A Magnetic/Piezoelectric-Based Thermal Energy Harvester

Tien-Kan Chung*[a], Ujjwal Shukla[b], Chia-Yuan Tseng[a], Chin-Chung Chen[a] and Chieh-Min Wang[a]
[a]Department of Mechanical Engineering, National Chiao Tung University, Hsinchu 30010, Taiwan
[b]Department of Mechanical Engineering, Indian Institute of Technology (Banaras Hindu University), Varanasi 221005, India

ABSTRACT

In this paper, we demonstrate a non-contact magnetic/piezoelectric-based thermal energy harvester utilizing an optimized thermal-convection mechanism to enhance the heat transfer in the energy harvesting/converting process in order to increase the power output. The harvester consists of a CuBe spring, Gadolinium soft magnet, NdFeB hard magnets, frame, and piezoelectric PZT cantilever beams. According to the configuration, the energy harvesting/converting process under a temperature-difference is cyclic. Thus, the piezoelectric beams continuously oscillate and subsequently produce voltage responses due to the piezoelectric effect. The maximum voltage response of the harvester under a temperature-difference of 25°C is 16.6 mV with a cycling frequency of 0.58 Hz. In addition, we compare the testing result of the harvester utilizing the new thermal-convection mechanism reported in this paper and using previous thermal-convection mechanism reported elsewhere. According to the comparison, the results show the harvester utilizing the new thermal-convection mechanism has a higher cycling frequency resulting in a higher power output than the previous mechanism.

Keywords: Energy Harvester, Power Generator, Piezoelectric, Magnetic, Thermomagnetic, Temperature, Thermal

1. INTRODUCTION

To date, wireless sensors network is comprehensively used in all kinds of environmental sensing and monitoring applications [1, 2]. The sensors are used in remote areas where the importance is given towards the use of energy source abundant in nature rather than using batter as the energy source [3]. Some potential energy sources are available and easily harnessed, such as vibrational energy, strain energy, fluidic energy, solar energy, thermal energy. Among these energy sources, the thermal energy source exists in everywhere. Therefore, harnessing the thermal energy becomes an important issue for the wireless sensors network. Recently, researchers utilize thermoelectric generators, one kind of the thermal energy harvesters, to harness the thermal energy to power the wireless sensors [4, 5]. Thermoelectric generators utilizing seebeck effect possesses a high potential for thermal-energy harvesting. However, in general, lots of thermoelectric generators have to be used together in order to have sufficient energy to power a wireless sensor of a wireless sensors network. Thus, utilizing the other energy sources together with the thermal energy source, if possible, would be the best energy solution for the wireless sensors network. More recently, researchers demonstrated novel thermomagneto-mechanical energy harvesters capable of converting a thermal energy to a mechanical energy [6-9]. Chung, et al, modified the thermomagneto-mechanical energy harvesters as a hybrid energy harvester demonstrating thermal, magnetic, and mechanical energy-harvesting approaches [10]. Therefore, Chung's harvester is able to be a candidate as the best energy solution for the wireless sensors network. However, Chung's harvester utilizes a non-optimized thermal convection mechanism as the heat transfer mode for the energy harvesting process. Due to this, the harvester has a low and limited cycling frequency resulting in a low power output. Hence, to address this issue, we present a new thermal convection mechanism for the harvester in this paper.

*tkchung@nctu.edu.tw; phone +886-3-5712121 ext. 55116; fax +886-3-572-0634

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2. DESIGN

The design of the thermal energy harvester utilizing the new thermal convection mechanism we proposed in this paper and previous thermal convection mechanism published elsewhere is illustrated in figure 1(a) and 1(b), respectively. The only difference between the two thermal convection mechanisms is the configuration of the energy harvester. That is, the configuration of the energy harvester in the new and previous design is a vertical and horizontal configuration, as shown in figure 1(a) and 1(b), respectively. Excluding the difference, the other parts of the two designs are identical. In both designs, the energy harvester consists of a spring with a soft magnet fixed at the center of the spring, mechanical frame with hard magnets attached on the frame, and piezoelectric cantilever beams sandwiched between the spring and frame, shown in figure 1.

The thermal energy harvesting process is shown in figure 2. According to the harvester's configuration, the energy harvesting/converting is a two-step process. Figure 2 (a) shows the first step (i.e., the initial state) of the energy harvester. That is, the soft magnet is close to the cold side resulting in the soft magnet's temperature lower than its Curie temperature. Lowering than the soft magnet's Curie temperature causes that the soft magnet becomes a ferromagnet. Due to magnetic attractive force between the soft and hard magnet, the soft magnet (fixed on the spring) moves toward the hard magnet (on the hot side), as shown in figure 2(c). When the soft magnet approaches to the hard magnet (hot side), the soft magnet's temperature is increased. When the soft magnet's temperature is higher than its curie temperature (i.e., the second step), the soft magnet loses ferromagnetic property resulting in eliminating the magnetic-attractive force. Thus, the soft magnet fixed on the spring bounces back to its initial location/state due to the spring-back force. Through the cyclic process, the spring would continuously oscillates under an environmental temperature-difference (i.e., the environmental temperature-difference causes a thermal gradient in the harvester, that is, produces a hot and cold sides for the harvester). While the spring is oscillated, the piezoelectric beams (sandwiched between the spring and frame) are cyclic-deformed. Due to the piezoelectric effect, continuous voltage response is produced by the cyclic-deformed piezoelectric beams.

In the energy harvesting process, when the soft magnet moves toward either the hot or cold side, the heat transfer occurs by only thermal convection [i.e., because no contact of surfaces between the soft and hard magnet during the motion shown in figure 2(b) and 2(d) is existed, no thermal conduction is occurred). Thus, the energy harvesting process is dominated by the convection rather than conduction. For the convection, because the vertical configuration is built in a way so as to help in natural convection (both hot and cold air flow vertically in the air gap between the soft and hard magnets, thus the air flow wound not be blocked by any part of the harvester), the energy harvester utilizing the vertical configuration is more efficient in the heat transfer than using the horizontal configuration. More efficient in the heat transfer cause the spring/piezoelectric-beams oscillated with a higher cyclic frequency. Due to the higher cyclic frequency, more power output is produced by the piezoelectric beams.

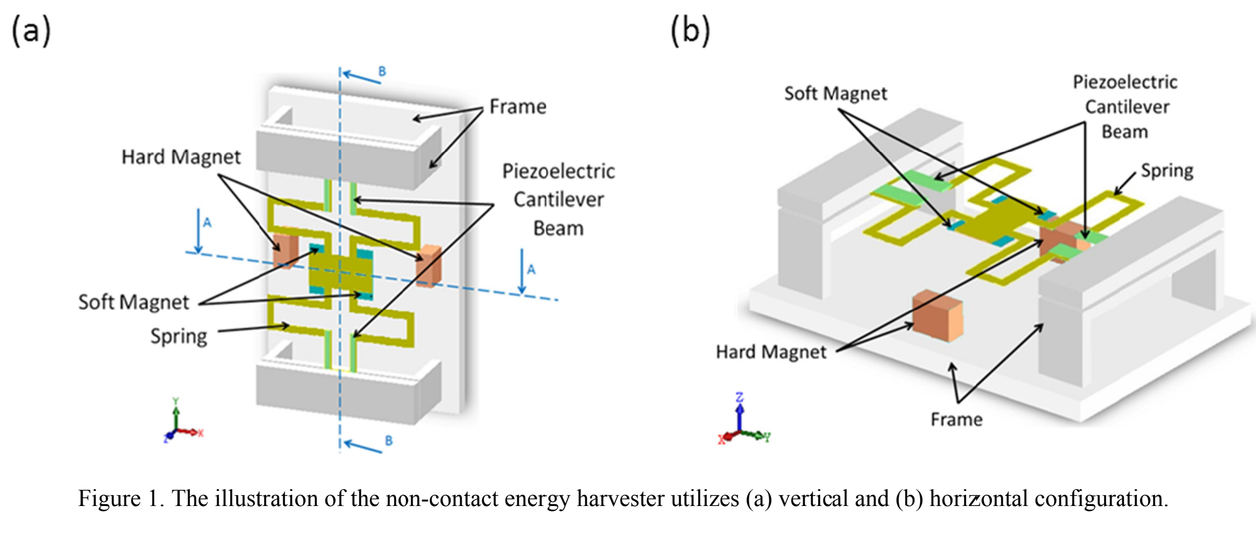

Figure 1. The illustration of the non-contact energy harvester utilizes (a) vertical and (b) horizontal configuration.

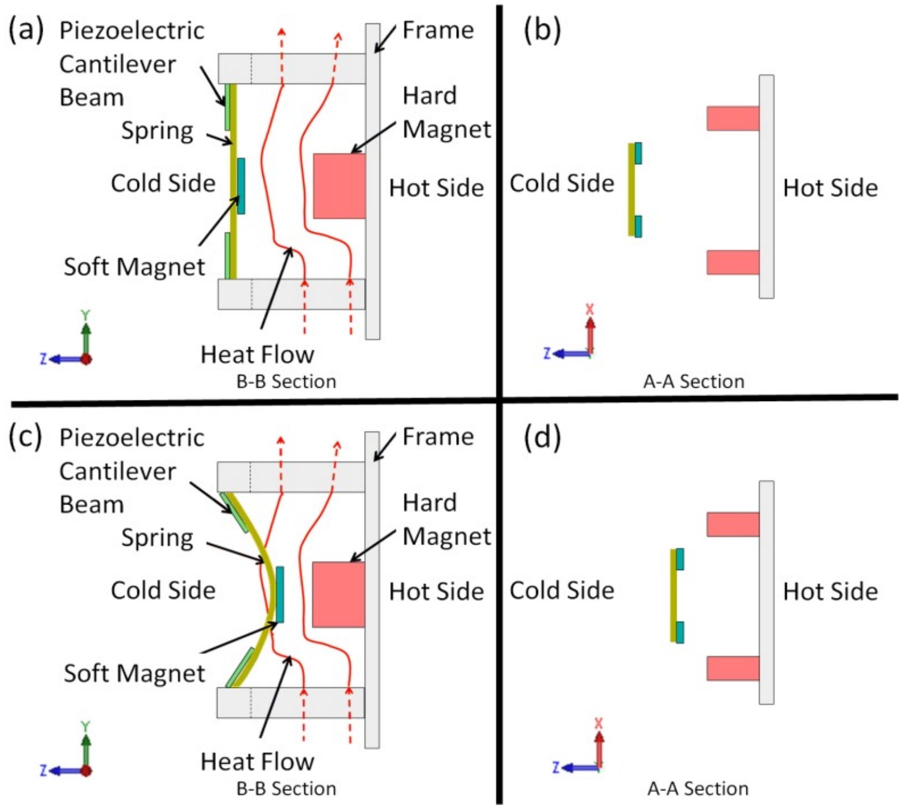

Figure 2. (a) and (b) is the B-B and A-A cross-sectional view of the energy harvester in figure 1, respectively. Both (a) and (b) are the first step (i.e., initial state) in the thermal-energy harvesting process. (c) and (d) is the B-B and A-A cross-sectional view of the energy harvester in figure 1, respectively. Both (c) and (d) are the second step (i.e., second state) in the thermal-energy harvesting process.

3. FABRICATION

According to the design, the energy harvester we fabricated is shown in figure 3. The harvester consists five parts: CuBe spring, NdFeB hard magnets, Gd soft magnet (Curie temperature is approximate 21˚C), PZT piezoelectric cantilever beams, and glass frames. The spring with a width and thickness of 2 mm and 100 μm is altered from a thin sheet CuBe. The Gd soft magnet with a length x width x height of 16 mm x 3.5 mm x 127 μm is altered from a thin Gd sheet. After the CuBe spring and Gd soft magnet are fabricated, the Gd soft magnet is bound on the CuBe spring. The PZT piezoelectric cantilever beam is altered from a strip of PZT-5H plate. After altered, the PZT cantilever beams are assembled with the CuBe spring and glass frame. Finally, the NdFeB magnet with a length x width x height of 12 mm x 4 mm x 8 mm is fixed on the frame. After this, the energy harvest is fabricated.

4. TESTING

The magnetic moment of the Gd soft magnet at difference temperature is measured by Superconducting Quantum Interference Device (SQUID). Through analyzing the magnetic moment at different temperature, the Curie temperature of the Gd soft magnet is estimated. After the Curie temperature is estimated, the temperature difference we applied to the harvester to drive the energy harvesting process is defined.

Figure 4(a) and 4(b) is an illustration of the testing for the energy harvester utilizing the vertical and horizontal configuration, respectively. Through the testing, the voltage response produced by the harvester under the temperature difference is obtained. As shown in figure 4(a) and 4(b), the heater and ice cube separated by a certain gap is used as the hot and cold side, respectively, to create the temperature difference for the harvester. The voltage response of the piezoelectric beams are measured by the oscilloscope. According to the illustration of the testing, figure 5 and 6 shows the corresponding actual testing setup of the harvester utilizing the vertical and horizontal configuration, respectively.

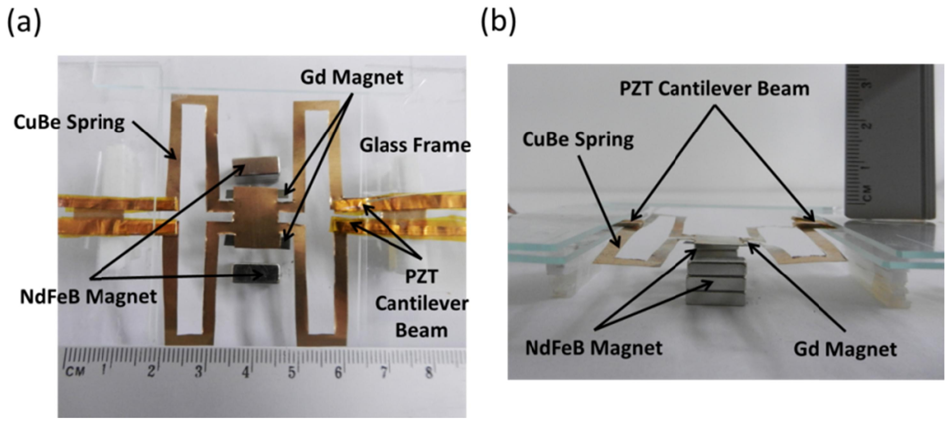

Figure 3. The photographs of the energy harvester we fabricated: (a) front view and (b) side view of harvester

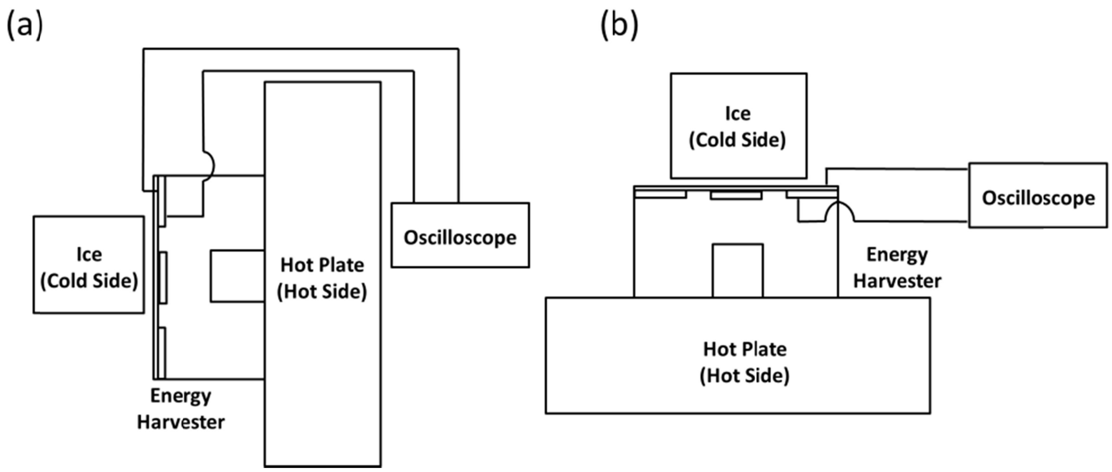

Figure 4. The illustration of the testing setup of the energy harvester utilizing (a) vertical and (b) horizontal configuration.

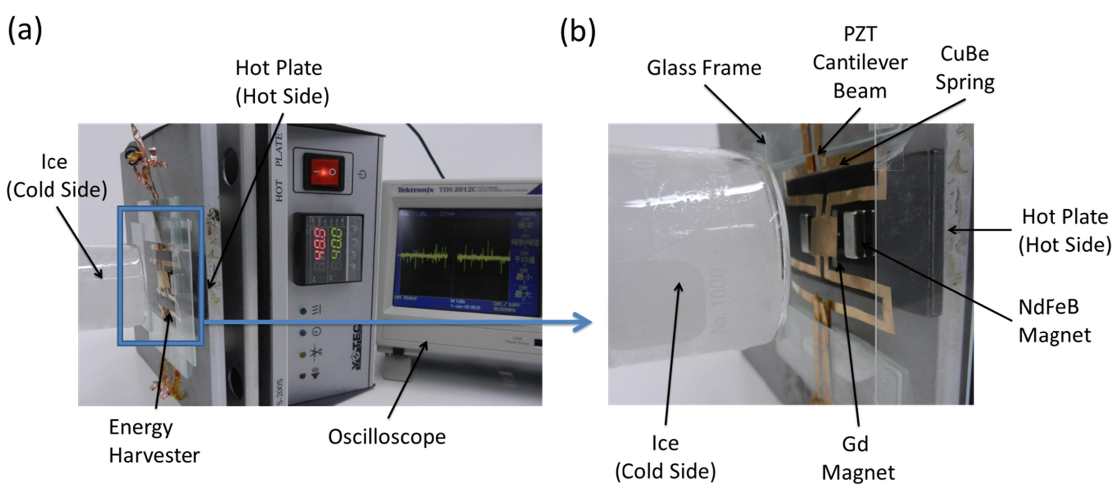

Figure 5. (a) The photograph and (b) enlarged photograph of the testing setup of the energy harvester utilizing the vertical configuration.

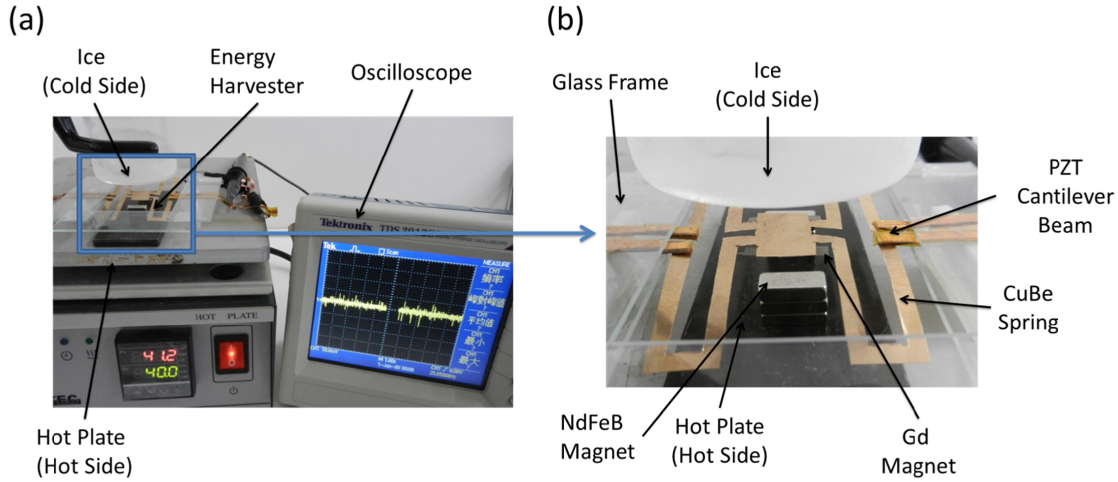

Figure 6. (a) The photograph and (b) enlarged photograph of the testing setup of the energy harvester utilizing the horizontal configuration.

5. RESULTS AND DISCUSSION

Figure 7 shows the measured magnetic moment of the Gd soft magnet at difference temperature. Through analyzing curve in figure 7, the Curie temperature of the Gd soft magnet is in the range of 20°C - 30°C. This experimental result shows the Gd soft magnet we used is capable of driving the energy harvesting process as we expected.

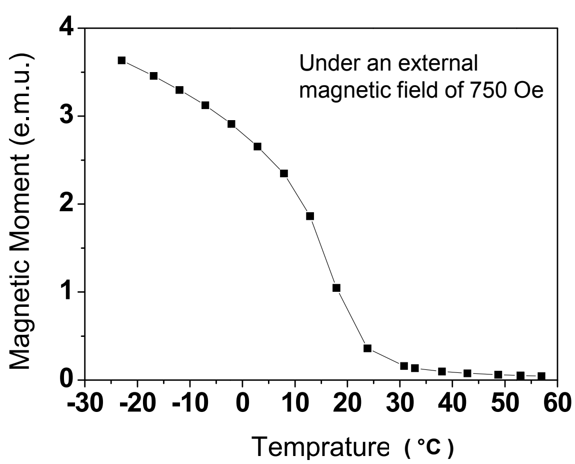

Figure 7. Measured magnetic moment of the Gd soft magnet at different temperature.

The figure 8 and 9 shows the voltage response of the energy harvester utilizing the vertical and horizontal configuration under a temperature difference of 25°C, respectively. In both figures, the high peaks of the voltage response are obtained when the Gd soft magnet approaches the cold side. In contrast, the low peaks of the voltage response are observed when the Gd soft magnet bounces back to the hot side. Due to these, the voltage response of both configurations is cyclic. The cyclic frequency and the magnitude of the voltage response of both configurations are summarized in table 1. Based on the results, cyclic frequency of the harvester utilizing vertical and horizontal configuration is 0.58 Hz and 0.33 Hz, respectively. That is, a significant increase of the power output of the energy harvester is achieved when the configuration of the harvester is changed from the horizontal to the vertical configuration.

In addition, according to the table 1, the magnitude of the voltage response of both configurations is comparable. Although there is no difference between the magnitudes of the voltage response of both configurations, the power out is significantly different due to the increase of the cyclic frequency. Due to these, the vertical configuration does have a better efficiency in the thermal convection resulting in a better power output.

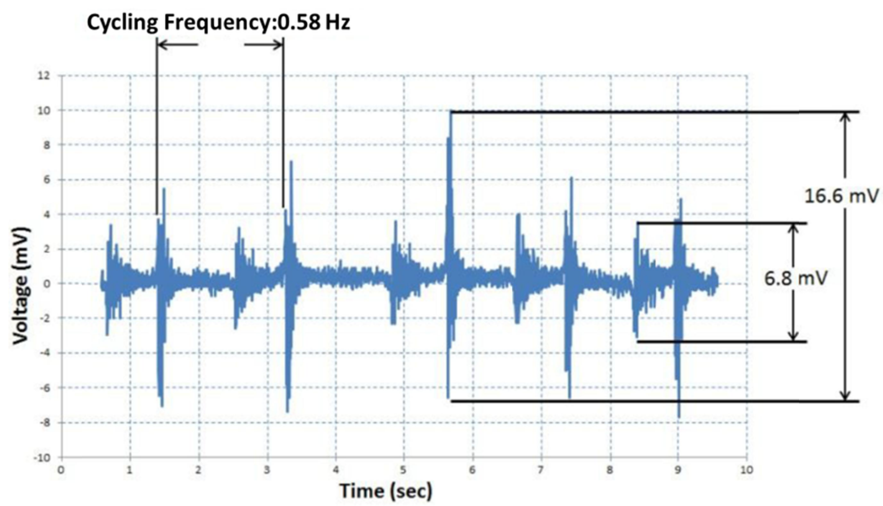

Figure 8. The voltage response of the energy harvester utilizing the vertical configuration under a temperature-difference.

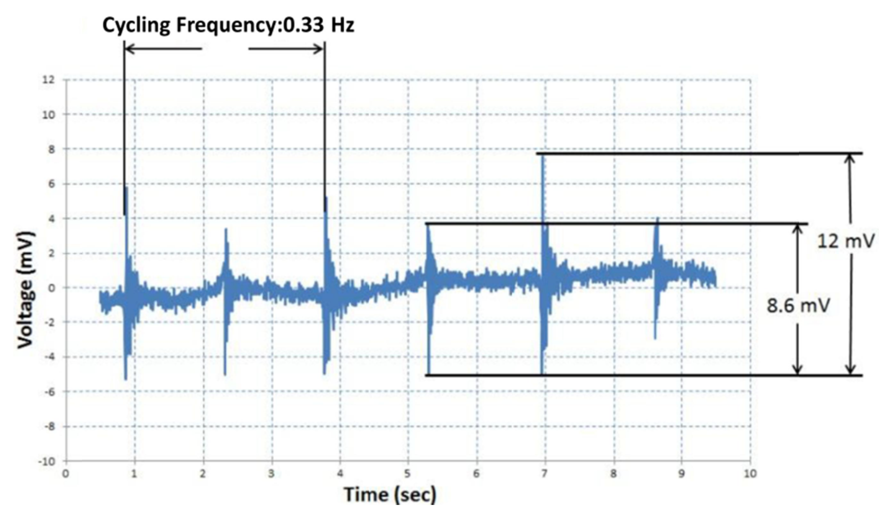

Figure 9. The voltage response of the energy harvester utilizing the horizontal configuration under a temperature-difference.

Table 1: Summary of the testing results

	Vertical Configuration	**Horizontal Configuration**
Min: V_{P-P}	6.8 mV	8.6 mV
Max: V_{P-P}	16.6 mV	12 mV
Cycling Frequency	0.58 Hz	0.33 Hz

6. CONCLUSION

Under the same temperature-difference, we successfully demonstrated the energy harvester utilizing a vertical configuration has a better efficiency in the thermal convection than using the horizontal configuration. The better efficiency in the thermal convection produces a higher cyclic frequency of the piezoelectric beams resulting in a higher power output of the harvester. The maximum voltage response of the harvester under the temperature-difference of 25°C is 16.6 mV with a cycling frequency of 0.58 Hz.

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