

# Development of Shoe-heating System based on Piezoelectric Energy Harvesting

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## 압전 에너지 하베스팅을 이용한 신발용 발열 시스템 개발

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### ABSTRACT

Soldiers have been exposed to the risk of chilblains in cold winters. Recent studies have described sensors and IOT devices that use independent power sources based on piezoelectric energy harvesting. Therefore, the heated shoes with an independent power source have been developed. For the application of energy harvesting to shoes, it is necessary to develop a unique harvester by considering human gait characteristics. Energy harvesters and ceramics were designed and fabricated in this study. The performances of these harvesters and ceramics were evaluated experimentally. Then, the harvesters and ceramics with superior performance were selected and applied to the system. Thereafter, the heating and charging performance of the system was tested under real walking conditions. The results show that the developed system can generate adequate energy to charge the battery and heat the shoes.

**Key Words** : Multi-layered Piezoelectric Element(적층형 압전소자), Energy Harvesting(에너지 하베스팅), Carbon Fiber Heater(탄소섬유발열체), Charging Circuit(충전회로), Heated Shoes(발열신발)

### 1. Introduction

Most of the Korean men are required to serve in the military. These men are easily exposed to the risk of chilblains on toes because they usually work outdoors, for example, at guard posts and during training in cold winters.<sup>[1]</sup> Presently, to mitigate this

risk, soldiers wear double socks and move as much as possible within the limited areas assigned to them. In this scenario, heated shoes may help prevent chilblains and help with the treatment of chilblains.

Recently, eco-friendly energy has been attracting attention owing to fossil fuel depletion and environmental problems.<sup>[2]</sup> Energy harvesting is an eco-friendly method of generating electricity from commonly discarded energy. Through the piezoelectric,

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Seebeck, photoelectric effects, electricity can be harvested from various types of energy.<sup>[3]</sup> Specially, piezoelectric energy harvesting refers to the conversion of mechanical energy, such as vibration or impact, into electricity by using a piezoelectric ceramic that generates electricity under an applied mechanical stress. In recent years, sensors and IOT devices with independent power sources based on energy harvesting have been studied.<sup>[4-6]</sup>

Considering those two backgrounds, the development of shoes with a heating system seems to be possible by harvesting soldier's gait energy.

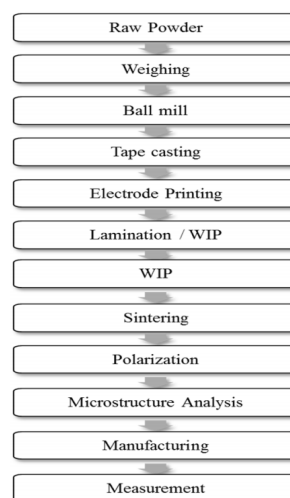
Ingenious harvester development is needed to consider the characteristics of human gait. In this study, two types of energy harvesters, indirect and direct, are developed using multi-layered ceramics and considering their energy-conversion efficiency.

## 2. Design and Manufacture of Energy Harvesting

### 2.1 Piezoelectric Ceramic

The piezoelectric effect refers to the phenomenon in which dielectric deformation occurs when an applied mechanical stress deforms a piezoelectric material such that the charge density at the interface between the electrode and the piezoelectric element changes instantaneously. The coupling between mechanical energy and electronic energy in the piezoelectric effect is characterized by linearity and reversibility, and the electrical energy output increases as the polarization increases.<sup>[2,7]</sup>

Piezoelectric energy harvesting offers the advantages of high energy efficiency and high energy density.<sup>[8]</sup> Moreover, there is considerable scope for application development because of the relatively simple manufacture methods involved. Most of the latest applications of piezoelectric ceramics use lead zirconate titanate(PZT), a compound with a perovskite structure. Perovskite compounds



**Fig. 1 Fabrication process of piezoceramic thick film actuators<sup>[9]</sup>**

exhibit remarkable levels of the piezoelectric effect and offer great advantages in terms of physical properties, such as electro- mechanical coupling coefficient and mechanical characteristic coefficient.<sup>[7]</sup>

Many types of piezoelectric ceramics are available, such as unimorph, bimorph, multi-layered and cymbal etc. Among them, the structure of multi-layered piezoelectric ceramics is formed by arranging piezoelectric ceramics in a stack. If thin ceramic layers are stacked on the same pole, they are connected in parallel. Stacking increases the structural stiffness and lifetime of a piezoelectric ceramic.<sup>[7]</sup>

The process of manufacturing multi-layered piezoelectric ceramics is shown in Fig. 1, and the ceramics used herein were manufactured with the same process.

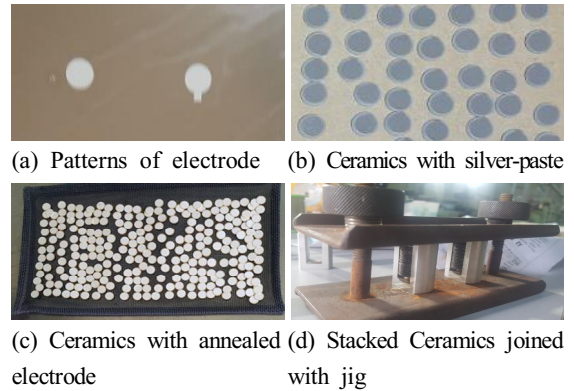
First, a slurry is prepared by mixing raw PZT powder and organic binder. The slurry is arranged into a tape-like shape by using the doctor blade method, and then an electrode is printed on the tape-shaped elements. Thereafter, the tape-like slurry with the electrode is annealed in an oven.

Single-layer ceramics fabricated in this manner are eventually stacked after polarization.<sup>[9]</sup>

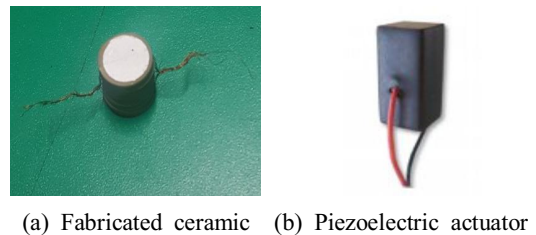
To evaluate the performance of multi-layered piezoelectric ceramics, multi-layered ceramics were fabricated manually in the ceramic factory by us. Thereafter manufactured ceramics were experienced and compared with PiezoDrive's product. Raw PMN-PZT powder, solvent, and binder were mixed to form a slurry, which was matured for 24h. A tape-like ceramic sheet was formed from the matured slurry by using the doctor blade method. The ceramic sheet was cut into  $\varnothing 8$  rounds that were then placed under a silkscreen, which is shown in Fig. 2-(a). Then, silver paste was spread on the single-layered piezoelectric ceramics, as shown in Fig. 2-(b), after which the ceramics were annealed for 8h at 800 °C. The annealed electrode is shown in Fig.2-(c). Then, the ceramics were polarized at 600 V and stacked in a parallel configuration by using epoxy. Thereafter, the polarized ceramics were fixed using a jig, as shown in Fig. 2-(d), and baked in an oven at 110 °C for 90 min. The fabricated ceramics are shown in Fig. 3-(a). The thickness of the ceramic sheet is 0.3 mm and four piezoelectric ceramics comprising stacks of 30-layers were fabricated. The dimension of these ceramics were  $\varnothing 8$ , 10 mm height. The capacitances of the fabricated ceramics were 37.8 nF, 53 nF, 32.2 nF, 22.8 nF. Moreover, SA050510, a product manufactured by PiezoDrive, was used in this study. It is shown in Fig. 3-(b). Its capacitance and dimensions are 630 nF and  $5 \times 5 \times 10$  mm, respectively.

## 2.2 Mechanical Design of Energy Harvester

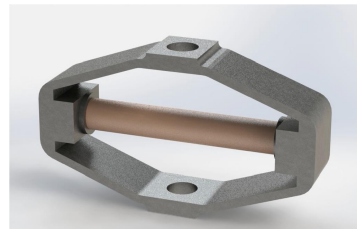
An indirect energy harvester was designed based on the amplified piezoelectric actuator. Anil Can Turkmen adopted this design and devised an energy harvester, which is shown in Fig. 4; the loop is deformed by the working load, and it pulls the ceramics.<sup>[10]</sup>



**Fig. 2 The process of manufacturing multi layered piezoelectric ceramic**

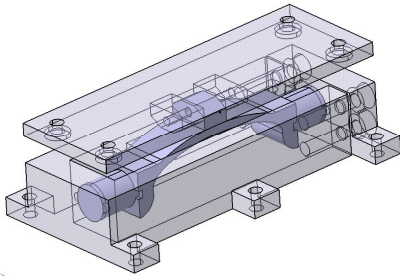


**Fig. 3 Multi-layered piezoelectric ceramic**



**Fig. 4 Energy harvester design of Turkmen A.C. <sup>[10]</sup>**

The indirect energy harvester shown in Fig.5 was designed to apply compressive force to the ceramics as the loop deforms. By design, this harvester can be assembled easily, and it offers greater stability. Moreover, the shape of its loop has been changed to half ellipse because the harvester housing holds the loop, which means the loop need not be a full ellipse. With changes to the design of its loop to reduce weight and size, this harvester can be easily incorporated into a shoe.



**Fig. 5 Indirect type energy harvester**

The indirect energy harvester consists of a pedal, loop, and housing. The pedal is coupled with the loop by pin joints to convert multi-direction forces into vertical forces. The loop is the core of the harvester. The loop deforms under an applied impact force and transfers an amplified load to the multi-layered piezoelectric ceramics installed on both sides of the loop.

Through ANSYS, a finite-element analysis program, we can predict deformation of the harvester. The analysis results obtained by applying a force of 600 N to the harvester are shown in Fig. 6. The axial strain of the ceramics is approximately 0.00015 mm/mm. When a force is applied to the harvester, a compressive force is applied to the ceramics by the deformed loop, as shown in Fig. 6.

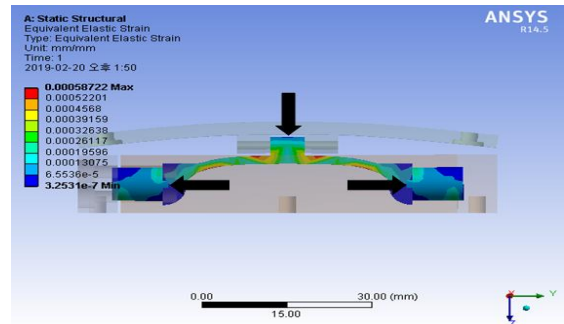
We selected Al6061-T6 as the material for manufacturing the indirect energy harvester. Aluminum alloys have high specific strength, which means an energy harvester made using the selected alloy is light-weight and has high-strength.

The indirect energy harvester was made using several machine tools. Most of the outward line was fabricated with a wire cutting machine. An end milling and drilling machine was used to machine harvester details. In addition, a 0.5-3 mm tapping screw was used for tapping. The machined workpieces were assembled with the ceramics fabricated in this study by using bolts.

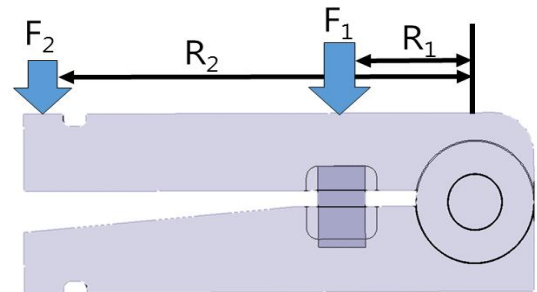
A direct energy harvester was designed, as shown in Fig. 7. This harvester has three functional

components, namely, the pin as the fulcrum, ceramic as the effort, end of the harvester as the load point, and it acts as a class 3 lever. Therefore, the load is amplified according to the leverage principle and applied to the ceramics. Assuming that a concentrated load is applied at the end of the harvester, the load amplification ratio is determined by the ratio of  $R_1$  and  $R_2$ , and in this study, the load amplification ratio was set to 1:3.

The direct energy harvester consists of an upper plate, under plate, and pin. The upper plate amplifies the applied load and transfers it to the ceramic. The ceramics are fixed to the under plate, which is coupled with the outsole. The pin joins the upper and the under plates, such that the direct energy harvester can rotate along the pin joint. Moreover, the pin acts as a fulcrum.



**Fig. 6 Finite element analysis result (ANSYS)**



**Fig. 7 Direct type energy harvester**

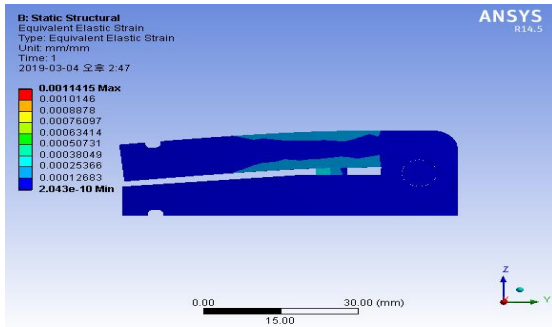


Fig. 8 Finite element analysis result (ANSYS)

Deformation analysis of the direct energy harvester was conducted through ANSYS. The analysis results obtained by applying a force of 600 N to the end of the harvester are shown in Fig. 8, According to the results, the strain of the ceramic is 0.00189 mm/mm.

The direct energy harvester was fabricated using a three-dimensional printer because of time and cost constraints. However, adequate stiffness and strength were secured by using ABS, which shrinks considerably under heat but is relatively strong and selecting options such as inner density of 100%(solid)

### 2.3 Composition of Shoe heating System

The shoe-heating system developed herein consists of an energy harvester, AC-DC conversion circuit, charging circuit, and heater, and the system performs the functions of electricity generation, charging, and heating. The energy harvester, battery, and circuit are installed in the heel of the shoe, and a carbon fiber heater is installed in the toe area of the shoe, as shown in a schematic of the heating system in Fig. 9.

The AC-DC conversion circuit consists of a rectifying circuit and a flattening circuit. The rectifying circuit consists of four diodes, and it converts the AC energy generated by the energy harvester into DC energy.

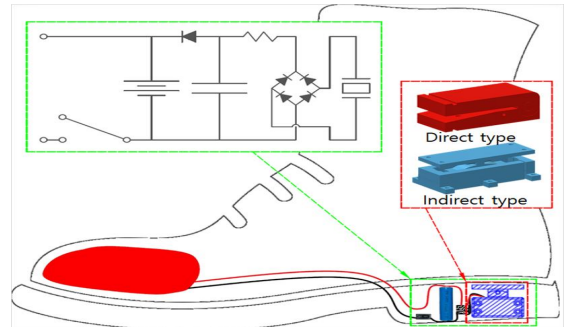


Fig. 9 Schematic of heating system

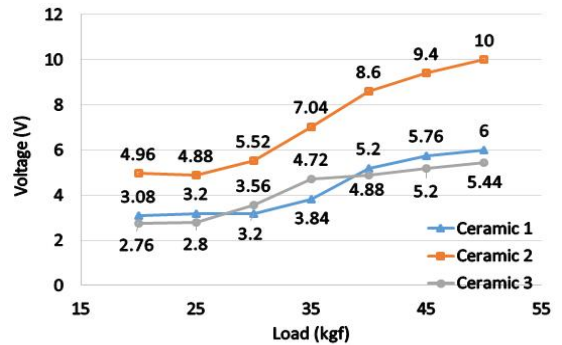


Fig. 10 Output voltage of fabricated piezoelectric

This DC energy is stabilized by the flattening circuit, which is composed of a capacitor and a resistor.

The charging circuit consists of a diode and a rechargeable secondary Li-ion battery. The diode prevents current backflow from the battery.

## 3. Performance evaluation

### 3.1 Performance Evaluation of Multi-layered Piezoelectric Ceramics

Several experiments were conducted for evaluating the performance of the fabricated multi-layered piezoelectric ceramics. First, the fabricated ceramics were fixed to jig, which was installed on a ultimate testing machine. The testing speed was set to 10

mm/min. Figure 10 shows the variation in the output voltage when a compressive load was applied to the ceramic.

The capacitances of ceramics (1), (2), and (3) are 37.8 nF, 53 nF, and 32.2 nF, respectively. Figure 10 shows that as the applied load increases, the output voltage increases. Among the three ceramics, ceramic (2) has the highest capacitance and the highest output voltage. According to Fig. 10, the capacitance of a ceramic affects its output voltage. SA050510, a product manufactured by PiezoDrive, was tested as well. In the prior test, which is evaluating ceramics fabricated in this study, compression speed affected the output voltage. Therefore, the experimental method was changed, and the experiment was conducted using triceps-pushdown machine. We set the weight to be applied and placed the jig to which the ceramics were fixed on the testing machine. Then, we eliminated the weight holding force. In contrast to the prior test, the load is applied in a step function instead of a ramp function.

The results shown in Fig. 11 indicate that the output voltages of ceramics are proportional to the applied load. The output voltage magnitudes of ceramics are twice the output voltage of the fabricated ceramics for the same load. According to the prior tests, the output voltage of ceramics is high when the capacitance of ceramics is high and a large load is applied. Therefore, the ceramic manufactured by PiezoDrive, which has a high capacitance and high output voltage, was selected and used in this study.

### 3.2 Performance Evaluation of Energy Harvester

The energy harvester was coupled with the piezoelectric ceramic, and the performance of the combination was tested. The test was conducted with the same method as that in the previous experiment by using a pushdown machine.

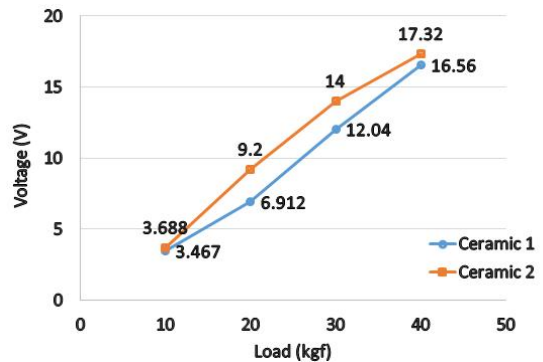


Fig. 11 Output voltage of SA050510

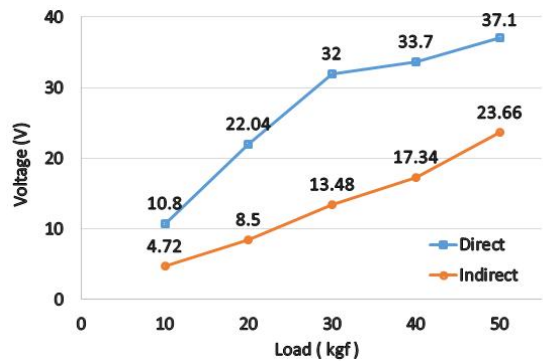


Fig. 12 Output voltage of piezoelectric with harvester

The test results are shown in Fig. 12. The indirect and the direct energy harvesters generate output voltages proportional to the applied load, as shown in Fig. 12.

Moreover, the output voltage generated by the direct energy harvester is thrice the output voltage generated by ceramic own. This result is similar to the design value. However, in case of the direct energy harvester, the gradient shown in Fig. 12 decreases when the applied load is 30 kgf. This is because the ends of harvester come into contact with each other under this load, and consequently, the principle of leverage does not hold.

For the same load, the output voltage of the direct energy harvester is higher than that of the indirect energy harvester. In addition, the structure of the direct energy harvester is more stable, and its

fabrication is simpler. Therefore, the direct energy harvester was selected in this study.

### 3.3 Performance Evaluation of Shoe-heating System

The shoe-heating system was built using the direct energy harvester and SA050510 (product of PiezoDrive) based on the results obtained earlier in this study. To evaluate the performance of the system and the effects of real-world conditions, we conducted two experiments. In the first of these experiments, a man weighing 90 kgf was asked to wear shoes equipped with the developed system and walk around, and the resulting changes in battery voltage and shoe temperature were measured.

The results of this experiment are shown in Fig. 13. The battery voltage increased by approximately 0.12 V from 2.62 V to 2.74 V when the man walked for 10 min while wearing shoes equipped with the developed system. Therefore, it can be concluded that the energy harvester can charge the battery by harvesting human gait energy.

In addition, a heating experiment was conducted. A man was asked to wear a shoe equipped with the developed heating system on one foot and a shoe without the heating system on the other foot.

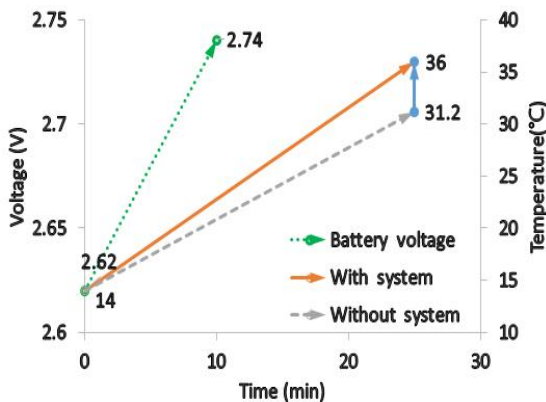


Fig. 13 The experiment results of shoes heating system

The toe temperature on the foot with system-equipped shoe increased from 14 °C to 36 °C and that on the foot with the ordinary shoe from 14 °C to 31.2 °C.

The toe temperature on the foot with the heating-system-equipped shoe was 15.4% higher than that on the foot with the ordinary shoe. This result demonstrates the effectiveness of the developed heating system.

## 4. Conclusion

In this study, we focused on a piezoelectric energy harvesting system optimized for shoes and developed a heating system based on it. To develop a system optimized for shoes, a scheme for energy harvesting considering human gait characteristics was proposed. In addition, a heating system that uses an independent power source based on energy harvesting was developed. The conclusions of this study are as follows.

1. The results of the experiments conducted with two types of piezoelectric ceramics show that the ceramic mass-produced by PiezoDrive has higher capacitance and higher output voltage than the ceramic fabricated in this study.
2. According to the experimental results, the direct energy harvester provides stronger load amplification and a higher output voltage.
3. In the charging experiment involving real walking, the battery voltage increased by approximately 0.12 V from 2.62 V to 2.74 V, which demonstrates that the developed energy harvesting system can charge the heating system battery.
4. In the heating experiment, the toe temperature on the foot with the heating-system-equipped shoe was approximately 4.8 °C higher than that on the foot with the ordinary shoe. This result indicates that the heating system with the independent power source can generate sufficient heat.



## Acknowledgment

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