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Research Article

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Miniature Shape Memory Alloy Heat Engine for Powering Wireless Sensor Nodes

Abstract: Shape Memory Alloys (SMAs) exhibit temperature-dependent cyclic deformation. SMAs undergo reversible phase transformation with heating that generates strain which can be used to develop heat engine. In this study, we build upon the concept where environmental heat is first converted into mechanical energy through SMA deformation and then into electrical energy using a microturbine. This SMA heat engine was tailored to function as a miniature energy harvesting device for wireless sensor nodes applications. The results showed that 0.12 g of SMA wire produced 2.6 mW of mechanical power which was then used to drive a miniature electromagnetic generator that produced 1.7 mW of electrical power. The generated electrical energy was sufficient to power a wireless sensor node. Potential design concepts are discussed for further improvements of the SMA heat engine for the wireless sensing platform.

Keywords: energy harvesting, shape memory alloy (SMA), wireless sensor nodes

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Wireless sensing nodes are becoming ubiquitous addressing the requirements on variety of platforms including structural health monitoring, smart healthcare system, and industrial automation. The challenge with the implementation of wireless nodes lies in powering them over a long period of time, in most cases greater than 5 years. This need has driven research on the energy harvesters that can convert the locally available energy into electricity and replenish the storage media. Along this line of thought, we demonstrate here a thermal energy harvesting concept that has significant promise in the constant temperature environment.

Conventional methods for low power energy harvesting from heat are mainly based upon the thermoelectric or pyroelectric effect. Thermoelectric (TE) devices convert temperature gradient across the device into electricity. Pyroelectric devices generate electricity in response to the alternating temperature variations. Pyroelectric materials have been reported to possess higher efficiencies compared to other thermal harvesters approaching up to 50% (Sebald, Pruvost, and Guyomar 2008). Results have shown that power densities of 12.9 μW/cm^2 can be obtained for $Pb(Zr,Ti)O_3$ and 100–169 μW/cm^2 for piezoelectric relaxor single crystals (Sebald, Guyomar, and Agbossou 2009). However, the requirement of cyclic temperature variations, rarely found in nature, limits the use of pyroelectric effect for energy harvesting applications. Unlike pyroelectrics, TE devices are most commonly used as heat recovery agents. TEs can reach power density of 200 μW/cm^3 for dimensions on the order of 0.25 cm^3 (Roundy et al. 2004). However, TE devices require an effective heat sink which adds to the size, cost, and complexity of the device. In addition, the efficiency for these devices at temperatures below 200°C is below 5% and at temperatures below 100°C efficiency drops to much less than 1% (Ismail et al. 2009).

This study focuses on an alternative heat energy recovery mechanism for applications where temperatures are less than 100°C. The mechanism is based on the shape memory alloy (SMA) that exhibits memory effect which translates into a mechanical force when driven beyond the austenite finish temperature. SMAs have been utilized in numerous actuations and sensing applications (Kudva 2004; Morgan 2004; Villanueva et al. 2010; Villanueva, Smith, and Priya 2011; Tadesse et al. 2012). They have also been explored for heat engine applications, where the first one was developed more than half a century ago (Banks 1975). Since then, several researchers have utilized the SMAs for converting heat energy into mechanical energy (Johnson 1977; Pachter 1979; Wakjira 2001; Wang 1981), but none of these designs are commercially available for thermal energy harvesting. Further, prior research has mainly targeted large-scale conversion of thermal energy into mechanical energy and has not been able to provide complete solution for continuous harvesting and storing the generated electricity. Sato et al. have demonstrated a functional SMA heat engine (Sato et al. 2008) that produced 1.16 W using five SMA belts and the size of system without generator was on the order of 1850 mm × 550 mm × 500 mm.

We provide an optimum solution for the SMA heat engine suitable for implementation at miniature scale that could lead to new generation of power sources for wireless sensor nodes. The fundamental challenge at smaller dimensions lies in the fact that the torque generated by the SMA wire should be sufficient to overcome the cogging torque of the electro-magnetic generator. We demonstrate that this challenge can be overcome by designing generator that is able to self-start. Three basic measurements were conducted to evaluate the capability of the system: angular speed as a function of temperature, mechanical power as a function of angular velocity, and electrical power as a function of the mechanical power generated. Using the miniature SMA heat engine, we were able to develop a fully functional self-powered wireless sensor node.

The design of a small-scale heat generator is based on the concept proposed by (Wang 1981) almost 30 years ago. The design of the "Heatmobile" as it has been referred to in the literature is composed of three main components: hot water reservoir, pulley system, and an SMA wire. Figure 1 shows the description of the experimental setup as well as a diagram outlining the operation principle of the device. The key components of the device are SMA loop wire of 300 µm diameter (Grand Illusions Inc.) and two pulleys offset from each other at a specified distance limited by the length of the SMA loop wire. Cold pulley is attached to an electromagnetic generator developed in our laboratory and hot pulley is submerged in a hot water reservoir. The temperature of the hot water is regulated by a hot plate and was measured using a thermocouple. Just besides cold pulley, a propeller from a micro-wind turbine is used to cool the SMA wire through forced convection of room temperature airflow. A tachometer was used to measure the angular velocity of the blades, i.e. the electro-mechanical generator.

Due to the shape memory effect, as the SMA loop wire comes in contact with the hot water, it transforms from the martensite to austenite phase as shown in Figure 1(B), therefore causing the wire to return to its original shape (which was initially straight). As the SMA wire strains, torque is generated around hot pulley, causing the pulley to rotate. Since the pulleys are connected via the SMA wire, cold pulley rotates as well and consequently turns the generator. The SMA wires have very low heat capacitance which allows the SMA part that was submerged under water to cool-off almost immediately after it leaves the hot water medium. The part of the loop wire that follows next, comes in contact with the hot water, heats up and as a result strains, thus repeating the process all over again. The system can run continuously as long as the temperature of the hot water is maintained above the transition temperature. In addition to the strain created at the bottom of the hot pulley, during operation, vibration in the SMA wire is another factor that aids the continuous rotation of the SMA turbine.

By regulating the temperature of the water reservoir and monitoring the angular speed, we were able to derive the relationship between the angular speed and

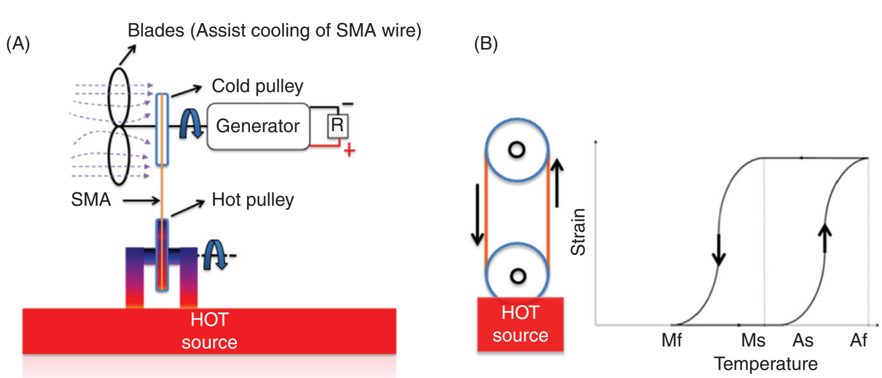

Figure 1 Measurement technique: (A) Illustrative diagram of experimental setup, (B) Experimental setup used for characterization

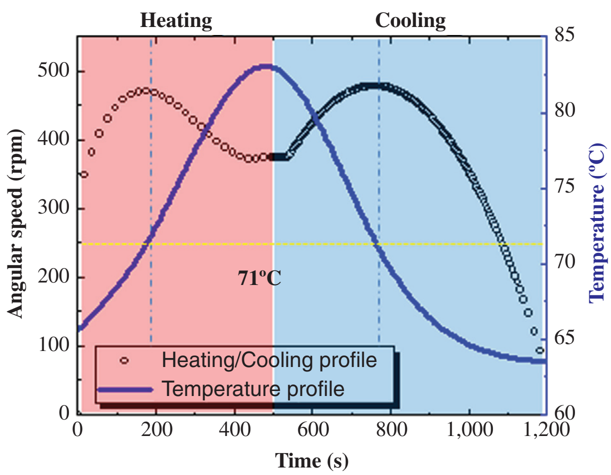

Figure 2 Angular speed of the generator as a function of temperature

temperature in both the heating and cooling stages. Figure 2 illustrates how the temperature affected the angular velocity in both the heating and cooling stages. As seen here, the highest angular speed was achieved at 71°C, corresponding to 480 rev/min. A small hysteresis of about 1.5°C was also observed. The generator started spinning at 65.5°C during the heating phase and then came to a halt at a temperature of 64°C toward the end of the cooling phase. The hysteresis was expected since additional energy (higher temperature) was initially required in order to overcome the cogging torque of the generator.

Once we identified that highest angular speed occurred at 71°C, the temperature of the water reservoir was fixed and the mechanical power of the device was measured. Figure 3 shows the angular speed measured as a function of time. The experimental results of the angular speed are represented by a sixth-order polynomial shown in Figure 3(A). The torque was calculated following the methodology described elsewhere (Avirovik et al. 2012). The angular speed reached steady state in a very short time period; therefore, in order to obtain the torque generated by the device, the focus was mainly on the transient response of the speed curve. By differentiating the speed expressed as a sixth-order polynomial, angular acceleration was obtained. The torque generated by the device was calculated using eq. [1]:

$$\tau = J_{\text{total}} \times \alpha \qquad [1]$$

where α is the angular acceleration and J_{total} is described through eq. [2] as:

$$J_{\text{total}} = J_{\text{pulley}} + J_{\text{blades}} + J_{\text{generator}} \qquad [2]$$

where J_{pulley} is 4.71E–7 kg/m^2, J_{blades} is 8.74E–7 kg/m^2 and $J_{\text{generator}}$ is 6.046E–6 kg/m^2.

Lastly, the mechanical power curve illustrated in Figure 3(B) was calculated using eq. [3]:

$$P_{\text{mech.}} = \tau \times \omega \qquad [3]$$

From these results, the maximum mechanical power from the current design was calculated to be 2.57 mW at the angular speed of 226 rev/min as shown in Figure 3(B).

The next step was converting the mechanical energy to electrical energy through the utilization of the micro–electro-magnetic generator. In this experiment, the device was run at its optimal condition, i.e. 71°C. A resistor sweep study was conducted where the voltage was measured across different load resistances ranging from 1 Ω to 1000 Ω as shown in Figure 4(A). Figure 4(B) represents the electrical power generated by the system at different resistance values. The maximum electrical power measured was 1.76 mW at 80 Ω load resistance.

Next we designed a wireless sensor network powered by the SMA heat engine. In this system, the SMA powered generator was charging a buffer storage, which once

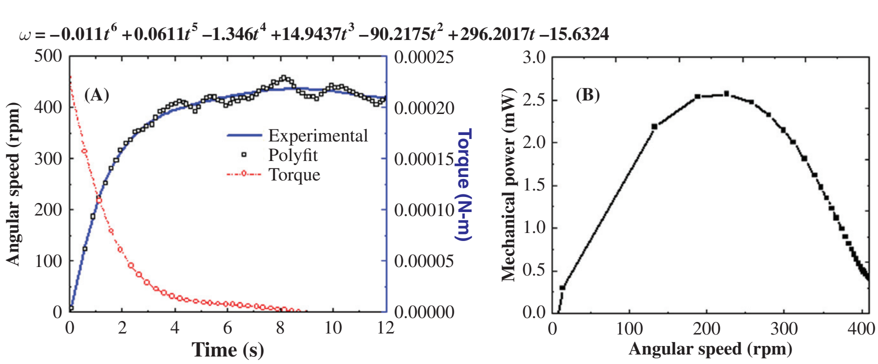

Figure 3 Mechanical characterization of SMA turbine: (A) Angular velocity and torque curves, (B) Mechanical power as a function of angular speed

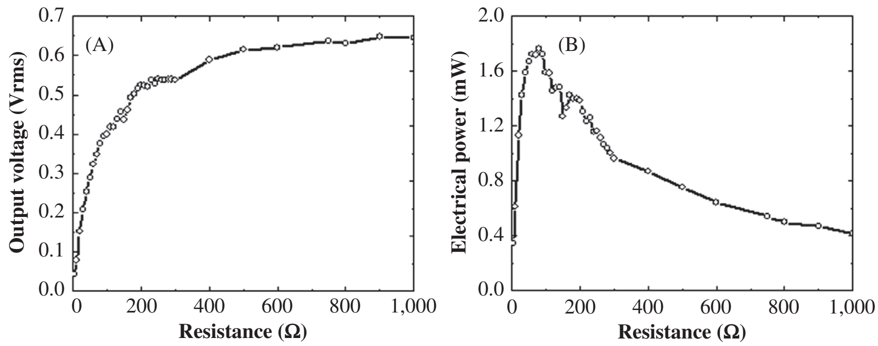

Figure 4 Electrical characterization of SMA turbine: (A) Output voltage as a function of resistance, (B) Electrical power as a function of resistance

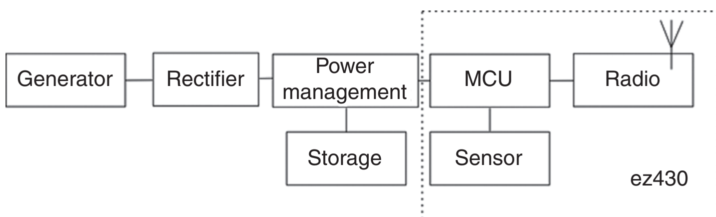

Figure 5 Block diagram of the wireless node

filled, provided energy to a wireless sensor node, that in turn, transmitted the measured ambient temperature to a nearby base station, which displayed the data on a computer screen. Figure 5 shows the block diagram of the electrical system. The first step in utilizing the available power generated was converting the alternating current output of the generator into direct current. Due to low currents on the order of mA, voltage drop over the diodes in the rectifier introduced significant power losses. In order to provide higher efficiency, a voltage doubler was chosen as a rectifier circuit bringing the efficiency to 56%. The power management unit consisted of a BQ25504 circuit (Texas Instruments Inc.) which had an integrated DC/DC step up converter on the input together with a power management module that controlled the connection between the load and the storage. By doubling the input voltage, as stated previously, the relative difference between input and output voltage was reduced allowing the DC/DC converter to operate at higher efficiency compared to the efficiency in case of a standard diode bridge. BQ25504 circuit has integrated power management features that allowed for the load to be disconnected from the storage until the storage reached predefined voltage level. Our application had this threshold level set to 3.1 V. Once active, load drained the energy stored until the voltage on the storage reached 2.2 V. Storage used was a 2.2 mF aluminum electrolytic capacitor. This storage was chosen based on the load of the system, which in our application was a wireless sensor platform ez430 (Texas Instruments). This platform consisted of a low power MSP430 microcontroller with onboard temperature sensor and an attached 2.4 GHz CC2500 radio module.

The network was setup in a way that once active, the microcontroller performed a set of measurements and transmitted the data over radio to the base station. Microcontroller measured ambient temperature and storage voltage. Following transmission, the microcontroller put the radio module to sleep, disabled the temperature sensor, and entered a low power sleep mode for duration of 1 s. After the sleep time expired, the microcontroller would wake up and the cycle would repeat itself. The cycle of sleeping-waking up-measuring-transmitting-sleeping continued as long as there was sufficient energy in the storage. In case, where there was not enough energy, the power management module would power down the microcontroller and wait until the storage voltage level reached predefined value. The storage was being actively charged as long as there was power coming from the SMA generator and the charging process was not affected by microcontroller operation.

Unlike all the previous studies, this study focuses on the development of a miniature heat recovery system which can be integrated in different residential and

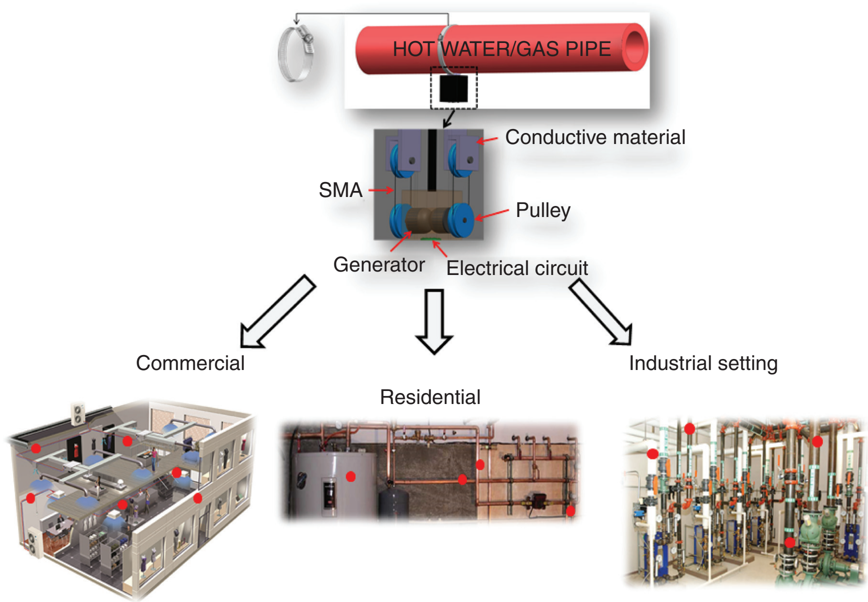

Figure 6 Conceptual illustrations for implementation of miniature SMA heat energy harvester

industrial environments. Different scenarios for providing the heat to the miniature SMA heat engine can be designed. One of the alternative ways is to deliver the heat wirelessly through microwaves or laser light and then converting the light energy into electrical energy in order to power wireless sensor nodes. The objective is to heat a small section of the SMA wire to a specific temperature. Figure 6 shows the practical scenario that can be built using the SMA heat engine concept. A common heat source in commercial, residential, or industrial setting is hot water/gas pipe. By simply replacing the hot water source with a hot pipe source and attaching the SMA heat engine onto the outer shell of the pipe, electrical energy can be continuously generated.

Most SMAs operate at temperatures of 70°C or 90°C depending on their classifications low temperature (LT) or high temperature (HT) SMAs respectively. These temperatures are high for the outside environment; however, temperatures greater than 40°C are very realistic in variety of scenarios. Villanueva, Gupta, and Priya (2012) have shown the potential for lowering the martensite to austenite transition temperature by changing the composition of the SMA. The results showed that increased Ni content in conjunction with Cu doping results in significant shift of the transition temperature. The power generation capability is highly dependent on the electro-magnetic generator characteristics. The electromagnetic generator used in this study can produce up to 257 mW power at angular velocities of 4,200 RPM. Introducing gear system will allow the increase of the RPM while sacrificing the torque. The torque can be increased to by adding more SMA wires to the system. At present 4:1 gear ratio with a single wire was achieved, but future studies will include even higher gear ratios in order to maximize the output power.

In summary, this study presented a concept of a miniature heat engine utilizing a 300 μm SMA wire that generated enough torque required for turning an electromagnetic generator. We characterized the mechanical and electrical component of the device and developed a complete wireless sensor system where a hot water reservoir was used as a heat source and the SMA device as a heat recovery generator. The generator was able to produce 1.7 mW of electrical power which was more than enough to charge a wireless sensor node. Finally, the study shows concepts for developing various common applications.

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