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Harvesting Raindrop Energy with Piezoelectrics: a Review

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Harvesting vibration energy from piezoelectric material impacted by raindrops has proved to be a promising approach for future applications. A piezoelectric harvester has interesting advantages such as simple structure, easy fabrication, reduced number of components, and direct conversion of vibrations to electrical charge. Extensive research has been carried out and is still underway to explore this technique for practical applications. This review provides a comprehensive picture of global research and development of raindrop energy harvesting using piezoelectric material to enable researchers to determine the direction of further investigation. The work published so far in this area is reviewed and summarized with relevant suggestions for future work. In addition, a brief experiment was carried out to investigate the suitable piezoelectric structure for raindrop energy harvesting. Results showed that the bridge structure generated a higher voltage compared with the cantilever structure.

Key words: PVDF, raindrop energy, vibration, energy conversion, microelectromechanical systems, power generator

INTRODUCTION

In recent years, the demand for self-powered electronic devices such as wireless sensors, industrial automation, and electronic devices has increased rapidly. In most cases, a conventional electrochemical battery is used to power such applications. This kind of battery is no longer appropriate due to shortcomings such as short lifetime, limited power storage, maintenance issues, and large weight and size compared with the device they power. Once the battery is flat, a replacement is required to repower the device.[1] Replacing a battery is problematic because the electronics could fail at any time, and this could become a very expensive task for microelectronic and wireless sensor devices.[2–5] An effective way to overcome such battery changes is to utilize energy from the environment to recharge the battery. The most typical energy harvesting sources are solar energy, wind energy, thermal energy, hydroelectricity, and vibration energy.[6–12] Amongst these, harvesting of vibration energy has the advantage of being clean and stable.[3] Recent solutions to convert kinetic energy into electrical energy have been mainly accomplished through the use of electromagnetic,[13–15] electrostatic,[16,17] and piezoelectric[18–22] methods. Comparing the methods used, the piezoelectric approach is the simplest, offering direct conversion of vibration energy into electrical energy without an external power supply or amplifier. Piezoelectric materials are widely available in many forms, including single crystal, piezoceramic, thin film, screen-printable thick film using piezoceramic powder, and polymeric material.[23] The topic of energy harvesting by the piezoelectric method has attracted great interest in recent years.[24–28] The most common types of piezoelectric material being used are polyvinylidene fluoride (PVDF)[29–32] and lead zirconate titanate (PZT).[33–35] Several recent reviews of vibration energy harvesting can be found in Refs. [36–44]; however, an exclusive survey on droplet energy harvesting by using piezoelectric

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material is still lacking. This paper presents a detailed review of raindrop energy harvesting. "Conceptual Background" section presents the conceptual background of this kind of vibration-based energy harvesting. "Review of Piezoelectric Raindrop Energy Harvesting" section discusses ongoing research on raindrop energy harvesting using piezoelectric materials, whereas "Important Parameters for Raindrop Energy Harvesting" section describes some of the important parameters in raindrop energy harvesting. Some preliminary experimental results on this topic are presented in "Preliminary Experimental Results of Raindrop Energy Harvesting" section. "Issues and Challenges" section discusses the issues and challenges in this particular research area. Finally, in "Conclusions" section, the conclusions are drawn.

CONCEPTUAL BACKGROUND

To convert vibration energy into electricity, the piezoelectric method is used. The piezoelectric material will vibrate as a raindrop impacts on it. The vibrating piezoelectric material consequently generates a charge Q. This generated charge is then collected by two electrode plates. Finally, a voltage, U, is created across the electrode plates according to

$$U = Q/C_{\mathrm{piezo}} \tag{1}$$

where the capacitance $C_{\mathrm{piezo}} = \varepsilon_r \varepsilon_0 A/t$, ε_0 is the electrical permittivity in vacuum, ε_r is the relative permittivity of the medium between the electrode plates, A is the electrode area, and t is the separation of the electrode plates.[45] Thus, the generated power can be calculated as

$$P = E/t_{\mathrm{impact}}, \tag{2}$$

where the stored energy $E = C_{\mathrm{piezo}}U^2/2$ and t_{impact} is the period of water droplet impact on the piezoelectric structure.

Since the vibrating piezoelectric material generates an alternating-current (AC) signal whereas most electronic devices need a stabilized direct-current (DC) voltage, an AC to DC full-bridge rectifier is required, followed by a filtering capacitance to smooth the rectified DC voltage. A regulator is located between the filtering capacitance and the battery to regulate the output voltage. This battery could be the power source for an electronic device. The general principle for conversion of mechanical energy to electrical energy using a piezoelectric is shown in Fig. 1.[46–48]

The output power of a piezoelectric transducer is affected by various factors. During impact, not all the generated energy is converted into charge, as a result of damping effects. During the process of conversion, energy losses via heat dissipation must be considered. Finally, the output power is given by

$$P_{\mathrm{out}} = \eta_{\mathrm{impact}}\eta_{\mathrm{piezoelectric}}\eta_{\mathrm{rectify}}P_{\mathrm{max}}, \tag{3}$$

where P_{max} and P_{out} are the output power with and without consideration of energy loss, and η_{impact}, $\eta_{\mathrm{piezoelectric}}$, and η_{rectify} are the efficiencies of the collision, the piezoelectric mechanism, and the power conversion, respectively.

REVIEW OF PIEZOELECTRIC RAINDROP ENERGY HARVESTING

Piezoelectric materials have been used to convert mechanical energy into electrical energy for decades. Most previous studies on piezoelectric energy harvesting have concentrated on machine, human, and other ambient sources of vibration. To date, a very limited number of studies have been conducted on energy harvesting from raindrops using piezoelectric technology. This section discusses ongoing research on raindrop energy harvesting using piezoelectric materials.

Guigon et al.[49,50] produced a system that harvested vibration energy from a piezoelectric material (PVDF) impacted by a falling droplet. The material was selected for its flexibility, smoothness, and lead-free nature. The system worked with water droplets created by a syringe pump with diameter ranging from 1 mm to 5 mm. The results showed that it was possible to recover up to 12 mW from downpour drops. In their study, a thickness of 25 μm monostretched PVDF material with a piezoelectric strain coefficient d_{31} of 15 pC N^{-1} was much more effective than a thickness of 9 μm of bistretched PVDF material with a piezoelectric strain coefficient d_{31} of 5 pC N^{-1}. They found that droplets dropped from a low height resulted in electrical energy proportional to the square of the drop's mechanical energy, whereas the voltage and mechanical energy were directly proportional to each other. The recoverable energy depended directly on the size of the raindrop and its falling velocity.

Sahaya Grinspan and Gnanamoorthy[51] constructed a system to measure the droplet impact force using piezoelectric technology. It converted the voltage generated by the impact of a droplet on the piezoelectric material to an impact force. In their experiments, they used PVDF film as the piezoelectric material. The film had dimensions of 35 mm × 80 mm × 52 μm, being sandwiched by two silver electrode plates. The film was attached to a machined aluminum alloy block. A water droplet was produced using a syringe with a flat-tipped needle. The system generated around 0.1 V for a droplet with diameter of 3.57 mm, weighing 23.83 mg, which impacted with a speed of 2.96 m s^{-1} when dropped from a height of 0.45 m, showing an impact force of 0.8 N for 600 μm. They also found that the impact velocity (fall height) strongly influenced the impact force (output voltage).

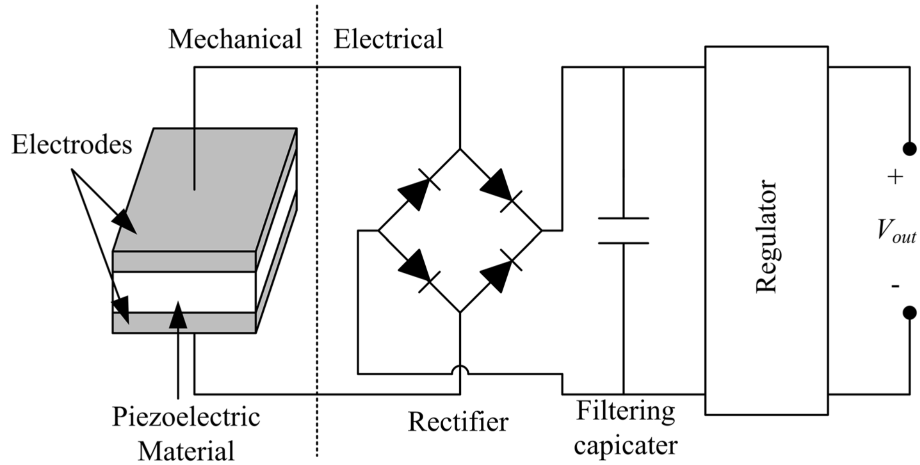

Fig. 1. Piezoelectric energy conversion circuit.

Vatansever et al.[52] investigated raindrop energy harvesting using a cantilever structure. In their work, two kinds of cantilever piezoelectric transducers were compared, namely PVDF and PZT, with dimensions of 16 mm × 4 mm × 0.2 mm. PZT is a ceramic-based piezoelectric material which produces a higher voltage than PVDF-based piezoelectric. However, in the raindrop application, the PZT material generated a relatively lower peak voltage compared with PVDF due to the mass of the water drop, which was insufficient to activate the PZT material. PZT materials are rigid and fragile, which limits the range of their application, whereas PVDF materials provide various advantages such as being lead free, inexpensive, easy to process, lightweight, flexible, and smooth.[49,50,52,53] Results showed that the PVDF material generated a higher peak voltage than PZT when a 50 mg water droplet was released from a height of 1 m and impacted on a 16 mm × 4 mm × 0.2 mm unimorph cantilever. The maximum peak voltage generated by the PVDF cantilever was 12 V, whereas the PZT cantilever generated only 3 V. This showed that PVDF material is suitable for use in piezoelectric raindrop energy harvesting.[52]

However, Ahmad and Jabbour,[54] Alkhaddeim et al.,[55] and Ahmad[56] claimed that PZT material is also suitable for raindrop energy harvesting when using a multimorph cantilever structure. In their studies, the cantilever consisted of five PZT layers stacked on top of one another and a structural shim layer residing under the piezoelectric materials. The system generated a maximum peak voltage of only 0.8 V across an optimum load of 10 kΩ due to the impact of a simulated water droplet from a micropump with mass of 0.23 g falling at 0.22 m s^{-1}.

Valentini et al.[57] utilized poly(methyl methacrylate)/graphene oxide (PMMA/GO) for droplet energy harvesting. Their investigation showed that the PMMA/GO device generated 6 nW when a 5 μg water droplet was released and impacted from a height of 0.2 m.

Viola et al.[58] also compared the output power generated by the impact of droplets from commercial-ready piezoelectric cantilever transducers made of PVDF and PZT materials. The PZT transducer had dimensions of 25.4 mm × 3.81 mm × 0.7874 mm, whereas the PVDF transducer was modified to 3.3 mm wide and 25 mm to 30 mm in length. In this study, three experiments were conducted, comparing a single PZT cantilever transducer, a single PVDF cantilever transducer, and two sets of PVDF transducers arranged in parallel. Loads ranging from 10 kΩ to 470 kΩ were selected for investigation. Their results showed that the PVDF material generated more power than the PZT material. The maximum power, 4.5 μW, was produced by a single PVDF cantilever transducer with a load of 47 kΩ, compared with the two parallel PVDF cantilever transducers. This was due to the parallel cantilever mechanism, which was triggered by consecutive droplets, thus generating delayed oscillating pulses with opposite phase that resulted in a reduction of the voltage at the terminals. On the other hand, the experiments carried out by Oh et al.[59] also showed that the voltage generated was higher for piezoelectric material connected in series compared with parallel.

Lee et al.[60] produced a system that harvested energy from ambient acoustic noise using oscillating droplets. The concept of this system was that it will vibrate and generate electrical charge as a water droplet sitting on a piezoelectric material is excited by an acoustic wave. In their experimental studies, they used a PVDF cantilever structure with dimensions of 73 mm × 15 mm × 0.2 mm. The system generated 72.2 μW with a load of 470 kΩ when actuated by a 6 μL acoustically oscillating droplet, as measured by a full-bridge rectifier. They found that the vibration amplitude of the droplets, the cantilever displacement, and the generated output voltage depended on the applied frequency and were proportional to the droplet size.

Table I. Comparison of potential raindrop energy generators

Researchers	Year	Piezoelectric Material	Vibration Source	Mechanism and Dimensions	Output	Load Impedance
Guigon et al.[49,50]	2008	PVDF	Impact by droplet with $D_{\mathrm{drop}} = 5$ mm, $v = 5.7$ m s^{-1}	Bridge, 100 mm × 3 mm × 0.25 mm	12.5 mW	N/A
Sahaya Grinspan and Gnanamoorthy[51]	2010	PVDF	Impact by droplet with $D_{\mathrm{drop}} = 3.57$ mm, $v = 2.96$ m s^{-1}	Solid film, 35 mm × 80 mm × 52 μm	0.1 V	N/A
Vatansever et al.[52]	2011	PVDF	Impact by droplet with $m = 50$ mg, $h = 1$ m	Cantilever, 16 mm × 4 mm × 0.2 mm	12 V_p	N/A
Ahmad and Jabbour[54] Alkhaddeim et al.[55] Ahmad[56]	2012 2012 2013	PZT	Impact by droplet with $m = 0.23$ g, $v = 0.22$ m s^{-1}	Cantilever, 8 mm × 20 mm × 0.58 mm	0.8 V_{pp}	10 kΩ
Valentini et al.[57]	2013	PMMA/GO	Impact by droplet with $m = 5$ μg, $h = 0.2$ m	N/A	6 nW	N/A
Viola et al.[58]	2013	PVDF	Impact by droplet with $D_{\mathrm{drop}} = 5$ mm	Cantilever, (20 mm to 25 mm) × 20 mm × 0.58 mm	4.5 μW	47 kΩ
Lee et al.[60]	2014	PVDF	6-μL droplet actuated by acoustic wave	Cantilever, 73 mm × 15 mm × 0.2 mm	72.2 μW	470 kΩ

D_{drop} is the droplet diameter, v is the fall velocity, m is the mass of droplet, and h is the droplet release height.

Table I compares the technical ratings and the main characteristics of existing potential raindrop energy generators suitable for raindrop energy harvesting, providing an overview of the raindrop energy harvesting literature review. Based on ongoing research on raindrop energy harvesting, the amount of electricity generated depends on the dimensions, structure, and orientation of the piezoelectric material.

IMPORTANT PARAMETERS FOR RAINDROP ENERGY HARVESTING

To understand raindrop energy harvesting, knowledge about important parameters is required. The parameters are the size, fall velocity, impact type, and kinetic energy of a droplet.[61–65]

Size of Raindrop

The shape of a raindrop is normally inconsistent, because during the process of dropping, the raindrop might collide with its neighbors or break due to air resistance. A few researchers have studied these aspects. Partovi and Aston[66] stated that raindrops falling through mist will experience air resistance and a change of shape. Mason[67] reported that the deformation and disintegration of large raindrops under the influence of aerodynamic forces progressively flattens the bottom, develops a concave depression in the lower surface, and eventually blows up to form a rapidly expanding bubble or bag supported by a toroidal ring of liquid. Finally, the bag bursts to produce a fine spray of droplets.

Several research groups have explored methods to predict raindrop size using the photographic method.[68–75] Once the droplet size is obtained, the terminal velocity can be calculated.[76–79] Based on the data collected by Gunn and Kinzer,[80] the falling raindrop velocity is

$$v = 0.055D_{\mathrm{drop}}^3 - 0.893D_{\mathrm{drop}}^2 + 4.935D_{\mathrm{drop}} - 0.179, \tag{4}$$

where D_{drop} is the diameter of the droplet and v is its terminal velocity. This is only valid for diameters between 0.1 mm and 5.8 mm.

Velocity of Raindrop

McDonald[81] stated that the surface tension, hydrostatic pressure, and external aerodynamic pressure of raindrops are physical factors that influence their terminal velocity. De Lima and Wageningen[64] stated that two droplets with different sizes will fall at equal accelerations in a vacuum, but unequally in the presence of air. This is due to air molecules, which cause a frictional force that opposes the motion of the droplets. For smaller raindrops, the air resistance will build up faster than for larger drops due to the lower weight and surface area of the smaller drops. After a certain fall distance, the air resistance and gravitational force of the droplet are equal, the net force is zero, and the acceleration has terminated. Therefore, the droplet will then fall at its terminal velocity, and as a result larger droplets will fall faster than smaller droplets. On the other hand, if the raindrop falls from a lower height, the fall velocity will decrease, whereas the fall velocity will increase for droplets dropped from greater height.[51]

Rain often falls naturally under the effect of wind. The effect of oblique rain will alter the drop velocity and direction of fall.[64]

Impact Types of Raindrop

Droplet impact dynamics was studied by Marengo et al.,[82] Yarin,[83] Durickovic and Varland,[84] and Erica. Based on their studies, the air resistance, drop inclination angle, and shape of the droplet will influence the impact type and kinetic energy of the water droplet.

Different sizes of raindrop will generate different types of impact behavior. When a droplet impacts on a piezoelectric material surface, the kinetic energy is transferred to surface energy. The droplet then bounces off from the surface. A few different cases of impact can be distinguished according to the circumstances under which the impact happens. The outcome of the collision depends on the properties of the droplet, the impacted surface, and the fluid through which the droplet is traveling before impact.[50]

Drop impacts are classified into three categories according to the Weber number, We, and the Ohnesorge number, Oh. At very low impact velocities, i.e., We $\ll$ 1, the flow is controlled by capillarity forces. At higher speeds, i.e., We $\gg$ 1, a deposition mode (formation of a liquid film on the surface) takes over. A splash mode occurs at even higher impact velocities.[49,50,85] It is very useful to estimate the recoverable energy during the impact of a droplet. This energy will establish the output power obtainable from this approach. The splash mode leads to significant energy loss. Larger raindrop impact without splashes causes larger vibrations of the membrane, which generates a greater amount of electrical energy.[49,50]

Kinetic Energy of Raindrop

The kinetic energy of a raindrop is related to its size and fall velocity. The larger the droplet, the faster it falls.[85,86] Theoretically, to estimate the kinetic energy of a raindrop, its volume V, mass m, and velocity v are required. The kinetic energy E_K of the raindrop can then be calculated as

$$E_K = mv^2/2, \tag{5}$$

where the mass of the droplet is $m = \rho V = \rho(4/3)\pi(D_{drop}/2)^3$, V is the volume of the droplet, D_{drop} is the droplet diameter, ρ is the density of water, and v is the terminal velocity of the droplet. In Eq. (5), the shape of the droplet is assumed to be spherical and the volume constant while falling. The amount of electrical energy E_U extracted can be expressed as[50]

$$E_U = (k^2 Y^2 \vartheta S^2)/2, \tag{6}$$

where k is the material coupling coefficient, Y is the Young's modulus of the piezoelectric material, K is the active volume covered by conducting electrodes, and S is the average volume deformation variation during impact.

Based on Eq. (5), the kinetic energy of a raindrop increases as its diameter and fall velocity increase. Although theoretically it can be shown that larger raindrop size or velocity produces greater kinetic energy after impact, practically a raindrop with higher velocity and larger size will lose some energy due to splashing on impact.[50]

PRELIMINARY EXPERIMENTAL RESULTS OF RAINDROP ENERGY HARVESTING

In this section, some experimental results of raindrop energy harvesting using PVDF film are presented. In this experiment, a simulated single raindrop from a syringe pump was used. The experimental setup comprised a syringe pump, protection box, oscilloscope, and PVDF as illustrated in Fig. 2.

A box with dimensions of 60 cm × 60 cm × 100 cm was designed to protect the raindrops from wind, which might otherwise vary the magnitude and direction of fall of the raindrops.

To simulate and model the raindrops, water droplets were created using a NE 300 New Era Just Infusion syringe pump with a blunt needle attached to a syringe. The size of the water droplets, as shown in Fig. 3, can be calculated from the expression[49]

$$D_{drop} = \sqrt[3]{((6D_{needle}\gamma)/\rho g)}, \tag{7}$$

where D_{drop} is the diameter of the droplet, D_{needle} is the external diameter of the capillary, g is the constant gravity, γ is the water surface stress at the liquid interface, and ρ is the density of water.

Figure 4 shows the rigid holder for the piezoelectric raindrop energy harvesting device. The stand was designed to support both cantilever and bridge piezoelectric structures. It consisted of two clips; one clip was fixed at a position, while the other clip was adjustable. The clip in the fixed position was metalized with aluminum to act as an electrical contact for both the cantilever and bridge structures. The other clip acted as an insulator for the bridge structure. The aluminum clip was then connected to the oscilloscope probe via a wire. To measure the no-load output voltage, a digital

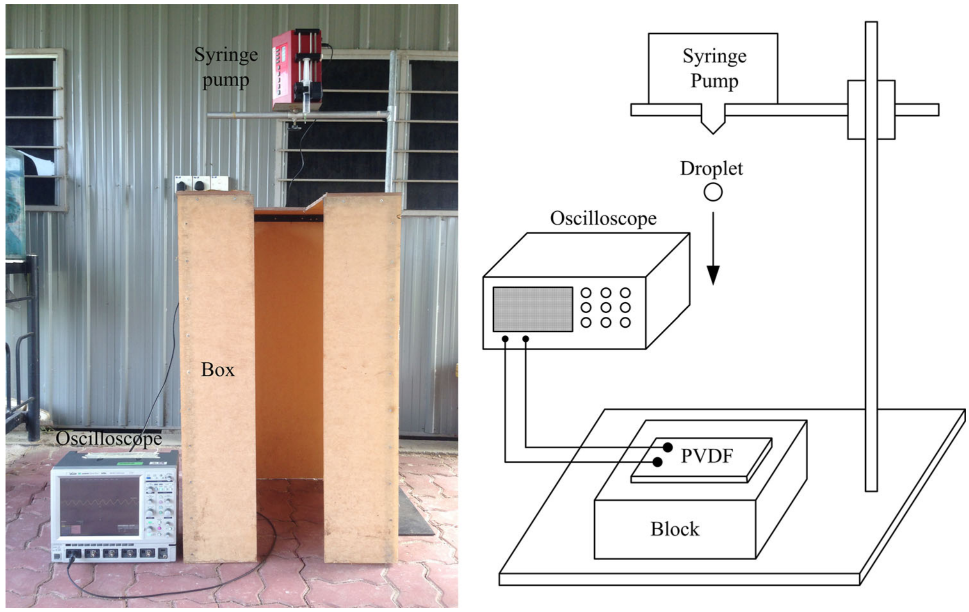

Fig. 2. Experimental setup for vibration-based piezoelectric raindrop energy harvesting.

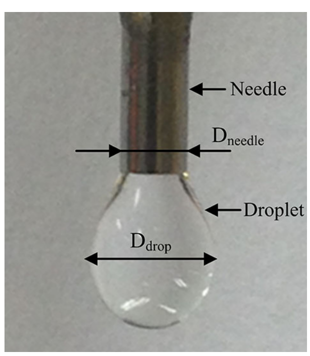

Fig. 3. Water droplet generated from a blunt needle.

LeCroy WaveSufer™ 64Xs 600 MHz oscilloscope was used. This allowed us to perform measurements with a low noise level and to observe a millisecond electric signal with minimum attenuation.

An experiment to investigate raindrop energy harvesting using PVDF material with different structures was conducted. The PVDF polymers were commercially available from Piezotech S. A. S. (Hésingue, France).

The structures selected for investigation were 4 mm wide and 30 mm long with thickness of 9 μm, 25 μm, and 40 μm for the cantilever and bridge structures, sandwiched by 80 to 100 nm thick Cr. A water droplet with diameter of 5.6 mm was released from a height of 1 m and made to impact on both the cantilever and bridge structures. The procedure was repeated 10 times to obtain the average voltage generated. Figure 5 shows the experimental results for the voltage generated as the water droplets impacted on both structures.

Based on these observations, the 9 μm thick cantilever structure was not suitable because it was too soft and initially deformed at the free end. When a water droplet impacted on it, only a few millivolts was generated. The experimental results in Fig. 5 show that the bridge structure generated a higher voltage compared with the cantilever structure, reaching a maximum of 3.502 V compared with 1.003 V, for the thickness of 25 μm. This is because the design of the cantilever structure is embedded at one end, being more deformable than the bridge structure supported at both ends. For the cantilever structure, the droplet only touched and passed the free end before splashing on the ground, which reduced the energy absorbed by the beam. The energy loss due to splashing was neglected. However, more energy was absorbed by the bridge structure, as the droplet impacted at the center and the splashing occurred on the beam. In this circumstance, the energy loss due to splashing is considered. Figure 6 shows the maximum voltage generated by the bridge structure as displayed on the oscilloscope. Equation (1) indicates that, the thicker the PVDF, the higher the voltage generated; however, for this particular droplet size, the impact force might not be large enough to fully oscillate both 40-μm structures.

ISSUES AND CHALLENGES

The major issues and challenges for raindrop energy harvesting are related to the fact that piezoelectric raindrop energy harvesting devices must be designed and optimized for outdoor use; therefore, they have to be resistant to sunlight, withstand wind, and be waterproof. The most important characteristic of a piezoelectric transducer is that it must be sensitive to raindrops. The efficiency of a

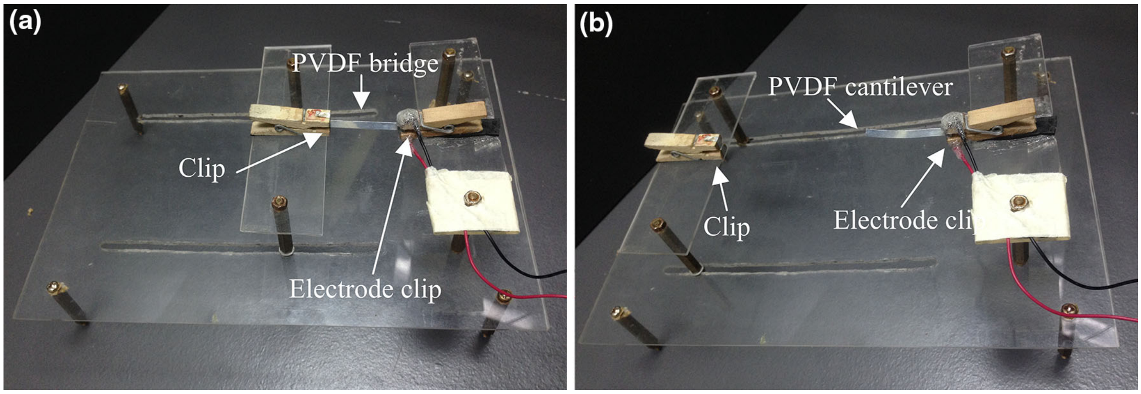

Fig. 4. Holder for the (a) bridge and (b) cantilever structures.

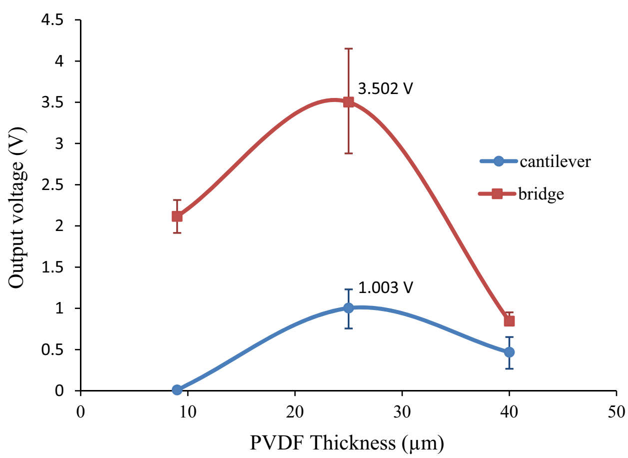

Fig. 5. Experimental results of the impact of water droplets with diameter of 5.7 mm from height of 1 m on cantilever and bridge structures.

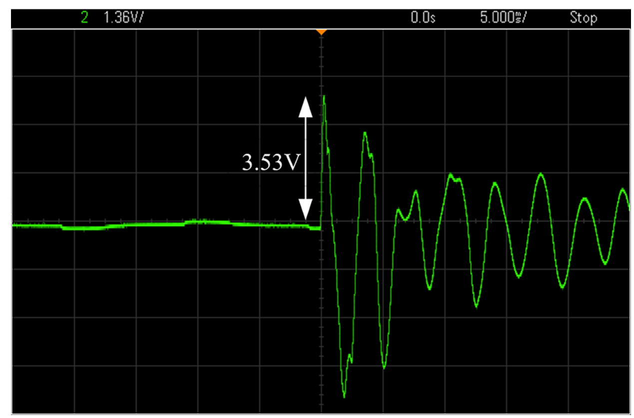

Fig. 6. Maximum voltage generated from the 30-mm-long bridge structure.

piezoelectric generator is limited by the piezoelectric properties of the material used. Therefore, the design should focus on power efficiency management to optimize the power output.

Although the recent trend in electronic device development is towards miniaturization; in this case, we have to be realistic when determining the size of this particular energy harvester. The development of the device must be appropriate for typical raindrop sizes and be able to withstand the impact force from the largest raindrops. Based on the data collected by Gunn and Kinzer,[80] the range of the size of raindrops is between 0.5 mm and 5.8 mm. This implies that miniaturization of this particular raindrop energy harvesting device is not practical in this case. Furthermore, the fundamental relationship between the energy harvested and the size of the harvester is that the output power generated by the piezoelectric material is directly proportional to the inertial mass and the amplitude of the displacement. This means that a smaller energy harvester will harvest less energy than larger systems.[87]

Another challenge to be taken into consideration is that this harvester would not be able to supply energy at a constant rate over long periods of time. It can only produce electrical energy when subjected to stress or strain. However, most electronic devices require a constant source of electrical energy. The generated output voltage must therefore be processed before it is delivered to the load. To achieve this, addition of an electrical storage device such as a battery or supercapacitor is required. When excess power is harvested, it can be stored in this storage component and later discharged to supply the load when insufficient energy is being harvested.

CONCLUSIONS

A thorough review of published work on raindrop energy harvesting using piezoelectric material is presented. This technique is still not fully adopted in practical applications due to its complexity in operation. There are many opportunities for researchers in this area to develop practical techniques and operational methods. The experimental approach can be improved further by incorporating more parameters that critically influence the harvester in a practical perspective. According to the literature review, it appears that the delivered power output of piezoelectric raindrop energy harvesters is small, although the prospect for improvement appears positively inclined. If properly developed, such devices could be excellent candidates to replace batteries for use in certain applications. Since raindrop energy provides a low-power source, a potential application is to power up light-emitting diode (LED) lights or wireless sensor networks.

Based on the raindrop energy harvesting literature presented in "Review of Piezoelectric Raindrop Energy Harvesting" section and the experiment results presented in "Preliminary Experimental Results of Raindrop Energy Harvesting" section, the most suitable piezoelectric material is PVDF in the form of a bridge structure. This generates a higher voltage compared with PZT material and the cantilever structure. Moreover, PVDF material is cheaper and nontoxic compared with PZT material.

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CONFLICTS OF INTEREST

The authors declare that they have no conflicts of interest.

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