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Article

Study on Pyroelectric Harvesters Integrating Solar Radiation with Wind Power

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Abstract: Pyroelectric harvesters use temperature fluctuations to generate electrical outputs. Solar radiation and waste heat are rich energy sources that can be harvested. Pyroelectric energy converters offer a novel and direct energy-conversion technology by transforming time-dependent temperatures directly into electricity. Moreover, the great challenge for pyroelectric energy harvesting lies in finding promising temperature variations or an alternating thermal loading in real situations. Hence, in this article, a novel pyroelectric harvester integrating solar radiation with wind power by the pyroelectric effect is proposed. Solar radiation is a thermal source, and wind is a dynamic potential. A disk generator is used for harvesting wind power. A mechanism is considered to convert the rotary energy of the disk generator to drive a shutter for generating temperature variations in pyroelectric cells using a planetary gear system. The optimal period of the pyroelectric cells is 35 s to harvest the stored energy, about 70 μJ, while the rotary velocity of the disk generator is about 31 RPM and the wind speed is about 1 m/s. In this state, the stored energy acquired from the pyroelectric harvester is about 75% more than that from the disk generator. Although the generated energy of the proposed pyroelectric harvester is less than that of the disk generator, the pyroelectric harvester plays a complementary role when the disk generator is inactive in situations of low wind speed.

Keywords: pyroelectric harvester; solar energy; wind power; waste heat harvesting

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1. Introduction

Heat sources are an important source of energy, which can be harvested for driving electronic devices and systems. For example, solar radiation can be directly utilized as a thermal energy source for powering many devices and systems. Solar thermoelectric generators produce an electro-motive force using the Seebeck effect. Direct energy conversion using thermoelectric generators mainly relies on this effect to convert a steady-state temperature difference at the junction of two dissimilar metals or semiconductors into an electromagnetic force or electrical energy. Thermoelectric generators need fixed temperature differences, and cannot generally work in environments with spatially uniform and time-dependent temperature fluctuations with short periods. Alternatively, pyroelectric devices can directly convert time-dependent temperature oscillations into electricity [1–3]. Pyroelectricity is a property whereby a charge is generated on the surface of pyroelectric materials as a result of a change in temperature, and manifests itself in polar materials due to the temperature dependence of its electrical polarization. The direction of the pyroelectric current changes with the changing nature of the thermal gradient. When the temperature of pyroelectric materials increases ($dT/dt > 0$), polarization decreases due to the re-orientation of the dipole moment, resulting in an electrical current in an external circuit. Conversely, when the temperature of pyroelectric materials decreases ($dT/dt < 0$), polarization increases as dipoles gain their orientation. This also results in an electrical current in the reverse direction. Hence, utilization of the pyroelectric effect for energy generation from solar temporal variations looks to be a promising strategy. The pyroelectric current is given by [4,5]:

$$i_p = dQ/dt = \eta \times P \times A \times dT/dt \text{ or } Q = \int_{t_b}^{t_t} \eta \times P \times A \times dT/dt\, dt \quad (1)$$

where η is the absorption coefficient of radiation; A is the electrode area; dT/dt is the temperature variation rate of the pyroelectric materials; Q is the induced charge; t_t and t_b are, respectively, the considered terminal and beginning times; and P is the pyroelectric coefficient of the pyroelectric materials given by:

$$P = dP_s/dT \quad (2)$$

where P_s is the magnitude of the electrical polarization vector. Pyroelectric cells are sandwiched between the top and bottom electrodes, as flat-plate capacitors, and poled along the axis perpendicular to the plates. P_s is perpendicular to the electrode surface when its magnitude is equal to the electrode charge density. The thermal-isolation structure, pyroelectric material properties, electrode layout and absorption coefficient of the pyroelectric materials are the most important factors for enhancing qualities. From Equation (1), it can be seen that a higher temperature variation rate in the pyroelectric cells leads to a higher response current in the pyroelectric devices. However, the temperature variation rate is difficult to extract from pyroelectric layers by experimental measurement. Some finite element models have been built using the commercial software package COMSOL to explore the temperature variation rate in pyroelectric cells, with cavities by wet etching, trenches by a precision dicing saw and grooves by sandblast etching designed to improve the energy conversion efficiency of PZT pyroelectric cells by pyroelectricity [6–8]. Therefore, pyroelectric materials with high P values and applications with large temperature variations over time should be considered. Moreover, increasing the surface of the pyroelectric cells produces an increase in the current at parity with the incident thermal power density per unit area.

Moreover, the great challenge for pyroelectric energy harvesting lies in finding promising temperature variations or an alternating thermal loading in real situations. Although Zhang *et al.* [9] developed a proposal for integrating solar radiation and wind flow fluctuation to drive pyroelectric generators, a strong and a weak wind, respectively, were used to bring about temperature variation rates by strong forced and natural convection. However, the temperature variation rates in pyroelectric cells could not be obvious due to the uncertain wind velocity. Furthermore, the pyroelectric cells could not be periodically and consecutively heated and cooled. In this research, we have proposed a novel pyroelectric harvester integrating solar radiation with wind power by the pyroelectric effect. Solar radiation is a thermal source, and wind is a dynamic potential. A disk generator was used to harvest wind power. A mechanism was considered to convert the rotation energy of the disk generator to drive a shutter for generating temperature variations in pyroelectric cells (Lead Zirconate Titanate, PZT) by means of a planetary gear system. The temperature variation rate in the pyroelectric cells was generated by a shutter designed to transmitted airflow. The objectives of this research were the design and construction of a pyroelectric harvester driven by solar radiation and wind power. The performance of the harvester was analyzed in terms of optimizing the work cycle of pyroelectric cells under a controlled airflow.

2. Materials and Methods

2.1. Design for Pyroelectric Harvesting System

A PZT pyroelectric cell with the dimensions of 9 mm × 9 mm × 0.214 mm was used. The cell comprised a 0.2 mm-thick PZT sheet sandwiched between a top and a bottom electrode. The electrodes were made of 7 μm-thick silver film. The PZT samples were provided by Eleceram Technology Co. Table 1 shows the properties of the commercial PZT pyroelectric cell. A thick PZT sheet with a low electrical capacitance is more likely to generate higher voltages than a thin PZT film with a high electrical capacitance under a given temperature variation [5]. However, a thick pyroelectric material has a high thermal capacity, which hinders quick temperature variations. Obviously, a thin pyroelectric material has a high temperature variation rate. Although thin film deposition technology can be used to grow films with a lower thickness, their pyroelectric properties usually decrease quickly [10]. Moreover, a commercial PZT bulk material possessing acceptable pyroelectric properties together with the trenched electrode design is useful for improving the temperature variation rate and enhancing the efficiency of pyroelectric harvesters [6–8].

Table 1. Properties of the commercial PZT (Lead Zirconate Titanate) pyroelectric sheet.

Sample ID	**Thickness (μm)**	**Area (mm^2)**	**Size (mm × mm)**	**Relative Dielectric Constant ($\varepsilon_{33}^T/\varepsilon_O$)**	**Density (g/cm^3)**	**Poling Field (V/μm)**	**Pyroelectric Coefficient ($10^{-4}\cdot cm^{-2}\cdot K^{-1}$)**
KA	200	81	9 × 9	2100	7.9	3.5	6.97

The proposed pyroelectric harvesting system integrated solar radiation with wind power. The main components of this system were the PZT pyroelectric cells, a pyroelectric module, a shutter, a disk generator and a planetary gear system. Figure 1 shows a schematic diagram of the pyroelectric harvesting system. The disk generator was provided by HAO-CHUEN ENERGY COMPANY Co (Chupei city, Hsinchu county, Taiwan). The disk generator was driven by wind power, supplying the shutter via the planetary gear system with wind power. This planetary gear system consisted of two gear trains in series connection. Each gear train possessed a ring gear, three planet pinions and a sun gear. The number of teeth of the ring gear, the sun gear and the planet pinion were 60, 12 and 24, respectively. The rotary speed of the gears is inversely proportional to the gear ratio. When the ring gear was fixed and the sun gear was an input, an output at the planet pinions possessed the highest deceleration rate. The rotary energy from the disk generator as the input was set in the sun gear when the output to the shutter was set in the planet pinions when the ring gear was fixed. Hence, the planetary gear system was designed as a reducer with a speed reduction ratio of 1:36 by a two-gear train reduction. The output from the planet pinions was further used to drive the shutter, and by that the rotary velocity of the shutter determined the periods for raising and lowering the temperature in the pyroelectric cells. In other words, the rotary velocity of the shutter determined the temperature variation rates in the pyroelectric cells. A pyroelectric module fabricated by a printed circuit board (PCB) was adopted to arrange the pyroelectric cells, and the location of the pyroelectric cells was related to the shape of the shutter. The geometry and the location of the shutter and the pyroelectric cells are shown in Figure 2.

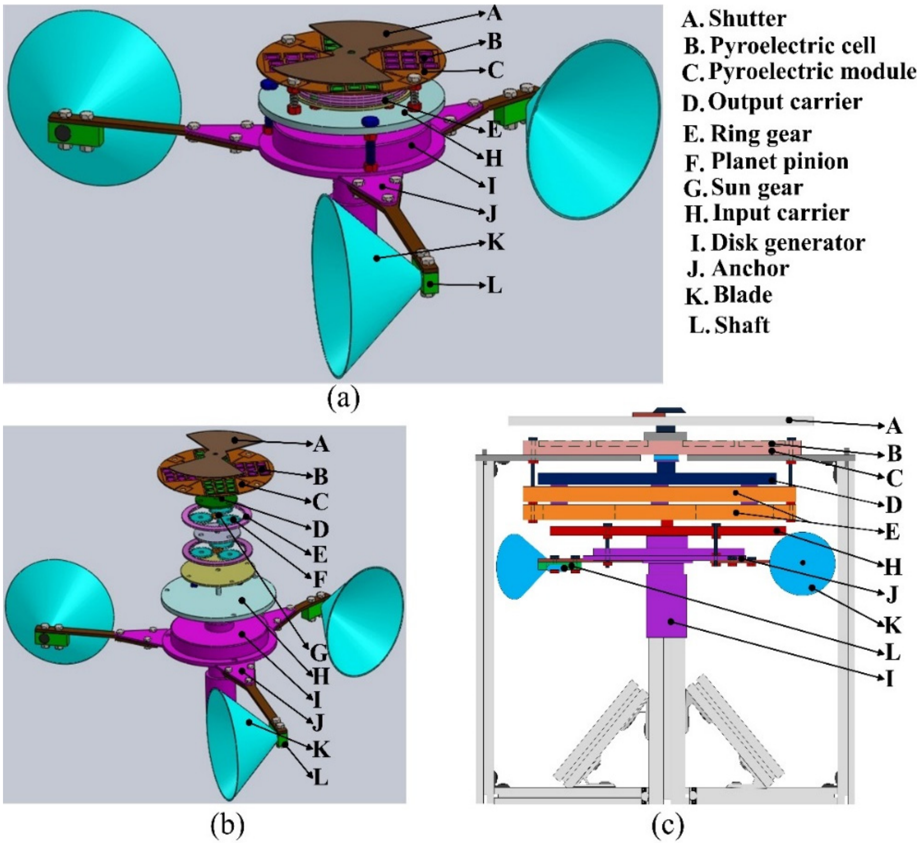


Figure 1. Schematic diagram of the pyroelectric harvester integrating solar radiation with wind power: (**a**) assembly drawing; (**b**) exploded view; and (**c**) lateral view.

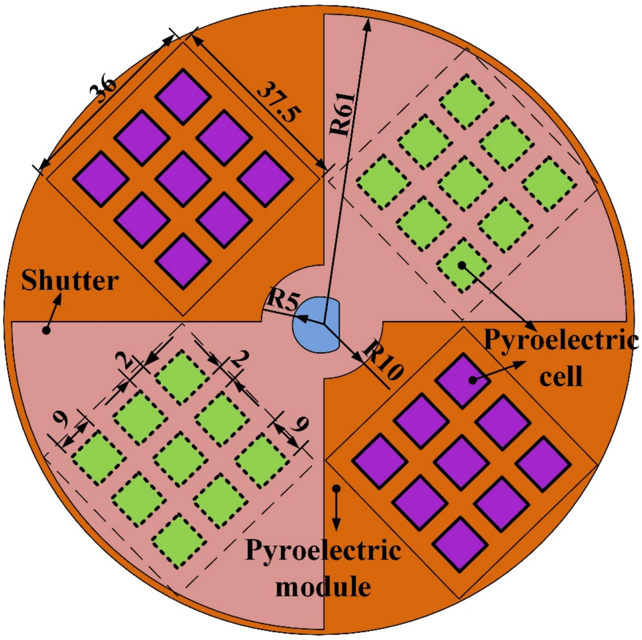


Figure 2. The geometry and the location of the shutter and the pyroelectric cells in the pyroelectric harvester (unit: mm).

2.2. Measurement

A measurement-coupled thermal and electrical system, as depicted in Figure 3, was used to estimate the performance of the proposed harvester. The thermal source was a radiating heat lamp (Heat Plus 250 W, 110 V, Philips, Amsterdam, Netherlands) for the resulting temperature fluctuations with the shutter in two ranges, 55 °C to 65 °C and 65 °C to 75 °C. The distance between the heat lamp and the PZT element was about 5 cm. Type K (Chromel/Alumel) thermocouple sensors, used to probe the temperature variations in the pyroelectric cells, were attached to the bottom electrode at the center of the PZT element, thereby ensuring good thermal contact. The PZT pyroelectric cells were attached and arranged in the pyroelectric module for measuring the electrical outputs via the SMA connectors. Thirty-six sheets of the pyroelectric cell in parallel were used to harvest the thermal cyclic energy. Because the shutter was divided into four parts, two heating and cooling zones were generated via its rotation. The pyroelectric cells placed on the pyroelectric module were also divided into four parts. The pyroelectric cells in the heating zone possessed the reverse polarization field to those in the cooling zone. The radiating heat lamp was the heat source for the simulated solar radiation, which was projected onto the PZT pyroelectric cells through the apertures of the shutter. In this way, the shutter prevented the PZT cell from absorbing the heat from the radiating heat lamp aperture. The disk generator was driven by a blower to generate the resulting the rotary energy. The ratio of the rotary speed of the disk generator (RPM) to wind speed (m/s) was measured and set at about 31.82:1 in this system. As the shutter rotated, the PZT pyroelectric cells were periodically heated and cooled. Subsequently, the output data of temperature, current and voltage were measured simultaneously with a computer-controlled data acquisition apparatus (Agilent 34980A).

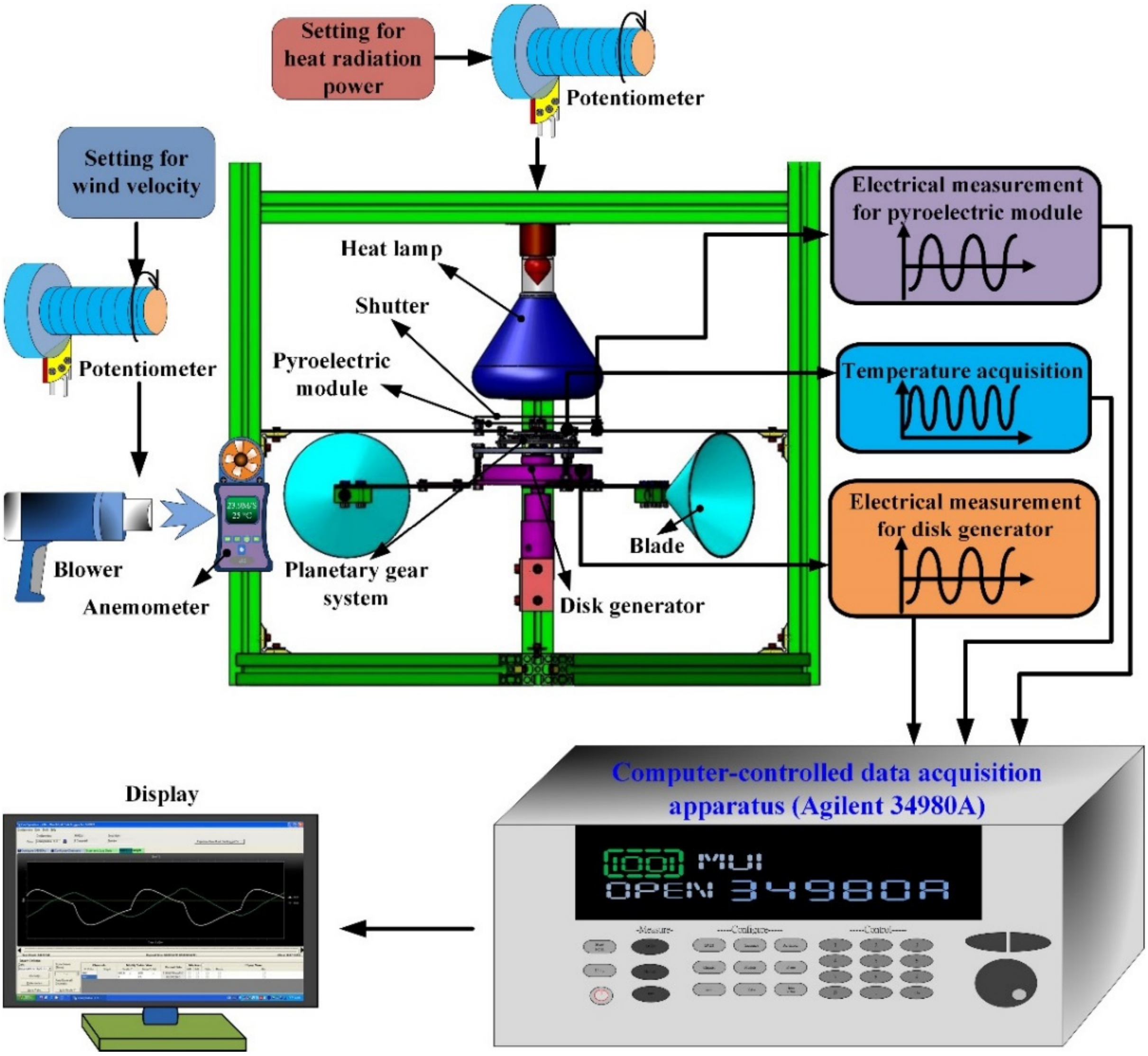


Figure 3. Measurement setup for the pyroelectric harvester integrating solar radiation with wind power.

The induced charge generated from the pyroelectric elements and the disk generator was stored in a capacitor, C_L, as a storage element, using a full-wave rectifier circuit, as depicted in Figure 4. Thus, the charge accumulated in a capacitor, taking advantage of both heating and cooling periodic cycles. The capacitor (C_L) was a 10 μF electrolytic capacitor with a 50 V maximum voltage. The measured forward voltage drop of the diodes (Model: 1N4148, IHS, Englewood, CO, USA) was 0.62 V. During the heating cycle, the two forward-biased diodes (D_1 and D_3) allowed the generated current flow, i_P, through to charge C_L. The other diodes (D_2 and D_4) were reverse-biased, and blocked the current flow. During the cooling cycle, the direction of i_P was reversed, and C_L was charged through D_2 and D_4. The temperature in the PZT sheets and the output voltage of the circuit (V_0) were also measured with the data acquisition unit (Agilent 34980A).

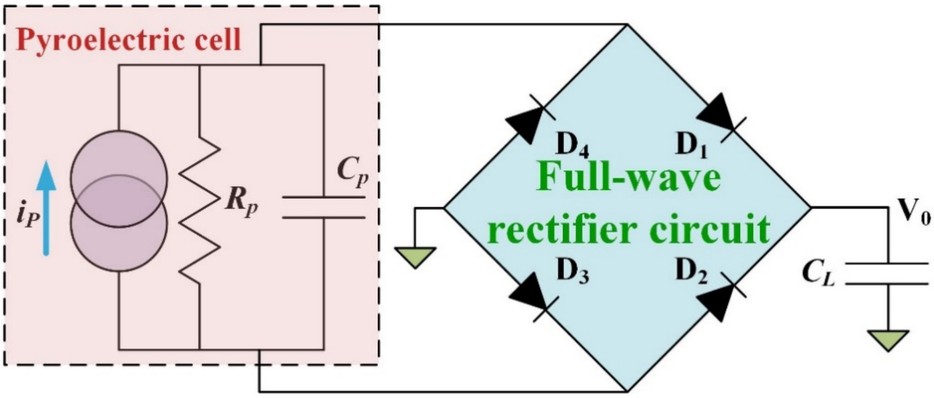


Figure 4. Full-wave rectifier circuit used to store the induced charge from the pyroelectric cell and the disk generator.

3. Results and Discussion

Pyroelectric energy conversion requires a periodic temperature profile applied to pyroelectric cells in order for the resulting temperature fluctuations to generate an electrical output. The critical consideration in the periodic temperature profile is the frequency or work cycle, which is related to environmental conditions, radiation power and material properties, as well as the dimensions and structure of the pyroelectric cells. Therefore, the efficient period band was first investigated in order to increase the efficiency of the power output. The planetary gear system was used to connect the disk generator and the shutter. The disk generator needed a higher rotational speed to generate the electrical output, while the pyroelectric harvester needed a lower rotational speed. The planetary gear system was designed as a reducer, with a speed reduction ratio of 1:36 by a two-gear train reduction while the input from the disk generator was set in the sun gear and the output to the shutter was set in the planet pinions under the ring gear fixed. Although the speed reduction ratio was a constant, the ratio was decided in a light breeze environment. In a higher wind speed, the disk generator was the main force generating the electrical output. In a lower wind speed, the proposed pyroelectric harvester played a complementary role by generating the electrical output when the efficiency of the disk generator was low. Therefore, the proposed pyroelectric harvester possessed a complementary function in cooperating with the disk generator in the electric output generation.

Figure 5 shows the stored energy in the storage capacitor of 10 μF through a full-wave rectifier acquired from the disk generator under various rotational speeds. It was revealed that the stored energy rate and the stable stored energy increased as the rotational speed of the disk generator increased. This presented a larger promotion in the stored energy rate and the stable stored energy when the rotational speed of the disk generator was greater than 100 RPM. Moreover, the energy storage efficiency was greatly reduced when the rotational speed was lower than 100 RPM in a light wind speed of 3.1 m/s. Moreover, Figure 6 shows the open-circuit voltage (V_{OC}) and the short-circuit current (I_{SC}) of the disk generator. The electrical outputs of the disk generator were proportional to rotational speeds, except when the rotational speed of the disk generator was lower than 40 RPM. Therefore, the pyroelectric harvester plays a complementary role when the disk generator is inactive. The speed reduction ratio of the planetary gear system, about 1:36, was used to reduce the rotational speed of the disk generator so as to match the longer period of the PZT pyroelectric harvester in situations of a weaker wind source.

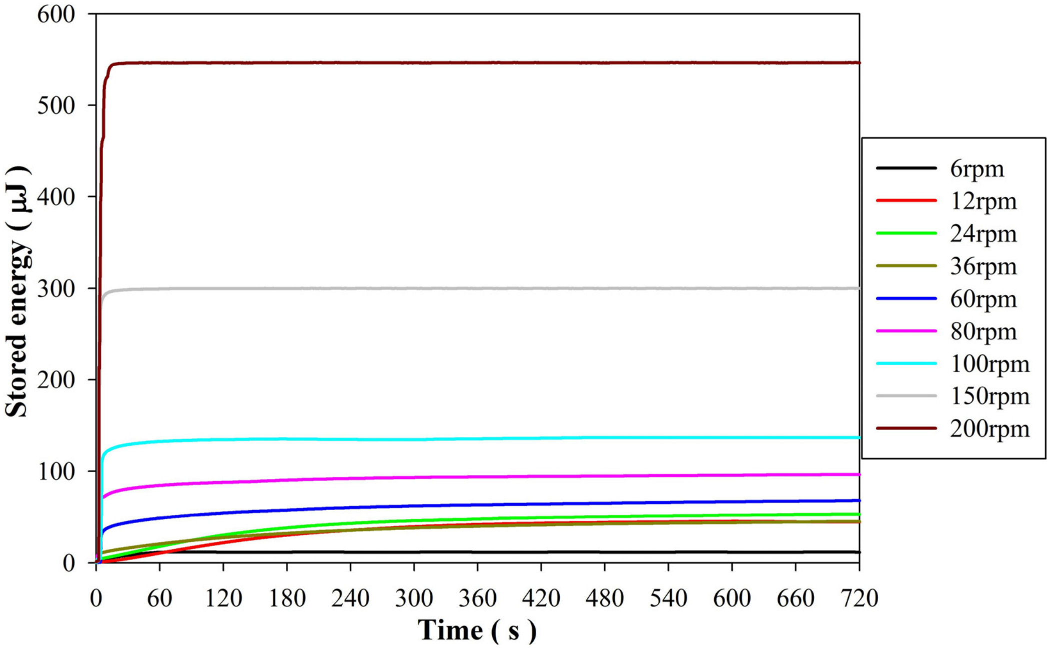


Figure 5. Stored energy in the 10 µF storage capacitor from the disk generator under various rotational speeds.

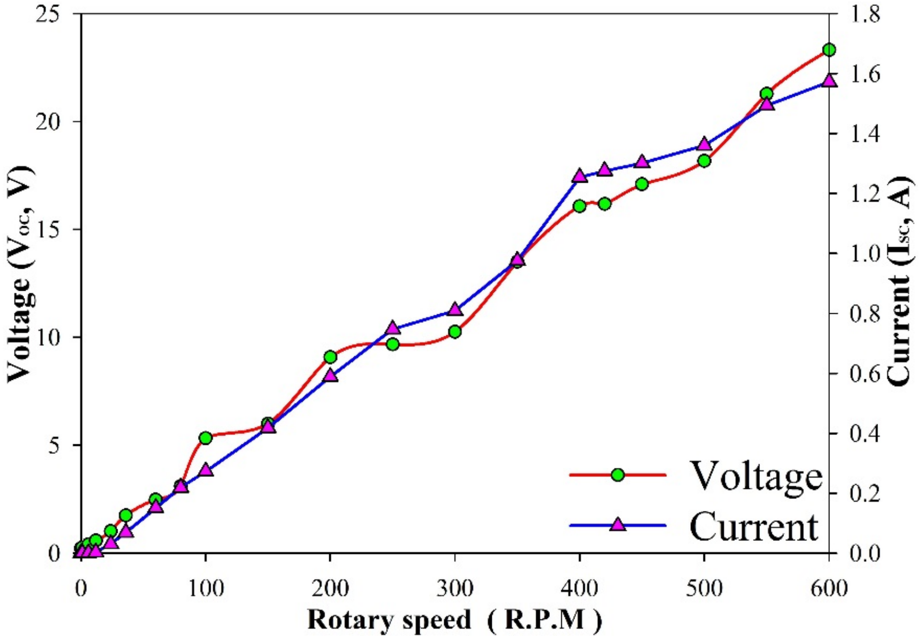
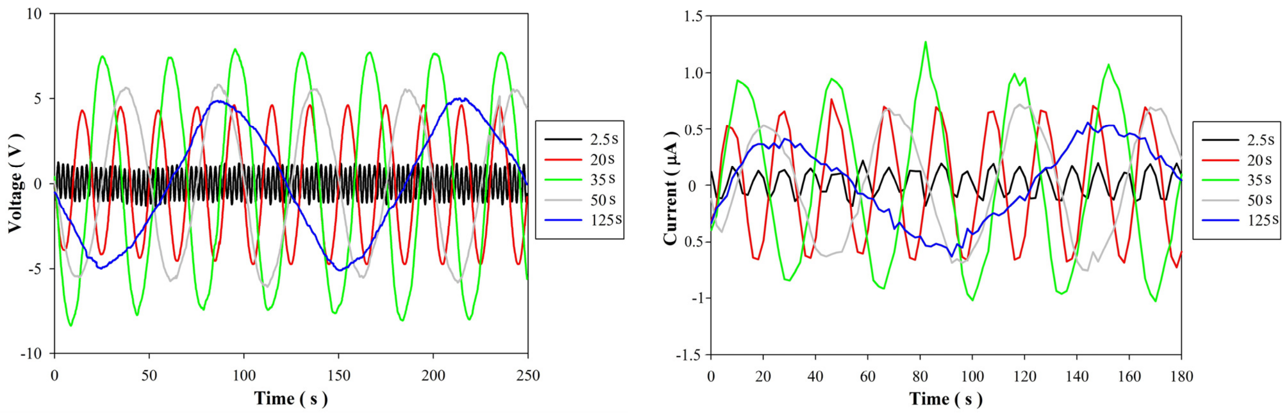


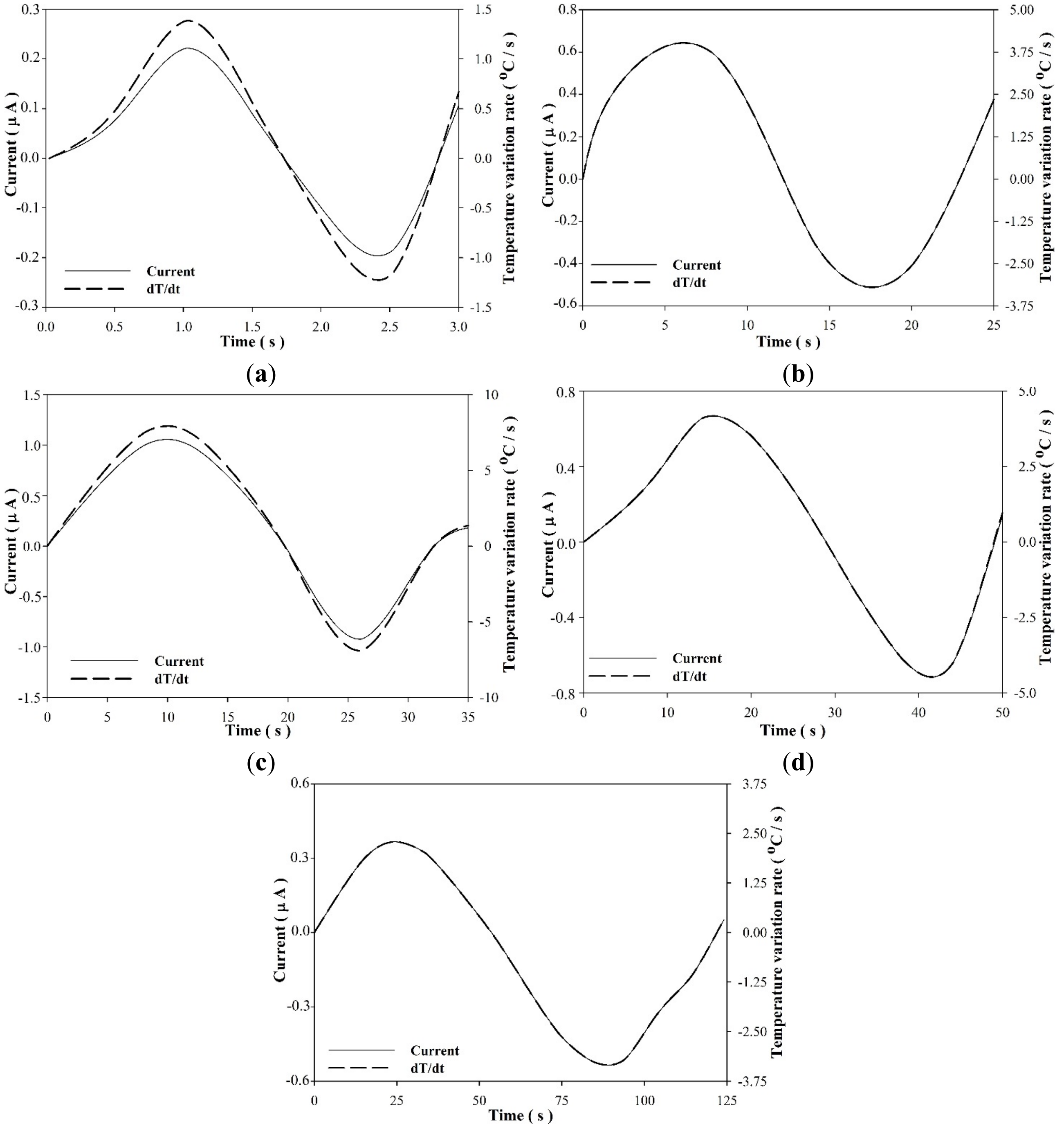
Figure 6. The open-circuit voltage and the short-circuit current of the disk generator under various rotational speeds.

The radiating heat lamp with the shutter resulted in temperature fluctuations in the range from 65 °C to 75 °C. Figure 7 shows the relationships between voltage, current and time for five periods, 2.5 s, 20 s, 35 s, 50 s and 125 s, when using the PZT pyroelectric harvester. It was obvious that the curves had the best peak value at about 35 s. The induced current was also proportional to temperature variation rates according to Equation (1), as shown in Figure 8. The optimal electrical output attributed to the largest temperature variation rate at about 35 s. The induced current and the temperature variation rate presented an appearance of time delay in the shorter periods of 2.5 s and 20 s due to the thermal capacity of the PZT cell. The induced charge was inferred from the integration of the area under the current curves by a numerical integration of Simpson's rule. Figure 9 shows the relationships between the induced charge per second and the stored energy per period in the 10 μF electrolytic capacitor at various period times when using the PZT pyroelectric harvester. The optimal period was also about 35 s for generating the best performance in the induced charge and the stored energy. Figure 10 shows the relationship between the stored energy in the 10 μF electrolytic capacitor at the various period times. A longer time was more beneficial when harvesting thermal energy than a shorter time. However, neither the shorter nor longer times allowed for pyroelectric energy to be harvested efficiently. In shorter times, the pyroelectric harvester was weak due to the thermal capacity of the PZT pyroelectric cell. In other words, the PZT pyroelectric cell needed a thermal time constant ($\tau_T = H/G_T$, H: Thermal capacity, G_T: Thermal conductance) to harvest sufficient thermal energy. In the longer times, the PZT pyroelectric harvester was also ineffective due to the lower temperature variation rate over the period. The frequency of ripples in the stored energy curves was related to the period of the shutter. The amplitude of ripples in the larger period was larger than that in the smaller period. This could be attributed to an excellent temperature variation rate firmly held over the longer period. The period of 35 s was suitable for the storing of thermal energy of about 70 μJ by using the proposed pyroelectric harvester. This energy could also be stored when using only the disk generator at a speed of about 80 RPM. The optimal period of 35 s in the pyroelectric harvester was with the disk generator at a rotary velocity of about 31 RPM, a wind speed of about 1 m/s and the planetary gear system having a speed reduction ratio of 1:36. This optimal situation occurred in the weaker wind power. However, the stored energy of the disk generator was about 40 μJ, while the rotary velocity of the disk generator was about 31 RPM. In this state, the stored energy acquired from the pyroelectric harvester was about 75% more than that from the disk generator. Hence, the pyroelectric harvester was beneficial in a condition of a light breeze. Moreover, the period of raising and lowering the temperature in the pyroelectric cell was also a critical factor for enhancing the performance of the PZT pyroelectric harvester.



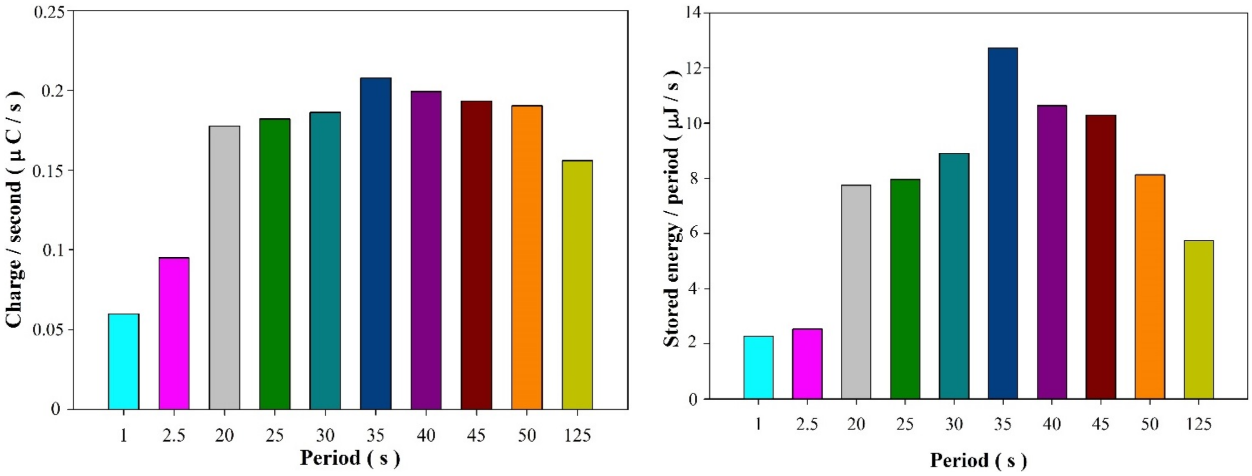
(a) **(b)**

Figure 7. Relationships between the voltage (**a**) and current (**b**) at five different period times (2.5 s, 20 s, 35 s, 50 s and 125 s) for the PZT (Lead Zirconate Titanate) pyroelectric harvester.



(**a**) (**b**) (**c**) (**d**) (**e**)

Figure 8. Induced current and temperature variation rate over time at five different period times (2.5 s (**a**); 20 s (**b**); 35 s (**c**); 50 s (**d**); and 125 s (**e**)) for the PZT pyroelectric harvester.



(**a**) (**b**)

Figure 9. Relationships between the induced charge per second (**a**); and the stored energy per period in the 10 μF electrolytic capacitor (**b**) at various period times for the PZT pyroelectric harvester.

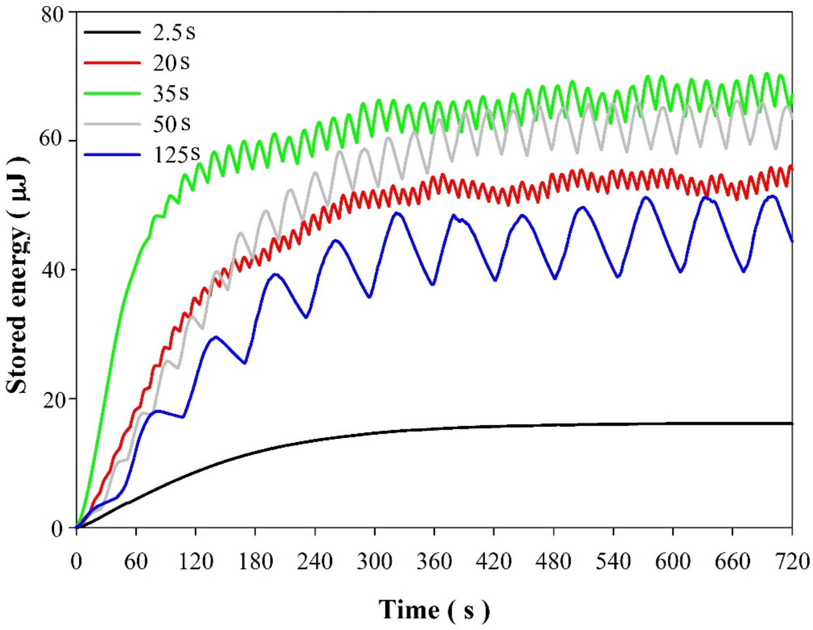


Figure 10. Relationships between the stored energy in the 10 μF electrolytic capacitor and times of various periods for the PZT pyroelectric harvester with temperature fluctuations in the range from 65 °C to 75 °C.

Decreasing the radiation power for evaluating the performance of the PZT pyroelectric harvester at a lower temperature fluctuation, the radiating heat lamp with the shutter resulted in temperature fluctuations in the range from 55 °C to 65 °C. Figure 11 shows the relationship between the stored energy in the 10 μF electrolytic capacitor and times of 2.5 s, 20 s, 45 s, 55 s and 125 s for the PZT pyroelectric harvester. It was obvious that the radiation power with temperature fluctuations decreased, the stored energy was also reduced. Moreover, the optimal period of the PZT pyroelectric harvester also increased to 45 s for harvesting stored energy of about 60 μJ. This could infer that the PZT pyroelectric cell needed more time to absorb the thermal energy when the radiation power was lower.

The stored energy rate in the range from 65 °C to 75 °C was apparently higher than that in the range from 55 °C to 65 °C. Hence, while the disk generator was active in a rich wind source, the pyroelectric harvester was active in a meager wind source with plentiful solar radiation. Although the generated energy of the proposed pyroelectric harvester was lower than that of the disk generator, the pyroelectric harvester played a complementary role, in cooperation with the disk generator, in the generating of electrical energy.

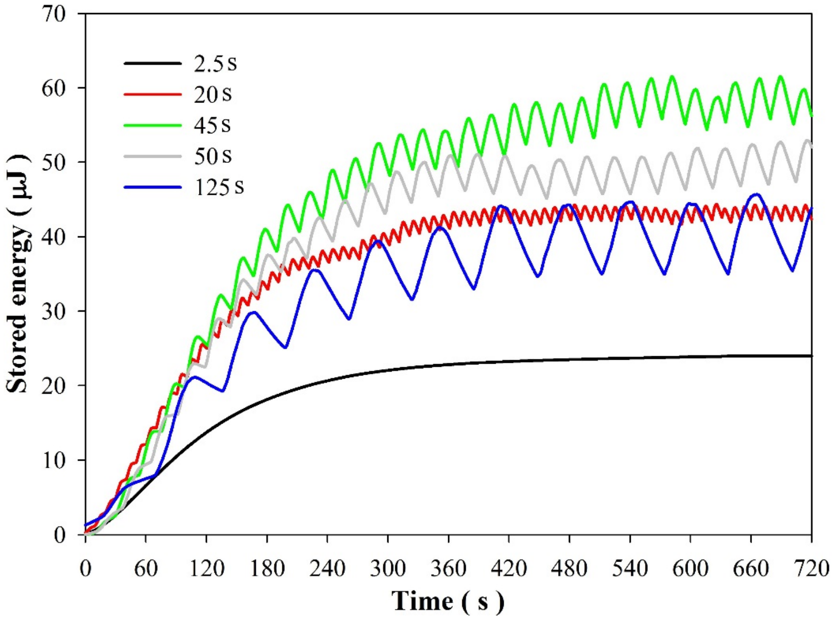


Figure 11. Relationships between the stored energy in the 10 μF electrolytic capacitor and times of various periods for the PZT pyroelectric harvester with temperature fluctuations in the range from 55 °C to 65 °C.

4. Conclusions

Pyroelectricity has been applied to power generators. Pyroelectric energy harvesting using a cyclic heating system to generate temperature variations transforms heat energy into electricity. A novel cyclic heating system was developed for varying the temperature in the PZT pyroelectric cells between the hot and cold regions. Therefore, a novel pyroelectric harvester was proposed for integrating solar radiation as a thermal source with wind power as a dynamic potential by the pyroelectric effect. A mechanism was designed to convert the rotation energy of the disk generator to drive the shutter for generating temperature variations in the PZT pyroelectric cells using a planetary gear system. The optimal period of the pyroelectric cells was 35 s to harvest stored energy of about 70 μJ, when the rotary velocity of the disk generator was about 31 RPM and the wind speed about 1 m/s. In this state, the stored energy acquired from the pyroelectric harvester was about 75% more than that from the disk generator. Although the generated energy of the proposed pyroelectric harvester was lower than that of the disk generator, the pyroelectric harvester played a complementary role, cooperating with the disk generator to generate the electrical output.

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Author Contributions

Jia-Wai Jhang and An-Shen Siao were involved in the data collection and experimental work under supervision of Chun-Ching Hsiao who carefully edited the paper, provided technical support and guidance, and directly contributed the results of this article.

Conflicts of Interest

The authors declare no conflict of interest.

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