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Performance of a piezoelectric energy harvester in actual rain

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ABSTRACT

When raindrops impact on the surface of a piezoelectric beam, strain energy produced by the impinging raindrop will be converted to harvestable electrical energy by the piezoelectric layers in a cantilever beam. The novelty of this study is to investigate the performance of the harvester in actual rain and provide practical insights on implementation. The influences of rain parameters such as rain rate, rainfall depth, raindrop count, and drop size distribution (DSD) are discussed in this study. The raindrops accumulated on the surface of the piezoelectric beam will form a water layer. It is described using added mass coefficient in this study. In an actual rain experiment, a piezoelectric beam with surface area of 0.0018 m^2 is able to produce 2076 μJ of energy over a duration of 301 min. The energy generation of a raindrop impact piezoelectric energy harvester is highly dependent on the rain rate. Due to the inconsistency of the energy generation, the piezoelectric energy harvester would require an integration of suitable energy storage device for continuous operation. Nevertheless, this work shows the feasibility of harvesting raindrop energy using a piezoelectric beam.

1. Introduction

The development of microelectronics has inspired smaller devices that consume less power [1]. These devices are now possible to be powered from energy scavenged by an energy harvester. An energy harvester is able to generate electricity from sources such as mechanical vibrations, thermoelectric, acoustic, and solar energy [2].

Piezoelectric is a smart material that can convert vibrations into electricity through direct piezoelectric effect. Due to this unique property, piezoelectric material has been used as an energy harvester. Several energy harvester prototypes are developed based upon wind energy [3], human motion [4], vehicle suspension system [5], and dynamic loadings on a high-rise building [6].

This paper focuses on the study of harvesting raindrop impact energy by using a piezoelectric beam. Tropical climate countries promise abundant annual rainfall. Hence, raindrop impact energy harvesting is a feasible form of alternative energy source. The potential of rainfall energy harvesting in Bangladesh was studied by Biswas et al. [7]. Raindrop impact energy harvesting is suitable for rainy outdoor environment especially when solar energy is difficult to harvest at night.

The aim of this study is to investigate the influence of rain parameters such as rain rate, raindrop count, rainfall depth and drop size distribution (DSD) on a rain impact energy harvester experimentally. Section 2 provides an overview of raindrop energy harvester in literature to date. Two rain parameters are introduced in section 3, which are rain rate and drop size distribution (DSD). The theoretical study of a raindrop impact is provided in section 4. Section 5 describes the effect of raindrop accumulation on the surface of the piezoelectric beam. Experiment methodology is detailed in section 6. Section 7 highlights the results and discussions for this study. In order to gain further knowledge on the performance of a piezoelectric rain energy harvester, section 7 is further divided into five subsections: rain rate and instantaneous voltage; raindrop count and instantaneous energy; rainfall depth and energy accumulation; added mass coefficient; implications of the results.

2. Raindrop energy harvester

Piezoelectric materials such as lead zirconatetitanate (PZT) and polyvinylidene fluoride (PVDF) are able to convert kinetic energy of raindrops into usable electricity through direct piezoelectric effect. Raindrop energy harvester can be an alternative energy source for a low-powered system operating in remote area. By integrating raindrop energy harvester with other types of energy harvesters into a microelectronic system allows the system to have an independency from battery. Removing bulky battery from the design of such system reduces the size and enables self-sustainable in energy consumption.

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Raindrop energy harvesting is not a new concept. Single droplet impact on a piezoelectric material has been well studied over the past few years. Theoretical [8] and experimental [9] studies were conducted based on a single droplet impact on a PVDF membrane. Results revealed that 3 mm diameter water droplet with an impact velocity of 4.5 m/s was able to generate power of 73 μW. Vatansever et al. [10] had experimented with water droplets with masses of 50 mg and 7.5 mg from different heights impinging on a PVDF and PZT composite structures. The maximum peak voltages generated by the PVDF and PZT cantilever structures were 12 V and 3 V respectively. The response of a single water droplet impacting on a PVDF beam has been studied by Viola et al. [11]. Both simulation and experimental results showed that a 0.12 g water droplet with a drop height of 0.8 m was able to generate a peak voltage of 6 V. Another experimental study based on single water droplet impact on a five layers PZT cantilever beam was conducted by Ahmad et al. [12]. The cantilever beam was able to generate power of 23 μW when a water droplet with mass of 0.23 g impacted on the beam with impact velocity of 3.43 m/s. A review on raindrop energy harvesting is conducted by Wong et al. [13]. The authors had also conducted a brief experiment to show the feasibility of raindrop energy harvesting. Experiment results revealed that using a PVDF cantilever structure and bridge structure, which were able to produce output voltage of 1.0 V and 3.5 V respectively. A more recent work conducted by Ilyas et al. [14] examined the behaviour of a piezoelectric beam due to water droplet impact. Raindrop was artificially generated using a burette and the drop size is fixed at 2 mm and it was tested under various fall heights. The reported energy output of the developed energy harvester was less than 90 nJ with a mean power below 2.5 μW. In addition, the authors had also developed a model based on empirical data to demonstrate the feasibility of a harvester array.

According to the literature, the voltage response of a piezoelectric structure due to single droplet impact is well established. However, in actual rain scenario, parameters such as rain rate, drop size distribution, and drop position on the piezoelectric energy harvester are important as well. A recent numerical simulation study based on a PVDF membrane, fixed by four edges was studied by Perera et al. [15]. Three rain types were considered in the study, namely light stratiform rain (LSR), moderate stratiform rain (MSR), and heavy thunderstorm (HT). Simulation results recorded a maximum power of 2.231×10^{-29} W can be harvested from a 1 m^2 area of a PVDF membrane during a heavy thundershower. A study on the effect of rain rate and drop position on the piezoelectric beam has been investigated by Wong et al. [16]. It has been shown that when the droplet impacts further from the clamp of the piezoelectric beam, more voltage will be generated.

During actual rainfall, the raindrop will accumulate on the surface of the piezoelectric energy harvester. The water layer accumulated on the surface of the piezoelectric beam can be modelled as an added-mass coefficient. The measurement and analysis of the water layer formed on the piezoelectric beam surface poses a challenge as during rainfall, the formation of the water layer is hard to be measured. Based on a theoretical and experiment study conducted by Wong et al. [17], as the water layer on the piezoelectric beam increases, the natural frequency of the beam will decrease. The output peak voltage will increase slightly after the saturation of water layer on the beam.

As a continual work of Wong et al. [16,17], the contribution and novelty of this study is to conduct an actual field test on raindrop energy harvester, investigate its performance and provide insights of practical implementation, which have rarely been reported in the published literature. The scopes of this study include the characterisation of the rain parameters, the behaviour of a raindrop impact on a piezoelectric beam, the experimental results collected from three rain events, and the method of measuring the raindrop accumulated on the surface of the piezoelectric beam by using added mass coefficient.

3. Rain parameters

The rain behaviour is stochastic and it is hard to predict using a single deterministic parameter. Rain is normally characterised by rain rate and drop size distribution (DSD) [18]. Rain rate describes the amount of rain water over a fixed time interval, which is measured in mm/hr. On the other hand, the DSD shows the total amount of raindrop count of a particular raindrop diameter class. In this study, the rain rate and DSD are measured by using a laser precipitation monitor sensor. The computation for DSD is given as:

$$N(D_i) = \frac{n_i}{v(D_i) \times A \times T \times \Delta D_i} \quad (1)$$

where, $N(D_i)$ is the number of drops per unit volume per unit interval of drop diameter D of the i-th bin; n_i is the number of drops in the i-th bin; v is the velocity of the droplet; A is the sampling area ($A = 0.0046$ m^2); T is the time duration ($T = 300$ s); ΔD is the bin width of each drop size class ($\Delta D = 0.5$ mm). The DSD for three recorded rain events are provided in Fig. 1.

The DSD graphs for the three rain events shown in Fig. 1 is lognormal distributed, where the histogram is skewed to the right. The modes of the distribution for the three DSD lie in the second bin, where the bin centre is 0.25 mm. The maximum raindrop diameter recorded for the three rain events is 7 mm.

4. Raindrop impact

When a raindrop collides on the surface of the piezoelectric energy harvester, an impact force will be generated. The average of this impact force can be expressed as:

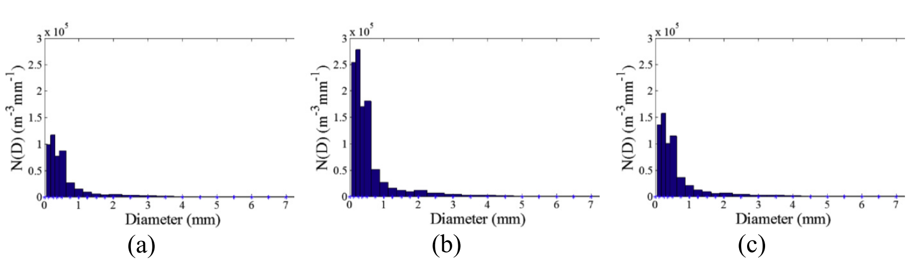

Fig. 1. Rain drop size distribution (DSD) for the (a) first, (b) second, and (c) third rain event.