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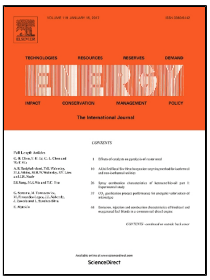

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Highlights:

- A technique is found to identify the efficiency of the impact mechanism
- A technique is also found for the mechano-electric conversion mechanism
- Values for the impact and conversion mechanism efficiencies are ascertained.
- The optimum arrangement for a single device is determined

Towards a prototype module for piezoelectric energy harvesting from raindrop impacts

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Abstract

It has been shown that scavenging energy from raindrop impacts has the potential as a power source for electronic devices and act as an alternative method of generating electrical power. In this paper an energy harvesting module is developed consisting of multiple piezoelectric devices which use impacts of raindrops to generate electrical power. The effect on efficiency of the module with non-rectified or rectified outputs of each device connected in parallel is investigated. Additionally, the voltage, power and energy were found for different surface angles, surface conditions and impact regions for single devices with a view to maximise module efficiency.

The main findings of this work are that: a) a technique is found to identify the efficiency of the impact mechanism as the droplet interacts with the device and the efficiency of the mecheno-electric conversion mechanism due to internal losses in the device; b) values for the impact mechanism efficiency and the conversion mechanism efficiency are ascertained; and c) the optimum arrangement for a single device is determined.

Key words: Piezoelectric; Raindrop; Efficiency

1. Introduction

The energy crisis and environmental pollution have been some of the main challenges for sustainable energy developmental [1]. Over the last decade there has been much research focusing on mechanical vibrations [2], solar [3], wind [4], biomass [5], hybrid systems in a combination of photovoltaic with thermoelectric generation [6], and electric vehicles with photovoltaic generation [7] are some examples of renewable energy sources of all scales. Energy harvesting offers an alternative approach, scavenging energy from the environment and particularly useful for low power-consuming devices. Moreover, the potential of raindrop impact energy harvesting has not been fully explored and this paper aims to propose a piezoelectric energy harvester module and presents an investigation of its efficiency.

A previous study [8] focused on the voltage output caused by various velocities of water droplet impacts on the harvester and showed that the oscillating voltage output has two distinct stages: a growth followed by decay stage. The work presented in this new paper further builds on the previous study. The effect of raindrop impacting the device at different regions, device angle and surface condition are investigated. This study particularly investigates the power output and efficiency of the single device and a multi-device module. The study shows that developing a module of interconnected devices is not a trivial matter when trying to ensure the available energy in the source is efficiently harvested. There are several points in the harvesting process where energy is lost and this is discussed in detail in the paper.

2. A Quick Review

A quick review of the important aspects of piezoelectric raindrop energy harvesters is presented focusing on devices developed and droplet surface interactions.

Piezoelectric materials have been used as a means of transforming externally available vibrations into electrical energy that can be used to power devices and potentially store that energy. With the recent surge of micro scale devices, piezoelectric power generation can provide a convenient alternative to traditional power sources. However, the energy produced by these materials in many cases has been reported to be very small and unable to directly power a substantial electrical device. Therefore, much of the research into energy harvesting has focused on methods of accumulating the energy until a sufficient amount is stored, allowing the intended electronics to be powered for short periods.

The topic of energy harvesting using piezoelectric materials has attracted great interest in recent years. The most common types of piezoelectric material being used are polyvinylidene fluoride (PVDF) and lead zirconate titanate (PZT). The piezoelectric material consequently generates a charge, which is collected by two electrode plates. The voltage created across the plates can be defined as:

$$V = Q/C_{piezo}$$

Equation (1)

where Q is the charge generated and C_{piezo} is the capacitance of the material. The capacitance can be expressed as:

$$C_{piezo} = \varepsilon_0 \varepsilon_r A/d$$

Equation (2)

where ε_0 is the electrical permittivity in vacuum, ε_r is the relative permittivity between the electrode plates, A is the electrode area and d is the separation of electrode plates.

2.1 Raindrop Energy Harvesting

Raindrop energy harvesting techniques using piezoelectric materials simply convert the impact energy and subsequent mechanical vibration of the device into an electricity supply. Most previous studies on piezoelectric energy harvesting have concentrated on machine, human, and other environmental sources of vibration. To date, a very limited number of studies have been conducted on energy harvesting from raindrop impacts.

One of the most recent studies conducted by Nayan et al [9] showcased the need of developing a rain harvester due to the favourable rainy condition in particular countries. The research focused on series and parallel connected devices and proposed a design for the piezoelectric plate. The output of the piezoelectric device was found to be dependent on the impact pressure on the piezoelectric body. The voltage output was measured for different droplet heights and simulations were carried out for different design approaches.

An in-depth study conducted by the current authors, Ilyas et al, [8] showcased detailed voltage and power output from a piezoelectric device. This study was performed under laboratory condition using different velocity of raindrop impacts and different electrical resistive load conditions. The results showed two distinct stages to the oscillating voltage output consisting of a relatively short duration growth stage followed by a longer decay stage. The study showed the growth stage contributed a significant amount of the overall power output of the device (total energy delivered of 90nJ and mean power of 2.5μW). Overall, the device efficiency was found to be very low but suggestions were proposed for improvement. For example, it was proposed efficiency could be significantly improved by modifying the droplet impact mechanism with the harvester surface by exploring new surface materials to maximise inelastic collision.

Another study by Guigon et al focused on PVDF materials with extensive work on theoretical [10] and experimental models [11]. The main motivation of these studies was to review the amount of energy that could be generated using these harvester types. The experimental set-up consisted of a syringe pump as a source of water droplets and a piezoelectric system. The

syringe pump created identical droplet sizes for precision measurements and reproducibility. Voltage was measured and energy calculated. The piezoelectric system consisted of two transparent PVDF bands embedded in a Plexiglas structure. Various experiments were conducted by changing the thickness of the PVDF beam which ranged from 9μm to 25 μm. The study concluded that the thicker material (25 μm) is more effective than the thinnest material (9μm) at harvesting energy. Various impact situations were studied (different drop heights and drop sizes) showing that the quantity of electrical energy that can be recovered using these structure types is close to the proposed theoretical quantities, i.e. approximately 1 nJ of electrical energy and 1μW of instantaneous power using raindrops. The simulations did not take into account the splash phenomena which may lead to reduction in energy transfer.

Another study [12] compared PVDF and PZT materials. The devices with these materials were exposed under rain to determine the voltage levels generated by the impacts. The study recommended the use of PVDF devices for raindrop energy harvesting because they showed these generated higher power output.

Another study [13] focused on a device with a combination of cantilevers and diaphragm structures forming the harvester. A comparison of empirical and simulation data was presented. The prototype developed consisted of several layers namely: silicon, polyamide, Al (aluminium), and a PVDF active layer. The focus in this work was on a meshed model of the harvester. Results show a displacement pattern for the centre of the diaphragm with various thicknesses of Al and PVDF. To achieve optimum results, thinner Al and PVDF are used, as thickness is inversely proportional to maximum displacement. On the cantilever surface, as the thickness of PVDF is increased the maximum displacement begins to decrease whereas the Al is directly proportional to the maximum displacement. It is concluded that PVDF thickness of 150 mm and Al thickness of 35 mm results in a maximum displacement of 2800 mm. However, at these thicknesses the maximum displacement on the centre of the diaphragm is relatively small. These thicknesses are able to withstand the impact pressure of a large droplet of 13.718 MPa. The maximum displacement limit is found to be 2800 mm.

A theoretical review [14] focused on the proposal of the idea of a "Piezoelectric Shingle" as a new energy harvesting system, based on meteorological precipitations as the rain. It presented a preliminary analysis about the state of art of energy harvesting systems, based on piezoelectric technology, showing potentiality, limits and other experiences in the field of interest. It reviews the main features of rainy phenomena, interesting for an energy harvesting system, reconsidering some theoretical/empirical models. Models are addressed to define the limit velocity of raindrops and a distribution law between dimension of raindrops and the nature of rainfall. After considerations about the annual quantity of water, fallen in a region, the authors propose the ideation of some key patterns for a piezoelectric energy harvesting system from rainy precipitations.

Maximum power output using a water vortex [15] on a macro fibre composite piezoelectric energy harvester was found to be around 1.32 μW with a water velocity of 0.5 m/s at the

158 cylindrical diameter of 30mm. By using an upright vortex-induced piezoelectric energy
159 harvester [16] the power output was found to be 84.49 μW using a velocity of 0.35 m/s.
160

2.2 Surface Interaction

The fluid mechanics of droplet impact with a surface is of importance in a variety of different fields. The fluid flow associated with impinging drops is nontrivial and not fully described in detail in the scientific literature. A raindrop impact on a liquid surface can splash or bounce as well as merge with any surface liquid whereas a raindrop impact on a solid surface will either splash or spread out on the surface. The phenomenon is discussed in more detail in an earlier publication [8].

For the purpose of this study a comparison is conducted for droplet impact on liquid and solid surfaces as both would be seen in the real application. A detailed study conducted by Rein [17] reviewed different scenarios of droplet impact. The liquid is described by its thermodynamic state, and by its surface tension, viscosity and compressibility. Most theoretical and numerical calculations in the publication are based on the assumption that the drops are spherical. Due to aerodynamic forces the shape of drops moving through a fluid will always be rendered slightly ellipsoidal. Another study looked at mixing water and gelatine to form well defined non-spherical shape droplets [18] and draw a comparison of the output.

Another feature to take into consideration is that the harvester surface can generally be either smooth or rough. It is reported [19] that splashing is reduced when highly polished surface are used. At small surface roughness the splashing threshold depends strongly on the roughness, whereas the threshold is little influenced by the surface roughness when it is large. In many problems the elastic response of the surface is insignificant. However, the elasticity of the surface can no longer be neglected when high speed drops collide with a surface.

During the initial stage of impact the drop is merely deformed and compressed at its base. Hence, surface tension forces and the viscosity of the liquid do not enter the scenario at this stage. The important parameters are density and compressibility of the liquid, and the impact velocity and diameter of the drop. In the contact zone between the drop and the surface pressure is not uniform. It is highest at the contact edge where it exceeds the Waterhammer Pressure, and is lowest at the centre. This is due to the spherical geometry of the drop [19] .

Splashing is a phenomenon often observed during liquid droplet impact onto a solid surface. The threshold of splashing is known to be related to droplet size, impact velocity, and physical properties of the liquid, but the mechanisms that initiate splashing are not understood completely. In accordance with the Kelvin-Helmholtz (K-H) instability analysis, recent studies [20] have shown that ambient gas density has a significant effect on the threshold and trajectory of splashing. Research has focused on the effects of droplet velocity, impact angle, and ambient gas pressure (or density) on the threshold of splashing and the motion of the ambient gas surrounding the droplet was examined. Experimental observations of splashing were carried out with a droplet of 1.7 mm in diameter, while varying droplet velocity, impact angle, and ambient pressure. An empirical correlation was derived using our and other published data to determine the threshold of splashing based on the aforementioned parameters. Also, a numerical simulation using the volume of fluid method was carried out to calculate the gas

velocities surrounding the droplet during impact. The results of this model gave supportive evidence that K-H instability is a suitable instability theory that helps explain the splash phenomenon with consideration of the gas motion surrounding the droplet

The ultimate aim is to present a combined energy harvesting technique that could use several sources to power low-consumption devices and self-powered systems. The study on triboelectric nanogenerator [21] has opened up new areas to be explored; for converting mechanical energy to electrical energy with conversion efficiency at 60%. A review on stretchable nanogenerators [22] showcased the potential of powering low-power devices with high conversion efficiency. It has been reported that the energy conversion efficiency is between 50% and 85%.

3. Methodology

3.1 Experimental Set-up

Water droplets are made to fall onto the piezoelectric device under laboratory conditions. The velocity of the droplets and thus the kinetic energy associated with them are calculated from the height of the droplet fall. Table 1 represents the velocity attained for the water droplet at various heights as previously published [8].

Velocity (m/s)	Kinetic Energy (µJ)
1.28	27.43
1.62	43.95
1.89	59.81
2.13	75.97

Table 1: *Table: Kinetic energy of water droplets [8]*

The device is mechanically fixed at one end so that it is free to move at the other end so that it can oscillate in a bending motion in the vertical direction. Figure 1a represents a device beam fixed at the left-hand side which has a water droplet impacting on the surface allowing it to oscillate along the length of the device (a pitching motion). This causes compressions and extensions in the piezoelectric material resulting in the charge displacements and energy conversion mechanism. Additionally, there are further possible vibrational modes, for example, in the wide of the device as in Figure 1b (a rolling motion).

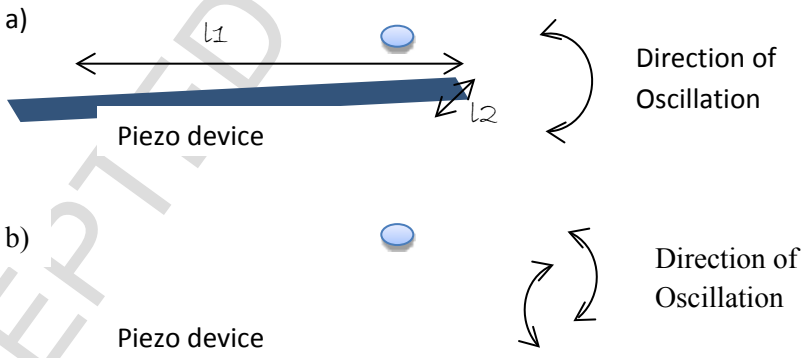

Figure 1: *Impact of Water droplets*

A commercially available piezoelectric device by Pro-Wave (FS-2513P) is used in this study. The piezoelectric film is coated with non-conductive material and has silver (Ag) electrodes on top and bottom of piezoelectric film.

The device is fitted in a test facility made of Perspex and is anchored on a stainless steel plate with rotary protractor to measure the angle of incline of the device (see Figure 2). The device is clamped into position on the test bench. The voltage output of the device is measured using a Digital Oscilloscope (Tektronix – TDS3032B) with differential probes (Testec – TTS19001). The probe was set at an attenuation of 1/10. Each test was repeated several times (usually 4 data points collected) to show reproducibility of the data.

The test facility allows consistency of clamping the device into position and flexibility of connecting various devices either in series or parallel to form a module. The device is simply slotted into the clamping mechanism which is made of rubber to provide firm support to the device.

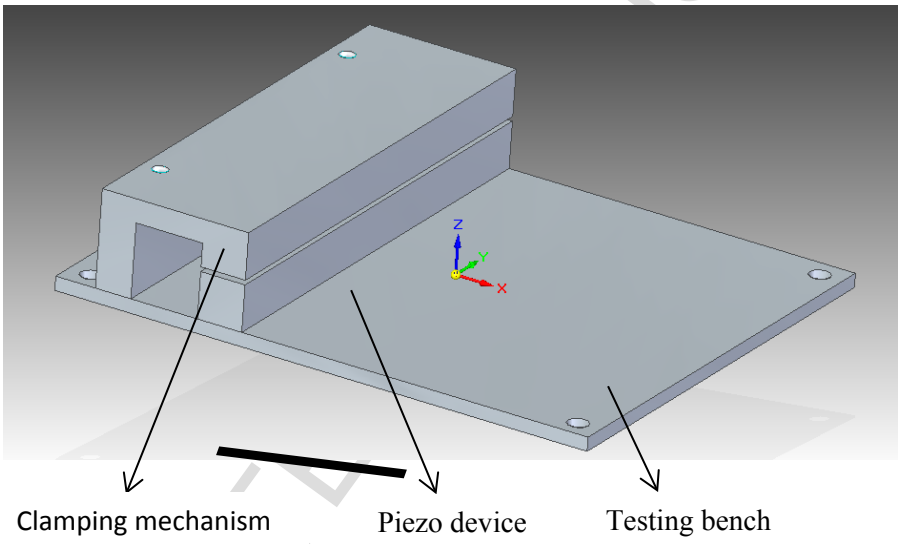

Figure 2: *Test facility*

The table below specifies the experimental parameters:

Dimension of device	**25 x 13 x 3 mm**
Capacitance of device	1.5 nF ±30%
Load connected	1MΩ
Operational temperature	-20 to +60 °C
Range of Angle	0 to 45 °

Table 2: *Experimental setup parameters*

Three impact regions are identified on the piezoelectric device surface as illustrated in Figure 3 for targeting of the droplet. The device is clamped towards the left-hand side as illustrated allowing the right-hand side of the device to move up/down freely. Voltages with time measurements are taken by using a Digital Oscilloscope.

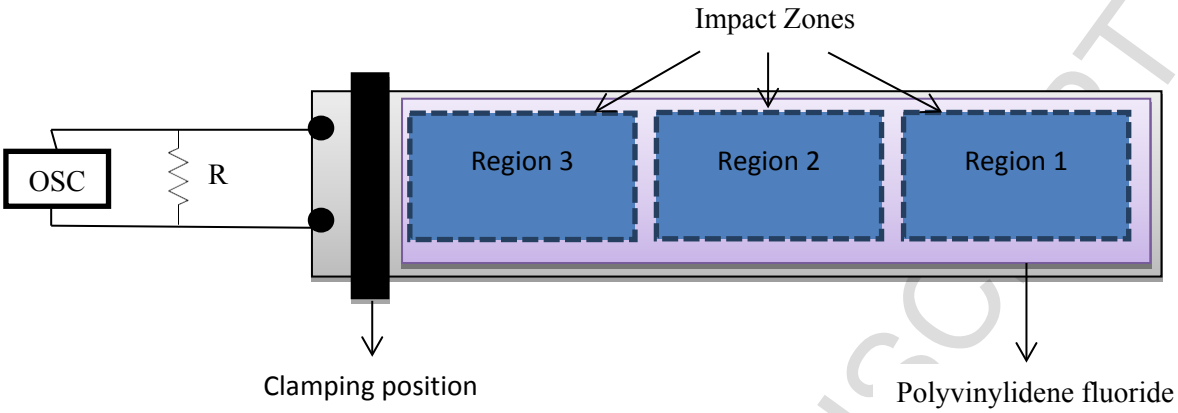

Figure 3: *Impact Zones*

3.2 Single and Multiple Device Module

For the single device tests, a single device is connected to the 1 MΩ resistive load and the voltage across the load captured on a digital oscilloscope. Figure 4a shows the general configuration. Tests are repeated a least 4 times for any one configuration.

The first series of tests with multiple devices is conducted with a number of devices connected in parallel to make a module which is connected in turn to the 1 MΩ resistive loads. The general configuration is illustrated in Figure 4a. The voltage output across the load is measured with time. During these tests on multiple devices, only one device is activated by the impact of water droplets as indicated by the arrow in Figure 4a. Tests are repeated at least 4 times for any one configuration.

The second series of tests with multiple devices is conducted with each device having its own rectification component and then these are connected in parallel to make up a module. These are then connected to the 1 MΩ resistive loads. The general configuration is shown in Figure 4b. During these tests on rectified multiple devices, only one device is activated by the impact of water droplets as indicated by the arrow in Figure 4b. Tests are repeated at least 4 times for any one configuration.

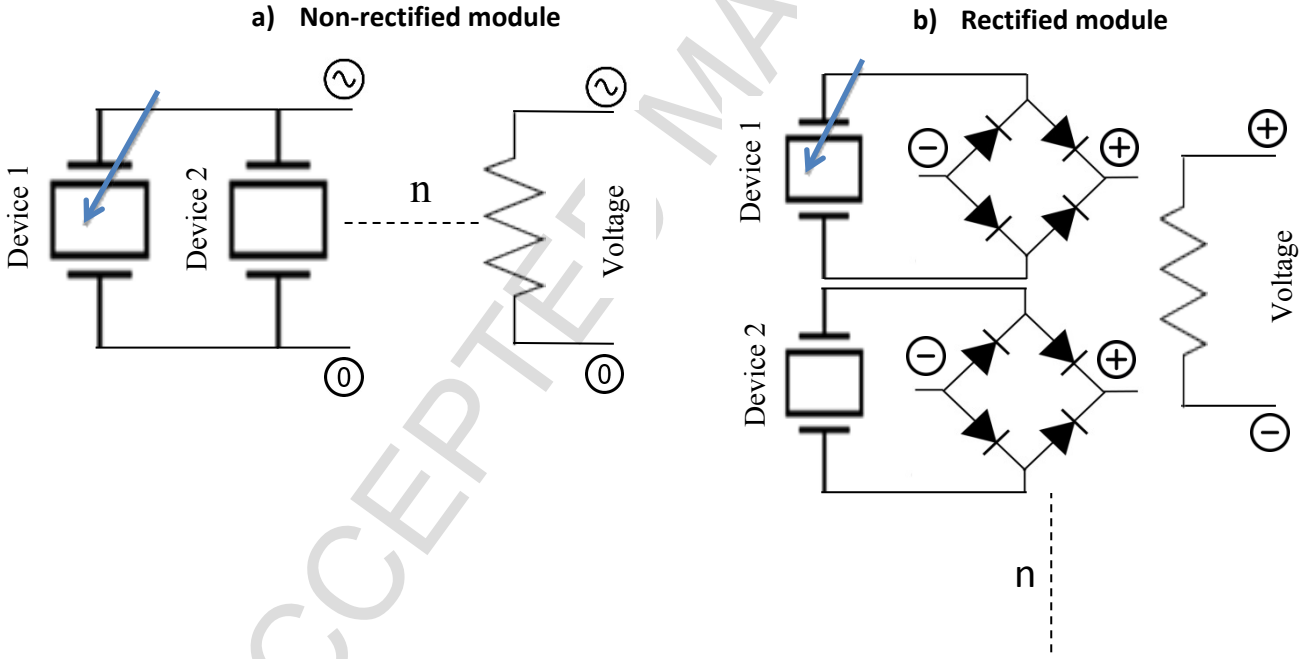

***Figure 4**: Circuit diagram (a) non-rectified module, (b) rectified module*

4. Results

4.1 Single Device Study

4.1.1 Voltage Measurements

Peak voltage over the three regions was measured over surface angle at which the device is declined. As discussed earlier, the impact mechanism plays an important role in the overall output of the device. The results in Figure 5a demonstrate that Region 1 gives out maximum voltage when the device anchored at horizontal position (surface angle set as 0°), therefore for all other calculations results obtained from Region 1 will be used.

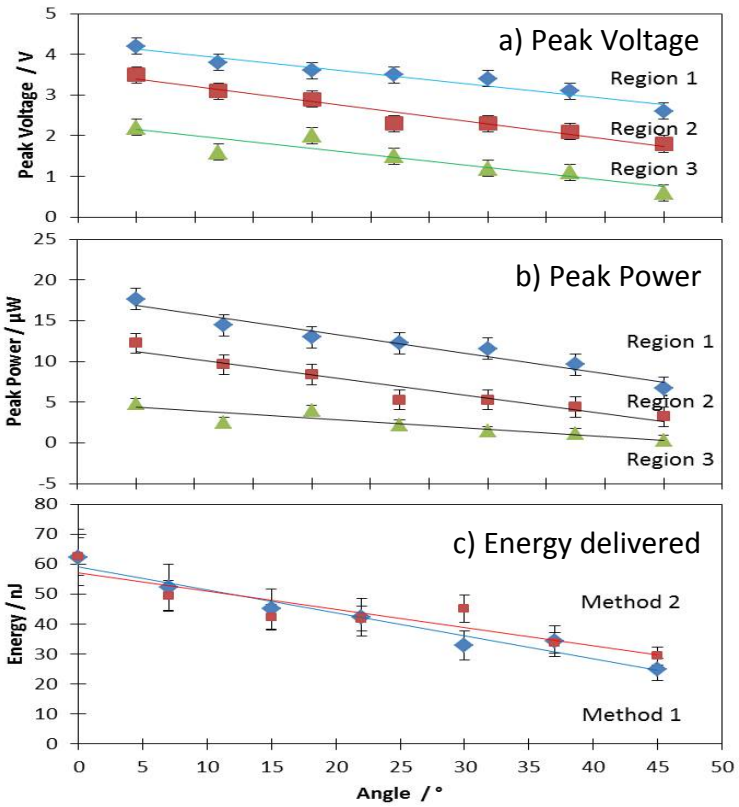

***Figure 5**: Parameters of single device (a) Peak voltage, (b) Power output from harvester, (c) Energy output using method 1 and 2*

The results are consistent with what was expected with different regions on the device. Experiments were conducted against different angles to deduce the best region and angle to drive maximum output. As the angle of the device is increased from 0° to 45° it was observed that the peak voltage decreases. This can be due to the impact position of the droplet. When the device is at 0° the droplet normally splashes on the device and most of it is retained on the surface of the device hence giving a higher output. When the droplet impacts the device at an angle most of it disperses and bounces off the device hence a lower output is observed. The peak power attained was in the region of 4 to 18 µW which is in line with the set of data obtained in the first publication.

Peak voltages were also measured additionally to study various surface conditions on the device. The results shown in Table 3 are for a resistive load of 1MΩ, 0° at Region 1. The surface conditions are altered by using cellulose based tape and vinyl based tape. The results do not show any significant change in the peak output voltage of the device.

Surface	Peak Voltage (V) (±0.2V)
Dry surface on sensor	2.9
Wet surface on sensor	3.0
Transparent Tape (Cellulose based)	2.9
Transparent Tape (Cellulose based) with holes	2.8
Insulation Tape (Vinyl based)	3.0
Insulation Tape (Vinyl based) with holes	2.9

Table 3: *Peak voltage at various surface conditions*

A series of results were captured for the ramp-up (initial impact) of water droplet to impacting on a dry and wet device. For consistency and repeatability the resistive load was 1MΩ, with 0° angle and impacting at Region 1.

For the dry condition, the device was wiped clean before every reading was taken. Any water droplets that may have been deposited on the surface of the device were wiped dry before each set of results were saved. This shows an 'edgy' initial impact with the surface of the device. The wet device replicates real rain conditions where the water droplets may already be deposited on the surface of the device. The results show a smoothing of initial impact as the water droplet impacts the surface of the device. The two different waveforms are shown in Figure 6.

Figure 6: *Device output in different conditions (a) Dry device, (b) Wet device*

As explained earlier there may be multiple modes of oscillation; vertical oscillations and width-ways oscillations. The dry device in Figure 6a shows the initial impact as a 'high-frequency wobble'. When the water droplet interacts with the surface of the device it can possibly be oscillating the device sideways thus giving us an edgy curve. Figure 6b shows a 'low-frequency wobble' as the curve is smoothed out indicating that the device has only oscillated in vertical direction. The difference between the peak voltage of wet and dry device is negligible. However, we have determined that the surface interaction and the way the device oscillates is of importance and needs further studies conducted to understand the behaviour of these oscillations.

The dominant fact is whether the device is dry or wet the peak voltage remains the same. The difference in the waveform in Figure 6 can be further explained by assuming the material is homogenous in every direction therefore the 'k' is defined as a constant and the two equations can be brought together as in Equation 3.

$$f_1 = \frac{k}{l1}, f_2 = \frac{k}{l2}$$
$$f_1 l_1 = f_2 l_2$$

Equation Set (3)

4.1.2 Peak Power & Energy Delivered

The instantaneous peak power (P) has been determined using Equation 4 for the data collected. The resistive load (R_{load}) in this experiment was set as 1MΩ (±5%) and peak instantaneous power was calculated as shown in Figure 5b.

$$Power = V^2/R_{load}$$

Equation (4)

The energy delivered to the load is calculated from the voltage data collected by two methods:

<u>Method 1:</u>

As detailed in our previous publication the impact of water droplet on the piezoelectric device was broken into two stages; log growth and exponential decay. The energy graph of the harvester is plotted in Figure 5c. The energy output of the impact was found by these steps:

- Instantaneous power was calculated for each data point using equation 4 and the average found.
- The duration of log growth (t_1) and exponential decay (t_2) was determined.
- Energy was calculated using equation (5).

$$E = (< P_g > \times t_1) + (< P_d > \times t_2)$$

Equation (5)

415 Method 2:

416 The energy output of the impact was found by these steps:

417 - Instantaneous power was calculated for each data point using equation 4.
418 - The time step for each data point, t_s, is calculated to be 0.00004 seconds.
419 - Energy was calculated using equation (6).

420

421 $$E = \sum_{0}^{n} (P_g \times t_s) + \sum_{x}^{y} (P_d \times t_s)$$

422 Equation (6)

423

424

4.2 Multiple Device Module Study

4.2.1 Voltage Measurements

Figure 7 shows the voltage waveforms obtained for up to 7 devices connected in parallel. There is a decline in voltage as more devices are connected in parallel. The voltage ranges from 0.9V to 3.1V. The experiment was repeated several times to ensure consistent results and rule out any issues in data collection.

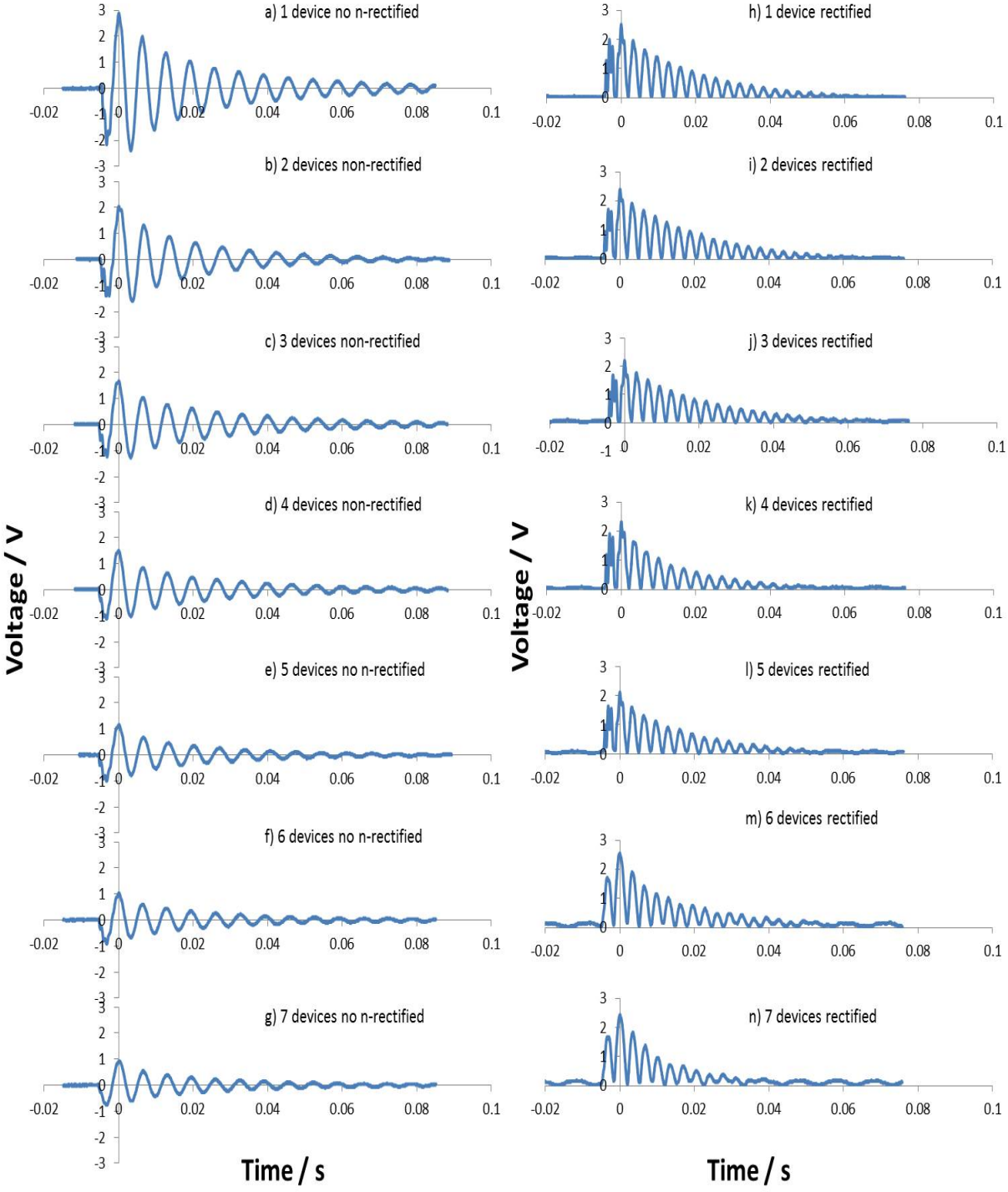

Figure 7: Voltage output with multiple devices connected in parallel

4.2.2 Peak Power & Energy Delivered

The peak power of module is calculated for devices connected in parallel. Figure 8a shows the peak power of the non- rectified devices and rectified devices in the module. The rms voltage of the non-rectified devices is plotted is Figure 8b. This output voltage is a function of n devices and is empirically modelled by equation (7)

$$V_{em}(n) = 0.9117n^{-0.629}$$

Equation (7)

The Energy output of the module is shown in Figure 8c. The non-rectified module shows a significant decline in energy output as more devices are added in parallel in the module. There is a general decline in the energy output as more devices are added in paralleled in the module.

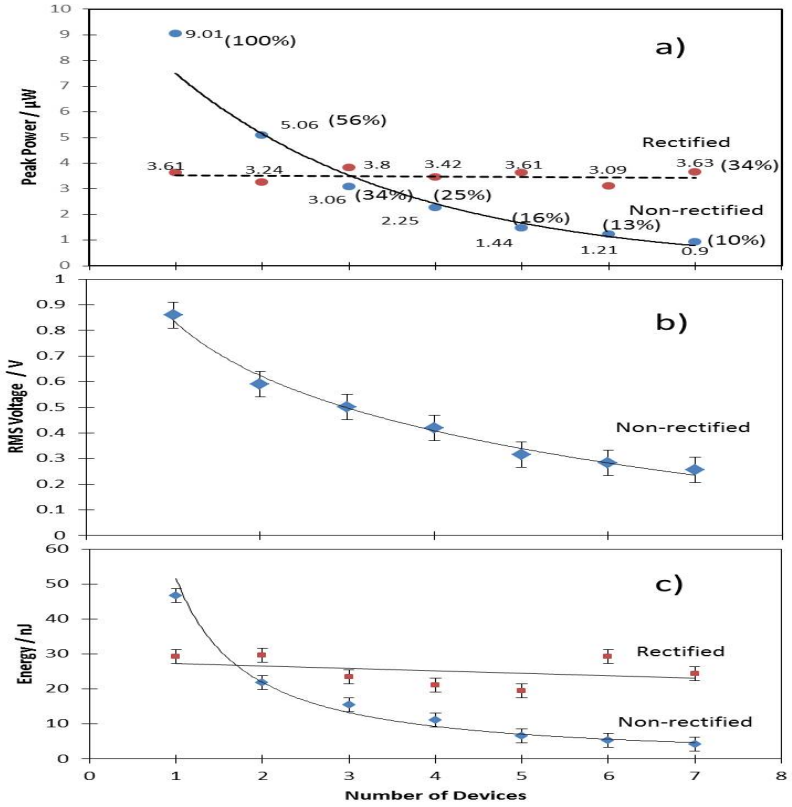

Figure 8: *Parameters of the module (a) Peak power, (b) rms voltage, (c) Energy delivered*

5. Analysis & Discussion

Limited research has been conducted in the field of raindrop energy harvesting. Results published earlier [8] demonstrated that piezoelectric materials can be effectively used to harness the energy of raindrop impacts. Detailed profile of the voltage output from the device was published which introduced the 'log growth' and 'exponential decay' stages. Even though the growth stage was the shortest stage but the impact process of the droplet had a significant contribution to the overall output of the device. The efficiency was found to be very low at the time with the old set-up and we have improved the set-up for this set of experiments to be able to closely examine the results and improve the efficiency.

It is found that the angle of device to the falling droplet have a significant effect on the output of the device. To maximise the power out, the device should be presented at 0^o to the falling droplet and the droplet should impact the end of the device to generate the maximum bending mode of oscillation. The surface condition of the devices was also investigated and no significant effect was found. Of particular interest was whether an already water saturated surface of the device behaved differently to a dry surface; no significant effect was found.

5.1 Analysis of Multi-Device Data

The analysis of non-rectified devices is discussed in detail first before considered the effect of rectification. Figure 9a illustrates the equivalent circuit for one device which has an impact event of a droplet where the device is connected to n number of devices with no droplet impacts. The electrical power sources in Figure 9a indicates the power which has been captured from the droplet – that is, the power available after the impact mechanism. The droplet falls with a particular kinetic energy, E_{KE} , for example 75.97 μJ as in Table 1, inelastically impacts the harvesting device. The droplet undergoes its impact mechanism with the water bouncing back and spreading across the surface taking a portion of the initial kinetic energy with it. Also, a proportion of this initial kinetic energy is captured, E_0, by the device and mechanically sets the device in damped simple harmonic motion. The mechanical characteristic of this simple harmonic motion is modelled with the equivalent circuit of L_m C_m R_m as in Figure 9a for Device 1. The L_m and C_m components model the behaviour of the transfer of kinetic and potential energy in the device as it vibrates. R_m models the mechanical losses. Also in Figure 9a for Devices 1 are equivalent components for electrical storage and losses. C_e is the capacitance of the device as it consists of two parallel plates across the piezoelectric and R_{e1} and R_{e2} are the electrical losses in the devices from, for example, current leakage across the piezoelectric.

Device 2 and n devices connected to the active Device 1 which undergoes an impact event have no power sources in as at this impact event of Devices 1. However, as n devices are electrically connected, these connected devices will be excited by the electrical power produced by Device 1. This is modelled as in Figure 9a consisting of mechanical and electrical behave modelled with the equivalent circuit.

Figure 9b is a simplified theoretical equivalent circuit of the n connected devices used to model the energy flow when Device 1 undergoes on impact event over the whole duration t_d of the event and damping of the vibration of the device, with duration of for example 0.06 s. The voltage drop across the source and load resistor R_{load} is given by Equation (8), the voltage of the simplified theoretical model (stm):

$$V_{stm}(n) = \left(\frac{E_0}{t_d}\right)^{0.5}\left(\frac{1}{R_{load}} + \frac{n}{R_0}\right)^{-0.5}$$

Equation (8)

It is assumed that the losses within each devices are the same, such that $R_1 = R_2 = R_0$. R_0 is a component which lumps together all mechanical and electrical losses in a single device. It is also assumed that the energy captured from the droplet impacted is not a function of n devices connected. It is assumed that no energy is returned back to the remains of the droplet water from energy that was captured.

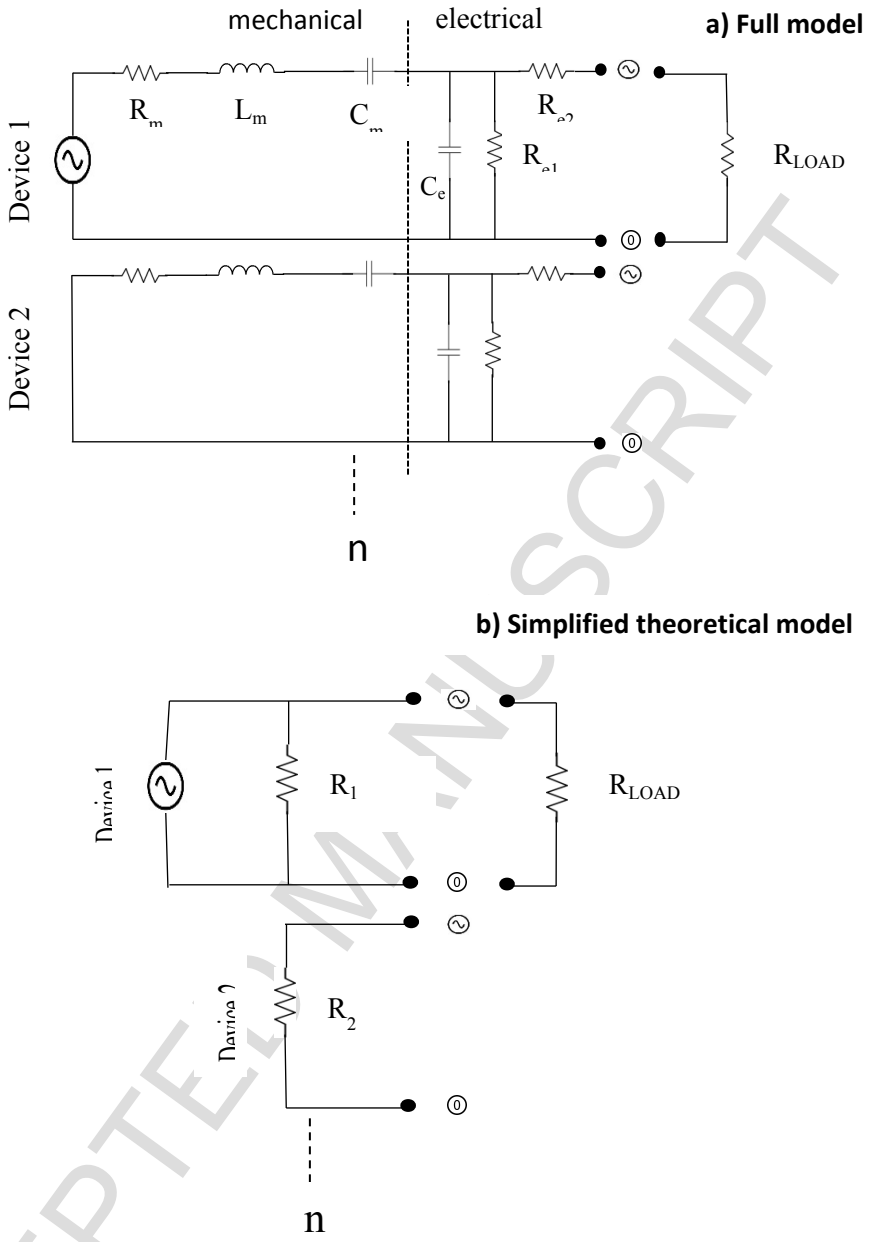

Figure 9: *Equivalent Circuit Model of Multiple Connected Devices*

5.2 Efficiency of the Impact Mechanism

Using the simplified theoretical model of Figure 9b and its Equation (8) with the experimental data empirically model in Equation (7), the energy captured from the impact mechanism E_0 can be found. This is the energy transferred from the droplet to the harvester as the droplet impacts the surface.

A simple procedure is presented which uses the decrease in the output voltage with the increase in n devices to extrapolate to give $V_{stm}(0)$, the excitation voltage of the device with no internal losses, to find E_0:-

a) Plot experimental data (circle data points in Figure 10) and fit a trend line to acquired empirical model $V_{em}(n)$. The best fit is a power function which is valid between the limit of $\{7 \geq n \geq 1\}$ and thus $V_{em}(0)$ cannot be found.

b) Find the change in V_{em} with the change in the number of device n for each n, $\Delta V_{em}/\Delta n$, from the empirical model $V_{em}(n)$ data. These data points are plotted as triangle on Figure 10.

c) Plot a best fit line for $\Delta V_{em}/\Delta n$ data to give $dV_{em}(n)/dn$ and extrapolate back to n=1 The data point for n=1 is plotted as a square in Figure 10.

d) Therefore the change is V_{em} from n = 0 to n = 1 can be found and thus $V_{stm}(0)$ is estimated. This value is plotted as a diamond data point in Figure 10. $V_{stm}(n)$ can be plotted once R_0 is found (see section 5.3). This is plotted as a dotted line on Figure 10.

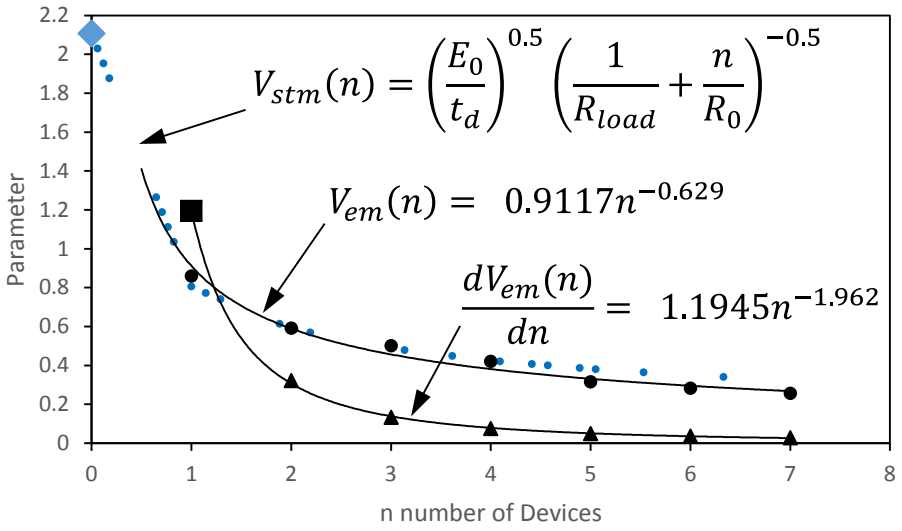

Figure 10: *Finding the Excitation Voltage $V_{stm}(0)$*

Using the data from the experiments for the velocity of droplet at 2.13 m/s, $V_{stm}(0)$ is found to be 2.106 ± 0.11 V. Given that the whole harvesting process duration is t_0, estimated at 0.06 s, E_0 is found to be 266.2 ± 29 nJ. Table 1 gives values for the kinetic energy of drops and thus the efficiency of the impact mechanism can be estimated and is found to be 0.350 ± 0.054 %.

5.3 Efficiency of the Mechano-Electric Conversion Mechanism

Again, using the simplified theoretical model of Figure 9b and its Equation (8) with the experimental data empirically model in Equation (7), and also knowing the energy captured from the impact mechanism E_0, the losses within a harvest R_0 can be found. This is realised by using a numerical method by inputting trial values of R_0 in Equation (8) to find best fit to the experimental data empirically model by Equation (7). This analysis is shown in Figure 11 with 3 trial values of R_0. Giving an estimate of $R_0 = 170 \pm 30$ kΩ.

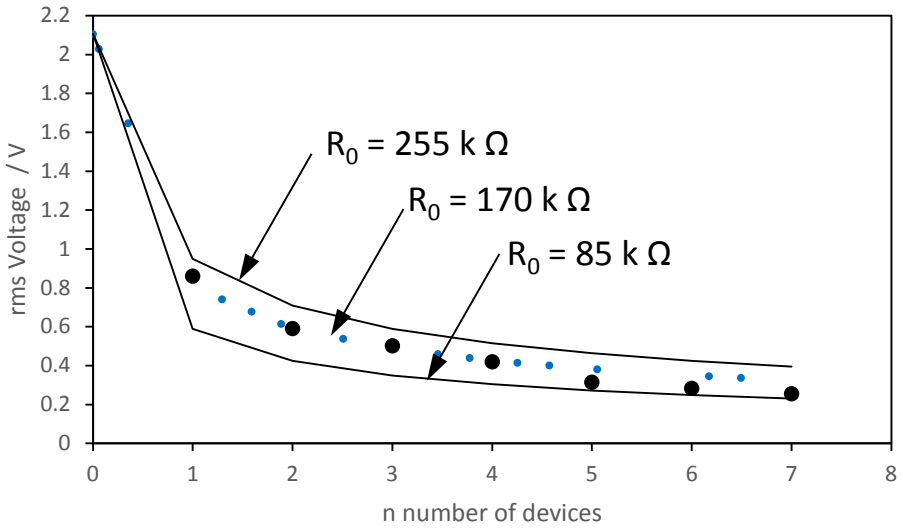

Figure 11: *Finding the Internal Resistance (losses) R_0 of a Harvester*

The energy delivered by a single device is found to be 51 ± 12 nJ, see Figures 5c and 8c. This energy comes from the energy delivered by the impact mechanism which is 266.2 ± 29 nJ giving and efficiency for the mechano-electric conversion mechanism as 0.334 ± 0.073 %

5.4 Efficiency With and Without Rectification

The overall efficiency of a single device without rectification is found to be 0.671 ± 0.158 %. By adding further devices in parallel in a harvesting module (without rectification) reduces the efficiency of the output during a single droplet impact. With 7 devices, the efficiency is reduced to 10% of the case with a single device. This is due to the additional devices being excited by the one device which has the droplet impact. A way to overcome this is to prevent the additional devices from being excited. One means is to use semiconductor diode rectification.

The rectified devices were connected in parallel to build a module of up to 7 devices. A disadvantage with using the silicon diode technology is that there is a voltage drop of the silicon

diode of around 0.7 V. The effect of this can be seen in the results. For the single device case, there is a drop of power output from the non-rectified device to the rectified device. As Figure 8c illustrates the rectified case maintains a constant power out as a function of n device which is around 34% of the single device non-rectified case. Using rectification ensures that the efficiency to not full with increasing number of device n as in the non-rectified case.

5.5 Application & Future Work

Due to the limitation of active piezoelectric material used in this study, the output of such a device is very low which therefore means it is likely be used in conjunction with other technologies such as photovoltaic or thermoelectric generators. The findings in this study will help develop a device that can be optimised as part of a combined energy harvesting device for consumer electronics with low power input. The device can be further integrated in remote locations where access to the grid is intermittent or non-existent.

For applications in low-power consumer devices, piezoelectric materials are required with the properties of wide degree of freedom in shapes and stretchable characteristics. These properties can then open various other applications beyond hand-held devices to wearable energy generating sources. Future work will comprise of fabricating piezoelectric materials with high piezoelectric property and sustainable material. In this study we have used commercially available materials that are not specifically designed to harvest energy using impact of raindrops. This study explored the effect of rectification which used silicon diodes with a voltage drop of around 0.7V, future experiments will be conducted on diodes with a very low voltage drop.

Another area to explore would be increasing the output of such a device by improving the conversion efficiency. The next stages of this work will focus on improving the impact, electro-mech and connection efficiencies. In addition, the devices will be trialled in real rainstorm presenting an opportunity to investigate the behaviour of devices in such conditions.

6. Conclusion

This paper presents voltage output of piezoelectric device using the active material Polyvinylidene fluoride under the impact of water droplets. Piezoelectric device was connected to resistive load and voltage measurements were taken to calculate the output of the device.

The effect on efficiency of the module with non-rectified or rectified outputs of each device connected in parallel is investigated. Additionally, the voltage, power and energy were found for different surface angles, surface conditions and impact regions for single devices with a view to maximise module efficiency.

The main findings of this work are that: a) a technique is found to separate the efficiency of the impact mechanism as the droplet interacts with the device and the efficiency of the mechano-electric conversion mechanism due to internal losses in the device; b) values for the impact mechanism efficiency and the conversion mechanism efficiency; and c) the optimum arrangement for a single device.

The energy delivered from the impact mechanism E_0 is found to be 266.2 ± 29 nJ. Given 7,597nJ of kinetic energy in the falling droplet, the efficiency of the impact mechanism is estimated to be 0.350 ± 0.054 %. The energy delivered from the device is found to be 51 ± 12 nJ. Given 266.2 ± 29 nJ of energy from the impact mechanisms, the efficiency of the mechano-electric conversion mechanism is estimated to be 0.334 ± 0.073 %. The overall efficiency of a single device is found to be 0.671 ± 0.158 %. Adding further devices to make a multi-device module further reduces the efficiency as other devices are a source of power loss for any one device that is impacted by a droplet. Rectification on the output of each device does improve the performance for a multi-device module.

One of the main contributions this works makes is that there are three points in the harvesting process where energy can be lost. This work also shows how to separate impact efficiency from mech-elec conversion efficiency. It also shows that care needs to be taken in interconnecting devices. All these aspects have not been published before.

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