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Thermal Energy Harvesting System to Harvest Thermal Energy Across Pavement Structure

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Abstract: Aging infrastructure requires a proactive strategy to ensure its functionality and performance. Innovative sensors are needed to develop infrastructures that are intelligent and durable. A power supply strategy is among the crucial components to reduce the instrument cost and to ensure the long term function of these embedded sensors. This paper describes the design of an energy harvest system that can be installed on the surface of pavements. The system will collect energy from the temperature difference between the pavement surface and the subgrade soil. The electronic circuit was designed to manage the voltage and power output, and store the energy for long-term monitoring applications. Experiments evaluated the performance of the system with encouraging results. This paper presents an innovative strategy for power supply in long-term monitoring of pavement performance.

Key words*: Energy harvesting; Smart pavement; Thermoelectric.*

Introduction

The United States oversees 1,000,000 miles of water mains, 600,000 bridges, and 4,000,000 miles of public roadway. Public expenditures on infrastructure continue to rise, accounting for about 1% to 1.2% of the U.S. gross domestic product. The Congressional Budget Office reported that Federal and state governments spent $67 billion on highway infrastructure and $28 billion on drinking water and wastewater infrastructure in 2004 (NIST 2009) [1]. Infrastructure deteriorates under various structural and environmental loads such as moisture. Advanced sensors capable of monitoring the spatial and temporal distribution of distresses along these critical infrastructures in real time would provide important information so that effective retrofit actions can be taken. Due to the distributed nature of these infrastructure components, together with long service life (typically in tens of years), power supply is an important challenge for a sensing program. The ability to harvest energy from the in-situ sources is appealing. This paper describes the concept of harvesting energy from the thermal gradient of road structure. A thermoelectricity-based energy harvesting system was developed and found promising to provide sensor power supply.

Background

The temperature of a road surface is affected by four major thermal exchange mechanisms: absorption of the incident solar energy, thermal radiation to the atmosphere, thermal convection with the air close to the road surface, and thermal conduction inside the road (Fig. 1). Beyond a certain depth, the embankment fill under the pavement maintains a constant temperature, which can be thermally treated as heat sink or heat source. Consequently, a thermal gradient arises across the pavement structure, although the magnitude of the thermal gradient can vary in time. It might be possible to take advantage of this thermal gradient to generate power using a thermoelectric device, thereby converting thermal energy into useful power for sensors.

Fig. 2 shows an example of daily temperature variations across pavement structures. As this figure shows, the ground temperature maintains approximately constant temperature (or as heat sink) beyond a certain depth (around 80 cm). A thermal gradient of variable magnitude exists between pavement base and subgrade throughout the day. This provides a potential source for electricity generation using the thermoelectrical principles. Analyses based on the current power generation efficiency indicate that for around five degrees of difference, electrical power of approximately 250 mW can be generated (Rowe 2006[4]), which is sufficient to power a low-power sensor for periodic monitoring purpose.

A thermoelectric generator has many advantages—it has no moving parts, allows continuous operation for many years, and contains no materials that must be replenished (Gao and Rowe 2002[5]). Currently, the major drawback of thermoelectric energy conversion is its low efficiency. Recent progress in material fabrications can further increase the energy production efficiency (Rowe 2006[6]).

Thermoelectric Generator

From historical inventions to current research, energy harvesting has evolved from long-established concepts into devices aimed at powering ubiquitously deployed sensors. Systems can scavenge power from human activity or derive energy from ambient heat, light, radio, or vibrations.

The basic principle behind any thermoelectric generator is the Seebeck effect (Besancon 1985[7]). Typically speaking, the Seebeck effect describes the phenomena occurring when there is a temperature difference between two points of an open circuit that is made up of two heterogeneous semiconductors. A thermal

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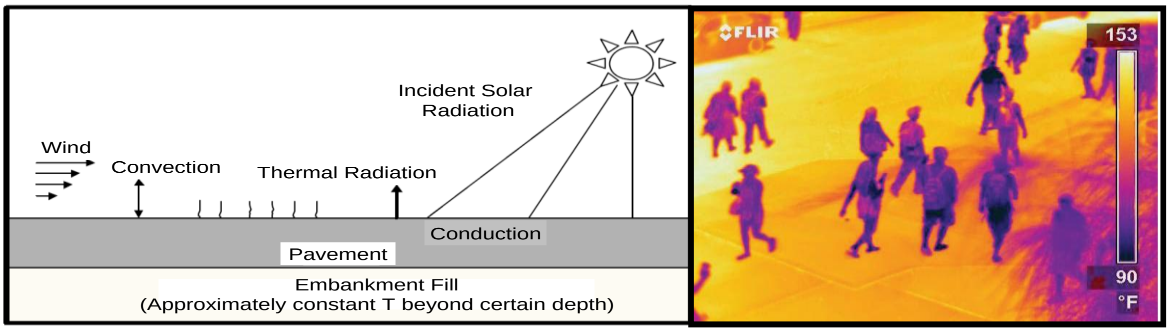


Fig. 1. a) Thermal Balance at the Surface of Road; b) Pavement Surface Temperature by Infrared Camera (EPA 2009)[2].

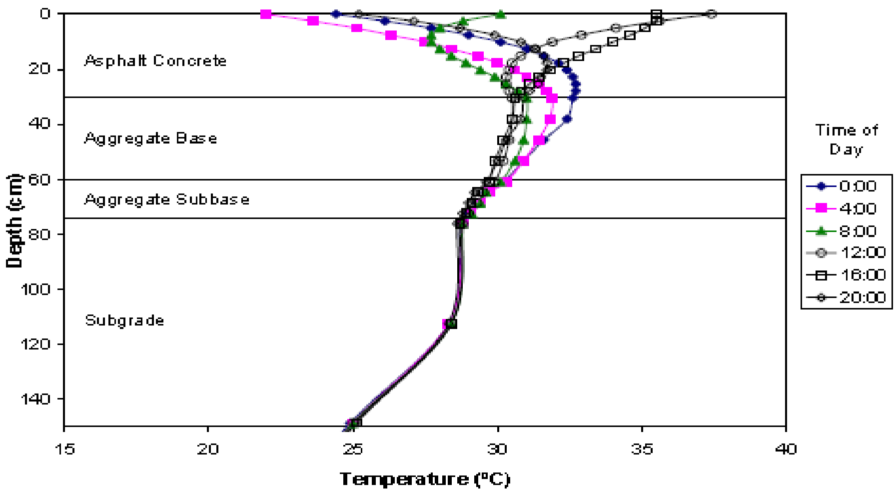


Fig. 2. Example Measured Daily Temperature Variations under Pavement (Ongel and Harvey 2004 [3]).

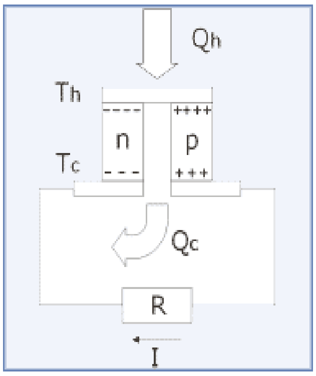


Fig. 3. Schematic of Thermoelectric Generator Principle.

electromotive force is produced, which is in direct proportion to the temperature gradient between the two points (Fig. 3). Electrical power available at the load is proportional to the squared differential temperature ΔT:

$$P = Qh - Qc = I^2 R \sim \Delta T^2 \quad (1)$$

where Qh - Qc is the heat flux due to temperature gradient, I is the current, R is the resistance of load resistor, and ΔT is the difference in temperature.

Although the principles and theory of thermoelectric generators have been rigorously developed for nearly 200 years, devices based on this technology have not been widely used. This is largely because thermoelectric efficiencies are considerably lower than comparable technologies. Nonetheless, thermoelectric generators are generally environmentally benign, contain no moving parts, and can be used to capture “free" waste heat for electricity generation. In the recent past, thermoelectric generators have been employed as power sources in satellites, space probes, and unmanned remote facilities--the heat released by the decay of radioactive material is converted to electricity. Moreover, the automobile industry is actively pursuing the capture of waste heat from car exhaust to provide additional power. Even though device efficiencies are very low (i.e. less than 1-5%), if power requirements are also low for periodic power supply to sensors, then these devices are very attractive candidates as power supply solutions.

While conventional batteries or electricity sources have been typically employed for conventional sensors, a thermoelectric energy harvester offers a revolutionary “green” power supply alternative.

Considerations in the Design of Thermoelectric Generator for Infrastructure Sensor

Efficiency

The design and application of thermoelectric devices depends on the simultaneous optimization of three parameters of interest: the

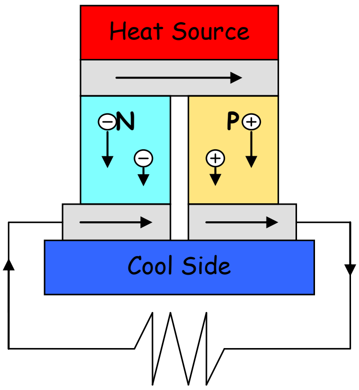


Fig. 4. A Thermoelectric Module Used as a Power Generator.

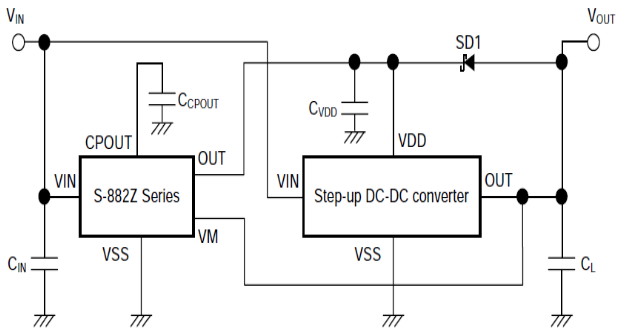


Fig. 5. Connection Diagram for the Circuit Design of the Energy Harvesting System.

electrical conductivity of the device σ $(\Omega m)^{-1}$, the thermal conductivity k (W/m*K), and the Seebeck coefficient S (V/K). The thermoelectric figure of merit, *ZT*, which is an intrinsic measure of material thermoelectric performance, depends on achieving a high electrical conductivity and Seebeck coefficient while sustaining a low thermal conductivity. Furthermore, device performance is also dependent on the temperature differential maintained across the device as well as various device configuration considerations. As shown in Fig. 4, typical devices are structured as alternating p-type and n-type semiconductor elements connected by metallic interconnects. Current flows through the n-type element, crosses a metallic interconnect, and passes into the p-type element. If a heat source is provided, the thermoelectric device may function as a power generator. The heat source will then drive electrons in the n-type element toward the cooler region, thus creating a current through the circuit. Holes in the p-type element will then flow in the direction of the current. The current can then be used to power a load, thus converting the thermal energy into electrical energy. For power generation or Seebeck operation, one may define the efficiency of a given thermoelectric device as:

$$\eta_{TE} = \frac{\dot{W}_{elec}}{\dot{Q}} \tag{2}$$

where $\dot{W}_{elec}$ is the useful electrical output power and $\dot{Q}$ is the heat flow through the device. Therefore, a high electrical conductivity (i.e., high *W*) and low thermal conductivity (i.e., low *Q*) is desired in order to convert heat into usable electrical work.

Optimization of Geometry Design and Materials Selection

The design schema, i.e., the geometry of the power harvester, needs to be optimized for the maximum efficiency. Most current thermoelectric units are for large thermal gradients. The geometry design needs to ensure there is a sufficient amount of heat flow that can be collected and converted, so that a relatively large thermal gradient can be maintained. The analyses of thermal flow under pavements can be conducted using computational simulations such as the Finite Element Method.

The selection of proper materials is another important aspect for thermoelectricity design. This includes the design of a proper thermoelectric harvesting unit. It is also important to select and match the thermal properties of materials to ensure the maximum efficiency in thermal energy conversion.

Thermal energy storage is another important issue. The storage schema will need to consider the reversal of thermal gradient and minimize the flow of electricity due to shunt circuit. For installation under pavement, the effects of moisture might be another important factor to consider in deploying the right energy harvesting schema.

Circuit Design for Power Management

The aim of a power management circuit is to accumulate the converted energy into storage components, for example, a super capacitor, which has a long lifetime and could be charged and discharged thousands of times. Actually, a 10F super capacitor stores enough energy to support mW consumption application (Fei et al. 2001 [8]). The output voltage generated by the thermoelectric is too low to directly power any electrical component, which usually requires at least 700mV voltage to work. Consequently, an ultra-low voltage operation charge pump, IC, is used to amplify the output voltage, from down to 300mV to a voltage higher than the start-up threshold. However, the voltage produced by the pump IC is not stable and high enough, which may have negative impact on performance of sensors. As a solution, a step-up DC-DC converter is used to stabilize the voltage output. The pins of chips are connected as follows (Fig. 5):

A Schottky diode (SD1) is added between the output pin (OUT) and the power supply pin (VDD) of the step-up DC-DC converter to be started up. As a result, it is possible to start up the step-up DC-DC converter by the capacitor with a small value. C_{VDD} in the figure above is the power supply smoothing capacitor of the step-up DC-DC converter.

During the charging cycle, the voltage of the super capacitor keeps increases until it reaches the threshold of discharge voltage. At that point, the discharge cycle begins where current drawn by the DC-DC converter flows from the charged super capacitor to power the load, such as a sensor. In the context of this study, a light-emitting diode (LED) is used as a load.

Experimental Evaluation of the Energy Harvesting System

Experiments were conducted in the laboratory simulated conditions. First, a hole was drilled in the middle of an asphalt concrete sample.

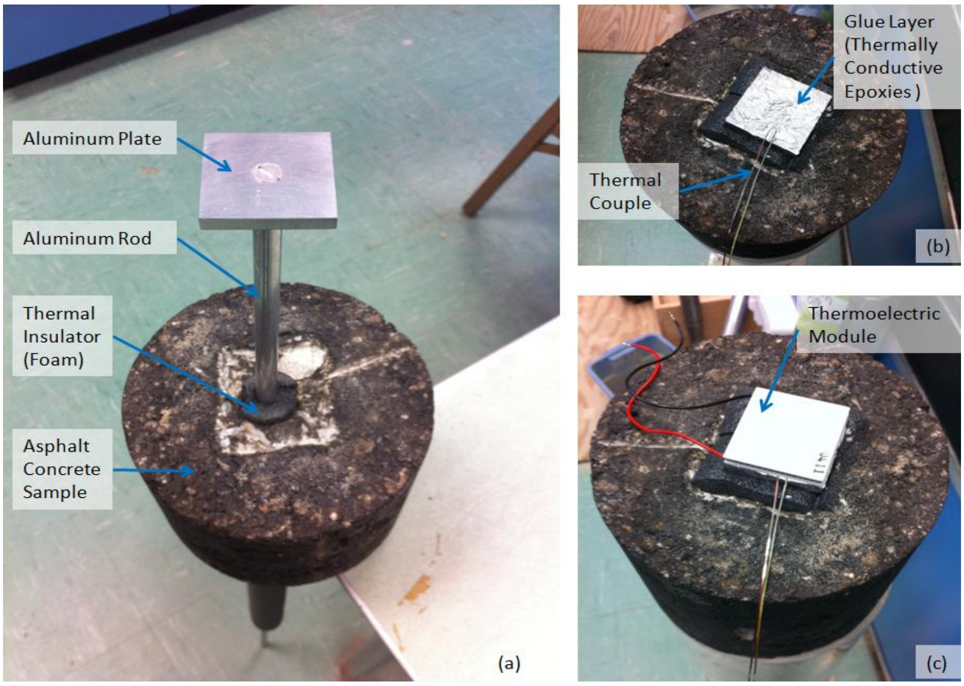


Fig. 6. Illustration of Thermal Harvesting System Set up.

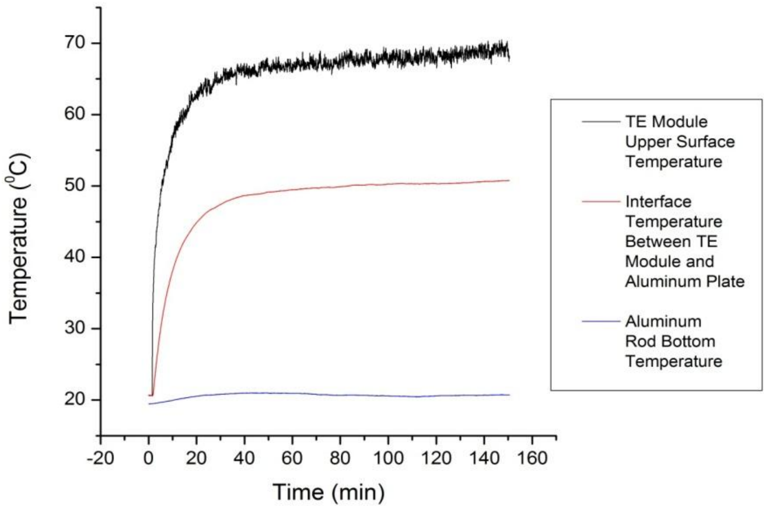


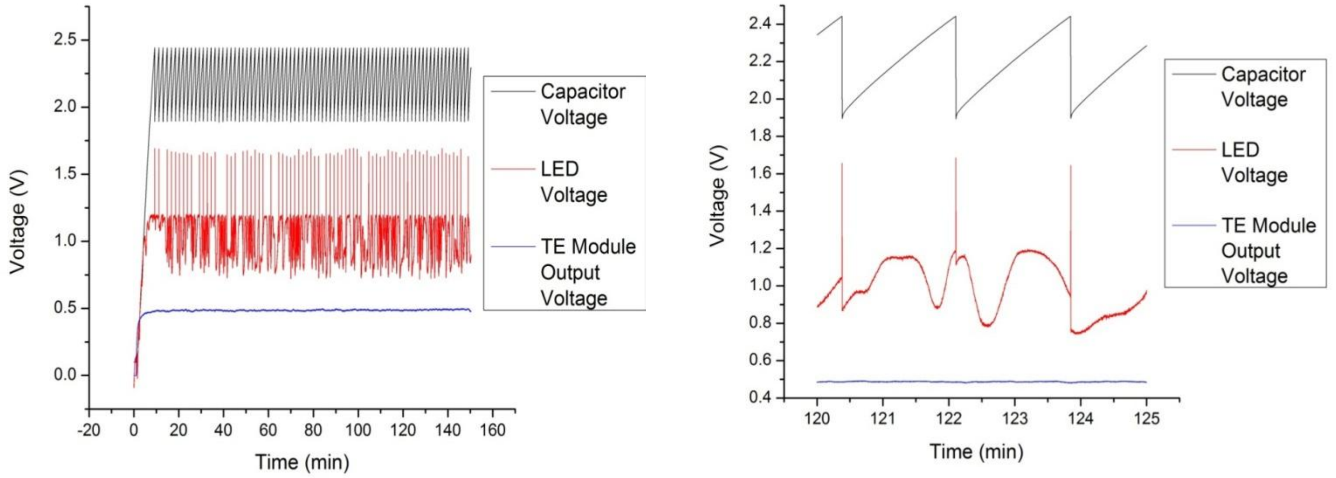
Fig. 7. Monitored Temperature Process at Different Locations in the Thermal Energy Harvesting System.

An aluminum plate and rod, which was covered by a thermal insulator, was installed through the hole (as is shown in Fig. 6(a)). Sequentially, thermally conductive epoxies, which served as the glue layer, were spread on the upper surface of the aluminum plate. Meanwhile, a thin thermal couple was laid on the surface (as shown in Fig. 6 (b)). Then, a thermoelectric module was installed on the surface of the aluminum plate, with the thermally conductive epoxies as the interface (as shown in Fig. 6 (c)). The whole set of equipment was surrounded by sand, which simulates the pavement subgrade.

A filament lamp was utilized to heat up the upper surface of the asphalt concrete, and therefore the thermoelectric (TE) module. The TE module produced powers due to thermal gradient. Since the voltage output from the TE is typically in the range of mV, which was too small to drive common sensors, a charge pump IC S-882Z produced by Seiko was used to amplify the voltage to 2 V, which is sufficient to charge a super capacitor of 2200uF. The electricity in the capacitor was then used to drive a light-emitting diode (LED).

Temperatures at the upper TE module surface, at the interface between TE module and aluminum plate, and at the bottom of the aluminum rod were monitored with Pico TC-08. LabVIEW software and data acquisition board NI USB 6251 were used to collect voltage outputs of the TE module output, the super capacitor, and light-emitting diode (LED). Experiment data is analyzed as follows:

a) Temperature distribution in the thermal energy harvester system



(a) (b)

Fig. 8. a) Voltage at the TE Element, Capacitor and LED, b) Zoom in between 120 to 125 min.

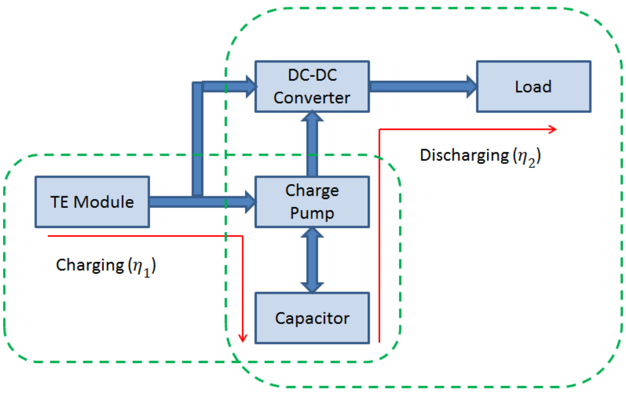


Fig. 9. Energy Flow in the Energy Harvesting System Circuit. (η_1 is the Efficiency when The Capacitor is Charging. η_2 is the Efficiency when the Capacitor is Discharging).

As is shown in Fig. 7, temperature of the TE module upper surface (blue line in the figure) increased quickly as soon as the lamp was turned on, approaching 70^{0}C from room temperature. The interface temperature between the TE module and the aluminum heat collection plate (red line in the figure) also increased and became stable at 50^{0}C. A 20^{0}C temperature difference was maintained between both sides of the TE module. The temperature at the bottom of the aluminum heat collection rod did not change greatly, indicating that heat flux coming from the aluminum plate mostly dissipated into sand surroundings before it arrived at the bottom of the heat collection aluminum rod.

b) Electricity output of the thermal energy harvesting system

Fig. 8a shows the voltage process at the output of TE element, the super capacitor, and the LED. Fig. 8b zooms in between 120 minutes to 125 minutes to show more details of the process. The following work sequence can be identified from the figure: when the temperature gradient was high enough for the TE module to generate 300 mV output voltage (the threshold voltage for the charge pump), the charge pump IC (Seiko, S-882Z) started to work and produced sufficient voltage to charge the capacitor. This caused the voltage at the capacity to increase. Once the voltage in the capacitor reached 2.45 V, the charge pump IC automatically connected to the DC-DC converter and discharged the capacitor. Electrical energy stored in the capacitor flew into the DC-DC converter output pin. A 1.7 V DC supply voltage was maintained for lighting the LED. When the voltage in the capacitor droped down to 1.9 V, the charge pump IC disconnected from the DC-DC converter. The power supply based on the DC-DC converter was shut down, and all circuits were turned into an ultra-low power sleep mode. Sequentially, the capacitor was charged again, and the next working cycle started.

c) Analysis of System Efficiency

Fig. 9 shows the energy flow of in the energy harvesting system, including both charging and discharging cycles. Blue arrows represent energy flow directions. Red arrows correspond to energy flow directions within a certain charging or discharging process. Electrical energy converted by the TE module powers the charge pump IC and the DC-DC converter IC, and charges the capacitor.

Energy contained in the capacitor E_{cap} can be calculated through Eq. (3):

$$E_{cap} = \frac{1}{2} \cdot C \cdot V^2 \quad (3)$$

Each time the capacitor discharges, its voltage drops from 2.45 V to 1.9 V. For the 2200 μF capacitor used in this system, the energy dissipating from the capacitor is 3.73 mJ per cycle. Assuming the discharging efficiency η_2 = 50%, which means 50% of energy stored by capacitor could be transmitted to light the LED, the energy used to power the LED load is 1.86 mJ each cycle.

According to the manual of the commercial TE module used in this study, the output power under 20^{0}C temperature gradient is about 50 μW . Considering that it takes 1.5 min (i.e. 90 s) to charge the capacitor, the output energy of TE module per cycle is 4.5 mJ (This leads to a charging efficiency $\eta_1 = 3.73 / 4.5 = 82.9\%$). The efficiency in the charging and discharging process is therefore 41.4% (η_1 x η_2). The overall energy is much lower. For example, assuming efficiency of TE elements of 5%, the overall efficiency of the energy harvesting system is about 2.05%. The system efficiency can be further improved with use of higher efficiency TE materials and elements.

Conclusions

Long-term infrastructure sensing calls for innovative methods for sensor energy supply. Harvesting energy in situ is near ideal since pavements are long and highly distributed. This paper describes the development and evaluation of a thermal energy harvesting system used to harvest the thermal energy across pavement structure. The system components amplify the low mV voltage output from a regular thermoelectric (TE) element to a workable voltage for sensor applications. The system includes a super capacitor for energy storage. Simulated experiments were conducted in the laboratory, and an LED light was used to simulate a sensor load. The systems were found to work properly and produced enough electricity to blink the LED periodically. This demonstrates the promise of this system to power an infrastructure sensor for periodic sensing purposes. Finally, the efficiency of the system was analyzed.

References

1. National Institute of Standards and Technology (NIST), Technology Innovation Program (2009). Advanced Sensing Technologies and Advanced Repair Materials for the Infrastructure: Water Systems, Dams, Levees, Bridges, Roads, And Highways. March, Gaithersburg, MD, USA.
2. Climate Protection Partnership Division, U.S. Environmental Protection Agency’s Office of Atmospheric Programs (2009). Reducing Urban Heat Islands: Compendium of Strategies Cool Pavements, Washington, DC, USA.
3. Ongel, A. and Harvey, J. (2004). Analysis of 30 Years of Pavement Temperature using the Enhanced Integrated Climate Model (EICM), Research Report of California Department of Transportation, Davis, CA, USA.
4. Rowe, D. M. (2006). *Thermoelectrics Handbook: Macro to Nano*. Taylor & Francis, Boca Raton, FL, USA.
5. Gao, M. and Rowe, D.M. (2002). Recent Concepts in Thermoelectric Power Generation, *IEEE 21st International Conference on Thermoelectronics,* Long Beach, CA, USA, pp. 365 – 374.
6. Min, G. and Rowe, D.M. (2002). “Symbiotic” application of thermoelectric conversion for fluid preheating/power generation, *Energy Conversion and Management,* 43, pp. 221-228.
7. Besançon, R.M. (1985). *The Encyclopedia of Physics*, Third Edition, Van Nostrand Reinhold Company, New York, NY, USA.
8. Fei, F., Maib, J.D., and Li, W.J. (2011). A wind-flutter energy converter for powering wireless sensors. *Sensors and Actuators A: Physical,* 173(1), pp. 163–171.