The effect of reciprocating motion of drum collector on electrospun PVDF nanofiber for energy harvesting application

WCMNM 2020

Mukesh Kumar[1], Poonam Kumari[2]

[1,2] *Department of Mechanical Engineering, Indian Institute of Technology Guwahati, Guwahati, India*

Abstract

The energy harvesting research community has been concentrating on this topic for the past few years. This paper describes in detail the fabrication and characterization of piezoelectric polymer-based poly(vinylidene fluoride) PVDF nanofiber, which was synthesized using the far-field electrospinning method. The electrospun nanofibers were prepared on the drum collector with no reciprocating, slow reciprocating, medium reciprocating, and fast reciprocating motion, respectively. During the deposition process, the collector was given 2 cm to move back and forth. Field emission scanning electron microscopy (FESEM), X-ray diffraction (XRD), and Fourier transform infrared spectroscopy (FTIR) was used to characterize the electrospun nanofiber. The open-circuit voltage was measured by a digital oscilloscope (DSO) under environmental conditions. The nanofiber webs were used as an active layer to create piezoelectric nanogenerator devices (PENG) as energy harvesting devices. The PENG was subjected to gentle finger tapping to apply external loading. In the energy harvesting device, piezoelectric output was enhanced as high as 272 mV at medium reciprocation, compared with 152 mV for the samples made on drum collectors with fast reciprocation. We believe that this work may promote the fabrication of small-size wearable self-powered electrical devices and systems.

Keywords: PVDF, Reciprocating motion, Energy harvesting, Electrospinning

1. Introduction

Energy scavenging from waste energy of surroundings or human activity has been attractive to the research community in recent times [1-6]. Supplying power to the mobile electronic device, wireless sensors, watches, capacitors, light-emitting diodes, and many others with conventional batteries is a great hurdle owing to replace or recharge them in the finite time interval [7-11]. In another way, if the small device can be operated through self-powered mode by using the energy available in the surrounding environments, then that would be a stable solution for replacing the battery. Hence, scavenging energy from the surroundings becomes a significant idea for making self-powered electronic devices. For this, the Piezoelectric nanogenerator (PENG) can be the alternative power source as vibration is available everywhere [12-15]. The PENG has been used to harvest the energy from different sources of mechanical vibration such as air blow, vibration (acoustic and ultrasonic wave), hydraulic forces (sea wave, blood flow, and waterfall), friction, and human activity (tapping, bending, twisting, stretching, clapping, breathing, etc.) [16-17]. Piezoelectric polymers have been employed for energy harvesting, artificial skin, and sensor [18-20].

However, from the material point of view, PVDF is a suitable piezoelectric polymer to fabricate as an sensing layer for the fabrication of piezoelectric nanogenerator (PENG) because it is having lightweight, flexible, cost-effective, and very easy to work with the electrospinning process as compared to the inorganic piezoelectric materials. PVDF exhibits more piezoelectric coefficient among the polymer [21-23]. PVDF is semi-crystalline and possesses five different crystalline phases (α, β, γ, δ, and ε), among which the nonpolar α phase is the most available form [24]. Moreover, the stretching and poling of the piezoelectric polymer in the electrospinning process at high voltage can make the dipole of PVDF polymer chains in a specific direction, resulting in a transformation from α to β crystalline phase [25]. The electroactive β phase is more desirable for mechanical energy harvesting. There are many methods to enhance the fraction of the β phase such as (electrical poling, stretching, heat treatment, etc.). But, electrospinning naturally increases the β phase during fiber fabrication because it operates at high voltage [26]. In this paper, the synthesis of electrospun PVDF nanofiber is reported. The fiber fabrication is carried out on a drum collector with or without reciprocating motion. The surface morphology, crystal phases, and electrical responses of the PVDF nanofiber were studied. The PENG was fabricated for mechanical energy harvesting applications.

2. Experimental

2.1. Materials

PVDF piezoelectric polymer was bought from Sigma Aldrich for the synthesis of electrospun nanofiber. The polymer has a molecular weight (M_{w} –

5,30,000) and vapor pressure of 15 mm of Hg at 32°C. N, N-Dimethylformamide (DMF) used as solvent was procured from Sigma Aldrich. All chemicals were used as received in the electrospinning process.

2.2. Synthesis of PVDF nanofiber

Electrospinning process was performed with the nanofiber unit of electrospinning made by E-Spin Nanotech Pvt. Ltd. (SIDBI Incubation Center, IIT Kanpur, India). The solution was obtained by addition of 16% w/v concentration of PVDF pellet in DMF solvent, which was placed in the beaker. The solution was stirred for 300 minutes at 35°C and 500 r.p.m. then, sonication was carried out for an hour to remove the bubbles. Again, the solution was placed on a stirrer for 30 minutes to make it a homogeneous solution to be used in the electrospinning process. The homogeneous solution was later filled in the plastic syringe with a diameter of 13.08 cm. The electrospinning parameter was applied as follows: The applied voltage was 14 kV, the distance was 11 cm, the drum collector was set at 1300 r.p.m, the flow rate was 9µl/min, the chamber temperature was at 30°C. All parameters were kept the same for the nanofiber, which has been deposited on the drum collector. The fibers were deposited on drum collector, drum collector with slow reciprocating, drum collector with medium reciprocating, and drum collector with fast reciprocating. All fibers were fabricated for a constant time of 70 minutes.

2.3. Fabrication of PENG devices

The PENG device was made using Electrospun nanofiber and electrodes. PVDF non-woven web was used as an active layer, aluminum and copper foil were taken as an electrode. The self-powered PENG was assembled with a small PVDF nanofiber with a functional area of 4 cm^2. The aluminum substrate attached with the electrospun nanofiber was treated as the bottom electrode and copper foil as the top electrode. Both electrodes were utilized as a part of an electrical circuit to find the piezoelectric output of PENG devices. Polyethylene terephthalate (PET) film was wrapped over the PENG device to protect it from the surrounding disturbance.

2.4. Material characterization

The surface morphology of the electrospun PVDF nanofiber was examined by FESEM (FESEM, model: JSM -7610F, JEOL Co.) test. The diameter distribution of the electrospun nanofiber was calculated using image analysis software. The thickness of the film was measured using a digital micrometer (Mitutoyo 293-240-30 micrometer). The XRD (model: Smartlab, maker: Rigaku Technologies, Japan) test was conducted on a diffractometer using Cu radiation 1.54 Å to confirm the crystalline structure of the electrospun fiber. The samples were scanned from 5° to 50° with a speed of 5°/minute. FTIR (model: Spectrum two, make: PerkinElmer, Singapore) test was performed using Bruker spectrometer in a range of 400-4000 cm^{-1} in attenuated total reflection (ATR) mode. The open-circuit voltage was recorded after finger tapping on PENG devices using a digital oscilloscope (GwINSTEK GDS-1102-U). The short circuit current was measured when the external load resistance was connected in parallel with an electrical circuit. The PENG devices were subjected to finger tapping for sensing the piezoelectric output.

3. Results and discussion

3.1. FESEM analysis of PVDF nanofiber

The electrospun nanofiber was deposited on different collectors such as drum collector with no, slow, medium, and fast reciprocating motion. The surface morphology and diameter variation of the PVDF non-woven web are shown in Figures 1& 2. The average diameter for the fabricated nanofiber was measured using the FESEM image. The diameter of the samples was found to be 144.8, 155.58, 132.86, and 143.86 nm, respectively. The average diameter of nanofiber webs is changed with the oscillation motion of the drum collector. Most of the nanofibers of the sample can be seen from 50 to 200 nm (Figure 2).

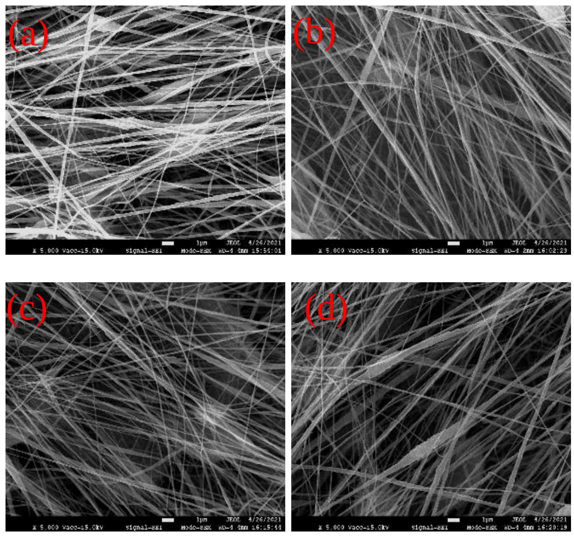

Fig. 1. FESEM image of PVDF nanofiber at different conditions (a) drum,(b) slow reciprocation motion with drum, (c) medium reciprocation motion with drum, (d) fast reciprocation motion with drum

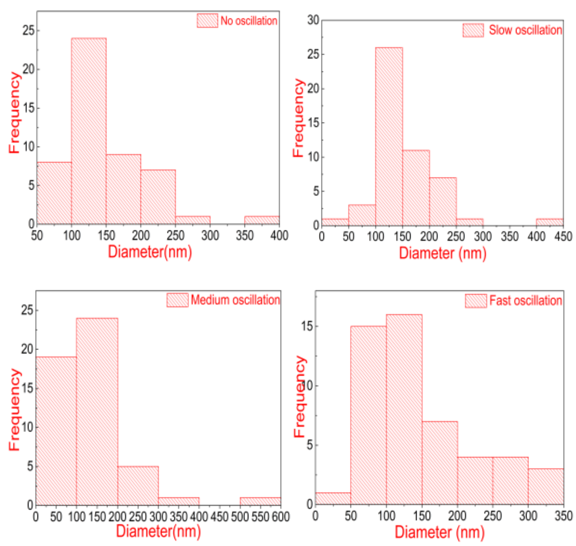

Fig. 2. Histogram of PVDF nanofiber diameter distribution

3.2. XRD analysis

The XRD test was carried out to confirm the crystalline structure of PVDF nanofiber. The XRD results unveil that the PVDF beta phase is found at 2θ = 20.18°, as shown in Figure 3 [27]. The strong peaks have been observed with the film fabricated at no reciprocation and medium reciprocating of the collector. Weak peaks are obtained for the samples that are synthesized at slow and fast oscillation with the drum collector.

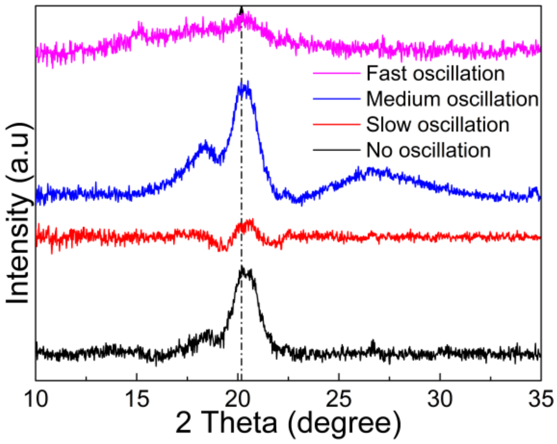

Fig. 3. XRD pattern of synthesized PVDF nanofiber

3.3. FTIR analysis

The FTIR test was performed for the fabricated samples to confirm the presence of the electroactive beta phase of the prepared PVDF nanofiber. The test has been successfully conducted in attenuated total reflection (ATR) mode, as shown in Figure 4. The vibration peaks for the electroactive beta phase of the PVDF nanofiber is found at 840, 877, 1177.40, 1276.93, and 1400 cm^{-1} [28].

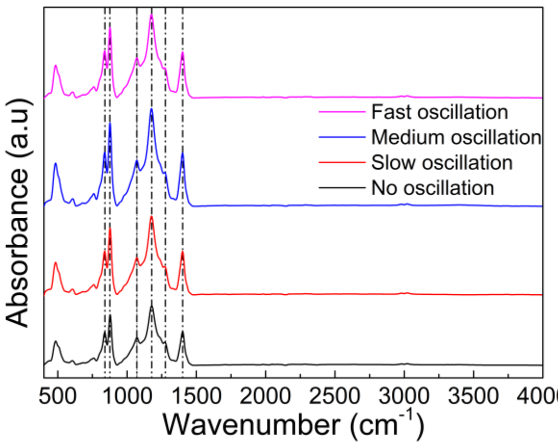

Fig. 4. FTIR spectra showing for the synthesized PVDF nanofiber

3.4. Piezoelectric output of PVDF nanofiber

The PVDF electrospun nanofiber-based piezoelectric nanogenerator is made for the energy harvesting application. A small part of the PVDF nanofiber web with an effective area of 4 cm^2 was positioned between two electrodes and then copper wires were added to the electrode for electrical connection. The PENG device was covered with PET film to make it safe from external noises and weather conditions. The PENG based on all fabricated fibers were tested at the same repeated compressive impacts (finger tapping) at atmospheric condition (humidity of 75% and temperature of 27°C). All PENG devices were subjected to the same loading and weather condition. The more piezoelectric output is measured for the sample, which is fabricated at medium reciprocating motion with the drum collector. The piezoelectric output of all the samples is shown in Table 1.

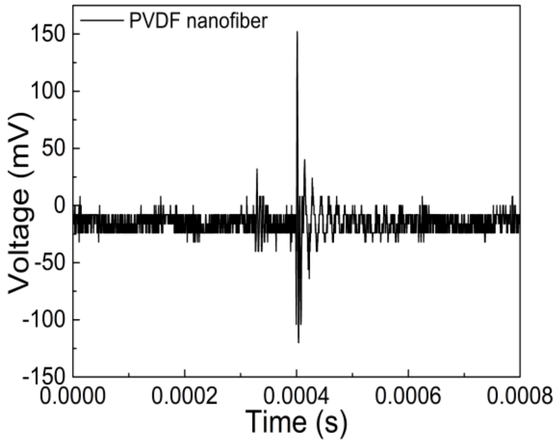

Fig. 5. The voltage output developed by the piezoelectric device (nanofiber made under the medium reciprocating motion of the drum collector)

Table 1 Piezoelectric output for the fabricated sample at different conditions

Sample No.	Drum condition	Voltage (mV)	PENG
1	No reciprocation	208	1
2	Slow reciprocation	184	2
3	Medium reciprocation	272	3
4	Fast reciprocation	152	4

4. Conclusions

The electrospun PVDF nanofibers were successfully synthesized with the different conditions of the drum collector using electrospinning method. The nanofiber diameter was obtained below 160 nm. The strong peak intensity was formed for the nanofiber at no reciprocation and medium reciprocation of drum collector The XRD and FTIR test has confirmed the presence of electroactive β phase in electrospun

PVDF nanofiber. The effect of reciprocating motion with the cylindrical drum collector has been studied on surface morphology, crystal structure, and the voltage output of PENG devices.

Acknowledgments

The authors would like to acknowledge the NEWGEN IEDC for giving the fund under the project IEDC/2019-20/PK2 for buying the raw material and equipment related to it. The authors also wish to thank CIF (IIT Guwahati) for availing the facility for FESEM, XRD, and FTIR testing.

References

[1] Y.Z. et al., "High output piezoelectric nanocomposite generators composed of oriented BaTiO3 NPs@ PVDF." *Nano Energy* 11 (2015): 719-727.
[2] T.H. et al., "Human walking-driven wearable all-fiber triboelectric nanogenerator containing electrospun polyvinylidene fluoride piezoelectric nanofibers." *Nano Energy* 14 (2015): 226-235.
[3] V.N. et al., "Environmental effects on nanogenerators." *Nano Energy* 14 (2015): 49-61.
[4] C.D. et al., "Recent progress in flexible and stretchable piezoelectric devices for mechanical energy harvesting, sensing and actuation." *Extreme mechanics letters* 9 (2016): 269-281.
[5] C.D. et al., "Energy harvesting from the animal/human body for self-powered electronics." *Annual review of biomedical engineering* 19 (2017): 85-108.
[6] J.P. et al., "Smart sensors/actuators for biomedical applications." *Measurement* 45.7 (2012): 1675-1688.
[7] Z.L. Wang et al., "Self-Powered Nanosensors: Self-Powered Nanosensors and Nanosystems (Adv. Mater. 2/2012)." *Advanced Materials* 24.2 (2012): 279-279.
[8] V.B. et al., "Energy harvesting for assistive and mobile applications." *Energy Science & Engineering* 3.3 (2015): 153-173.
[9] S.R. Anton et al., "A review of power harvesting using piezoelectric materials (2003–2006)." *Smart Materials and Structures* 16.3 (2007): R1.
[10] J.L. et al., "Unlocking the potential of cation-disordered oxides for rechargeable lithium batteries." *Science* 343.6170 (2014): 519-522.
[11] B.K. et al., "Battery materials for ultrafast charging and discharging." *Nature* 458.7235 (2009): 190-193.
[12] G.N. Schädli et al., Pratsinis. "Nanogenerator power output: influence of particle size and crystallinity of BaTiO3." *Nanotechnology* 28.27 (2017): 275705.
[13] C.R. Bowen et al., "Piezoelectric and ferroelectric materials and structures for energy harvesting applications." *Energy & Environmental Science* 7.1 (2014): 25-44.
[14] C.R. Bowen et al., "Energy harvesting technologies for tire pressure monitoring systems." *Advanced Energy Materials* 5.7 (2015): 1401787.
[15] X.W. "Piezoelectric nanogenerators—Harvesting ambient mechanical energy at the nanometer scale." *Nano Energy* 1.1 (2012): 13-24.
[16] A.S. et al., "An effective electrical throughput from PANI supplement ZnS nanorods and PDMS-based flexible piezoelectric nanogenerator for power up portable electronic devices: an alternative of MWCNT filler." *ACS applied materials & interfaces* 7.34 (2015): 19091-19097.
[17] M.M. Alam et al., "Native cellulose microfiber-based hybrid piezoelectric generator for mechanical energy harvesting utility." *ACS applied materials & interfaces* 8.3 (2016): 1555-1558.
[18] M.S. Kim et al., "A dome-shaped piezoelectric tactile sensor arrays fabricated by an air inflation technique." *Sensors and Actuators A: Physical* 212 (2014): 151-158.
[19] L.T. Beringer et al., "An electrospun PVDF-TrFe fiber sensor platform for biological applications." *Sensors and Actuators A: Physical* 222 (2015): 293-300.
[20] H.M. et al., "A flexible pressure-sensitive array based on soft substrate." *Sensors and Actuators A: Physical* 222 (2015): 80-86.
[21] M.M. Alam et al., "Improved dielectric constant and breakdown strength of γ-phase dominant super toughened polyvinylidene fluoride/TiO2 nanocomposite film: an excellent material for energy storage applications and piezoelectric throughput." *Nanotechnology* 28.1 (2016): 015503.
[22] J.L. et al., "Electrical energy storage in ferroelectric polymer nanocomposites containing surface-functionalized BaTiO3 nanoparticles." *Chemistry of Materials* 20.20 (2008): 6304-6306.
[23] H.K. "The piezoelectricity of poly (vinylidene fluoride)." *Japanese journal of applied physics* 8.7 (1969): 975.
[24] P.M. et al., Lanceros-Mendez. "Electroactive phases of poly (vinylidene fluoride): Determination, processing and applications." *Progress in polymer science* 39.4 (2014): 683-706.
[25] A.G. et al., "Piezoelectric electrospun nanofibrous materials for self-powering wearable electronic textiles applications." *Journal of Polymer Research* 21.7 (2014): 1-7.
[26] D.M. et al., "Origin of piezoelectricity in an electrospun poly (vinylidene fluoride-trifluoroethylene) nanofiber web-based nanogenerator and nano-pressure sensor." *Macromolecular rapid communications* 32.11 (2011): 831-837.
[27] W.X. et al., "Dependence of dielectric, ferroelectric, and piezoelectric properties on crystalline properties of p (VDF-co-TrFE) copolymers." *Journal of Polymer Science Part B: Polymer Physics* 50.18 (2012): 1271-1276.
[28] D.M. et al., "Bandgap determination of P (VDF-TrFE) copolymer film by electron energy loss spectroscopy." *Bulletin of Materials Science* 33.4 (2010): 457-461.