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Piezoelectric energy harvesting from raindrop impacts

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ABSTRACT

PEH (piezoelectric energy harvesting) techniques can be used to capture vibration, motion or acoustic noise, to be converted in to electrical output. In recent years there has been an increased interest in scavenging energy using alternative sources. This study focuses on the impact of raindrop on a PEH device and the possibility of harvesting energy from this source. Impact of water droplets on a PEH are analysed after having been released from various heights to replicate a rain shower. Detailed experimental results show features which have not been published in the literature before. The results show two distinct stages in the voltage and power output; first, a log growth, then an exponential decay during an impact event. A model is also developed to characterise the output power for one unit device which is then applied to an array of rain impact harvesters. The experimental results show a power output for one unit at around 2.5 μW that is typical of the data produced in other publications. However, there is significant room for improvement as the efficiency of the system is found to be no more than 0.12% of the total kinetic energy in a typical raindrop in freefall.

1. Introduction

EH (energy harvesting) is a process whereby energy is captured from external sources such as solar, wind or other means. The challenge is to provide efficient and “clean” power for micro to macro level applications. EH techniques at the micro-level can mainly be categorised into three forms: piezoelectric, thermoelectric and photovoltaic. The present study examines harvesting energy from raindrop impact using a PEH (piezoelectric energy harvesting) device.

PEH devices use vibrations, motion or acoustic noise as the source of external energy which can be converted to electrical energy. These are typically used for application with low power requirements such as powering sensor equipment from ambient vibrations [1], MEMS (microelectromechanical systems) [2], wireless sensor [3], and military applications [4]. Although significant progress has been made in this field in the development of microscale power supplies, power management and consumption, there remains a need to improve these further with the advent of the “Internet of Things”.

A piezoelectric material is capable of producing an electric charge when the material undergoes mechanical stress. There are many materials such as quartz and tourmaline crystals that exhibit this piezoelectric effect. Such materials have in the past been actively used as electromechanical transducers [5]. The ferroelectric group of materials which exhibit the piezoelectric effect are also known as piezoelectric materials. Ferroelectric ceramics such as PZT (lead zirconate titanate) are widely used in EH due to their favourable properties and much discussion can be found in the literature on these, for example [6,7]. PZT devices have been considered to be a prospective replacement for batteries in some applications due to their high piezoelectric character and energy output. Organic materials such as PVDF (polyvinylidene fluoride) are mainly used in applications requiring a higher degree of mechanical flexibility and optical transparency. These polymers are relatively cheap and can be easily integrated into various applications; in garments or shoes [8]. These polymers also exhibit unique features such as demonstrating excellent mechanical behaviour, being corrosion resistant, having the ability to withstand stress without structural fatigue and illustrating an ease of processability on dielectric thin films. In particular, these polymers have the potential to be integrated into flexible devices [9].

The focus and novelty of this study is to show the behaviour of a harvesting system scavenging energy from raindrops. Three points in particular have been found from the work:-

- A detailed voltage output profile from the piezoelectric device shows that there is an initial impact stage and a decay stage with

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an oscillatory character to the harvesting event of an impact. These features have not been demonstrated until now.

- The initial impact stage, of the interaction mechanism between the droplet and device, lasts for a significant period when compared to the duration of the entire harvesting event.
- The power output is at a very low level and is consistent with other researchers' work. However, the efficiency is found to be very small as well, providing an opportunity for future improvement of the transfer function of the device, for example, by modifying the harvester's surface.

1.1. Raindrop energy harvesting

EH from the impact of raindrops has been gaining significant research interest over recent years by a handful of groups, and the potential still has not been fully unlocked. It is this REH (raindrop energy harvesting) that is the focus of this study. Many geographical locations receive a moderate to heavy rainfall which can then be utilised to generate electricity as an alternative method to conventional and other mainstream renewable techniques. Energy output using such a system is very low in comparison to other forms of renewable power generation, but may be sufficient to power electronic devices in specialist low power applications where replacing batteries is not a feasible option. Additionally, the battery-less application is becoming more frequent because of the limitations due to size, weight, environmental impact and life of the battery. Applications like wireless micro-sensor networks [10] and MEMS (microelectromechanical systems) [11] are examples of such emerging technologies that have integrated energy harvesting methods.

The energy output in REH devices depends on the mass of the droplet, the velocity and the mechanism of impact at which it strikes the harvesting device. The radius of rain droplet can vary between 1 mm and 5 mm depending on geographical location and type of rain [12]. The maximum output reached experimentally using these techniques is 12 mW as detailed in Ref. [13].

1.2. Impact velocity

There are many factors that affect the output of a REH device. The key factors of the droplet are; volumetric size, mass, and velocity of impact. A raindrop in freefall towards the ground experiences two forces that are exerted vertically on it: a force acting upwards, known as the drag force, and the force acting downwards, the gravitational force resulting in the weight of the droplet.

The drag force on the droplet is represented in Equation (1), where ρ_a is the density of air, A is the projected frontal area of the droplet, v is the velocity of the droplet and C is the coefficient of drag.

$$F_{air} = \frac{1}{2}\rho_a A C v^2 \tag{1}$$

The weight of the droplet is represented in equation (2), where ρ_w is the density of the water droplet, r is the radius of the droplet and g is the acceleration of the droplet due to gravity.

$$F_{gravity} = \frac{4}{3}\pi r^3 \rho_w g \tag{2}$$

When these forces are in balance the droplet reaches its terminal velocity, v_T, the maximum velocity if no other forces act on the raindrop. This is shown in Equation (3), where d is the diameter of the droplet.

$$v_T = \sqrt{\frac{\pi d^3 \rho_w g}{6 \rho_a A C}} \tag{3}$$

The assumption made in this study is that all rain droplets are spherical in shape. In reality, this can vary depending on the type of rain shower and the air resistance. Most experiments conducted under laboratory conditions, as reported in the literature, using a standard burette or pipette arrangement will typically have the diameter ranging between 0.5 mm and 2 mm, for which the droplet remains in a spherical shape. With an increase in the diameter of the droplet, it has been shown that the shape can change depending on wind speed and air resistance [14]; however that discussion is beyond the scope of this study.

1.3. Raindrop impact mechanism

The impact mechanism is another factor which will significantly influence the energy transfer function of the harvesting device and its power output. Generally, the impact mechanism of a droplet falling onto a solid surface can be divided into three main categories: 1) bouncing, 2) spreading and 3) splashing. The water droplet can either fully bounce leaving no water residue on the solid surface, which is depicted in Fig. 1a, or partially bounce leaving water residue, as depicted in Fig. 1b. The second category of the water droplet is spreading on impact, when the water adheres to the surface at impact, as depicted in Fig. 1c. The third category of the water droplet is splashing, when the droplet breaks into many parts and adheres to the surface. The droplet will then be distributed on the surface as depicted in Fig. 1d. The impact of a droplet on a harvesting device is expected to demonstrate all or a combination of these mechanisms. Studies have shown these types of droplet impact mechanisms on solid surfaces [15,16].

Various studies show the dominant impact mechanism of a water droplet is one that involves splashing [14]. An empirical relation as represented in Equation (4) is developed by Stow et al. [17] and by Mundo et al. [18] from experiments, where R_e is the Reynolds number (a dimensionless number defined as the ratio of inertial forces to viscous forces), W_e is the Weber number (a dimensionless number with relative importance of fluids inertia compared to surface tension) and K defined as a constant (which depends on the roughness of solid surface and thickness of layer).

$$K = W_e^{\frac{1}{2}} \times R_e^{\frac{1}{4}} \tag{4}$$

The Reynold's and Webber's numbers are found from the equation (5) below where ρ_w is the density of fluid, μ_a is the viscosity, σ is the surface tension of the fluid and v is the velocity:

$$Re = \frac{\rho_w v d}{\mu_a}; \quad We = \frac{\rho_w v d}{\sigma} \tag{5}$$

It was proposed that the behaviour of the water droplet can be determined by Equation (4), which will either deposit on the surface or splash. If K is found to be smaller than a particular K_c, a

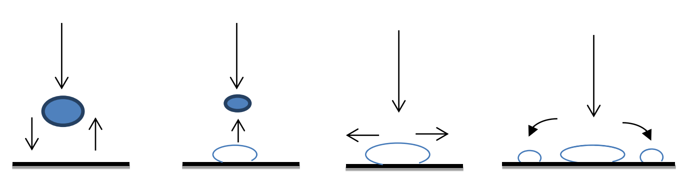

Fig. 1. Water droplet impact on solid surface.