Thermal Energy Harvesting Using Pyroelectric and Piezoelectric Effect

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Abstract. This paper presents a prototype of a thermal energy harvesting mechanism using both pyroelectric and piezoelectric effect. Thermal energy is one of abundant energy sources from various processes. Waste heat from a chip on a circuit board of the electronic device involves temperature differences from a few degrees C to over 100 °C. Therefore, 95 °C of a heat reservoir was used in this study. A repetitive time-dependant temperature variation is applied by a linear sliding table. The influence of heat conditions was investigated, by changing velocity and frequency of this linear sliding table. This energy harvesting mechanism employs Lead Zirconate Titanate (PZT-5H), a bimetal beam and two neodymium magnets. The pyroelectric effect is caused by a time-dependent temperature variation, and the piezoelectric effect is caused by stress from deformation of the bimetal. A maximum power output 0.54 μW is obtained at an optimal condition when the load resistance is 610 kΩ.

1. Introduction
Energy harvesting is promising as a replacement for batteries [1]. Waste heat is produced by many processes and is, therefore, a promising source for energy harvesting technology, and various methods have been proposed. Thermoelectric generators based on the Seebeck effect have been widely researched [2]. The efficiency of these generators is limited by the figure of merit of the thermoelectric materials, ZT.
Due to high conversion efficiency, the pyroelectric effect with spontaneous polarization has attracted research attention as an alternative [3, 4]. However, one of the challenges of pyroelectric energy harvesting is to establish a temporal temperature oscillation. S. K. T. Ravindran et al. developed an engine chamber with sealed air and a bistable membrane [3]. Gilhwan Cha et al. used a macro-scale mechanical actuator [4], and Marcel Gueltig et al. adapted magnetic shape memory alloy films [5]. In this paper, a thermal energy harvesting mechanism is investigated, which consists of PZT-5H, a bimetal beam and two neodymium circular disc magnets with a simple structure.

2. Design and Operating Principle
The system is composed of PZT-5H, a bimetal beam, two neodymium circular disc magnets, a heat reservoir, and a linear sliding table. The schematic of the harvester is shown in Figure 1. The linear sliding table is used for time-dependent temperature variation; in a complete system an oscillating structure will be used to obtain temporal variation from a fixed heat source.
Figure 1. Schematic of the structure.

Figure 2. Schematic of the heat cycle.

Figure 2 shows the schematic of a heat cycle. Grey dotted lines show removable parts, that is, the heat reservoir, the linear slide and magnets. When the heat reservoir is under the bimetal beam, the beam gets hotter and bends up as shown in Figure 2(a). When the heat reservoir is away from the bimetal beam, the beam loses heat and returns to its initial position as shown in Figure 2(b). Consequently, a reciprocating motion of the sliding table enables to convert thermal energy into electric energy.

3. Simulation and Experimental Set-Up

The bimetal beam is composed of Fe-Ni and Fe-Ni-Cr, with total thickness of 0.5 mm. The PZT-5H supplied by Piezo Systems, Inc. was cut into a beam of $50 \times 0.9 \times 0.127$ mm$^3$. Figure 3 shows a simulation of temperature distribution using COMSOL Multiphysics. This result shows heat transfer from 95 °C of the heat reservoir to 25 °C of the bimetal beam through air convection and conduction at a stationary condition. Figure 4 shows the prototype of this harvesting mechanism. The heat reservoir was mounted on the linear sliding table that allowed the heat reservoir to move under the beam.

4. Results

Figure 5 shows the open-circuit output voltage of PZT-5H as a function of velocity of the sliding table at the same table displacement frequency of 0.08 Hz. This frequency was used due to limitation of the sliding stroke at a comparative high speed of 48 mm/s and over. As velocity is decreased output voltage is slightly increased. This shows the bimetal beam obtained more thermal energy from the heat reservoir due to the longer heating period. Figure 6 shows the output voltage at different beam conditions. Measurements were made in both fixed end and free end conditions in order to help distinguish between piezo- and pyro-electric effects. The results
indicate that pyroelectric effect dominates, since there is little effect of preventing beam motion; however the pyroelectric effect shows sensitivity to heating rate as expected. The output is dominated by pyroelectric effect in these cases. The voltage amplitude shows little change with frequency, which is consistent with pyroelectric effect since the slider velocity, and thus heating rate, are constant. Figure 7 shows a time-dependent simulation using COMSOL Multiphysics.

Temperature of the beam is simulated as the temperature of the heat reservoir is oscillated from 25°C to 95°C at 0.05 Hz. Figure 8 shows measurement of temperature distribution using a thermal imaging camera. These images indicate temperature at a cross target focusing symbol, as the sliding table moves with a velocity of 12 mm/s for 0.05 Hz. When the heat reservoir is away from the beam as shown in Figure 8(a), temperature of the beam is 38.3 °C. When the heat reservoir is under the bimetal beam as shown in Figure 8(b), it is 39.1 °C.

To improve the influence of piezoelectric effect, two neodymium circular disc magnets with the diameter of 5 mm and thickness of 3 mm are applied as shown by grey dotted lines in Figure 2(a). Magnets are shown as an effective method of “plucking” of a piezoelectric beam [6]. Figure 9 shows the open-circuit output voltage with the force of attraction of two magnets. Sharp peaks are seen, when two magnets are attached or released. The peaks decay due to the internal resistance of PZT-5H. Temperature changes on the beam cause broad curves between peaks. When the sliding table moves with 0.1 Hz, adjustment of the gap between the two magnets
is demanding due to a small deformation of the bimetal beam. Magnets were stuck easily as shown after 23 seconds of Figure 9(a). Figure 10 shows peak power output at a velocity of 12 mm/s for 0.05 Hz. Without magnets, the maximum power output 26.7 nW is obtained at an optimal condition when the load resistance is 9 MΩ as shown in Figure 10(a). With the force of attraction of two magnets, the maximum power output 0.54 μW is obtained at an optimal condition when the load resistance is 600 kΩ as shown in Figure 10(b).

5. Conclusions and Future Work
In this paper, a new simple thermal energy harvesting mechanism is shown. This mechanism consists of PZT-5H, a bimetal beam, and two neodymium magnets, enables both piezo- and pyro-effect. A prototype was built and then tested under different conditions using a heat reservoir on a linear sliding table. A maximum power output 0.54 μW is obtained at the optimal condition when a load resistance is 610 kΩ. This result is achieved when the linear sliding table works with a velocity of 12 mm/s for 0.05 Hz. Without the use of magnets, pyroelectric effect appears to dominate. Using magnets to achieve greater motion range, a stronger piezoelectric response is obtained with higher power output.
Future study will aim to improve power output and make a complete system.

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