THERMOELECTRIC ENERGY HARVESTING IN SMALL-CALIBER PROJECTILES

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Abstract: Energy harvesting is an attractive alternative to chemical batteries in powering intelligent munitions. This paper demonstrates the feasibility of thermoelectric energy harvesting to capture thermal energy from friction in small-caliber weapon systems. An experimental mock-up of a bullet containing a thermoelectric generator demonstrates the potential of this concept. Finite-element modeling is used to predict the power output of a conceptual thermoelectric bullet. The code predicts a peak power output of 19.2 mW and a sustained power output of 15 mW over most of a 60-meter trajectory.

Keywords: Thermoelectric energy harvesting, finite element methods, ballistics

INTRODUCTION

Intelligent weapon systems are deployed for the purposes of guiding munitions, optimizing fuzing logic, and providing real-time assessment of the battlefield environment. Over time, these technologies have been deployed in ever-smaller weapon systems, with the leading edge currently found in man-portable grenade launchers [1], [2]. Extrapolating this trend, it is feasible that microelectromechanical system (MEMS) technology will soon bring intelligent capabilities to small-caliber munitions, considered here as .50 caliber (12.7 mm) and smaller.

Energy harvesting will be an enabling technology for intelligent small-caliber munitions. Compared to chemical batteries, energy harvesting systems do not require a maintenance regimen to recharge or replace units at the end of their shelf life. Energy harvesting also eliminates the logistical and administrative efforts necessary to support a battery maintenance program. This advantage is multiplied in small-caliber munitions, for which annual procurement is on the order of billions.

The ballistic environment is rich in sources from which useful energy can be extracted, including as inertia, pressure, and temperature. Previous works on energy harvesting technologies, applied in larger weapon systems, include resonant piezoelectric energy harvesting [3], [4], setback electromagnetic energy harvesting [5], and ram air electromagnetic turbine generators [6]. The latter is notable as it is in service with the U.S. Army.

This work explores thermoelectric energy harvesting in rifled, small-caliber weapon systems. Rifling is necessary as it primarily responsible for elevated temperatures. Finite element simulation and experimental results demonstrate the feasibility of thermoelectric harvesting in this application. To the knowledge of the author, this work is unique in its scope and approach.

FINITE-ELEMENT SIMULATION

High temperatures are common in small-caliber firearm systems. Rapid-fire firearms often require cooling mechanisms, and/or impose limits on the duration of sustained fire, to prevent thermal damage to the weapon. Temperatures in propellant combustion gasses can reach 3000°C [7], and the in-flight surface temperature of a bullet has been measured at 267°C [8]. The presence of elevated temperatures suggests that a thermoelectric device can be employed to harvest energy in this environment.

To understand the distribution of temperatures in a projectile over time, a finite-element simulation of temperatures during the ballistic cycle was written in MATLAB. The simulation models temperatures in a .40 S&W-caliber bullet, 10 mm in diameter and 15.5 mm in length. The projectile consists of a lead core inside a uniform copper jacket, 0.25 mm thick. Assuming temperatures are constant in the circumferential direction $\left(\partial T/\partial \phi = 0\right)$ allows the projectile to be modeled as an axisymmetric body, with its geometry defined in the $r-z$ half-plane. The finite element mesh used in this study has 940 points and 1748 elements.

The finite-element expression of the heat diffusion equation is expressed as,

$$\mathbf{M}\dot{\mathbf{T}} + \mathbf{K}\mathbf{T} = \mathbf{Q} \qquad (1)$$

where **M** is the global thermal capacity matrix ($W\cdot s\cdot K^{-1}$); **K** is the global conduction matrix ($W\cdot K^{-1}$); **Q** is the heat vector representing boundary conditions (W), and; **T** is the nodal temperature vector (K). The **M** and **K** matrices are assembled from elemental matrices. The temperature rate may be expressed explicitly as,

$$\dot{\mathbf{T}} = \mathbf{M}^{-1}\left(\mathbf{Q} - \mathbf{K}\mathbf{T}\right) \tag{2}$$

As the values of specific heat and thermal conductivity change with temperature, the simulation updates the values of **M** and **K** in each integration step. The common fourth-order Runge-Kutta method is used in integrating temperature. Boundary conditions considered in the simulation are frictional heating at the gun barrel-projectile interface and convection with combustion gasses during internal ballistics, and; convection and radiation heat transfer with the environment during external ballistics. Due to uncertain factors, conduction heat transfer with the gun barrel is not modeled. Instead, its effect is captured by a correction factor, *e*, applied to the frictional heating, as it occurs over the same surface. The value of *e*, 0.025, was empirically selected to force surface temperatures to be similar to those measured by Richards [8]. Fidelity of the simulation is established through the modeling of steady-state and transient situations, for which analytical solutions exist.

The simulation yields two principle findings. The first is that friction is primarily responsible for elevated temperatures in a projectile fired from a rifled barrel. Figure 1 shows the predicted temperatures through a cross-section of the projectile, as it exits the gun barrel. Elevated temperatures are present only near the bearing surface, where frictional heating with the gun barrel occurred. Although the base of the projectile is in contact with high-temperature combustion gasses, the net heat transfer to the projectile is almost negligible. An analysis of the effects of uncertain parameters demonstrates that the friction boundary condition has the only significant effect on temperatures in the projectile. A ±25% change in friction results in a ±60°C change in surface temperatures seen in Fig. 1.

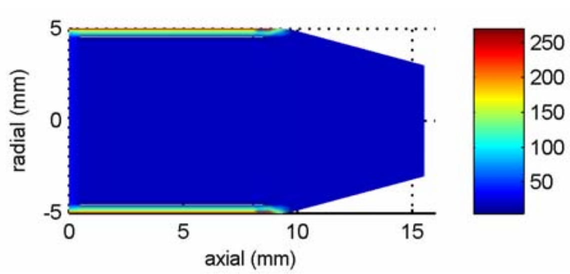

Fig. 1. Temperature distribution in a small-caliber projectile at muzzle exit.

The second key finding of the simulation is that diffusion of heat energy into the projectile is slow with respect to internal ballistics. Figure 1 depicts temperatures after 725 μs, which is a fraction of the 145 ms needed for the projectile to travel 40 m downrange. Diffusion of heat to the core of the projectile occurs almost entirely during external ballistics.

ENERGY HARVESTING EXPERIMENT

The simulation findings suggest that a projectile can be engineered to direct frictional heat to a thermoelectric generator. To test this concept, a thermally-similar mock-up of a small-caliber projectile is manufactured (Fig. 2). The body is manufactured from half-inch (12.7 mm) aluminum round stock, selected for its high thermal conductivity. A thin web conducts heat from the cylindrical surface to an MPG-751 thin-film thermoelectric generator, manufactured by MicroPelt, GmbH (Freiburg, Germany) [9]. A heat sink maintains a favorable temperature differential across the generator. Aluminum is selected for the heat sink as it provides a good combination of high thermal conductivity to draw heat from of the generator's cold side, and high specific heat to minimize its temperature rise. A thin layer of dielectric grease is applied to fill irregularities in, and improve thermal conduction between, the thermoelectric generator and the aluminum body and heat sink.

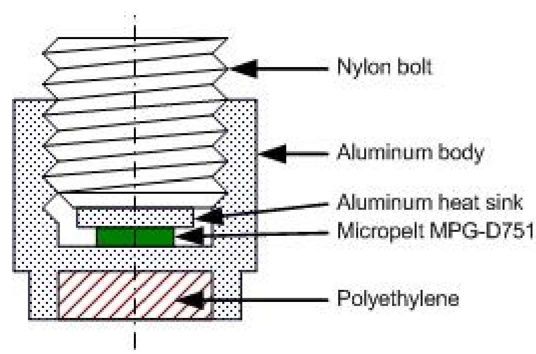

Fig. 2. Cross-section of test article.

A polyethylene insulating plug at the base prevents heat flow in the axial direction. A nylon bolt, used to secure the generator, insulates the top of the test article. Plumbers putty at the top of the test article seals the gap between the bolt and the threads. In lieu of friction, the test article is immersed in water just below the boiling point of 100°C. Boiling is avoided, as the convection could be unpredictably changed by turbulence and vapor bubbles. The configuration of the insulating materials in the test article ensures that the heat conducted to the thermoelectric generator comes from the lateral surface of the cylinder, rather than the ends. The test article, therefore, mimics the frictional heating that occurs at the bearing surface of a projectile.

Voltage from the thermoelectric generator is measured using a National Instruments SCC-series analog voltage input module in an SC2345 chassis. Voltage is measured across an open circuit, and across resistive loads of 218 Ω, 385 Ω, 509 Ω, and 809 Ω.

The simulation code discussed in the previous section is used to model the test article. Holman cites the free convection coefficient for a similarly-sized horizontal cylinder in water is cited as 890 $W \cdot m^{-2} \cdot K^{-1}$ [10]; this value is used here. Thermal contact resistances at the interfaces are unknown, and assumed to be negligible. Two independent methods estimate the thermal properties of the bismuth telluride junction layer in the thermoelectric generator, developing values that agree to within 2% of each other. Estimation is necessary as the micrometer-sized details are too small to model individually in the finite element mesh.

Figure 3 shows the open-loop voltages from four experiments, and compares them to the open-loop voltage predicted by the simulation. The simulation and experimental data show a good level of agreement, in both magnitude and time. Differences between the two are attributed to uncertainty in the exact values of material thermal properties.

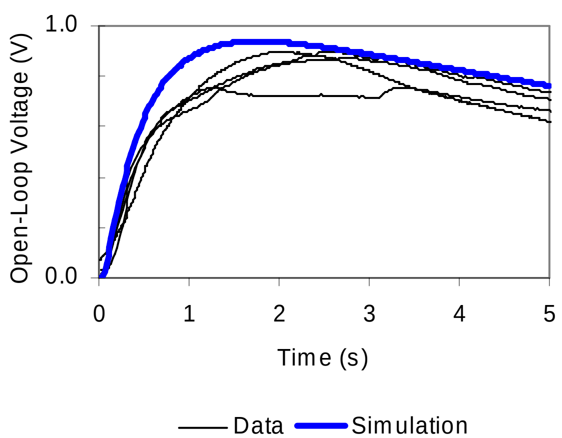

Fig. 3. Open-loop voltage in the test article and in simulation.

Figure 3 also shows variation in the open-loop voltage obtained in different experiments. The thermoelectric generator was observed to be very sensitive to disturbances in the heat flow at the test article's surface. In conducting the experiments, the test apparatus was supported by the head of the nylon bolt, using pliers. The author observed that any unintentional motion of the test article was reflected in changes in the voltage output. To gauge the effect of motion, the test article was intentionally stirred around in the water during one experiment. Figure 3 compares the power output obtained through stirring the test article with one obtained holding the test article stationary. Stirring roughly doubles the power output. This is attributed a higher forced convection coefficient in stirring than the free convection coefficient with the stationary test. The higher coefficient increases the temperature differential across the thermoelectric junction, resulting in the higher power. This experiment also demonstrates the sensitivity of temperature to heat transfer at the surface, predicted earlier in the simulation.

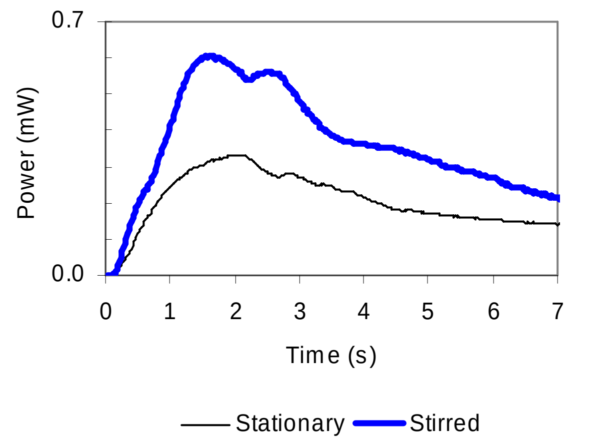

Fig. 4. Power profiles with 509 Ω load, test article held stationary and stirred in water.

APPLICATION

The simulation is applied to predict the power generated by a thermoelectric generator in a small-caliber firearm. Figure 5 shows the conceptual design. A MEMS device at the base of the projectile is modeled as a 250 µm silicon wafer, encapsulated in PMMA. A copper body, selected for both high thermal conductivity and ductility, supports the sensor and provides a planar mounting surface for the thermoelectric generator. Ductility is necessary as the projectile must be deformed by the gun barrel rifling. The bulk of the projectile consists of copper-jacketed lead. Its mass is necessary to maintain a high ballistic coefficient, defined as the ratio of a projectile's mass to its coefficient of drag. A projectile with a high ballistic coefficient will travel further, following a flatter trajectory, than a similar projectile with a low ballistic coefficient. The projectile in Fig. 5 is identical in size to a .40 S&W-caliber bullet. A 400 Ω

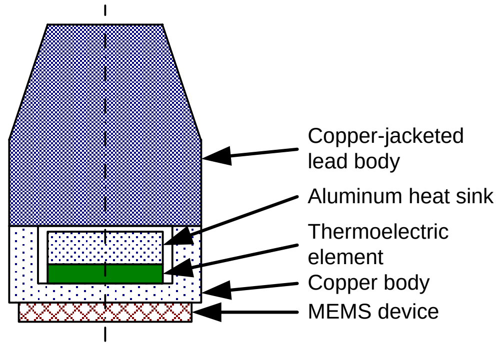

Fig. 5. Cross-section of simulated energy-harvesting projectile.

load is selected to maximize power output [9].

Figure 6 depicts the power and voltage outputs over 60 m of travel. Peak power from the thermoelectric generator, 19.2 mW, occurs at 28 m (104 ms) downrange. The corresponding voltage is 2.8 V. The delay in reaching full power is caused by the time needed to diffuse heat to the thermoelectric generator. In effect, this design stores energy thermally in the material, rather than electrically in batteries or capacitors. This method of energy storage allows the generator to deliver power through most of the ballistic trajectory.

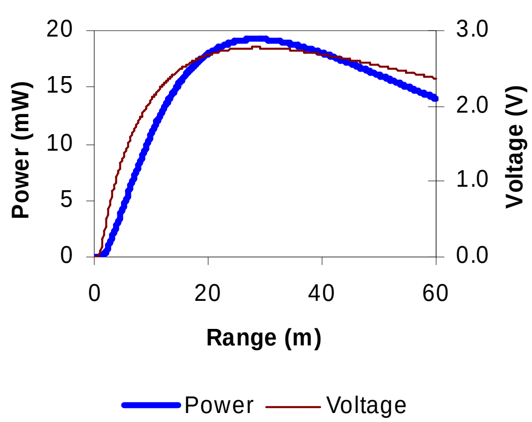

Fig. 6. Simulated power and voltage as a function of distance traveled.

It is important to note that the design illustrated in Fig. 5 has not yet been optimized for power output. Additional improvement in the power output may be achieved by redesigning the thermoelectric element specifically for this application.

CONCLUSIONS

Energy harvesting will be an enabling technology for intelligent munitions. Past works presented piezoelectric and electromagnetic energy harvesting in munitions. This work demonstrates the potential of thermoelectric energy harvesting for future generations of intelligent, small-caliber munitions. Simulation of a conceptual design shows that at least 15 mW of power can be delivered over most of a bullet's trajectory. Ongoing research at Cleveland State University will further develop this concept.

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