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Energy Harvesting Technologies: roadway transportation and atmospheric water gathering in Smart City

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Annotation:
One of the main parts of the "Smart City" concept is energy sustainability. The increasing number of people in cities increases the consumption of electrical energy. To solve this problem, energy harvesting and conversion devices (EHCDs) are developed. These devices convert environmental energy to electricity. Roadway transportation and the atmosphere are renewable sources with a large potential. The aim of the article is to present prototypes with their output characteristics.

Anotace:
Jednou z hlavních části konceptu "Chytré Město" je energitická stabilita. S rostoucím počtem lidí ve městech se zvyšuje spotřeba elektrické energii. Pro řešení dáného problému se vyvijí zařízení, které sbírají energii a transformují ji. Uvedená zařízení transformují energii okolního prostředí v elektřinu. Dopravní prostředky a atmosfera jsou obnovitelné zdroje energie s velkým potenciálem. Cílem tohoto článku je prezentovat prototypy s jejich výstupními charakteristikámi.

INTRODUCTION

Nowadays, more than half of the global population is living in cities, and the speed of urbanization continues to increase. As a result, energy consumption increases sharply in the cities, which leads to increased energy production. The existing fossil energy supply resources are gradually becoming insufficient. Based on environmental protection and energy-saving, energy harvesting devices have attracted the attention of researchers. Subsequently, two technologies have rapidly become the focus of attention and research. There are energy harvesting technologies in roadway transportation and atmospheric water gathering.

The roadway transportation system is one of the major civil infrastructures. Moreover, the road consumes large energy. The typical sources of energy are solar radiation energy, geothermal heat, and mechanical load (the former and last energy sources are described in the article). Energy harvesting technologies (such as a thermoelectric generator or piezoelectric energy harvester) can convert energies in road systems to electricity. Although most of them are still in the laboratory research stage [13].

The water molecules in the surrounded air are one of the main parts of the atmosphere. The moisture in the air can be used as a source of the energy. Devices capture atmospheric water and convert the water energy to electricity. The water gathering energy harvesting technology has the advantage of stable energy output [10].

The objective of the article is to review the energy harvesting prototypes used in roadway transportation and atmospheric water gathering. This paper presents the results of experiments and describes structures of energy harvesters and basic principles.

BASIC PHYSICAL PRINCIPLES OF ENERGY HARVESTING

Piezoelectric effect

The piezoelectric effect is based on converting the deformation of a piezoelectric material into electric energy. The strain generates in the material when it is applied force (direct piezoelectric effect) or is exposed to an electric field (converse piezoelectric effect). Furthermore, the value of the output voltage depends on the applied stress [3, 4].

Typically, the piezoelectric energy harvester devices (PEHD) are designed based on the direct piezoelectric effect. The PEHDs use one of the configurations: cantilever structure for resonant mode (RM) [3] or sandwiched structure for non-resonant mode (NRM) [4].

Triboelectric effect

The triboelectric effect is based on contact electrification. Two different materials become electrically charged after their separation. For example, when the materials, such as polytetrafluoroethylene and aluminum, become physically in contact, there is a charge transfer. If they are separated by a gap, there is a voltage generated on electrodes due to electrostatic induction. The electric potential depends on triboelectric charge density and interlayer distance [6].

The triboelectric phenomenon works in two fundamental modes: contact-separation mode (CSM) and lateral-sliding mode (LSM). Moreover, as an extension of CSM, there are two basic modes: single-electrode modes (SEM) and freestanding triboelectric-layer mode (FTLM) [6].

Thermoelectric effect

The thermoelectric effect is based on converting temperature gradients into electricity. A design of thermoelectric devices produces from p- (positive Seebeck coeficient) and n-type (negative Seebeck coeficient) doped materials. If segments are combined in «П» structures, there are to increase an output voltage and spread hear flow [7].

ATMOSPHERIC WATER GATHERING

One of the main parts of atmospheric EHCD is a hygroscopic material that collects water molecules from the atmosphere. The captured water as a medium realizes for the conversion energy [10].

Thermoelectric atmospheric energy harvester (THAEH)

Yang et al. designed and fabricated a hygroscopic aerogel (denoted as G-PDDA) with a highly porous structure (pure size is from 5 to 340 um). The main components of G-PDDA aerogel are graphene oxide (GO) and poly diallyldimethylammonium chloride (PDDA) with a relatively concentration of 10 mg/ml and 20 wt% PDDA solution. This composition has the best balance between water sorption capacity and kinetics.

The combination of G-PDDA aerogel and thermoelectric module (TEM) creates the device which uses a thermoelectric effect (see the Basic Principles section) for conversion energy. In this device, the aerogel is fixed on the hot side of a TEM with a small air gap, the other side is plated on a cooling head to maintain the established constant temperature.

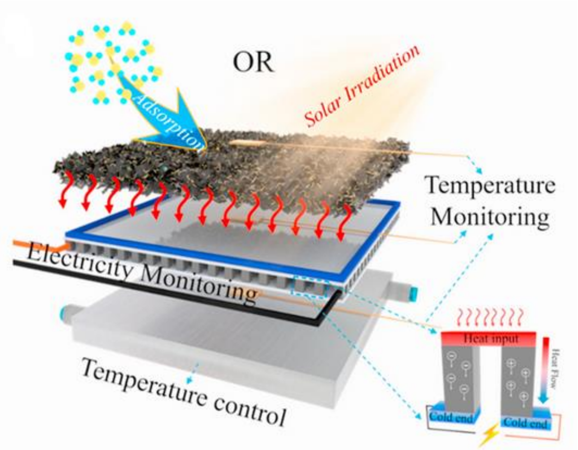

Figure 1: Diagram of the device that consists from G-PDDA aerogel and TEM [9].

To test the device was placed in an environment of 60% relative humidity (RH) and 20 °C. In the adsorption process the mass of the sorbent layer quickly increased, as a result the temperature of the layer rose. The device produced the maximum output power density 6.6 mW/m^2 that was measured using an external load resistance. The detected open-circuit voltage V_{oc} and short-circuit current I_{sc} were 9 mV and 5 mA, respectively (temperature difference ~1 °C). In the deposition process (the sorbent layer released the captured water, therefore, the weight lost) with 1 kW/m^2 solar irradiation, the device produced 520 mW/m^2. The V_{oc} and I_{sc} increased and stabilized after 3 min at 78 mV and 45 mA, respectively (temperature difference ~5 °C). Finally, the device demonstrated very quick responsible, stability, and effective light-to-heat conversion [9].

Triboelectric atmospheric energy harvester (TRAEH)

Wang et al. designed the triboelectric nanogenerator (TENG) for harvesting mechanical energy from the environment. The TENG is based on the triboelectric effect (see the Basic Principles section). The effect exists not only between solid materials but also between a solid material and a liquid substance. Based on the solid-liquid friction Chen et al. designed TENG with two types of electrodes: flat and tapered. The dielectric coating with hydrophobic properties, such as fluorinated ethylene propylene (FEP), is adhered to the high-purity copper foil. It is bonded to a polyamide substrate (PI) so that creates a planar electrode. The size of the flat electrode is 30 × 20 mm^2. This electrode has a coaxial micro-hole for the tapered electrode (electrodes are electrically separated). The tapered electrode is created from 99.99% purity copper wire (diameter and length are from 1 mm and 50 mm, respectively) and is covered with a hydrophilic layer for capturing moisture from the air. The electrode is developed with geometric gradient differences that produced a Laplace pressure from the tip to the end on the electrode (water droplets move axially from the place with a large curvature to the place with a small curvature) [11].

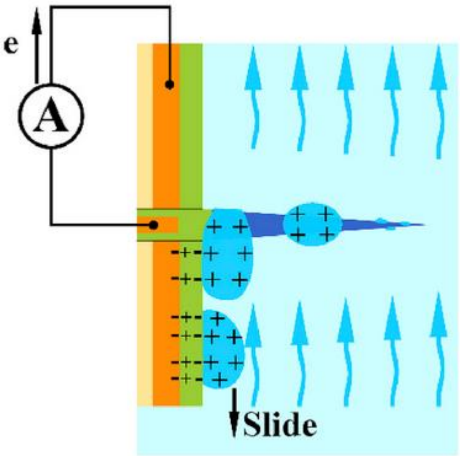

Figure 2: Diagram of the TENG with tapered structure [11].

When the water droplet locates on the hydrophilic-hydrophobic junction or slides on the hydrophobic surface, the electric potential difference is generated. This is because the moisture in the air already contains triboelectric charges (positive charges) on its surface because of the friction on the air. When the water droplet slides on the FEP film surface, the negative charges are induced in the planar electrode. Therefore, negative I_{sc} (approximately 70 nA) and V_{oc} (approximately 8 V) are generated between flat and tapered electrodes. When the droplet moves off the surface of the FEP film, the negative charges negate and the electrons at the flat electrode flow back to the tapered electrode. As a result, the positive current is produced (approximately 30 nA) and the electric potential difference is decreased. There is when only one water droplet is used. The hydrophilic layer continuously collects the water molecules from the air. When the one water droplet moves down, the other droplet creates on the hydrophilic-hydrophobic junction (figure 2). As a result, fewer charges are transferred, therefore, the V_{oc} and absolute I_{sc} (I_{asc}) caused by a single droplet decreasing to 5.3 V and 63.8 nA. Furthermore, the induced voltage was accumulated and the saturation voltage is defined as a value of 100 V (saturation time T_{sat} is 480 s).

Based on the results of experiments, the V_{oc} and I_{sc} depend on the diameter d of the tapered electrode, quantity n. The performance of the device increases (and the saturation time decreases) linearly when the tapered electrode is used with the increasing d and (or) n. This is because the water droplet increases the contact area between the droplet and FEP. If the size of the planar electrode is 30 × 20 mm^2 and the diameter of four tapered electrodes is 1mm (with pitch 3mm), the T_{sat}, V_{oc}, and I_{asc} are 580 s, 9.5 V, and 157.7 nA, respectively. Also, the TENG with tapered electrode depends linearly on the spray flow rate (correspond with RH) and ambient temperature T. The performance of the TENG increases with increasing RH and (or) decreasing T. Moreover, the composition of the moisture influences the TENG performance but the effect is still not clear.

HARVESTING TECHNOLOGIES IN ROADWAY TRANSPORTATION

One of the main parts of civil infrastructure is roadways which can be used as an energy source. Asphalt as a surface uses for the conversion of energy [13].

Piezoelectric energy harvester (PEH)

Yang et al. create the piezoelectric boxes (rectangular and circular) which are based on the piezoelectric effect (see the Basic Principles section). Considering the load of the device, the PEH was designed with good compressive ability, fatigue resistance, waterproof, and anti-corrosion performance. Each box is buried in the road and is used to collect the energy of mechanical vibrations. When the vehicle rolls to the box surface, electrical energy is generated. The main part of the piezoelectric box is the piezoelectric units. The unit consists of piezoelectric material (such as lead zirconate titanate (PTZ-5H)) which determines the energy collection efficiency [12]. Each unit of the PEH uses three PTZ-5H slices which are stacked together (with the parallel connection). The diameter and height of the piezoelectric unit are 20 mm and 23.2 mm, respectively. The external size of the rectangular PEH is 300 × 300 × 80 mm^3. The dimension of the circular PEH size is Φ300 × 80 mm. Each device uses 12 piezoelectric units. The structure of the device is shown in figure 3.

In the experiments were used vehicle, ten circular PEHs and ten rectangular PEHs. The weight of the vehicle, the tire pressure, and the axial load were 1.8 tons, 0.7 MPa, and 4.5 kN, respectively. The space between PEHs was 2.5 m. When the vehicle passed PEHs at the speed of 20 km/h (or 80 km/h), the pick V_{oc} was 250 V (or 400 V).

Based on the results of tests, the performance of the PEH depends on the wheel speed, the weight of the vehicle, and the axial load [12, 14]. But the effect of the tire pressure is still not clear.

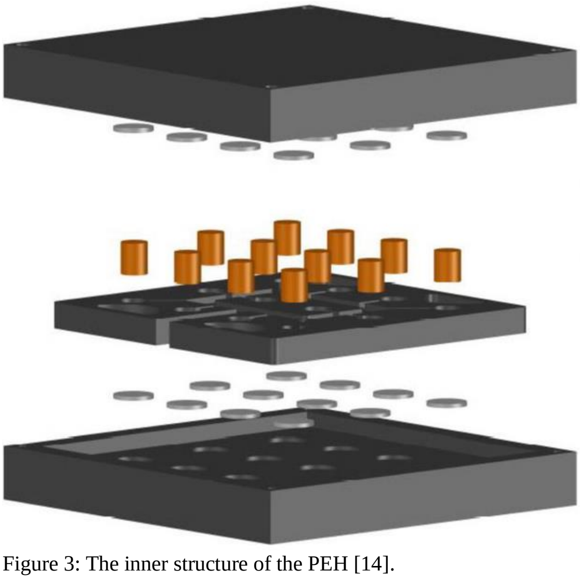

Figure 3: The inner structure of the PEH [14].

Thermoelectric energy harvester (THEH)

The pavement thermoelectric generation technology (PTGT) is based on the thermoelectric effect (see the Basic Principles section). The roadway accumulates the heat (solar radiation and ambient air) inside itself. As a result of exposure, it can induce a thermal gradient between the road layers. The ideal depth for experimental thermoelectric generation ranges from

20 to 30 mm. Jiang et al. create the power generation device (PGD) from aluminum vapor chambers, the water tank, and thermoelectric generators (TEGs). Three pieces of chambers with 300 × 60 × 3 mm^3 dimensions are placed in such a way that the depth is 20 mm and about 100 mm length of each chamber is exposed to the outside of the road. These chambers are connected to TEGs hot side (used the TEG-199). The water tank with 350 × 150 × 160 mm^3 sizes (and the aluminum vapor chamber at the bottom) is bonded to the TEGs cold side using the thermal adhesive glue. Aluminum heat sinks are appended to the water tank for better heat exchange between the water and ambient air [15].

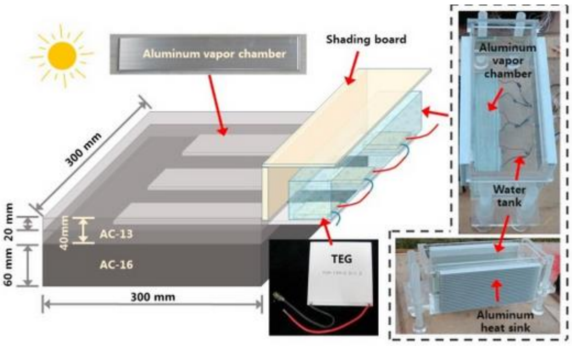

Figure 4: Diagram of the PGD [15].

Based on the results of experiments, the performance of the PGD depends linearly on the temperature difference and output voltage. The maximum V_{oc} and I_{sc} by the device, which is shown in figure 4, fluctuated about 0.4 V and 0.107 A, respectively, in the winter season (and 0.7 V and 0.187 A, respectively, in the summer season). The output power for this day was about 0.233 W h of electricity in 7.5 h. If the PGD was 1 km in the length and 10 m in the width, the output power would be about 26 kW h (and 160 kW h for the summer day).

CONCLUTION

The development of energy harvesting technologies is an important step toward energy sustainability. The review described energy harvesters as a THAEH, TRAEH, PEH, and PHEH. PEHs and PHEHs have a good performance and can be used for supplying LED lamps or information LED displays. Energy harvesters using atmospheric water gathering technology can be used for supplying sensors. Today, the implementation or the development of energy harvesters is expensive which creates some complications. But future developments of energy harvesting devices are recommended.

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