and is realized to increase controllability and efficiency. Sure, this EBS spinning process can also be drived by hand rotaedting within several minutes. Schematic diagram of the spinning processing is in shown the Fig. S3, the digital images of PEO, PAN and PVA solutions are in shown the Fig. S4. The fabrication process of PEO, PAN and PVA nanofibers membranes are shown in the Supporting Information (Movie S2-S3), and the screenshots of movie is in shown the Fig. S5. The thickness of PEO, PAN and PVA nanofiber membranes was shown in Fig. 4e, which were measured to be ~4.12, ~2.76 and ~2.35 μ m.Here, the thickness of PEO membranes has obviously different from other two membranes (PAN and PVA), and is about 1.6 times higher than their. This is because the thickness is largely influenced by spinning time, as it completed in a time was very short that was approximately 5 s in the whole fabrication processing, and thickness range is about within 5 μ m. So that, such differences in the thickness, because of a smallish difference in the start and end time of the EBS system. The SEM images of PEO, PAN and PVA membranes were shown in Fig. 4f and k. The macroscopical images of the three membranes is in shown the Fig. S6. The nanofibers are filamentous morphology, while the shape is regular and homogeneous, the diameter range of the nanofibers is between 500 nm and 1 μ m (Fig. S7), with the similar products as compared are close [30]. The results shown that the diameter of three nanofibers has a little different, which the diameter increases with the increased of viscosity and molecular weight. However, the diameter size of nanofibers has significantly decreased compared to the solution blowing spinning, achieves the similar compared to electro-spinning technology [40-42]. This is due to the high-voltage electric field provide by the CR-TENG and its effect of generated electrostatic force. When the fibers is been sufficient stretch under the higher electrostatic force, we can see



Fig. 3. The electric output performance of the CR-TENG. (a) The output open-circuit voltage of the CR-TENG. (b) The output short-circuit current of the CR-TENG. (c) The transferred charge of the CR-TENG under condition of the short-circuit. (d) Output current and instantaneous power of the CR-TENG with different load resistances. (e) Current density and power density of the CR-TENG with different load resistances. (f) The charging curves of the CR-TENG with different capacitance by through a bridge rectifier. Inset: circuit diagram of the charging.

that the nanofibers are straightened and spindly. So that, the experimental results prove that the EBS system has better practicability and reliability, with its fast, efficiency and diameter size is consistent with the need of industry production.

2.5. Applications of the prepared polymer nanofiber membrane

To investigate the triboelectric performance of prepared polymer nanofiber membranes, a contact-separation mode TENG was fabricated with the contacting area of 5 cm \times 5 cm. The nanofiber membranes and polytetrafluoroethylene (PTFE) film serve as triboelectric layers of the TENG, Cu foils serves as the electrode connected with the external load, they were attached the acrylic substrate by double-sided adhesive, respectively. The experimental testing apparatus for the TENG is shown in Fig. 5a, a linear motor was used to control the contact frequency, displacement and produce the uniform contact. The TENG's structure and digital images are illustrated in Fig. 5b, its working principle and charge distributions is based on the Z. L. Wang's contact electrification which consists of "four-cycle" operation [43–45], as shown in Fig. 5c. The electrical output measurements of the TENG, which were carried out at the conditions of 1 Hz contact frequency and 20 mm spacer distance, digital photographs of the testing process are shown in Fig. 5d. The output Voc of PEO, PAV and PVA nanofiber membranes were measured to be ~58.5 V, ~57.4 V and ~52.4 V, as shown in Fig. 5e. The output I_{sc} of PEO, PAV and PVA nanofiber membranes were measured to be ~6.81 μ A, ~6.89 μ A and ~5.03 μ A, as shown in Fig. 5f. The ΔQ_{sc} of PEO, PAV and PVA nanofiber membranes were measured to be ~34.0 nC, ~34.6 nC and ~30.5 nC, as shown in Fig. 5g. In addition, as an example of the PEO nanofiber membrane, the output V_{oc} , I_{sc} and ΔQ_{sc} are nearly 1.6, 1.5, and 1.7 times higher than the commercial PEO film (by tape-casting process, the thickness is nearly ~40 μ m), as shown in Fig. S8. Moreover, the results indicated that these of the produced membranes had reached a new level in just a case of a few microns thickness, which can also be used to power-supplying for dozens of green LED lamp beads directly, as shown in Fig. 5h and Movie S4. As we can see that, the fabricated nanofiber membranes by the EBS system has a positive effect on the TENG's electric output, that due to the unique nano-micro structure of nanofibers, which implies that the nanofiber membranes prepared by the EBS is comparable in quality to commercial processing technologies. Further, the CR-TENG made it possible to harvest various kinds of mechanical energy in our living environment to achieve a self-powered EBS system.



Fig. 4. The charging characteristic of the boosting circuit and the properties of the produced nanofiber membranes. (a) Working scenario of the boosting circuit. (b) The circuitry principle of the boosting circuit. (c) Digital images of the boosting circuit. (d) The high-voltage values of the boosting circuit with different amplification multiple at capacitance of 47 nF. (e) The thickness of the produced PEO, PAN and PVA nanofiber membranes. (f) and (i) The SEM images of the PEO nanofibers. (g) and (j) The SEM images of the PAN nanofibers. (h) and (k) The SEM images of the PVA nanofibers.

3. Conclusions

In summary, we developed an innovative EBS methodology based on a CR-TENG, that is fast, efficient, lower high-voltage and cost-effective for the fabrication of polymer nanofiber membranes. The CR-TENG serves as both a high-voltage source and as a receiver, it gave a stabilized elecric output that the I_{sc} and ΔQ_{sc} are ~75 μ A and ~0.78 μ C, and the σ reaches a maximum of ~ 2.23 W/m², respectively. Combined with assisted blowing technology, we have successfully achieved in driven the EBS system by a voltage 6250 V, which has saved more than 21% of highvoltage consumption. A test has proven that the thickness of produced nanofiber membranes had reached several microns level at manufacturing time within 5 s, that productivity is obviously increased compared with the electro-spinning, and the diameter size of nanofibers has significantly decreased compared to the solution blowing spinning. It overcame the disadvantages of solution blowing spinning and electro-spinning technologies, realized to efficiency, quality and controllability at the function of the CR-TENG's high-voltage electric field. Moreover, the results indicated that these of the produced membranes had reached a new level in just a case of a few microns thickness, take the PEO nanofiber membrane for example, the output V_{oc} , I_{sc} and ΔQ_{sc} are nearly 1.6, 1.5, and 1.7 times higher than commercial films, which can quite easily be used to power-supplying for dozens of green LED lamp beads directly, which verifies the the feasibility and effective of the EBS system. This work achieve combination of assisted blowing and TENG for the first time, give a new insight into the future spinning technologies suitable for the commercialization.

4. Material and methods

4.1. The fabrication of the EBS system based on CR-TENG

This innovative electro-blown spinning (EBS) methodology was fabricated by combined with assisted blowing and TENG technol-



Fig. 5. The triboelectric properties of the produced nanofiber membranes. (a) Testing scenarios of contact-separation mode TENG. (b) The structure and digital images of the TENG based on nanofiber membrane. (c) Working principle and charge distribution characteristics of the TENG. (d) Digital images showing the testing process of the TENG from separation to contact. (e), (f) and (g) The open circuit voltage, short-circuit current and transfer charge of the TENG with PEO, PAN and PVA nanofiber membranes (the size of 5×5 cm). (h) Digital images shows that the TENG based on the nanofiber membranes be applied in low-power LED bulbs.

ogy, which composed of a cylindrical rotating triboelectric nanogenerator (CR-TENG) unit, a matched boosting circuit and pneumatic system (including microinjection pump, an air compressor, a coaxial spinneret, pipelines) and protective covers. Fig. S1 shows the part names of the CR-TENG and its digital images in detail. In this experiment, the freestanding mode CR-TENG was composed of a inside stator, a outside rotor and supporting frames. The device which a size of ~70 mm (outer diameter) \times ~245 (length) mm of the stator and \times a size of ~60 mm (outer diameter) \times 245 (length) mm of the rotor in experiments, which the substrates are the acrylic cylinder with 3 mm thick. The schematic diagram was shown in Fig. 2b and c, for the stator part, in accordance with the order from the outside-in that is consists of PI triboelectic-layer (~60 μ m thick), Cu foil (~20 μ m thick) and acrylic hollow tube (~3 mm thick) fixed on a frame, which Cu foil serves as the back electrode of the CR-TENG. For the rotor part, two Cu foils are equispaced fixed on the inner surface of acrylic hollow tube, play dual roles as a sliding triboelectic-layer and as a electrode. Finally, the stator and rotor are installed onto self-developed fixture by scaffoldings and bearings, with the double-sided foam layer (~2 mm thick) attached onto outer surface of the central stator as a buffer to ensure intimate contact for each other. The boosting circuit is consists of multiple capacitors and diodes for this system to get enough operating voltages [30,38,39], which the high voltage ceramic capacitors are 3 kV-473 and the high voltage diodes is 2 kV-0.5 A (**Fig. S2** e and f).

4.2. Electrical measurements

For investigate the output performance of the CR-TENG quantitatively, a rotary motor was utilized in the whole testing and spinning process with a speed of 400 rpm (nearly ~13 Hz frequency). Electrical outputs were measured by an electrometer (Keithley voltage preamplifier, 6514), a data acquisition card and oscilloscope (Agilent, DSO-X 2014A). The software platform is constructed based on LabVIEW, which can realize real-time data acquisition

control and analysis. The high-voltage range of the boosting circuit was measured by a noncontact electrostatic probe (Trek-347). Numerical simulation steps, the potential distribution in the CR-TENG was calculated from a finite-element simulation using COM-SOL software.

4.3. Fabrication process of nanofiber membranes by the EBS system

Firstly, three solutions of PEO, PAN and PVA were prepared by mixing their pure polymers with different dispersions, as follow: pure PEO (8 wt%) with deionized water (92 wt%), pure PVA (8 wt%) with deionized water (92 wt%), pure PAN (10 wt%) with dimethylformamide (DMF, 90 wt%). These mixed solutions (10 ml per sample) were quickly stirred by a magnetic stirrer for 30 min separately and let stand for 15 min, the objective is that to obtain well-proportioned and stable sample solutions, as shown in Fig. S4. Then, the mixed solution was loaded in a syringe of 10 mL with a coaxial spinneret directly, which was connected to the positive electrode of the high-voltage source. The mixed solution was pumped out of the needle tip using a microinjection pump with the airflow loading pressure of about ~1.5 psi, with the injection rate of PVA, PEO and PAN solutions is 4.8 mL/h,4.5 mL/h and 4.5 mL/h, respectively. A piece of aluminum foil was connected to the negative electrode of the high-voltage source, and fixed on stator of the CR-TENG for the collection of polymer nanofibers, with the coaxial spinneret to receiver distance of 15 cm (Fig. S5a and c). During spinning of polymer nanofiber membraness, the temperature and relative humidity of electrospinning process will be maintained at between 25 and 30 Degrees Celsius and over ~70% by an electric heating lamp and dehumidifier, respectively. A contact-separation mode TENG based on the prepared polymer nanofiber membranes was fabricated, with the contacting area of 5 cm \times 5 cm. The nanofiber membranes and polytetrafluoroethylene (PTFE, ~60 μ m thick) film serve as triboelectric layers of the TENG, Cu films (~80 μ m thick) serves as the electrode connected with the external load, they were attached the acrylic substrate (~3 mm thick) by double-sided adhesive, respectively.

4.4. Characterization

The morphology of the prepared PVA, PEO and PAN polymer nanofiber membranes were characterized by a Hitachi SU8020 field emission scanning electron microscope (SEM). The thickness and roughness of the nanofiber membranes are measured by the step profiler.

Author statement

Yuntao Liu had made substantial contributions to the Acquisition and Interpretation of Data for the work; Jing Wen had made substantial contributions to the Numerical Simulation of Data and Validation for the work; Baodong Chen had made substantial contributions to the Writing-Original Draft Preparation and Drawing of the work; Mingli Zheng had made substantial contributions to the Investigation of the work; Di Liu had made substantial contributions to the Hardware of Electronic Circuits for the work; Yuan Liu had made substantial contributions to the Data Curation and Validation of the work; Wei Tang had made substantial contributions to the Visualization and Investigation of the work; Jun Liu had made substantial contributions to the Data Analysis of the work.

Ding Nan had made substantial contributions to revised it critically for important intellectual content, Supervision and Interpretation of the work; Zhong Lin Wang had made substantial contributions to the Conceptualization and Methodology, Writing- Reviewing and Editing of the work.

We agree to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved.

We have approved the final version to be published.

All persons who have made substantial contributions to the work reported in the manuscript, including those who provided editing and writing assistance but who are not authors, are named in the Acknowledgments section of the manuscript and have given their written permission to be named. If the manuscript does not include Acknowledgments, it is because the authors have not received substantial contributions from nonauthors.

Declaration of Competing Interest

The authors declared that they have no conflicts of interest to this work.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.apmt.2020.100631.

Appendix A. Supplementary data

Supplementary material related to this article can be found,in the online version

References

- [1] S. Zhang, Nat. Biotechnol. 21 (2003) 1171.
- [2] T.P. Knowles, A.W. Fitzpatrick, S. Meehan, H. R.Mott, M. Vendruscolo, C.M. Dobson, Science 318 (2007) 1900.
- X. Zong, K. Kim, D. Fang, S. Ran, B.S Hsiao, B. Chu, Polymer 43 (2002) 4403.
- [4] Paul Smith, Piet J. Lemstra, J. Mater. Sci. 15 (1980) 505.
- [5] J. Kayser, R.L. Shambaugh, Polym. Eng. Sci. 30 (1990) 1237.
- [6] T.C. Lin, G. Krishnaswamy, D.S. Chi, Clin. Mol. Allergy 6 (2008) 3.
- [7] Y. Xia, P. Yang, Y. Sun, Y. Wu, B. Mayers, B. Gates, Adv. Mater. 15 (2003) 353.
- [8] Z.M. Huang, Y.Z. Zhang, M. Kotaki, S. Ramakrishna, Compos. Sci. Technol. 63 (2003) 2223.
- [9] E.S. Medeiros, G.M. Glenn, A.P. Klamczynski, W.J. Orts, L.H.C. Mattoso, J. Appl. Polym, Sci. 113 (2009) 2322.
- [10] F.R. Fan, Z.Q. Tian, Z.L. Wang, Nano Energy 1 (2012) 328.
- [11] Z.L. Wang, Nano Energy 58 (2019) 669.
- [12] Z.L. Wang, Nano Energy (2019), doi:10.1016/j.nanoen.2019.104272.
- [13] Z.L. Wang, A.C. Wang, Mater. Today (2019), doi:10.1016/j.mattod.2019.05.016.
 [14] J.J. Shao, T. Jiang, W. Tang, L. Xu, T.W. Kim, C.X. Wu, X.Y. Chen, B.D. Chen, T.X. Xiao, Y. Bai, Z.L. Wang, Nano Energy 48 (2018) 292.
- [15] B. Chen, W. Tang, C. Zhang, L. Xu, L. Zhu, L. Yang, C. He, J. Chen, L. Liu, T. Zhou, Z.L. Wang, Nano Res. 11 (2018) 3096.
- [16] Z.L. Wang, Mater. Today 7 (2017) 845.
- [17] Z.L. Wang, T. Jiang, L. Xu, Nano Energy 39 (2017) 9.
- [18] Z.L. Wang, ACS Nano 7 (2013) 9533.
- [19] J. Chen, Z.L. Wang, Joule 1 (2017) 480.
- [20] Z.L. Wang, J. Chen, L. Lin, Energy Environ. Sci. 8 (2015) 2250.
- [21] J. Chen, Y. Huang, N. Zhang, H.Y. Zou, R.Y. Liu, C.Y. Tao, Nat. Energy 1 (2016) 16138

- [22] J. Chen, B. Chen, K. Han, W. Tang, Z.L. Wang, Adv. Mater. Technol. (2019) 1900337.
- [23] W. Zhong, L. Xu, X. Yang, W. Tang, J. Shao, B. Chen, Z.L. Wang, Nanoscale 11 (2019) 7199.
- [24] J. Wen, B. Chen, W. Tang, T. Jiang, L. Zhu, L. Xu, J. Chen, J. Shao, K. Han, W. Ma, Z.L. Wang, Adv. Energy Mater. (2018) 1801898. [25] J. Liu, T. Jiang, X. Li, Z.L. Wang, Nanotechnology 30 (2019).
- [26] G. Liu, J. Nie, C. Han, T. Jiang, Z. Yang, Y. Pang, L. Xu, T. Guo, T. Bu, C. Zhang, Z.L. Wang, ACS Appl. Mater. Interfaces 10 (2018) 7126.
- [27] J. Cheng, W. Ding, Y. Zi, Y. Lu, L. Ji, Liu F, C. Wu, Z.L. Wang, Nat. Commun. 9 (2018) 3733.
- [28] W. Tang, B. Chen, Z.L. Wang, Adv. Funct. Mater. (2019) 1901069.
- [29] H. Guo, X. Pu, J. Chen, Y. Meng, M.-H. Yeh, G. Liu, Q. Tang, B. Chen, D. Liu, S. Qi, [29] H. Guo, X. Pu, J. Chen, Y. Meng, M.-H. Yell, G. Liu, Q. Jang, D. Chen, D. Liu, S. Q., C. Wu, C. Hu, J. Wang, Z.L. Wang, Sci. Robot. 20 (2018) 2516.
 [30] C. Li, Y. Yin, B. Wang, Zhou T, Wang J, Luo J, Tang W, R. Cao, Yuan Z, N. Li, X. Du, C. Wang, Zhao S, Liu Y, Z.L. Wang, ACS Nano 11 (2017) 10439.
 [31] H. Zou, Y. Zhang, L. Guo, P. Wang, X. He, G. Dai, H. Zheng, C. Chen, A.C. Wang, C. Yu, Zh. Wang, Net Commun. 10 (2019) 1427.
- C. Xu, Z.L. Wang, Nat. Commun. 10 (2019) 1427. [32] C. He, C. Han, G. Gu, T. Jiang, B. Chen, Z. Gao, Z.L. Wang, Adv. Energy Mater. 7
- (2017) 1700644.

- [33] G. Zhu, B. Peng, J. Chen, Q.S. Jing, Z.L. Wang, Nano Energy 14 (2015) 126.
- [34] Q. Zhang, Q. Liang, Q. Liao, F. Yi, X. Zheng, M.Y. Ma, F.F. Gao, Y. Zhang, Adv. Mater. 29 (2017) 1606703.
- [35] B. Chen, W. Tang, C. He, C. Deng, L. Yang, L. Zhu, J. Chen, J. Shao, L. Liu, Z.L. Wang, Mater. Today 21 (2018) 88.
- [36] J.H. Wang, H. Wang, N. V.Thakor, C.K. Lee, ACS Nano 13 (2019) 3589.
 [37] Z. Wen, H.Y. Guo, Y.L. Zi, M.H. Yeh, X. Wang, J.N. Deng, J. Wang, S.M. Li, C.G. Hu, L.P. Zhu, Z.L. Wang, ACS Nano 10 (2016) 6526.
- [38] L. Xu, T. Bu, X. Yang, C. Zhang, Z.L. Wang, Nano Energy 49 (2018) 625.
 [39] J. Nie, Z. Ren, J. Shao, C. Deng, L. Xu, X. Chen, M. Li, Z.L. Wang, ACS Nano (2018) 1491.
- [40] D. Li, Y. Xia, Adv. Mater. 16 (2004) 1151.
- [41] N. Bhardwaj, S.C. Kundu, Biotech. Adv. 28 (2010) 325.
- [41] IN. DHATUWAJ, S.C. KUNGU, BIOTECH. Adv. 28 (2010) 325.
 [42] KENTY, C.T. Lim, Prog. Polym. Sci. 70 (2017) 1.
 [43] X. Yin, D. Liu, L. Zhou, X. Li, C. Zhang, P. Cheng, H. Guo, W. Song, J. Wang, Z.L. Wang, ACS Nano 13 (2019) 698.
 [44] P. Cheng, W. Tarra, T. Bia, A. El and K. Tarra, J. K. Kang, J. K. Shan, J. K. Shan
- [44] B. Chen, W. Tang, T. Jiang, L. Zhu, X. Chen, C. He, L. Xu, H. Guo, P. Lin, D. Li, J. Shao, Z.L. Wang, Nano Energy 45 (2018) 380. [45] S. Wang, Y. Xie, S. Niu, L. Lin, Z.L. Wang, Adv. Mater. 26 (2014) 2818.