Technical Paper

ISSN 1997-1400 Int. J. Pavement Res. Technol. 6(2):73-79

Computer-Aided Design of Thermal Energy Harvesting System across Pavement Structure

Guangxi Wu[1], and Xiong (Bill) Yu[2+]

Abstract: Long term monitoring of pavement requires a cost effective and sustainable power supply strategy. We developed an energy harvest system that can be installed in the pavement structure. The system can harvest energy from the temperature difference between the pavement surface and the subgrade soil using thermoelectric modules. In this paper, through computer-aided simulations, we come up with an optimum structural design for the energy harvesting system. The design will ensure a large thermal gradient for energy utilization. The system includes a 4cm × 4cm × 0.5cm aluminum plate and a 1m long aluminum rod, which is covered by 59 cm long heat insulator from the top. Its output power estimated as up to 0.02 W. The total energy that the system can produce is estimated to be in the order of 1000 J per day.

DOI: 10.6135/ijprt.org.tw/2013.6(2).73

Key words: *Computer-aided simulation; Thermoelectric; Temperature difference.*

Introduction

The nation has 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 of 1% to 1.2% of the U.S. GDP. 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 [1]. Infrastructure deteriorates under various structural and environmental loads. Advanced sensors with the ability to real time monitor the spatial and temporal distribution of distresses along these critical infrastructures 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 a major challenge for an infrastructure sensing program. The ability to harvest energy from the in-situ sources is appealing.

Methods to harvest energy from the environment have been widely researched in recent years. Generally speaking, there are four main approaches for energy harvesting, i.e. piezoelectric, thermoelectric (TE), photovoltaic, and electromagnetic. Logically the temperature difference between the pavement surface and subgrade soil is a perfect choice of energy resource to power sensor nodes through specifically designed thermoelectric energy generator.

Even though researchers have developed various types of TE energy transformers, the main interest has been in the generation of power from body heat, as a means to support wearable devices. For example, Seiko Instrument Inc. [2] announced a wristwatch powered by body heat. Leonov et al [3] designed a micro-fabricated poly-SiGe device for a body area network. The power density is reported as 4.5 μWCM^{-2} under a temperature gradient/difference of 5 K. Sodano et al. [4] proposed a novel approach to thermal harvesting using a small greenhouse device to capture thermal energy from solar radiation. The device was capable of recharging an 80 mAh and a 300 mAh nickel metal hydride battery in 4 and 18 minutes, respectively. Yang et al. [5] designed and verified a thermoelectric energy harvester with stacked poly-silicon thermocouples by CMOS process, which could achieve the power factor 0.0427 $\mu WCM^{-2}K^{-2}$ and voltage factor $VCM^{-2}K^{-1}$.

Our interest doesn't lie on improving the performance of TE module itself, but designing novel energy harvest system, based on commercial TE products. There are four engineering parameters which define the performance of the module: 1) Temperature difference ΔT, which is equal to the hot side temperature minus the cold side temperature; 2) Qc, which is total heat pumped by the TE device at the surface defined by the cold side; 3) I, i.e. the current drawn by the TE module and 4) V, which is the voltage produced by the TE module. In our case, we could calculate ΔT and Qc, then the current can be determined by drawing a vertical line downward from the intersection of ΔT and the Qc curve on the upper graph of Fig.1. Then, on the lower graph, the placement of the V line can be determined by making the ratio of AB/BC= EF/FG. It has to be pointed out that the performance chart is when the TE module is working as a cooler. It means that the TE module is consuming electrical energy and producing temperature difference, which is opposite to our application. Assuming that the TE module efficiency at a certain ΔT and Qc remains the same, we could derive the efficiency η, where $\eta = V \times I / Qc$. Finally, we multiply Qc by η and get the electrical power produced by the module.

Computer-Aided Heat Collection System Geometry Design

---

[1] Department of Electrical Engineering and Computer Science, Case Western Reserve University, Cleveland, OH 44106, USA.

[2] Department of Civil Engineering, Case Western Reserve University, 2104 Adelbert Road, Bingham 256, Cleveland, OH 44106, USA.

[+] Corresponding Author: E-mail xxy21@case.edu

Note: Paper presented at the 17th Great Lakes Geotechnical and Geoenvironmental Conference held on May 24th, 2012 at Case Western Reserve University, Cleveland, Ohio, USA. Revised January 31, 2013; Accepted February 1, 2013.

Our general idea is to install the thermoelectric (TE) module at the surface of pavement to utilize its high surface temperature. The thickness of TE module involved here is only 0.48 cm. In order to increase the power produced by the module, we have to ensure enough temperature difference between the upper and lower surface of the TE module. A possible way is to connect the lower surface with subgrade soil deep under the pavement, via high thermal conductivity material, (for example, an aluminum rod). To reduce the heat dissipation, the rod is covered by thermal insulating material (such as foam). According to investigation data (Ohio ODT), soil temperature at depth of 1.5 m could be considered as a constant of 15℃ . While the pavement surface temperature could be up to 40℃ in summer and down to -20℃ in winter. This ensures a temperature difference exist throughout different seasons. Even though there must be sometime that the temperature gradient doesn't exist at all, it is relatively short period of time and won't dramatically impact the performance of the energy harvester. In this way, the required temperature difference could be guaranteed.

The whole harvest system is illustrated in Fig. 2. It is composed of thermoelectric module, glue layer, aluminum plate and heat collection rod and thermal insulator. The pavement is made of asphalt concrete, granular base, sub base and subgrade soils. The corresponding geometry and parameters of different materials are defined in Table 1. Computation simulations were conducted to optimize the geometry design of the harvesting system.

In the following simulations, the influence of different parameters were studied to understand the system's operating principle and to optimize the design of the system. To save the computational time while not losing generality, it was assumed that geology layers are horizontal and the properties are uniform in each layer. Therefore, the simulation can be conducted based on 2D model (plane x-z in Fig. 2).

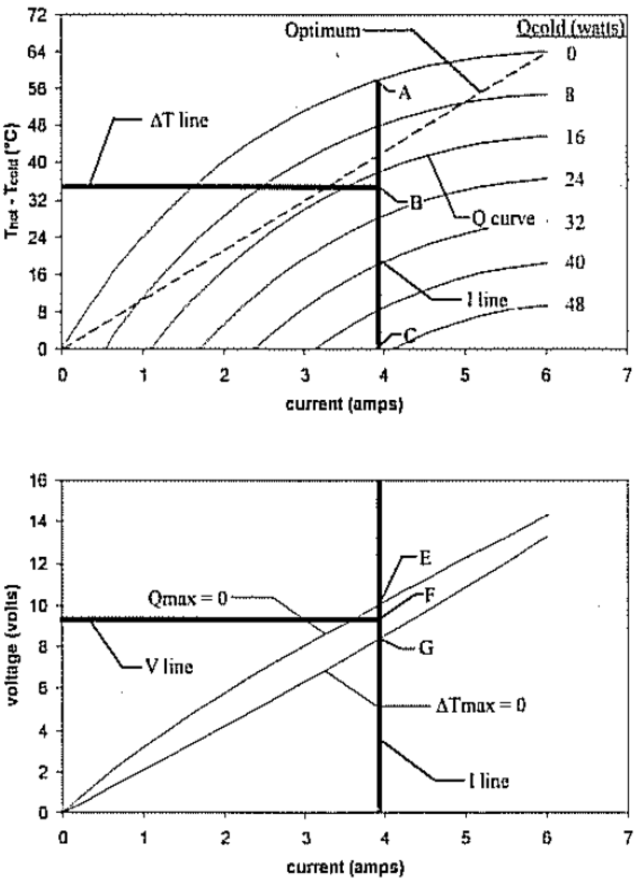


Fig. 1. Illustrative Use of Performance Chart to Define Engineering Parameters [6].

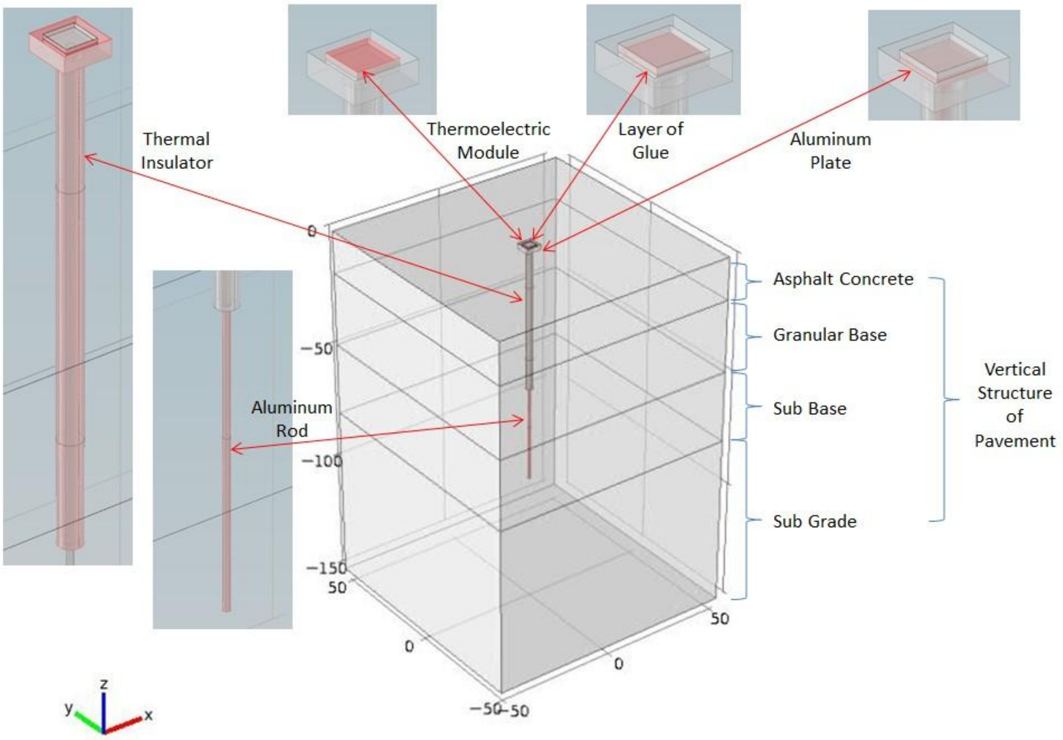


Fig. 2. Components of Energy Harvest System and Vertical Structure of Pavement (unit: cm).

Table 1. Parameters and Size Definition of Materials Involved in This Paper's Analysis.

Material	Heat Capacity J/(kg*K)	Thermal Conductivity W/(m*K)	Density kg/m^3	Width (x Axis) cm	Length (y axis) cm	Depth (z axis) cm
Aluminum Plate	900	160	2700	4	4	0.5
Aluminum Rod	900	160	2700	Radius: 0.5		100
TE module	2000	0.4	3125	4	4	0.48
Thermal Insulator	3000	0.04	1000	Thickness: 1		59
Glue	2000	60	1500	4	4	0.1
Asphalt Concrete	1200	1.6	2400	104	104	17.78
Granular Base	1400	1	2080	104	104	30.48
Sub Base	1600	0.8	1850	104	104	30
Sub Grade	1800	0.6	1800	104	104	71.74

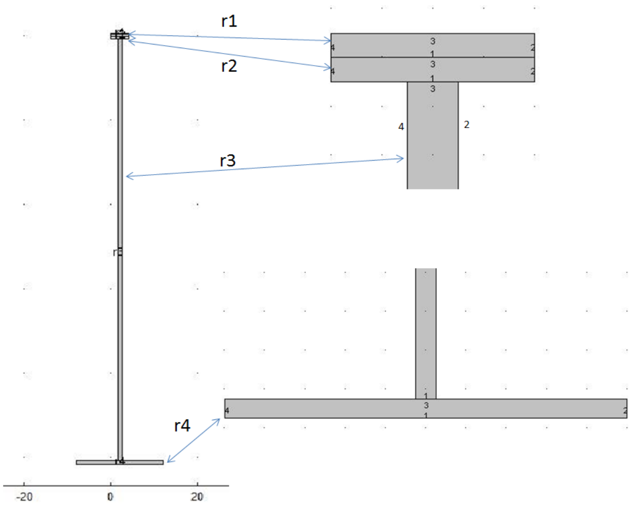


Fig. 3. Illustration of the Heat Collection System with a Base.

Effects of the Width of the Heat Collector Base

A based can be attached to the heat collector rod as illustrated in Fig. 3. The system is made up of thermoelectric module, aluminum plate, rod, and base. It is assumed that every part of the system is in perfect thermal contact with each other. All the side boundaries (boundary 2 and 4 of object r1, r2, r3 and r4) are assumed as thermally insulated, whereas the top boundary (3 of r1) and bottom boundary (1 of r4) are thermally conductive and defined as 30℃ and 15℃ respectively. Our aim is to understand the temperature and heat flux distribution in the heat collection system, to find out how the width of the aluminum base influence the power generated from the thermoelectric module and to decide whether the use of base is necessary.

The simulated temperature distribution is shown in Fig. 4 for base width of 20 cm. The temperature gradually drops from 303.15 K to 283.15 K vertically. Along boundary 1 of object r1, temperature distributes like a valley, with the lowest temperature lies in the middle. Through further calculation, the average temperature along boundary 1 is 296.71 K. So the temperature difference ΔT between upper and lower surface of the TE module is 6.44 K.

Distribution of vertical heat flux is illustrated in Fig. 4b. The heat flux in the TE module is small because of its low thermal conductivity, whereas in the aluminum rod, heat flux is much higher. It is also found that both the y component and x component heat flux at the edge of the heat collector base is small. This means that 20 cm base width is not effective. The wideth of collector base is varied from 1cm to 20 cm with step 0.5 cm, the corresponding average temperature difference across the TE element, the total heat flux across the TE module, and the TE output power are shown in Fig. 5. The output power is calcualted using the performance chart, the module efficiency is about 30% under conditions of Qc ≈ 0.75W and ΔT ≈ 6.4 K.

According to the result, the optimum bottom base width is about 5 cm. A wider base is inefficient and cause problem in installation (as it will require large borehole).

Simulations are also conducted to account for the effects of heat exchange with adjacent soils and for the effects of thermal insulation of the heat collector from the adjacent soils. It is found that 1) the use of thermal insulation reduces the heat dissipation and increase the power output by the TE elements; 2) the use of large base width does not effective collect heat. The output power corresponds to base width of 40 cm is only 15% larger than the value corresponds to base width of 1 cm. However, it is at the expense of much more aluminum material consumption and difficulty for installation. Therefore, the use of base might not be an optmal solution. We used the vertical rod as heat collectors.

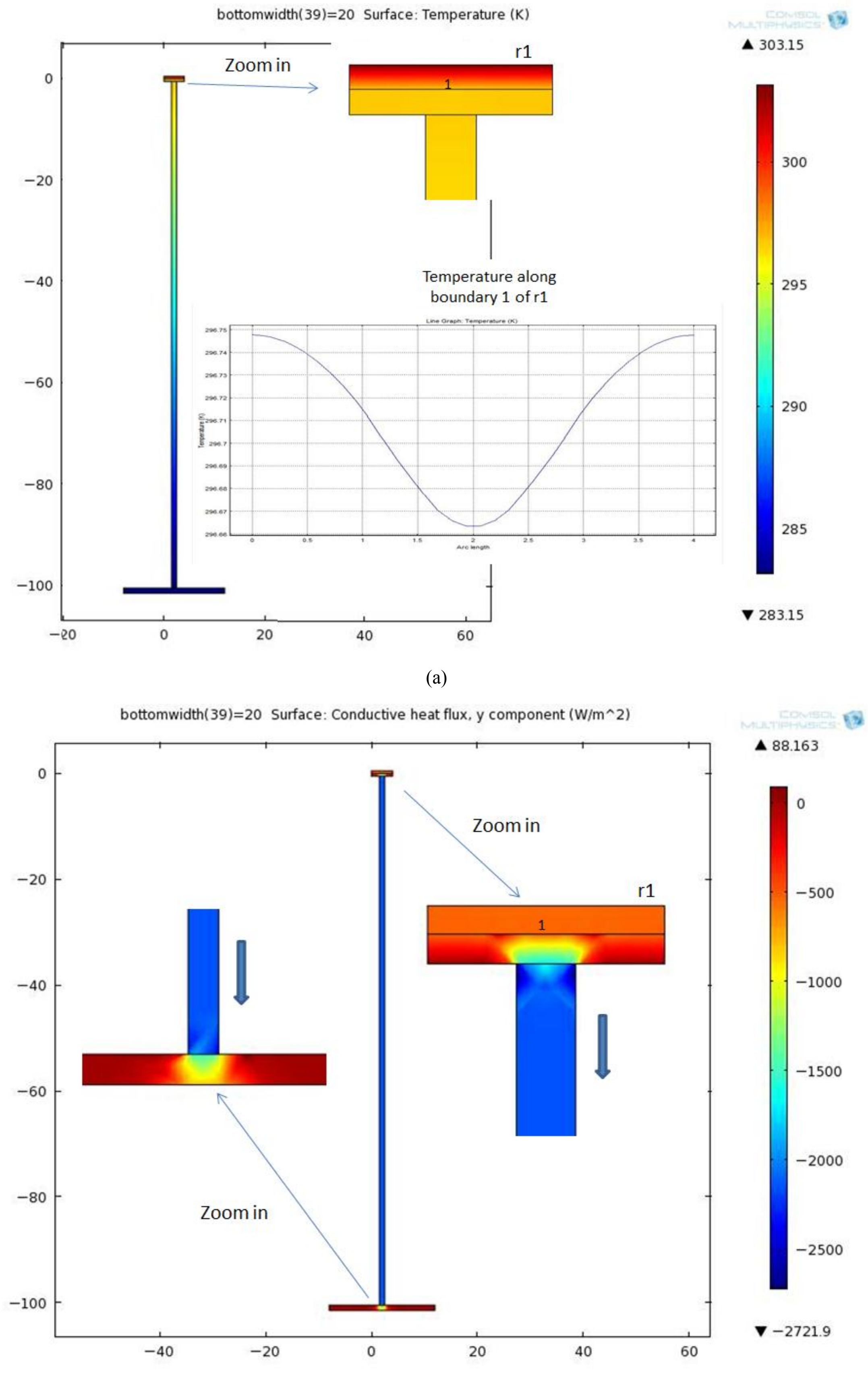
Influence of Thermal Insulator Length along the Heat Collector Rod

This analysis is to find out an optimum thermal insulator length for a fixed length heat collector that corresponds to the highest output power. In principle, thermal insulator too long reduces the effective areas for heat exchange; thermal insulator that is too short cannot effectively prevent heat dissipation. With the length of heat collection rod of 1 m, the insulator length is varied from 5 to 95 cm with a step of 5 cm to obtain the overall trend. After the optimum length's range is determined, a second sensitivity with a smaller variation of insulator length by 1 cm is then carried out. The results are shown in Fig. 6.

It is found the optimum insulator length is in the range between 50 and 70 cm. The second sweep is conducted between 50 cm and 70 cm with step 1 cm. The optimum insulator length is determined to be 59 cm, which could produce energy at the power of 0.011 W.

Effects of Thermal Contact

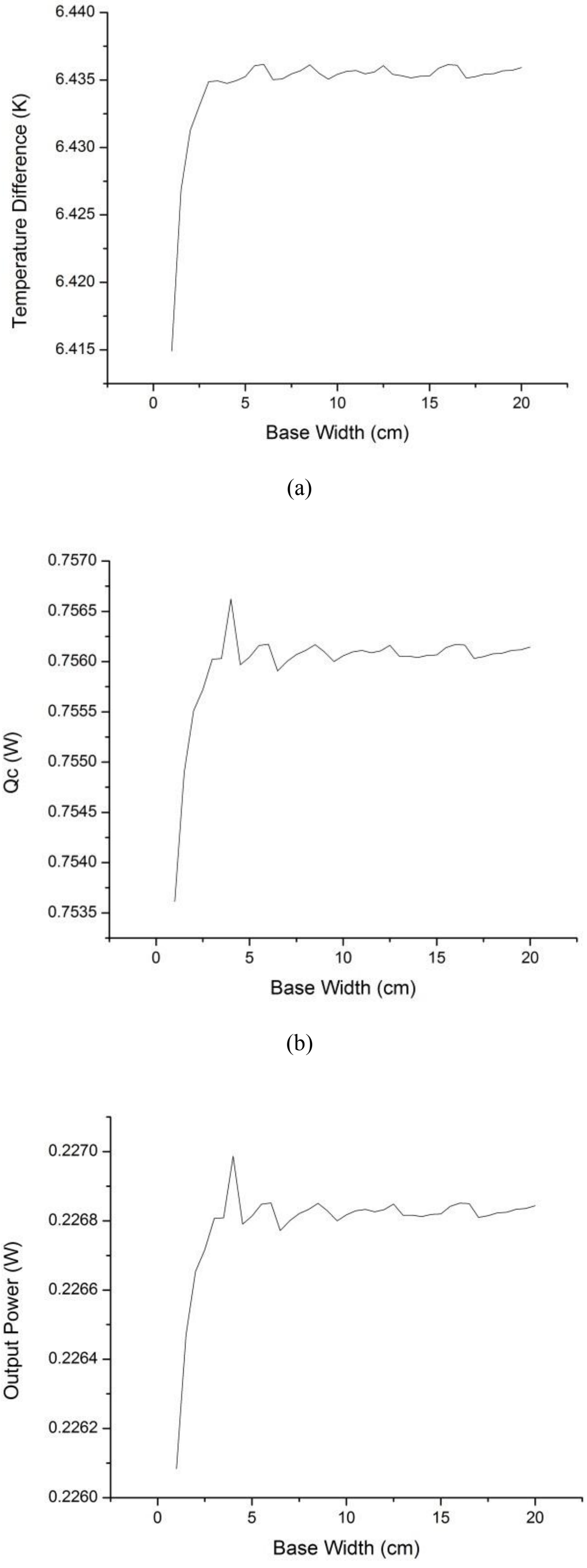
The previous simulations assumes the aluminum plate is in perfect



(a)

(b)

Fig. 4. a) Temperature Distribution in the Heat Collector and Along the Lower Surface of Thermoelectric Element r1; b) Distribution of Heat Flux in the y Direction.

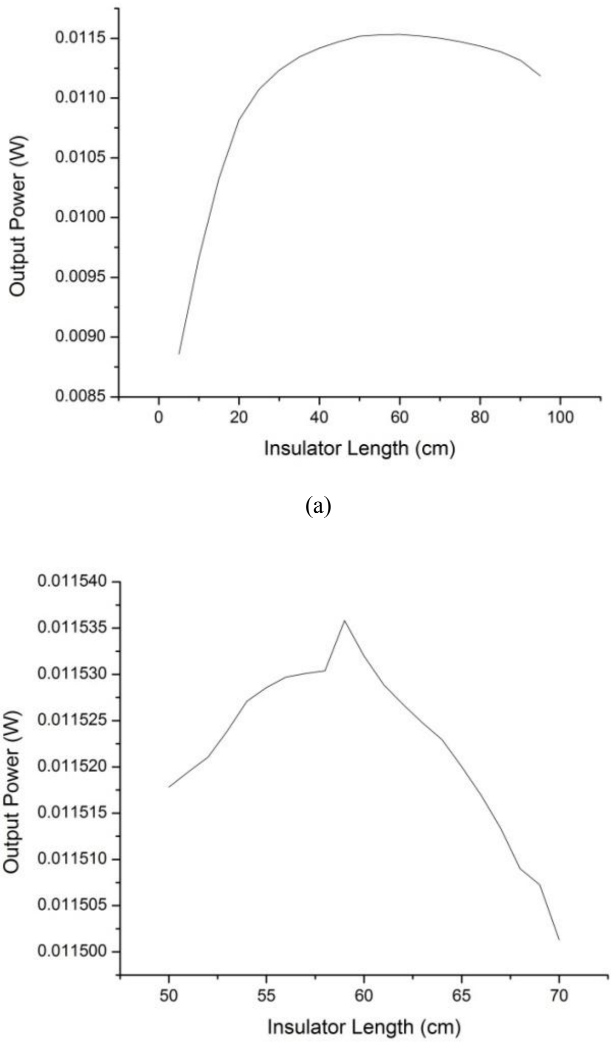


(a)

(b)

(c)

Fig. 5. a) ΔT VS Base Width, b) Qc VS Base Width, c) Output Power.



(a)

(b)

Fig. 6. Output Power vs Insulator Length (a) Sweep of Length at 5 cm Interval; (b) Sweep Length at 1 cm Interval Around the Optimal Length.

connect with the TE module. However, in actual installation, glue has to be applied to make thermal connection. The glue thermal conductivity is swept from 2 to 80 with step 2 W/(m*K), and the results are shown in Fig. 7.

The output power is smaller than perfect thermal connection as the thermal conductivity of glue is smaller than that of aluminum. Fig. 7 shows that glue with thermal conductivity larger than 20 W/(m*K) is desirable from efficiency perspective.

Estimation of Total Energy Output by the TE Harvesting System

An optimum system components design for the energy harvesting system is determined from the previous analysis. The following discussion estimates the total energy that the system can produce in one day. A set of typical pavement top surface temperature data in a day collected in Ohio DOT SHRP testing road is used for the estimation. The daily temperature variation and the temperature difference between road structure and subgrade are plotted in Fig. 8.

Fig. 9 shows the corresponding total heat flow (Fig. 9a) and power output (Fig. 9b) of the TE element using the optimal design geometry and thermal connection determined from previous simulation. The total energy produced with this day is determined by integration of the output power, which gives the output energy of 1293 J throughout the day. This amount of energy can power a typical IC device (drawing 100 mA, working at 1.5 V) for more than two hours. The system should be capable of providing power for periodic pavement monitoring purpose. Therefore, thermoelectric harvesting system is a promising method to resolve the power supply issue for long term pavement monitoring applications.

Conclusion

This paper analyzed the performance of a novel thermoelectric energy harvesting system that harvest energy using the temperature difference between the pavement surface and the subgrade soils. An

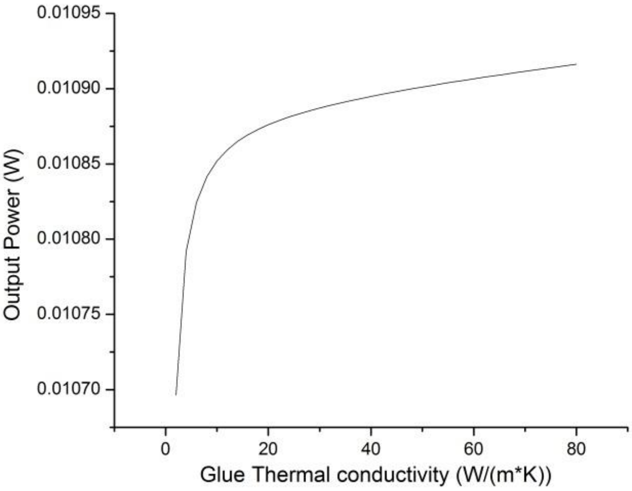
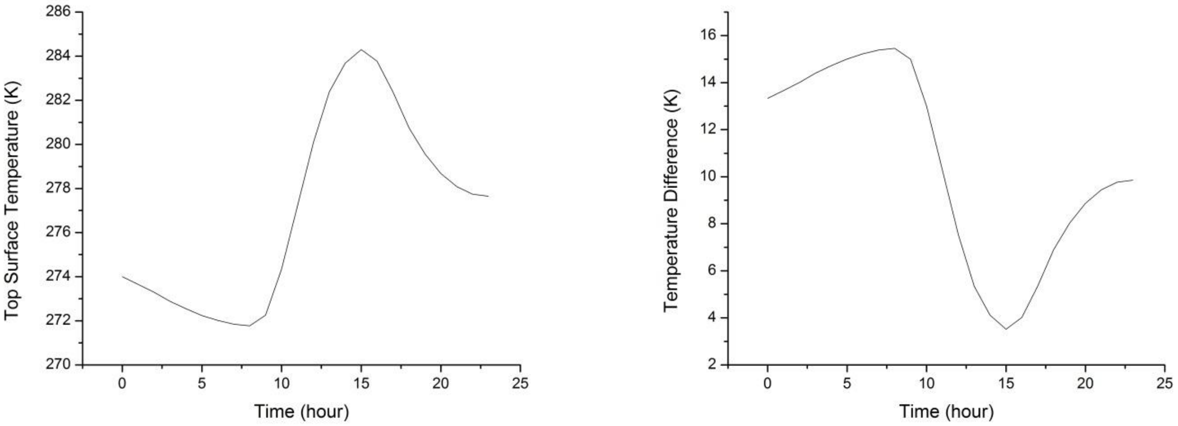
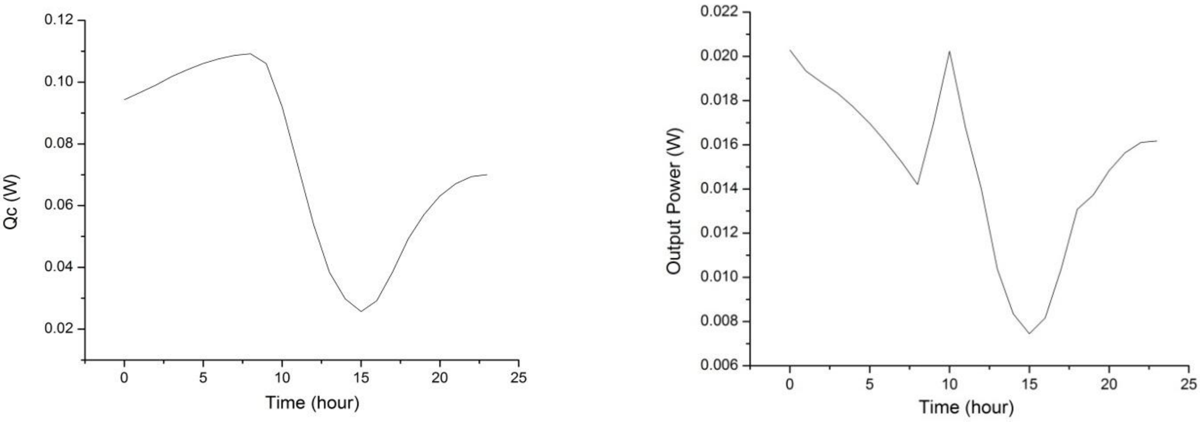


Fig. 7. The Output Power vs the Thermal Conductivity of Glue.



(a) (b)

Fig. 8. a) Daily Variation of the Surface Temperature of Pavement, b) Daily Variation of Temperature Difference between Pavement Surface and Subgrade.



(a) (b)

Fig. 9. a) Qc VS Time. b) Output Power vs Time.

optimal design of the harvesting system is developed using computational simulations, by analyzing the sensitivity of the system output to the width of heat collector, length of thermal insulation along the hear collector rod and thermal connection. With an optimal design, the system is estimated to provide power output of 0.02 W and energy output of over 1000 J on a typical day. This is sufficient to power IC sensor device for pavement monitoring purpose. Therefore, thermal energy harvesting is a potential way to resolve the power supply requirements for long term pavement monitoring applications.

References

1. Technology Innovation Program (TIP), National Institute of Standards and Technology (NIST) (2009). Advanced Sensing Technologies and Advanced Repair Materials For The Infrastructure: Water Systems, Dams, Levees, Bridges, Roads, And Highways, NIST, Gaithersburg, Maryland, USA.
2. Seiko Instruments Inc. Online http://www.seikowatches.com/heritage/worlds_first.html#wrapper, Last Accessed February 2012.
3. Leonov, V., Fiorini, P., and Sedky, S. (2005). Thermoelectric MEMS generators as a power supply for a body area network. *Transducers*, 1, pp. 291-294.
4. Sodano, H. A., Simmers, G. E., and Dereux (2007). Recharging Batteries using Energy Harvested from Thermal Gradients. Journal of Intelligent Material Systems and Structures, Vol. 18, pp. 3-10.
5. Yang, S M, T Lee, and M Cong (2010). Design and verification of a thermoelectric energy harvester with stacked polysilicon thermocouples by CMOS process. *Sensors and Actuators A: Physical*, 157(2), pp. 258-266.
6. Rowe, D. M. (1995). *CRC Handbook of Thermoelectrics*, 1st Edition, CRC Press, Boca Raton, Florida, USA.