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ENERGY HARVESTING FROM ROAD BY PYROELECTRIC EFFECT

Abd Mustaqim Abd Hadi, Siti Nooraya Mohd Tawil, Tengku Norliza Tengku Mohamad and
Murniati Syaripuddin
Department of Electrical and Electronic, Faculty of Engineering, Universiti Pertahanan Nasional Malaysia, Kem Sungai Besi, Kuala
Lumpur, Malaysia
E-Mail: norli@upnm.edu.my

ABSTRACT

Energy harvesting allows the usage of waste ambient energy such as solar, wind, thermal and vibration converted into another form of useful energy. In this paper, a study of waste heat energy harvesting from road by pyroelectric effect is presented. The main focus is to develop energy harvesting system that can modulate the high intensity sun radiation using a rotating cardboard to produce a higher rate of temperature variation on pyroelectric materials. Pyroelectric materials have the ability to generate a temporary voltage when subjected to temperature variation. In this study, Lead Zirconate Titanate (PZT) material is used as a transducer to capture heat and convert it into electrical energy for ultra-low power device usage. The developed system is applied onto road surface and heat is absorbed from the road and from the high intensity sun radiation. The maximum positive and negative voltages produced from the prototype are 133.9 mV and -146.4 mV respectively. Using the developed energy harvesting system, output voltage produced is higher compared to directly attaching the pyroelectric material onto the road which is 23 mV.

Keywords: energy harvesting, pyroelectric effect, ultra-low-power, lead zirconate titanate.

INTRODUCTION

Energy harvesting is a process of harvesting waste energy from the surrounding environment and converting it into electrical energy (Cuadras *et al.* 2010). Waste energy can be captured using different energy harvesting materials. One type of energy harvesting materials is pyroelectric materials. The idea of pyroelectric was invented in 315 BC by the Greek philosopher Theopratus (Sidney, 2005). The increasing interest in energy harvesting makes people to start exploring about it deeply because it can be a source of power for ultra-low-power microelectronic technology and can also be used for long-life application without the need for battery replacement in the devices (Adnan, 2011). For these reasons, energy harvesting has become one of the popular research topics nowadays and many electronic companies have started to produce micro energy conversion devices that are powered by ambient renewable energy. For example, some recent commercial products, such as Seiko Thermic wristwatch, use thermoelectric effect to run the mechanical component in the clock (Xie *et al.* 2008).

Recent advances in ultra-low power technology enable the development of smaller, portable and autonomous devices. In military environment, Wireless Sensor Network (WSN) is used in target tracking and detecting bio weapons (Yuksel *et al.* 2004). One type of sensor nodes used for this purpose is "Smart Dust" motes (Kahn *et al.* 1999). This device needs ultra-low power energy to operate but most energy storage cannot provide ultra-low power storage for long time usage. Battery for this device is tiny and can supply only for one day (Kaps, 2006). To overcome this problem, energy harvesting from road is required to sustain the ultra-low power needed for the devices. This is also very important during urban warfare for combat soldiers. Thus, the objective of this study is to develop an energy harvesting system using

pyroelectric effect which consider temperature variation from road as well as to increase the temperature variation of pyroelectric material in order to optimize the output voltage.

In order to achieve the objective, ISIS Professional v7.7 and Protel DXP 2004 is used to simulate the energy harvesting circuit design. PIC16F876A microcontroller and motor driver is used to control the motor speed. For pyroelectric, PZT material is used as harvesters. Finally, the voltage output from PZT material is measured for pyroelectric effect performance analysis.

LITERATURE REVIEW

Pyroelectric effect is a solid material that generates electric moment by temperature variation of the material. Due to spontaneous polarization, free charges accumulate on the surface of the material (Ashcon *et al.* 2010). When the temperature variation applies to the materials, the spontaneous polarization, dipole moment per unit volume, P_S will present. Pyroelectric materials consist of four types which are crystal, ceramic, polymers and biological materials (Hsiao *et al.* 2012). Some pyroelectric materials have high performance of pyroelectricity which are triglycinesulfate (TGS) family, lithium tantalite (LT), barium strontium titanate (BST), polyvinylidenefloride (PVDF) and its co-polymers, modified Lead Zicronate Titanate (PZT), and poly (vinylidenefluoride-trifluoroethylene), P(VDF-TrFE). They are widely used as detector materials in infrared detector and thermal imaging detector (Hsiao *et al.* 2012) (Capan, 2010).

In a paper written by (Lee *et al.* 2012) reported that temperature variation of the pyroelectric materials can be produced using conductors that have two different temperatures. The first conductor is heated using a cartridge heater and the second conductor is placed under

room temperature. After the element reaches the steady state temperature, it will be manually replaced using stamping techniques to a cold conductor. The temperature change is between 33.9 °C and 56.3 °C. The maximum power produced is 11.2 Watt. Previously, (Mane *et al.* 2011) proposed using an infrared radiation to increase the temperature of the material and decrease its temperature by using natural convection.

According to (Batra *et al.* 2013) fabricated PVDF thick-film can be used as a harvester to harvest energy from thermal energy available in the environment. Three selected places, which are Huntsville, USA (pavement), Saudi Arabia (ambient) and Mars (ambient), are used as corresponding variables to measure the voltage generated and the energy. The higher voltage generated is at Mars, which is 0.77 V and 2.95 x 10^{-7} J/cm^2. Larger surface area of PVDF will give higher voltage and energy.

In (Odon, 2010) simulation studies has implemented of a Laplace transfer function equation to model a pyroelectric detector in MATLAB/Simulink environment. This modeling is able to detect different types of radiation signal. This signal will be converted into voltage through three stages. The first stage is thermal conversion, second stage is thermal to electrical conversion and third stage is current to voltage conversion. These three conversions have their own equation:

$$G_1 (s) = p\eta / c'dC \tag{1}$$

$$G_2 (s) = \tau_{th} / (s\tau_{th} + 1) \tag{2}$$

$$G_3 (s) = s\tau_e / (s\tau_e + 1) \tag{3}$$

The transfer function model for the overall pyroelectric detector is:

$$G (s) = p\eta\tau_{th}s\tau_e/[c'dC (s\tau_{th} + 1) (s\tau_e + 1)] \tag{4}$$

where:
p = pyroelectric coefficient of radiation
η = absorption coefficient
τ_{th} = thermal time constant
τ_e = electrical time constant of detector-amplifier circuit
c' = volume specific heat
d = pyroelectric film thickness
C = total capacitance

Besides, several simulation methods have been modeled such as using Tina program in order to model pyroelectric detector from infrared radiation (Xie *et al.* 2008). The authors, (Ramos *et al.* 2002) and (Chung *et al.* 1996) have modeled pyroelectric detector using SPICE software. Table-1 shows a comparison of previous projects. Comparison has been made to detect the differences between previous projects and developed projects. Many researches have been done to improve the efficiency of pyroelectric materials by fabrication using different material selection and ratio but still from the same class. Thus, this project focuses on increasing the output voltage using a developed system. The differences between previous projects and developed system are based on availability.

Table-1. Previous projects comparisons.

Title	Energy Harvesting by Pyroelectric Effect Using PZT. (Xie et al., 2008)	Modelling and Simulation for PVDF-based Pyroelectric Energy Harvester (Batra et al., 2013)	This Work
Heat Sources	Thin resistance heater	Heat from road in USA	Heat from road and solar radiation
Pyroelectric Transducer	PZT	PVDF	PZT
Temperature Range	40 °C - 130 °C	28 °C – 42 °C	54.16 °C – 74.05 °C
Application	-	Road	Road
Maximum Output Voltage	0.58V	0.13 V	0.13V
Availability	Experiment on fabricated PZT	Experiment on fabricated PVDF	Experiment on developed system

METHODOLOGY

This project is mainly about energy harvesting from road by pyroelectric effect. Heat produced from road and high intensity sun radiation will be converted into electrical energy using pyroelectric material. The generated voltage will be shown on a Liquid Crystal Display (LCD) and can also be used for ultra-low power devices such as wireless sensor. Figure-1 shows the overall project block diagram. The main component in

energy harvesting system such as Programmable Integrated Circuit (PIC) microcontroller, LCD and pyroelectric material will be briefly explained in this section.

PIC16F876A microcontroller is an electronic circuit that can be programmed or reprogrammed to perform different task (PIC16F87XA Datasheet, 2001). It is best described as the brain of the system. HD4478 character LCD or character liquid crystal display is

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designed to interface with embedded system (HD4478 2-Lines Application Notes, 2012). Pyroelectric material is used to sense temperature change and converts it into electrical energy. In this study, the advantages using PZT material are that it can withstand high temperatures and is also durable. The view and size of the PZT material used is shown in Figure-2. The PZT surface area is 314.16 mm^2, capacitance at 120 Hz, Co = 22 ± 30% NF and operating temperature at -20 ~ 70 ºC. The metal material is brass.

The L293D, also called motor driver, is a dual h-bridge driver Integrated Circuit (IC). An h-bridge is ideal for driving motors. The L293D provides two h-bridges for driving both motors on the robot base (L293D datasheet, 2004). The motor direction is controlled by logic signals from the microcontroller. C Language Programming is used to give instruction to PIC microcontroller. Figure-3 shows the coding flow chart for programming. This system is able to control motor speed, detect battery and input voltage, and control charge and discharge of the battery.
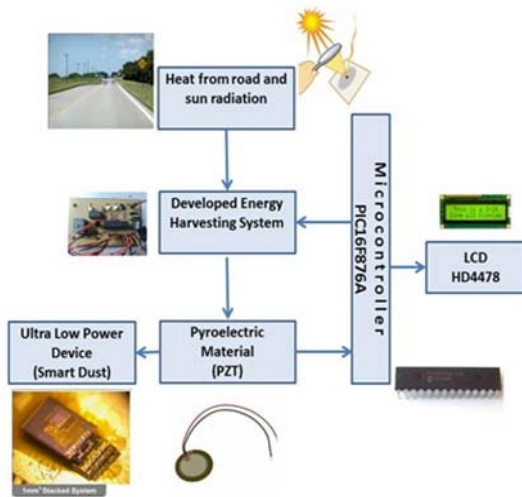

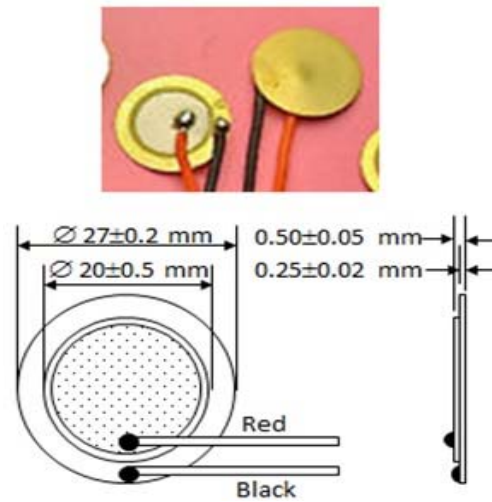**Figure-1.** Overall project block diagram.

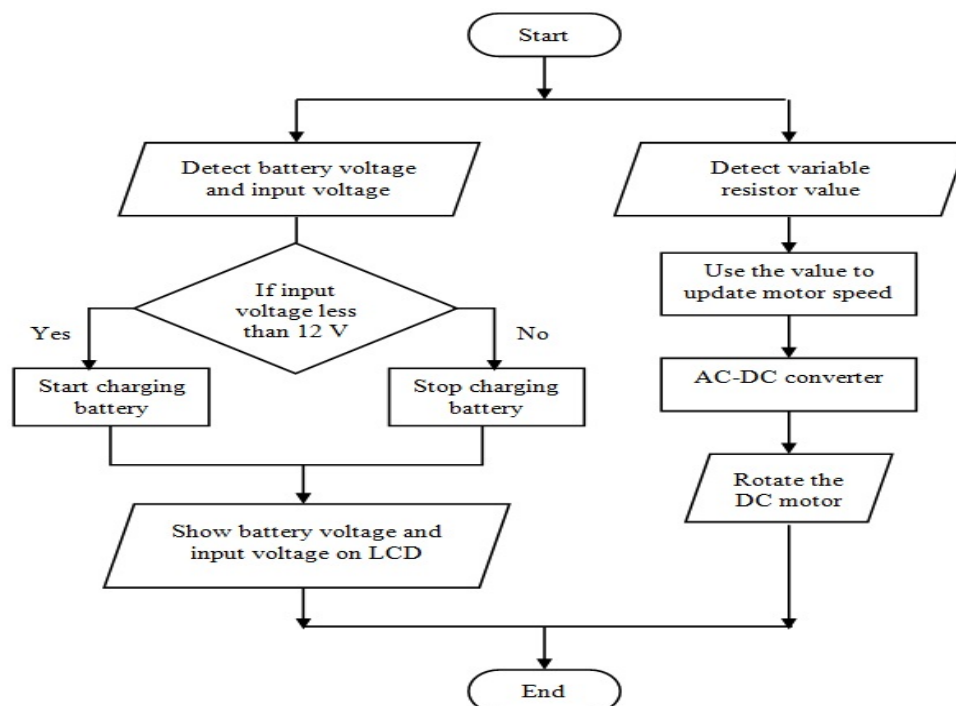**Figure-2.** Front and back view, and dimensions of the PZT.

Figure-3. Flow chart for programming.

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RESULTS AND DISCUSSION

Road surface temperature and material temperature

In this experiment, some data has been collected from road surface temperature and PZT temperature that is placed on the road. The main reason is to measure the maximum temperature that can be achieved by the road and the pyroelectric material. The equipments used to measure road surface temperature are digital thermocouple, and Data Acquisition System (DAQ) for pyroelectric material.

Figure-4 shows the comparison between road surface temperature and pyroelectric material temperature. Road surface and pyroelectric material reached their maximum temperature during 1200H, which is 55.4 °C and 57.3 °C respectively. At this time, the sun radiation is at the best condition and directly hits the road without being blocked by the cloud. Some other factors that influence the temperature value of the road are intensity of sun radiation, wind speed, air temperature and different measurement equipment used.
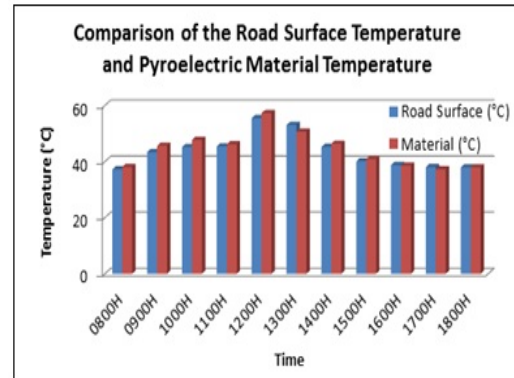

Figure 4: Road surface temperature and pyroelectric material temperature.

Energy harvesting system design

Figure-5 shows the developed energy harvesting system. The main objective of this system is to increase the pyroelectric temperature variation. Magnifying glass is used to capture solar radiation and concentrate it into a pyroelectric material. This concentrated radiation is modulated using a trench cardboard placed in between the magnifying glass and the pyroelectric material in order to get a high temperature variation. DC motor is used to rotate the trench cardboard. The speed of DC motor is controlled by using a potentiometer named motor speed controller. 12 V voltage source is used to run the main system while 6 V is used to run the motor driver.
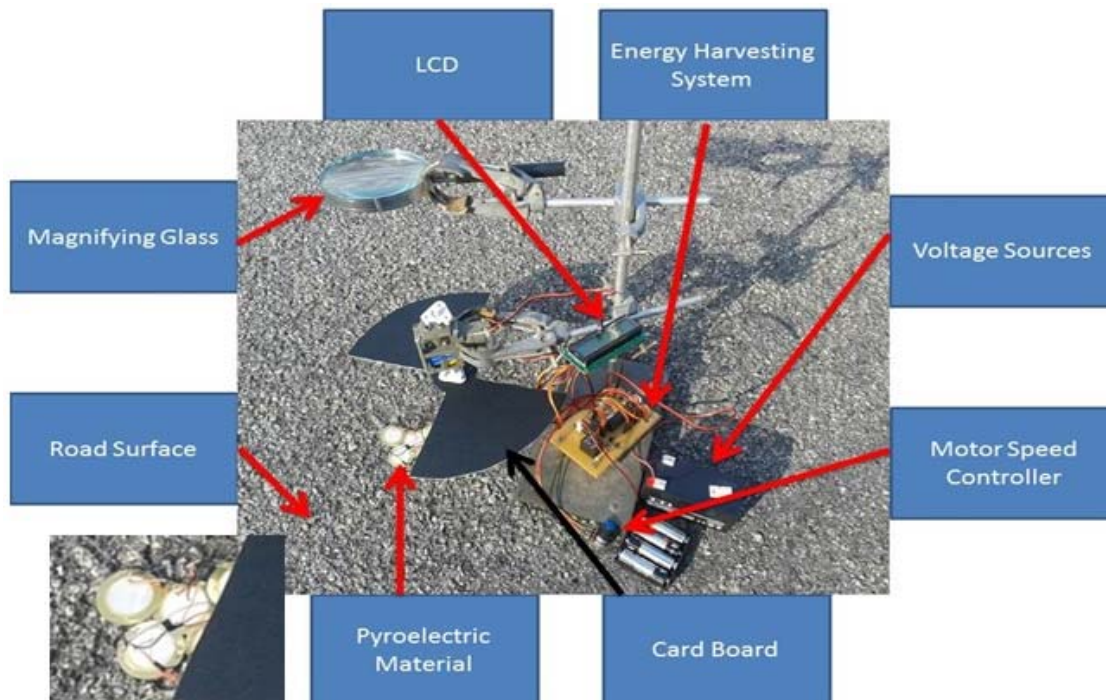

Figure-5. Developed energy harvesting system.

Experiment on developed system

Several experiments have been conducted to compare the output voltage and the temperature variation between the developed system and the pyroelectric material attached directly on the road surface. These experiments are conducted at 1200H and 1300H due to maximum sun radiation.

Experiment at 1200H

Temperature variation by using the developed system is higher than by using the pyroelectric material directly attached to the road because the concentrated sun radiation produces higher temperature. Figure-6 shows the comparison of temperature variation between the developed system and the directly attached PZT material to the road at 1200H.
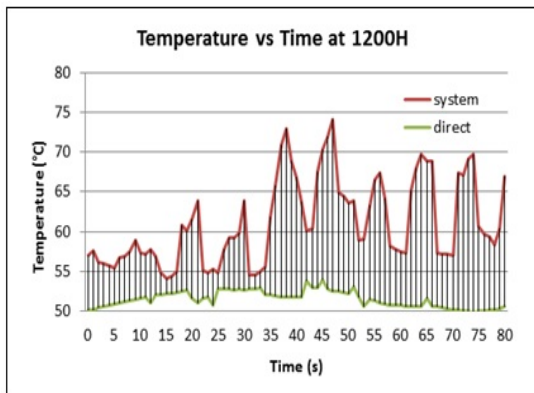

Figure-6. Temperature variation comparison at 1200H.

By using the developed system, the maximum temperature is 74.05 °C and the minimum temperature is 54.16 °C. The temperature difference is 19.89 °C. Its maximum positive and negative temperature variation per second is 10.42 °Cs^{-1} and -11.52 °Cs^{-1} respectively. However, by directly attaching the PZT material to the road, the maximum temperature is 53.89 °C and the minimum temperature is 49.93 °C. The temperature difference is 3.96 °C and its maximum positive and negative temperature variation per second is 2.08 °Cs^{-1} and -1.23 °Cs^{-1} respectively.

Higher temperature variation will produce higher output voltage as compared to directly attach the material on the road. The variation of the temperature depends on the rotation motor speed. Figure-7 shows the comparison of output voltage between the developed system and the directly attached PZT material on the road at 1200H. For developed system, the maximum and minimum output voltage within 80 seconds is 133.9 mV and -146.4 mV respectively. For the directly attached PZT material on the road, the maximum and minimum output voltage within 80 seconds is 23 mV and -13.4 mV respectively. However, there are several factors that affect the temperature variation of the road such as solar radiation, air temperature, cloud cover, cloud type and wind speed.
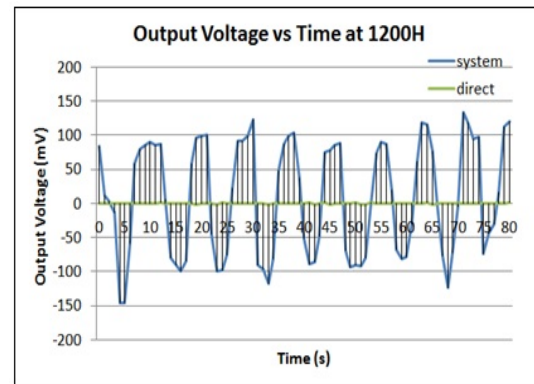

Figure-7. Output voltage comparison at 1200H.

Experiment at 1300H

Temperature variation of the material the using developed system at 1300H is lower than at 1200H because the diameter of concentration spot at 1300H is wider than 1200H. Figure-8 shows the comparison of temperature variation between developed system and the directly attached material on the road at 1300H.
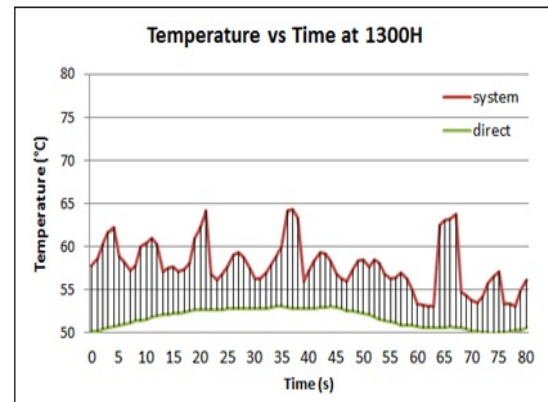

Figure-8. Temperature variation comparison at 1300H.

By using the developed system, the maximum and minimum material temperature is 64.31 °C and 53.01 °C respectively. The temperature difference between the maximum and minimum temperature is 11.3 °C. Its maximum positive and negative temperature variation per second is 9.36 °Cs^{-1} and -8.95 °Cs^{-1} respectively. By directly attaching the PZT material on the road, the maximum and minimum material temperature is 53 °C and 49.93 °C respectively. The temperature difference between the maximum and minimum temperature is 3.07 °C and its maximum positive and negative temperature variation per second is 0.23 °Cs^{-1} and -0.23 °Cs^{-1}.

Figure-9 shows the comparison of output voltage between developed system and the directly attached material on the road at 1300H. By using the developed system, the maximum and minimum output voltage within 80 seconds is 54.8 mV and –46 mV respectively. By directly attaching the PZT material on the road, the

maximum and minimum output voltage within 80 seconds is 4.5 mV and -3.9 mV respectively.
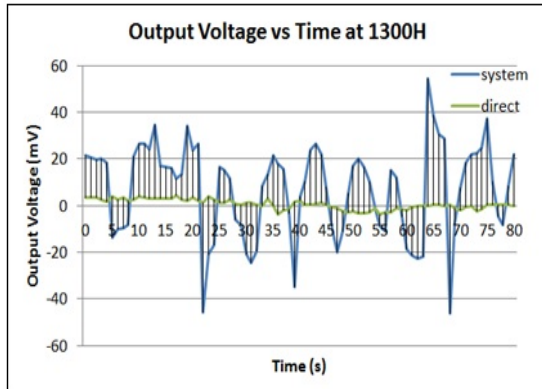

Figure-9. Output voltage comparison at 1300H.

CONCLUSIONS

The potential for energy harvesting from road by pyroelectric effect was studied using developed energy harvesting system and PZT material as harvesters. From the analysis, higher output voltage which is 133.9 mV, can be achieved by using the developed energy harvesting system compared to directly attaching the pyroelectric material onto the road which is 23 mV. Besides, the developed project can only be used between 12.00 pm to 1.00 pm due to the concentration point of the highest intensity sun radiation on the pyroelectric material.

Some improvement can be made in order to make this harvesting system totally renewable and output voltage can be reached at least 4.5 V to rotate the motor. Firstly, DC motor can be replaced with a wind. The wind turbine will make use of wind energy from the surroundings and change it into kinetic energy to rotate the cardboard. A system such as this will fully use renewable energy without depending on any voltage sources. Second, use a high ratio optical concentration system to increase the intensity of the solar radiation and improve the optical concentration design that can maintain the sun radiation spot at any incident angle of sun radiation. Third, increase the amount of pyroelectric material used and lastly, improve the efficiency of the PZT material by improving the design of the material during fabrication process.

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