Heating Performance by an Insole Energy Harvester

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Abstract. This paper reports the heating performance of the previously reported 4th generation shoe-insole-based hydraulic electromagnetic energy harvester (HEEH) [1] in connection with a micromachined polysilicon heater & a commercial copper heater [2]. The HEEH produced 455.77mW of power by using a 4-channel configuration under an actuation frequency of 3Hz. It was integrated with two types of heaters to produce temperature rises of 2.0 & 3.2°C and the heating rates of 12.0 & 1.6°C/min, respectively, from polysilicon (0.15×0.1mm², 6.05e-6s of the thermal time constant) and copper heaters (78×28mm², 8.31s of the thermal time constant). Such heating performance of the HEEH is the 1st results of its kind by energy harvester [3, 4, 5].

1. Introduction

Heating is one of the key challenging applications to energy harvesters due to its requirements for excessive power amounts above 100’s mW; however, no energy harvesters have been reported to produce a sufficient amount of heating to warm up the body beyond body temperature variations yet, as shown in Figure 1. For such high-power amounts, walking-based energy harvesting has been explored by several groups [6, 7]. However, either insufficient power amounts (<100mW), the use of high voltages (4.2kV) or discomfort to the walking motions have limited their practicality as a walking-based heating tool. Commercial energy sources for heating, thus, have relied on traditional rechargeable Li-ion batteries that, however, don’t last more than some hours and require periodic charging & replacements.

![Figure 1: Comparison of power requirement for different commercially available shoe insole heaters & HEEH-based shoe insole heater.](image-url)
To address such limitations, we have reported the development of a hydraulic electromagnetic energy harvester (HEEH) [1] which produced an average power of 455.77mW in a shoe-insole form of a total volume of 56.1cm³ within a thickness of 8.5mm. The HEEH consisted of 4 electromagnetic energy harvesting channels (inner diameter of 5mm and length of 100mm) where magnets moved to induce voltages in the surrounding coils. Each channel contained 6 rare-earth permanent magnets of D36-N52 (NdFeB, 4.76mm diameter, and 9.52mm length). The testing of the HEEH was performed with a stepper motor system in a precision-machined custom testing setup (Figure 2) to simulate a walking-triggered frequency of 3Hz, which actually mimicked the average fast running frequency of 3.2Hz [8].

2. **Hydraulic electromagnetic energy harvester**

A stepper motor-based acrylic system was manufactured to mimic the piston-like motions that would be triggered by human walking at a frequency range between 0.5 to 3Hz due to varying accelerations between 1.31 to 11.83ms⁻², covering the conventional range of human foot acceleration during walking [1, 9, 10]. The acrylic system was calibrated for mimicking human walking (3Hz and 11.83ms⁻²) and used as the input condition for the HEEH testing. The calibrated acrylic system allowed the precise control of walking frequency and acceleration, which was indeed hard to simulate in the real walking testing.

3. **Experimental Methodology**

To characterize the heating capability for HEEH for different heater types, two heaters were integrated including a polysilicon heater and a commercially-available copper heater.

3.1. **High-Thermal-Isolation Heater: Polysilicon heater**

The polysilicon heater was batch fabricated on top of a silicon wafer and heating capability was measured with an infrared thermometer gun. First, a bulk microfabrication process was initiated by depositing 140nm of SiO₂ and 600nm of Si₃N₄ on top of the silicon wafer. The deposited and patterned SiO₂ and Si₃N₄ was used to protect the silicon during KOH etching (Figure 3(b)). Subsequently, 650nm of polysilicon was deposited, patterned, and phosphorus-doped so that the input current could be passed through the polysilicon to heat it up. Finally, around the polysilicon heater in Figure 3(a, b), Al bond pads and temperature sensors were deposited and patterned so that input current could be applied by a power source and measure the temperature respectively. For heating characterization of the polysilicon heater, the temperature was measured with an infrared thermometer gun and compared with a TCR (Temperature coefficient of Resistance) model of the aluminum temperature sensor in Figure 5. For the TCR model, TCR of aluminum (α =0.00429/C) and the resistance change of the aluminum temperature sensor before (R₀) and after (R) the heating were used to measure the temperature rise (T−T₀) of the polysilicon heater by using the following equation.

\[ R = R₀ (1 + α (T - T₀)) \]  \hspace{1cm} (1)
3.2. Low-Thermal-Isolation Heater: Copper heater

A commercial copper heater (ProFLEX Heated Insoles, Thermacell) [2] in Figure 4(a) was characterized and was heated by different energy sources to measure heating capability. Initially, heating capability such as power consumptions and the temperature rise of the copper heater was found for different heating conditions provided by two energy sources (rechargeable batteries and a DC power supply). Finally, the copper heater was heated by the HEEH (4-channels and 7-layers) to evaluate the possibility of heating with an energy harvester in Figure 4(b).

4. Results

4.1. High-Thermal-Isolation Heater: Polysilicon heater

From the measurement in Figure 5, a heating calibration curve was established for the polysilicon heater by supplying a total power of 110mW from the DC power supply. The heating calibration curve showed that the temperature of the polysilicon heater increased by 16°C from a room temperature of T₀=20°C which was also verified by an infrared thermometer gun. The thermal resistance of the polysilicon heater was found as 0.132K/mW that was closely matched to a calculated theoretical value of 0.13K/mW.

Table 1 also showed the heating performance of the polysilicon heater by a 1-channel, 1-layer HEEH where the polysilicon heater was heated up by 2°C at a rate of 12°C/min. A low power producing 1-channel, 1-layer HEEH (19.2mW) was used for the testing to prevent the polysilicon heater from being burnt.

4.2. Low-Thermal-Isolation Heater: Copper heater

Experimental results in Figure 6 showed that the HEEH (4 channels, 7-layers, 455.77mW) generated a maximum temperature rise of 3.2°C from a commercial copper heater at an actuation frequency of 3.0Hz. The measured temperature rise of 3.2°C was above the standard deviation (2.6°C) of average human body temperatures, indicating the feasibility of heating functions.
A summary of temperature rise/min of the copper heater by the HEEH and the other power sources is shown in Figure 7 to compare the heating capability. Figure 7 shows that the copper heater with the HEEH produced a higher heating rate of 1.6°C/min in comparison to 0.51, and 0.56°C/min by the rechargeable batteries and 0.21, 0.46 & 0.58°C/min by the DC power source. The measurement results implied that the HEEH had 2.76 times more efficient heating performance in comparison to rechargeable battery and DC power supply.

5. Conclusion
This paper reports the development of a proof-of-concept HEEH and its performance as a heating source from energy harvesting. The developed HEEH prototype demonstrated heating performance of 2°C through an integrated polysilicon heater (a size of 0.15×0.1mm², thermal time constant of 6.05e-6s) and 3.2°C through a commercial copper heater (a size of 78×28mm², thermal time constant of 8.31s) under an actuation frequency of 3Hz that mimicked the fast running inputs.

6. References
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