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Potentials of piezoelectric and thermoelectric technologies for harvesting energy from pavements

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ABSTRACT

To harness renewable energy in the transportation sector,research on the application of thermoelectric and piezoelectric effects in energy harvesting pavements has progressed significantly over the last few years. This study provides a comprehensive literature review of recent advances in the application of thermoelectric and piezoelectric technologies in pavements to generate electricity. Most studies on the piezoelectric effect application with piezoelectric transducers (PZTs) showed its limitation in the amount of instantaneous electricity output, while a limited number of studies indicated that a pipe system cooperating with a thermoelectric generator (TEG) may produce more electric power, and so has more application potential in energy harvesting pavements. Studies have also indicated that supercapacitors and rechargeable batteries will be needed to appropriately store the electricity generated from pavements. As a case study, the potentials of thermoelectric and piezoelectric technologies were assessed and compared based on the Florida roadway network. Using results from previous studies as well as Florida weather and traffic data, it was estimated that if the entire Florida roadway network was covered by a proposed pipe system (PP-TEG system), it would collect 55 GWh electrical energy per day, while the one covered by a series of PZTs (PZT system) would only generate 4.04 MWh electrical energy per day. Based on the cost effectiveness analysis of the two systems, unless the PZT system is only paved on the roadway section with very high traffic volume, the PP-TEG system is more cost-effective than the PZT system.

1. Introduction

In the U.S., roadways play a critical role in the transportation sector. Among the national energy production, one third is consumed by the transportation sector, in which over 80% is used by road transportation [1,2]. Every day, on the 6-million km roadways in the U.S., rolling resistance from pavements and vehicle vibration waste a huge amount of vehicle kinetic energy [3–5]. Solar radiation absorbed by pavement surface is mostly unutilized, which may lead to a negative impact such as heat island effect in urban areas [6,7]. If these wasted energies can be collected and converted to a usable form, such as electrical energy, pavement can be turned into a new “energy farm” in the future.

The idea of harvesting energy from pavement has recently triggered a noticeable amount of research interest and effort in the academic community. Studies have been conducted on various aspects of energy harvesting pavement, including theoretical analysis of energy conversion and storage processes, structural design of energy harvesting facilities, laboratory testing with protocol models, and trials with field test sections. The last ten years have witnessed a significant increase in the numbers of research proposals and publications in this area. Most of the work, however, has focused on specific technical details of adding an energy harvesting device into pavement and evaluating its power output potential. There have been fewer discussions on some other aspects such as impact of energy harvesting facilities on pavement performance, comparison of various energy harvesting technologies, and the cost-effectiveness of applying an energy harvesting technology to a pavement network. To shed light on some of these less discussed topics and to better describe current knowledge status of energy harvesting pavements, a state-of-the-art literature review is needed. With knowledge of the latest achievements and limitations of various energy harvesting technologies, future research directions for energy harvesting pavements may be identified.

This paper begins with an extensive literature review of previous research on electricity generation and storage from pavements by piezoelectric and thermoelectric technologies, with a focus on the feasibility of applying these technologies to a broad pavement network. Then, using the information collected from the literature, a case study

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is presented based on the Florida roadway network, to mathematically assess and compare the potentials of two major energy-harvesting technologies for use in pavements.

2. Basic concepts of piezoelectric and thermoelectric effects

In the piezoelectric (PZ) effect, electricity can be generated when piezoelectric materials are mechanically deformed: once certain solid materials, such as crystals or biological matter, are pressed or pulled, electric charge will occur across these objects [8]. The conversion of mechanical stress into electrical charge is called the piezoelectric effect, which is often expressed by the following piezoelectric coupling equations:

$$S = s^{E}T + dE \tag{1}$$

$$D = dT + \varepsilon^{T}E \tag{2}$$

where:
T = stress;
S = strain;
E = electric field;
D = electric displacement;
s^E = elastic compliance for constant electric field;
d = direct or converse piezoelectric effect;
ε^T = dielectric permittivity for constant stress.

The physical meaning of each term in the above coupling equations is illustrated in Fig. 1.

In the thermoelectric (TE) effect, heat is converted into electrical energy based on the Seebeck effect, which is a constant temperature difference on two sides of dissimilar metals or semiconductors that can produce a steady electric current in a circular loop, as shown in Fig. 2. The principle behind the thermoelectric effect is:

$$V = a(T_h - T_c) \tag{3}$$

where:
V = voltage difference between two dissimilar metals or semiconductors;
a = seebeck coefficient;
$T_h - T_c$ = temperature difference between hot and cold junctions.

As can be seen from Eqs. (1)–(3), it is possible to produce higher electricity from higher stress or higher temperature differences. Coincidently, the stress on pavement surface under vehicle loads and the temperature difference between pavement layers can both be high.

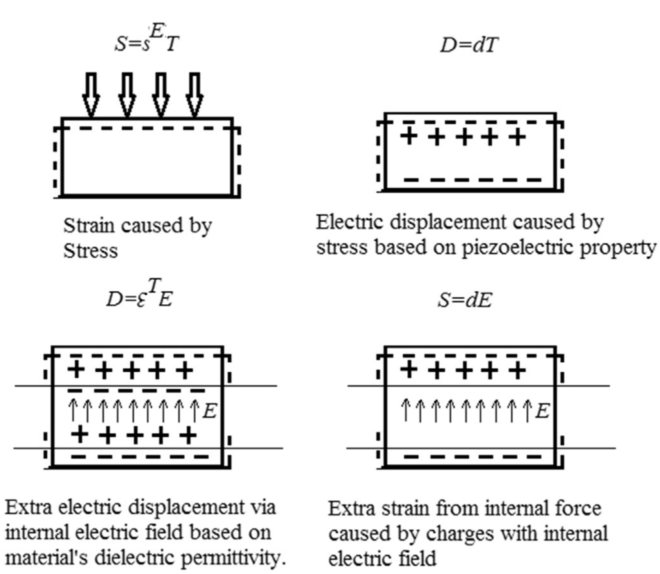

Fig. 1. Physical explanation for each term in the piezoelectric coupling equation.

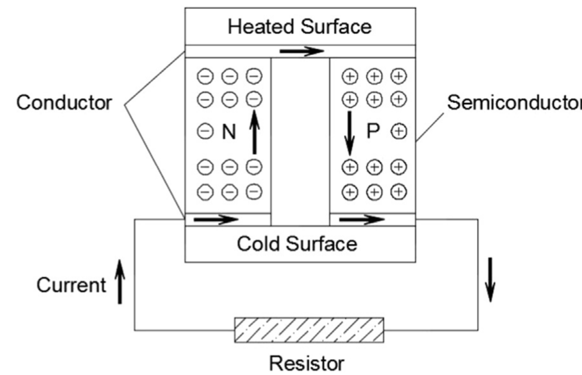

Fig. 2. Schematic diagram of thermoelectric generation.

3. Literature review

For the PZ effect applications in energy harvesting pavements, this literature review covers results from previous studies based on mathematical models, laboratory test evaluation, and field test sections. For the TE effect applications, the review focuses on two major technologies: pipe system and thermoelectric cell embedded in pavement layers. Potential electrical outputs from the PZ or TE technologies were reviewed and summarized from the literature, and later used as inputs in the case study of this paper. Current electrical energy storage technologies were also reviewed to determine the ones that are most suitable for use with the two energy harvesting technologies.

3.1. Development of piezoelectric technologies for energy harvesting pavement

3.1.1. Background of piezoelectric effect application for energy generation

After its initial discovery in 1880 by the Curie brothers [9], the piezoelectric (PZ) effect was first applied in sensors or transducers to detect signals, based on the fact that when a PZ material is bended by waves or vibration, voltage can be generated and measured in the PZ material. As inverse applications, PZ materials may also be used to emit signals, vibrate quartz (in a clock), or even offset sound waves. In the 2000s, several research projects started to seek practical PZ technologies to harvest energy from human movement. In 2000, the Defense Advanced Research Projects Agency (DARPA) designed a "heel-strike generator" for soldiers to convert mechanical energy to electrical energy, which can supply power to soldiers' portable electronic devices [10]. In 2007, two Massachusetts Institute of Technology (MIT) students raised an idea to harvest energy from human movement at crowded sites, which were called "crowd farms", and tested a prototype stool at a train station in Torino, Italy. The stool exploited the passive act of sitting and generated sufficient power to light four LEDs [11]. In 2008, the East Japan Railway Company installed a special flooring tile with piezo elements at ticket gates of a train station. An average 0.1 W of electricity was generated per second when a commuter took two steps across the tile [12]. However, the power generation efficiency of the tile was limited by the low foot traffic on the tile. In the same year, PZ materials were used with other green energy technologies to build the first eco-nightclub in London. The dance floor of the nightclub was made of piezoelectric crystals which produced electricity from dancing people to power up lights and air conditioning [13].

Although PZ has a long history of recognition and has already been widely applied in many fields, research on its application in pavements had not started until the late 2000s. In recent years, there have been a number of studies on this topic. A summary of them is given in Table 1. As can be seen, the main idea in the existing studies was to embed piezoelectric transducers (PZTs) into a pavement to generate electric power to supply sensors and some infrastructure utilities. So far, four