# AC 2012-3976: POWER AND EFFICIENCY MEASUREMENT IN A THER-MOELECTRIC GENERATOR

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# Power and Efficiency Measurement in a Thermoelectric Generator

**Abstract**

This paper documents a laboratory experiment to determine the efficiency of a commercial thermoelectric generator. Thermoelectric devices make use of the Seebeck effect to convert a difference in temperature into electricity. Thermoelectric devices are used or proposed for a number of different current applications including waste heat recovery. In the experiment, a LabVIEW data acquisition system measures real-time efficiency of the thermoelectric device under different testing conditions. The experiment is well-suited for an undergraduate thermal sciences lab or a demonstration for a thermodynamics lecture course. The experiment is also relatively low-cost aside from the data acquisition system. Results from the system as well as a detailed setup are presented.

**Introduction**

Thermoelectric generators convert heat into electricity through the Seebeck effect. The devices have no moving parts and can have a relatively long life which is a benefit. However, thermoelectric generators have lower efficiency when compared to many other power generation devices. Thermoelectric generators can be used in engineering applications ranging from automotive waste heat recovery[1] to powering a small wristwatch[2].

Thermoelectric devices have been incorporated into undergraduate courses in several different ways[3,4,5,6]. The devices offer the advantage of relatively low cost and small size, while still providing an excellent thermodynamic example of power generation. Although common undergraduate thermodynamic textbooks mention thermoelectric devices[7,8], as of now the content related to thermoelectric devices is fairly limited. Therefore, laboratory use of thermoelectric devices can help provide further information on the topic in an undergraduate setting.

The application of interest in this paper, and what sets this work apart from the previous work on thermoelectric devices, is the instantaneous measurement of efficiency for a commercial thermoelectric generator using LabVIEW data acquisition. Thermal efficiency is an important parameter and provides important information for designing systems. The setup described can be incorporated into an undergraduate thermodynamics laboratory, or also used as a demonstration in a thermodynamics lecture course.

**Experimental Setup**

A commercial thermoelectric device was used for the experimental testing and is a model TEC1-12706 Bismuth Telluride device with a physical size of 40mm x 40mm x 3.5 mm. The device has 127 couples and a photo of the device is shown in Figure 1 below.
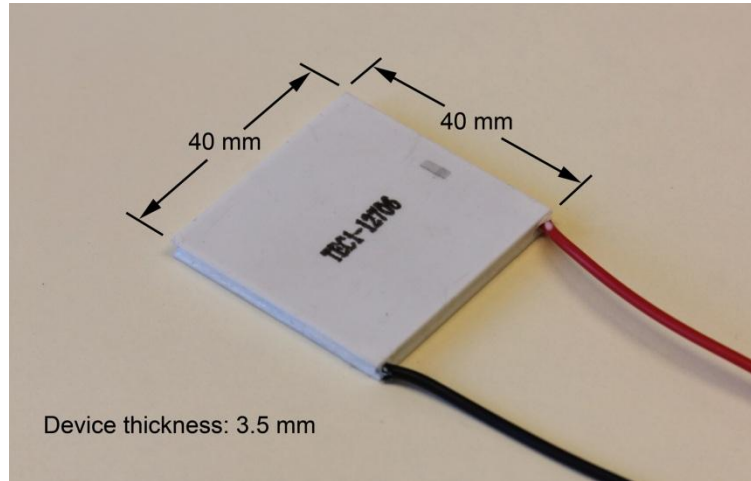


Figure 1: Photo of thermoelectric device used for testing (model TEC1-12706).

A testing assembly was constructed such that a known heat could be added to "hot" side of the device. By measuring the power output of the thermoelectric device through a load, the efficiency of the thermoelectric device can be calculated as follows:

$$\eta = \frac{P_{out}}{Q_{in}}$$
(1)

Where,  $\eta$ = thermal efficiency
$P_{out}$ = measured power output of the device (watts)
$Q_{in}$ = measured input heat to the device (watts)

An assembly was created to house the thermoelectric device for testing purposes. A diagram of the assembly is shown in Figure 2 with both an assembled view and exploded view. Starting at the bottom of the device, an end plate fabricated from copper is used to attach a thin Omega Kapton heater to the bottom plate which is also made from copper. Copper was chosen for construction due to its high thermal conductivity so that each plate will distribute heat well. The bottom plate has a small hole drilled in the side to accommodate a type-T thermocouple for temperature measurement. Above the bottom plate is the thermoelectric device (pictured in Figure 1). Silver conductive thermal grease was used on both sides of the thermoelectric device to provide good thermal contact in the assembly. Above the thermoelectric device is the top plate which is fabricated from copper and contains a channel for water cooling. The entire assembly is held together with plastic screws from the top plate to the end plate. Plastic was

chosen as the material for the screws to reduce heat transfer through the screws. The assembly is also surrounded with rigid insulation (2" thick housing type insulation) on all sides except for the top plate to ensure that the heat provided by the heater is transferred through the thermoelectric device and not dissipated elsewhere. The insulation is not shown on Figure 2, but it can be seen later in Figure 4.



**(a)**                                                          **(b)**
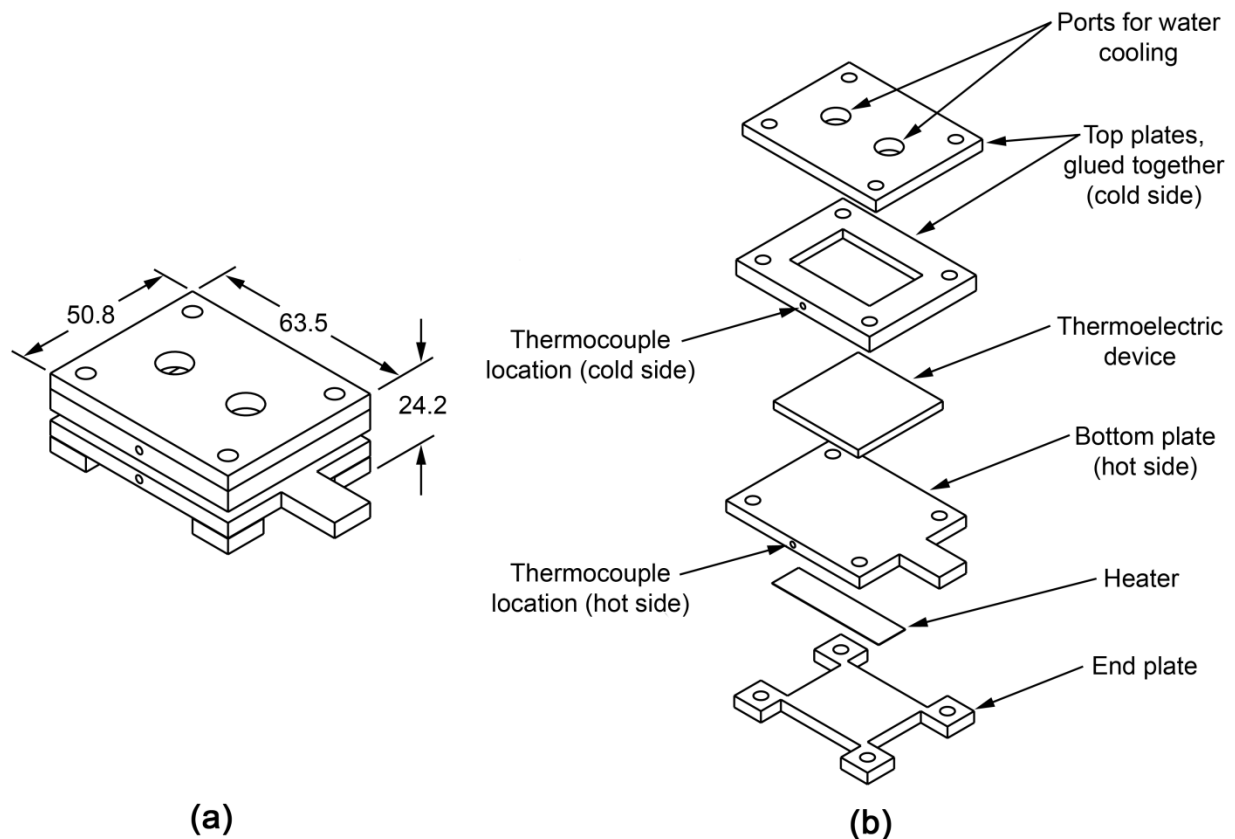
**Figure 2: (a) assembled view of thermoelectric testing device with dimensions in millimeters and (b) exploded view of thermoelectric testing device.**

A block diagram of the overall experimental setup is shown in Figure 3. In addition to the thermoelectric testing device described before, several other items are included. A data acquisition system and laptop are used for recording data. A small DC pump and cooling water tank (one gallon water container) are used to provide cooling for the system. A power supply is used to provide power both to the heater of the thermoelectric testing device and also the pump (a single power supply provides power independently to the two devices). Two resistors, 0.488 $\Omega$ and a 0-25 $\Omega$ rheostat, are used to provide the load for testing. A variable resistance was selected to best match the load resistance to the device resistance to provide maximum power. It also allows the user to easily see the effect of load resistance on power output, voltage output,

and efficiency.  A photograph of the actual test setup is shown in Figure 4 and a detailed listing of all of the equipment used including equipment cost is shown in Table 1.
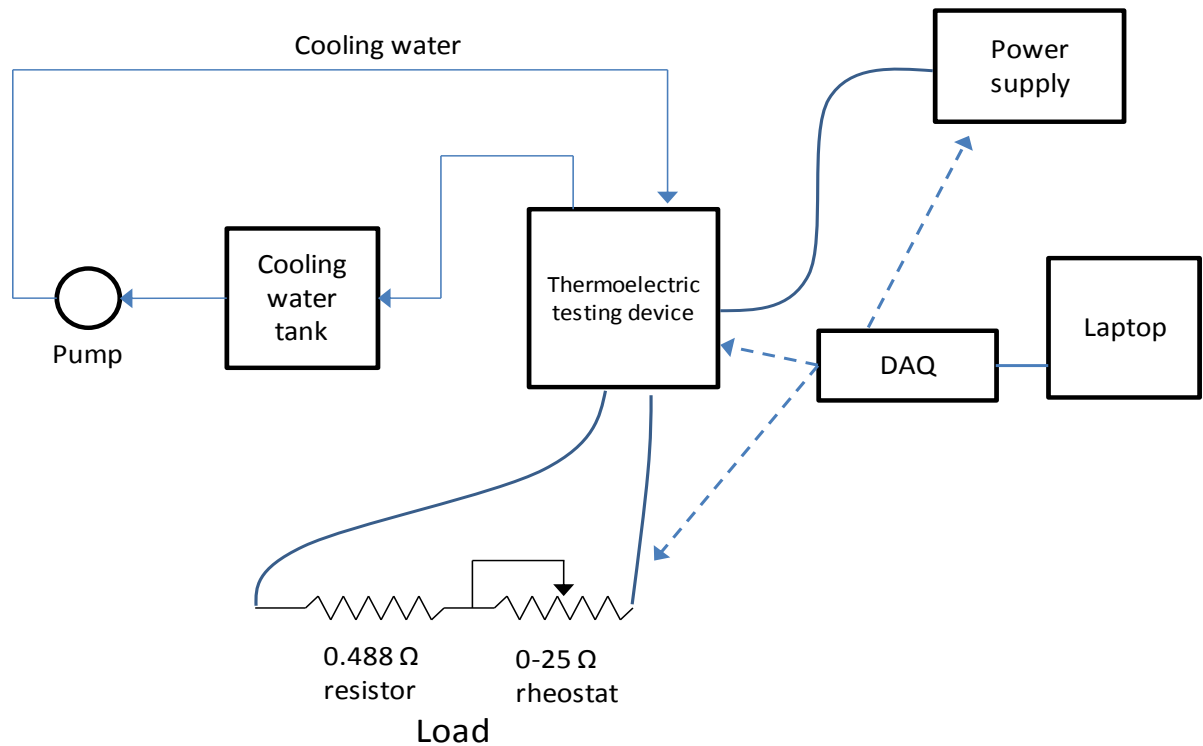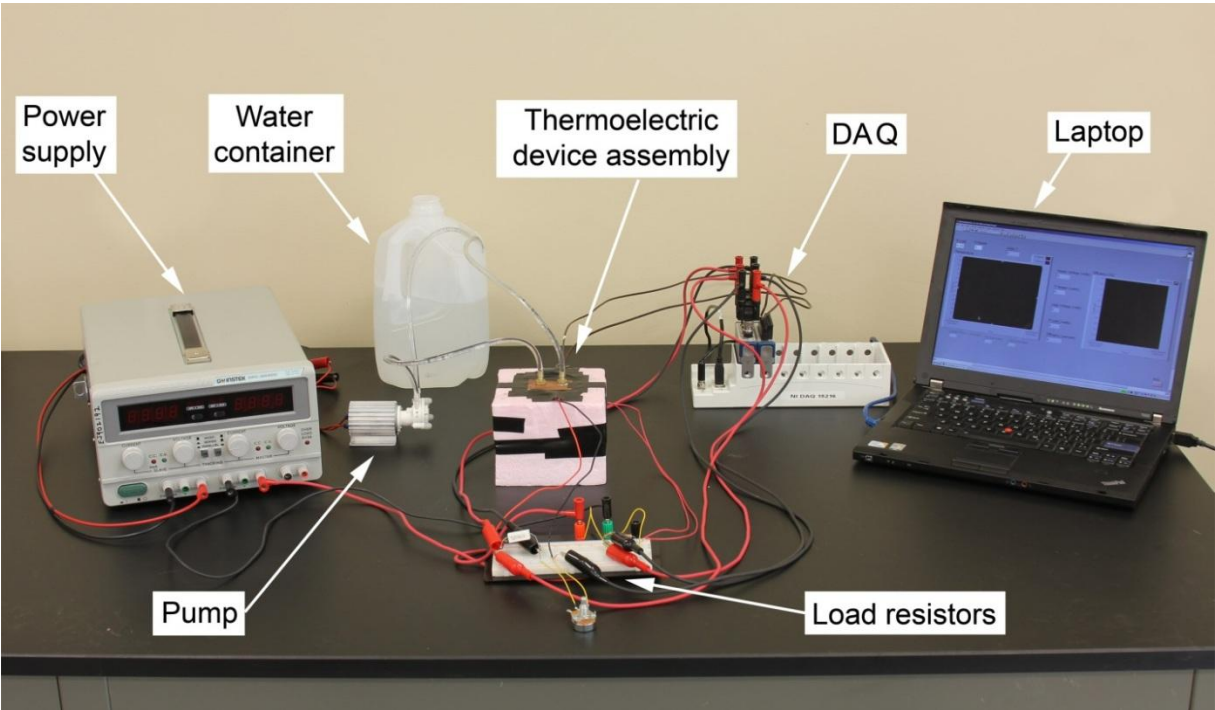


Figure 3: Schematic of overall experimental setup.



Figure 4: Photo of overall experimental setup.

**Table 1: List of Equipment Used**

| Item | Description | Cost |
|---|---|---|
| Thermoelectric device | Model TEC1-12706 | $3 |
| Laptop Computer | Lenovo T400 | $1000 |
| DAQ | National Instruments cDAQ-9172 | $1000 |
| DAQ Analog Input Module | NI 9215 | $400 |
| DAQ Temperature Input Module | NI 9211 | $300 |
| Heater | Omega Kapton flexible heater, 0.5" x 2", nominal resistance: 8.8 Ω (part # KH-KIT-EFH-15001) | $30 |
| DC Power Supply | GW Instek GPC-3030D | $400 |
| Pump | Cole Parmer mini DC gear pump (part # 07012-20) | $59 |
| Load Resistors | Radio Shack 0.488 Ω (measured), 5 watt resistor (part #271-0130) and Radio Shack 0-25 Ω rheostat, 3 watt (part #271-0265) in series. | $7 |

A LabVIEW program was created to measure the performance of the thermoelectric device (including instantaneous efficiency calculation). Five analog input channels were used to measure information from the setup and those inputs are listed below.

- Temperature of the hot side of the thermoelectric device (Type-T thermocouple)
- Temperature of the cold side of the thermoelectric device (Type-T thermocouple)
- Heater voltage, measured using a voltage divider (analog voltage input)
- Load voltage, measured across variable resistor
- Partial load voltage, measured across the 0.488Ω fixed resistor and used to calculate load current.

In order to calculate efficiency using Equation (1), the input heat, $Q_{in}$, and output power $P_{out}$, must be found. The input heat is found using the heater voltage and heater resistance as shown in Equation (2) below.

$$Q_{in} = \frac{V_{heater}^2}{R_{heater}} \qquad (2)$$

The heater voltage was measured by the data acquisition system and the heater resistance was measured as 9.00Ω prior to testing.

The power output was calculated using the load voltage and load current with equation (3) below.

$$P_{out} = V_{load} \cdot I_{load} \qquad (3)$$

The load voltage ($V_{load}$) is measured directly with the data acquisition system by measuring the voltage drop across both the 0.488Ω fixed resistor and the 0-25Ω rheostat. The load current ($I_{load}$) is found by measuring the voltage drop across only the 0.488Ω fixed resistor and calculating the current.

A screenshot of the block diagram of the LabVIEW program is shown in Figure 5 and a screenshot of the front panel is shown in Figure 6. The front panel allows the user to monitor the hot and cold side temperatures of the thermoelectric device (graph on the left side of Figure 6) as well as monitor the instantaneous efficiency of the device (graph on the right side of Figure 6). It is very easy to visually see the effect that changing the load resistance has on the device efficiency as seen in the spike in efficiency in Figure 6 (the load resistance was changed during testing at this spike).
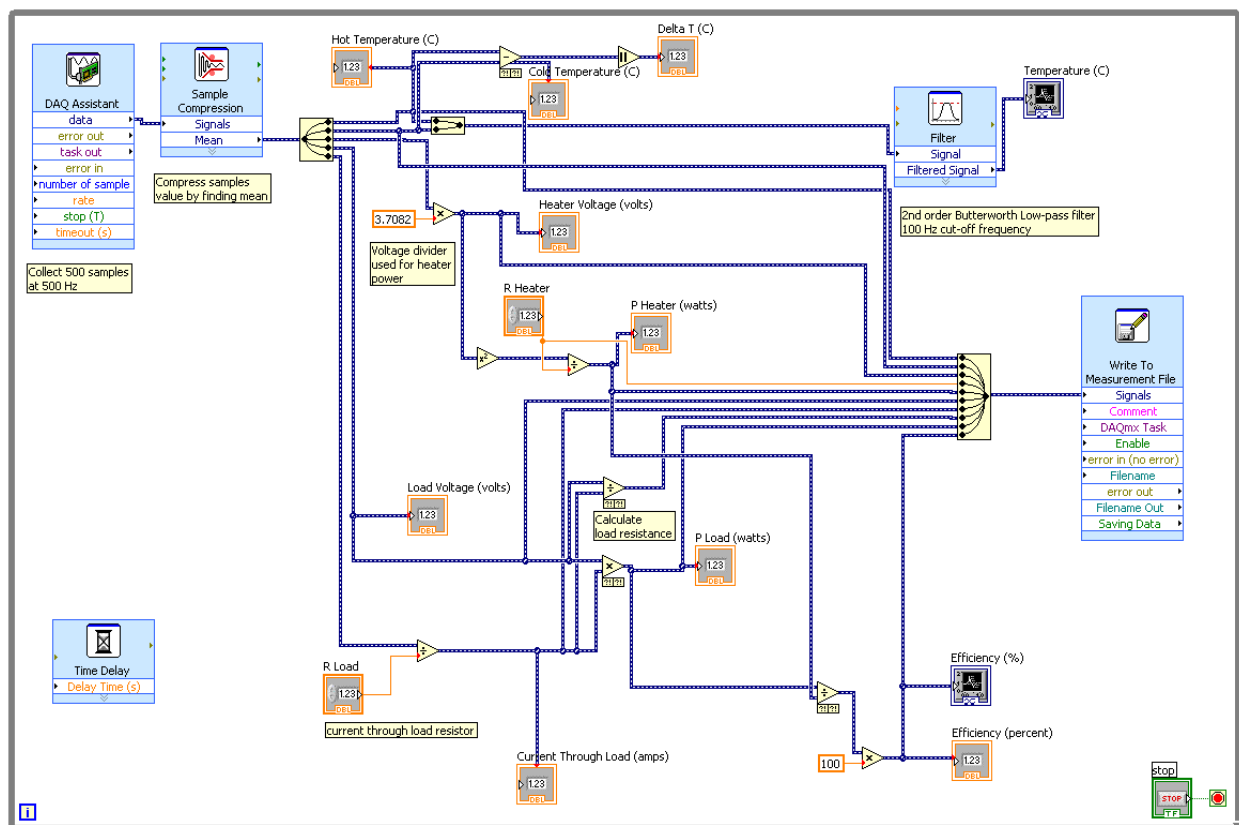


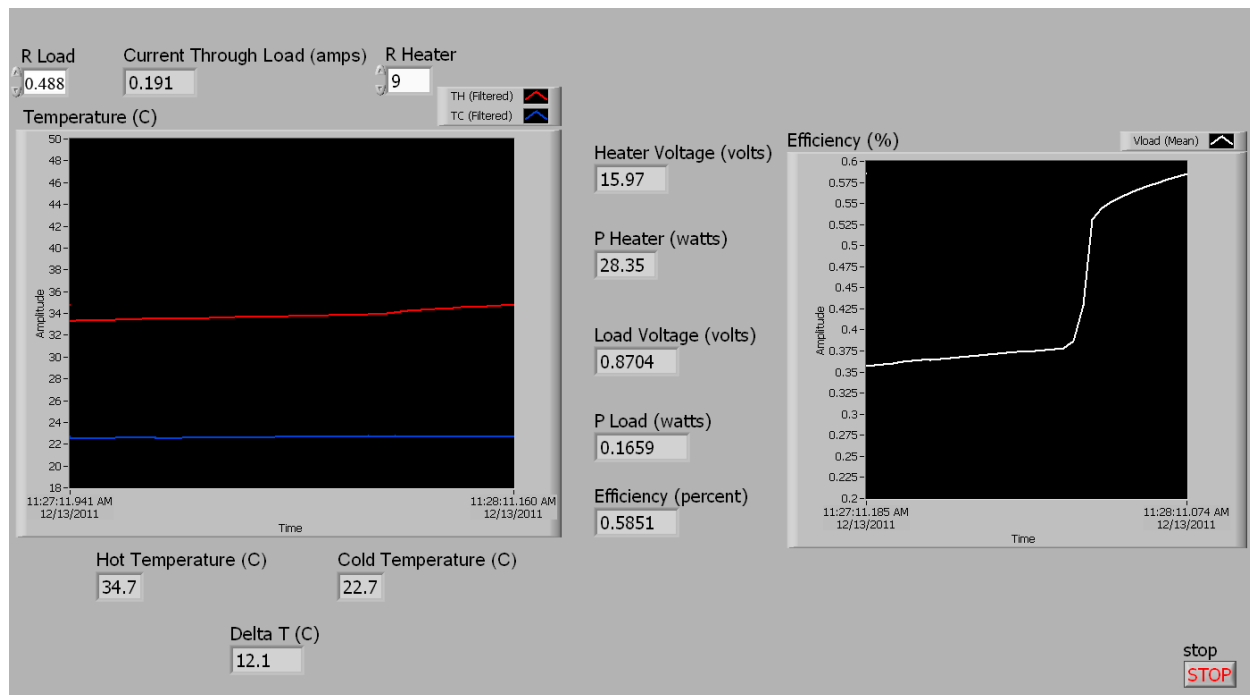Figure 5: Block diagram of LabVIEW program.

**Figure 6: Front panel of LabVIEW program.**

## Results

Six different tests were conducted with the commercial thermoelectric device. The heater voltage was tested at 12, 14, 16, 18, 20, and 22 volts. Increasing the heater voltage increased the temperature difference across the device. The key parameters of interest were the power output and efficiency of the thermoelectric device for a range of temperature differences and load voltages. The power output of the device depends on the output voltage (controlled by the load resistance), and this relationship changes for various temperature differences. Figure 7 shows the relationship between load power and voltage for each of the six tests. The data sets for each test were created by varying the load resistance using the rheostat. The lowest temperature difference tested was 20.6°C (corresponding to a heater voltage of 12 volts) and the highest temperature difference tested was 68.1°C (corresponding to a heater voltage of 22 volts). As expected the highest temperature difference produced the highest power output. For each curve, the highest power output occurs at the point at which the load resistance matches the device resistance. This allows the user to quickly see the benefits of load matching.
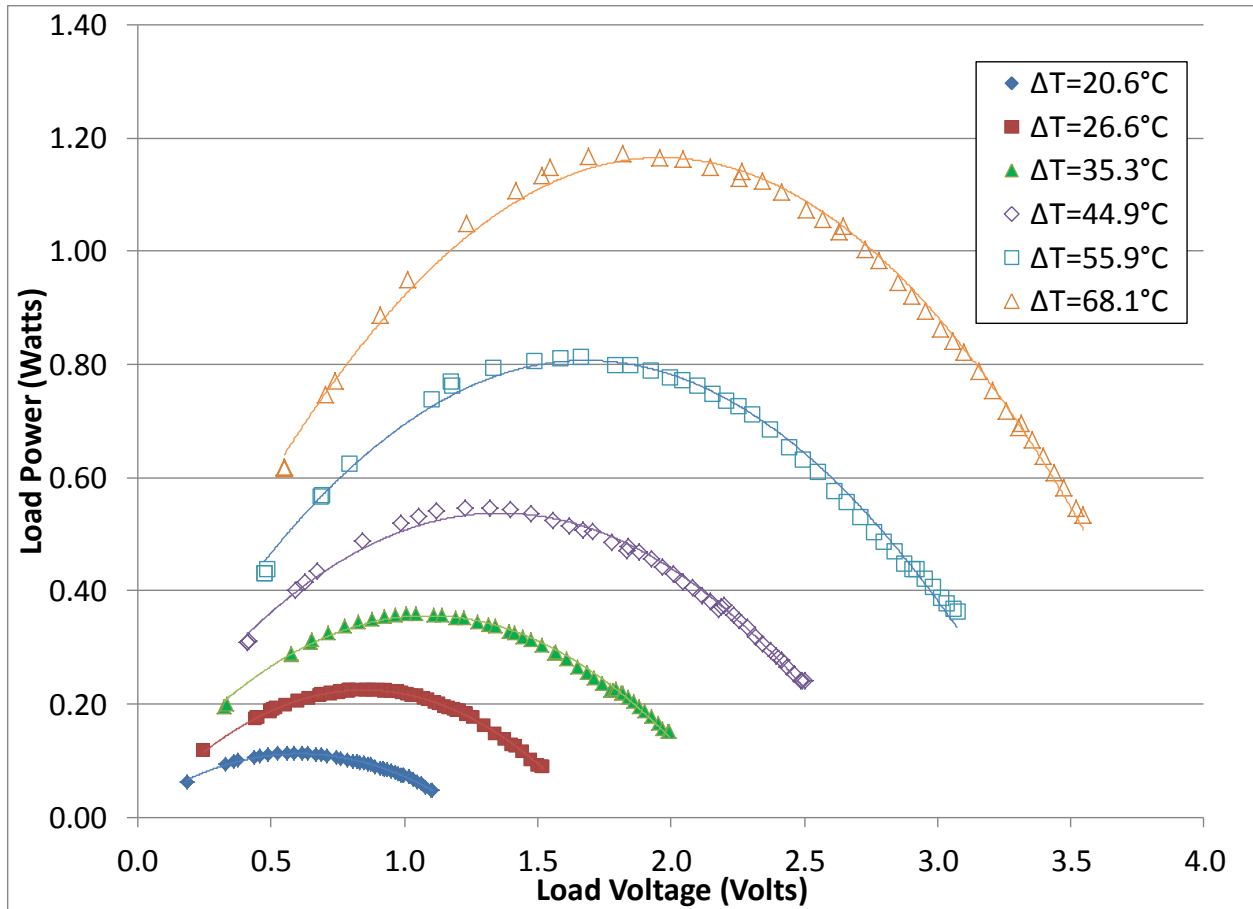
Figure 7 – Power output of thermoelectric device.

The efficiency of the device throughout the test was also calculated. Figure 8, below, shows the relationship between efficiency and load voltage for each of the six tests. The efficiency increases with increasing change in temperature and with the highest temperature change tested (68.1°C), the maximum efficiency was 2.22%.
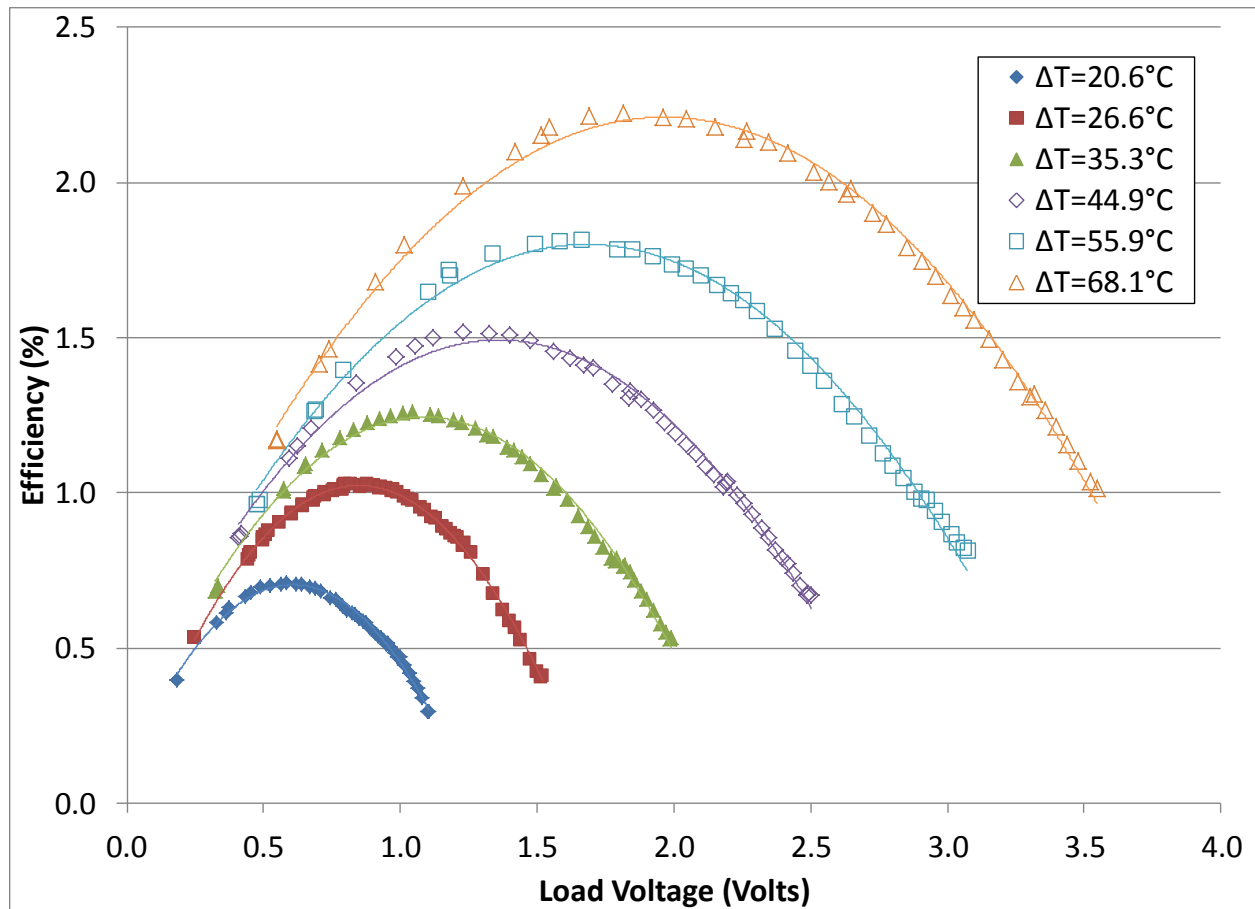
Figure 8 – Efficiency of thermoelectric device.

Table 2 shows data for each test including input heater voltage, average change in temperature, maximum efficiency, maximum power generated, calculated load resistance at maximum power/efficiency, and load voltage at maximum power/efficiency. The data collected can be used to predict the performance of the commercial devices in other applications.

Table 2 - Values at Maximum Efficiency

| Input Heater Voltage (V) | Average ΔT (°C ) | Maximum Efficiency (%) | Maximum Power Generated (W) | Calculated Load Resistance (Ω) (at max efficiency/power) | Load Voltage (V) (at max efficiency/power) |
|---|---|---|---|---|---|
| 12 | 20.6 | 0.71 | 0.11 | 3.01 | 0.58 |
| 14 | 26.6 | 1.03 | 0.23 | 2.81 | 0.80 |
| 16 | 35.3 | 1.26 | 0.36 | 3.02 | 1.04 |
| 18 | 44.9 | 1.52 | 0.55 | 2.76 | 1.23 |
| 20 | 55.9 | 1.82 | 0.81 | 3.38 | 1.66 |
| 22 | 68.1 | 2.22 | 1.17 | 2.81 | 1.82 |

**Summary and Conclusions**

This paper describes a LabVIEW based experimental setup for measuring the instantaneous power generation and efficiency of a commercial thermoelectric device. Results are presented for a particular Bismuth Telluride thermoelectric device (TEC1-12706). The load resistance is variable in the experimental setup and the power generation and efficiency are both plotted versus the voltage produced. The maximum temperature difference tested was 68.1°C and this produced an efficiency of 2.22% and an output power of 1.17 watts. While this efficiency might seem low, thermoelectric generators are noted for their relatively low conversion efficiency. Also, the maximum temperature difference tested (68.1°C) is fairly modest, higher temperature differences would result in higher efficiency. Typical thermoelectric devices require a temperature difference of approximately 500°C to achieve an efficiency of 10% [9,10]. Testing is planned for the future with higher temperature differences, but the current testing has been successful for the conditions tested.

It is planned to use this experimental setup both as an in-class demonstration for a lecture-based thermodynamics course as well as in a thermodynamics laboratory course. Aside from the data acquisition system (a National Instruments LabVIEW based system in this case) and laptop computer, the cost for the experimental setup is relatively modest and many of the needed components are likely already available in a thermodynamics laboratory. This lab experiment would have the advantage of exposing students to thermoelectric devices as well as incorporating data acquisition for real-time efficiency calculations.

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