A THERMOELECTRIC-BASED POINT OF USE POWER GENERATOR FOR STEAM PIPES

R. Dell, C.S. Wei & G. Sidebotham, The Cooper Union, New York, New York, USA
Magnus Thor Jonsson & Rúnar Unnþórsson, University of Iceland, Reykjavík, Iceland

ABSTRACT

A robust thermoelectric-based point of use power generation system with no moving parts that is designed to be clamped onto the outer wall of a steam pipe with a temperature of 160˚C plus was built and tested in ambient temperatures from 30 to 85˚C. The system consists of a pair of assemblies mounted on opposite sides of a pipe. Each assembly consists of a hot block, an array of three thermoelectric modules wired in series and a cold block heat pipe system. The steel hot block creates a thermal channel to the hot plates of the modules. The cold block consists of a 35 centimeters long heat pipe onto which 41 square fins are attached with a spacing of 0.6 centimeters. The first iteration produced a steady state direct current voltage of 17.2 (open circuit) and an amperage of 0.64 (short circuit) after more than a year of continuous operation. Later versions produced 31.5 volts (open circuit) and 0.89 amps (short circuit), and 21.36 volts open circuit volts and 1.14 short circuit amps in steady state. Additional installations using low temperature geothermal steam and hot water pipes in Iceland were also successful with ambient temperatures below zero degrees Celsius. For comparison purposes with other thermoelectric generators, this thermoelectric generator system produces more than 1 watt per thermoelectric module without any moving parts. These thermoelectric generators produce 6.9 watts steady state and the higher amperage unit produces 6.1 watts steady state.

INTRODUCTION

Geothermal power plants often employ monitoring systems at remote locations that require DC power. If available, standard AC power is easily converted to the required DC power. If not, a separate power line must be installed and maintained. DC power sufficient to run modern telemetry can be obtained by placing the hot block of a thermoelectric power system onto the exterior of a typical exposed steam pipe. A thermal image of a vortex steam meter is shown in Figure 1. The exterior temperature of the exposed pipe is of the order of 160˚C. The ambient temperature of an enclosed space with steam pipes can approach 60˚C, giving an available temperature difference between the high temperature source and low temperature sink on the order of 100°C. Greater temperature differences increases the system's power production.

A thermoelectric power system (Figure 2) consists of a thermoelectric module, a circuit load (rL), a high temperature heat transfer channel (hot block) and a low temperature heat transfer channel (cold block). The two heat transfer channels are required to maintain the temperature difference between the two plates.

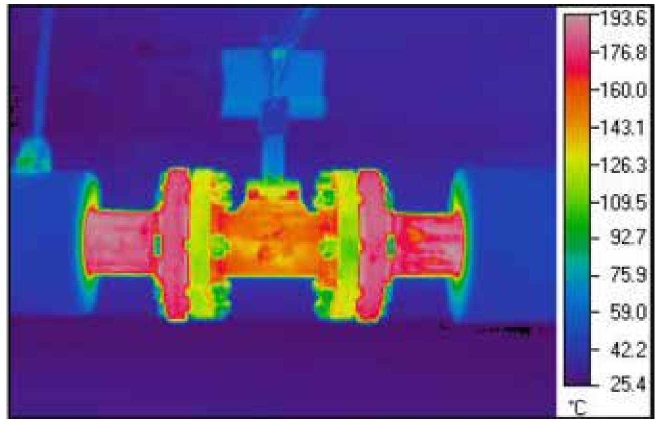

Figure 1: Thermal Image of Exposed Steam Pipe and Steam Meter.

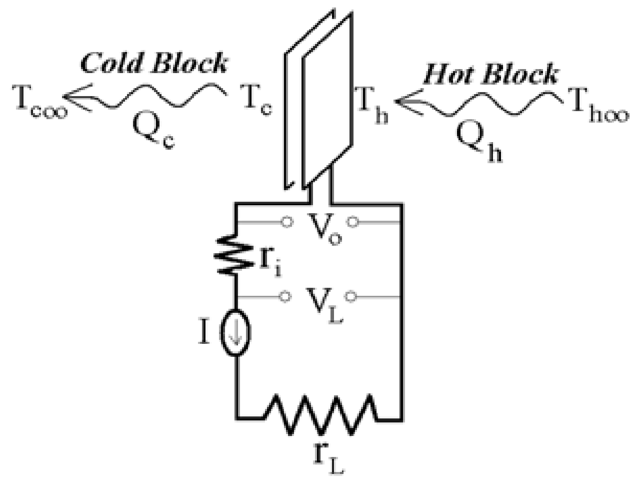

Figure 2: Schematic of a Thermoelectric Power System. The module is modeled electrically as a voltage source (Vo) with an internal resistance (ri)

MATERIALS AND METHODS

The thermoelectric power system is protected by European Patent Application No. 07862348.5, United States Patent Application 20080142067 and Canadian application 2671995. Preliminary per unit costs estimates are under $1,500 per unit.

Each assembly consists of a hot block, a module array, and a cold block. Figure 3 shows an exploded view of the generator assembly (left), assembled generator (center), and the generator mounted on a steam pipe (right).

The entire unit mass is 4.7 kilograms. The cold blocks' (heat pipes) mass is 3 kilograms. The remainder is the hot blocks and the thermoelectric modules. The dimensions are 52 centimeters along the pipe, 45 centimeters wide and 22 centimeters high. Unit variations permit mounting on vertical and oblique angle pipes.

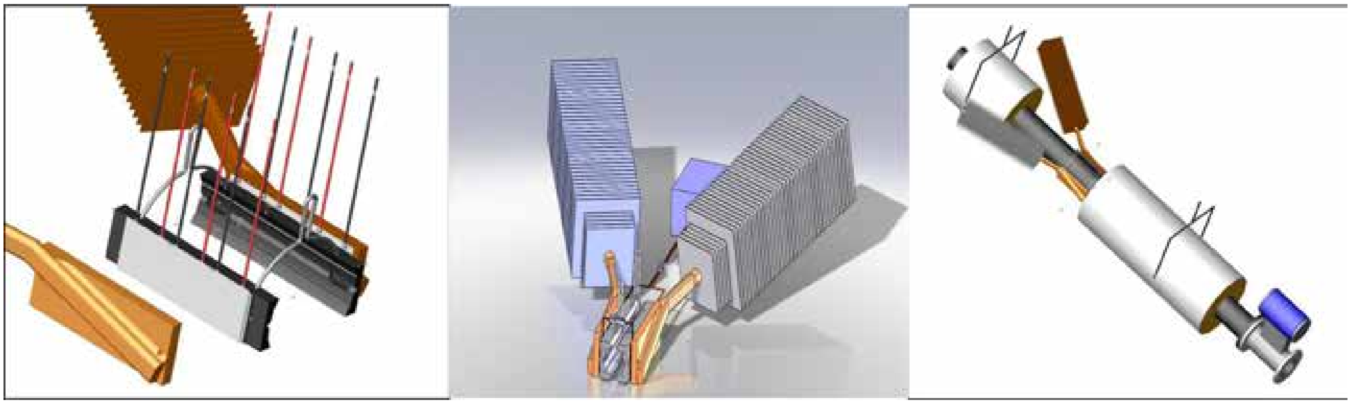

Figure 3: Solidworks rendering of the Thermoelectric Power System. It shows an exploded view of the generator assembly (left), assembled generator (center), and the generator mounted on a steam pipe (right).

Steam Pipe Connection

As shown in Figure 4, a clamp-on system was developed that could be readily attached directly to the surface of existing steam pipes. This low cost solution does not violate the existing steam system's integrity and as such precludes many safety and inspection considerations. The steam pipes surface is hand sanded with 120 grit sandpaper and then cleaned with damp cloth, followed by a solvent wipe. Both the hot blocks and the pipe are covered with Arctic Silver Ambrosia thermal grease. This simple installation protocol together with the clamping and onsite wiring take less than one man hour to complete.

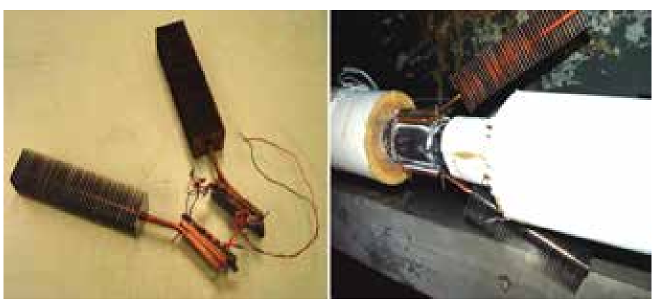

Figure 4: Photos of Thermoelectric Power System. Left photo is assembled, not mounted. Right photo is mounted on a bare section of steam pipe, as seen from underneath the generator.

Thermoelectric Modules

Laird Technologies Incorporated, a major developer of thermoelectric modules (TEMS) several years ago achieved a technical breakthrough in the development of high temperature modules that are designed to function in the temperature ranges of steam systems. These new modules meet U.S. Military specifications.

Although originally designed for thermoelectric cooling, TEMs can be used in reverse. In a cooling mode, electricity is added, and heat is transferred (or pumped) from one flat surface to the other. We use these in reverse, by creating a temperature difference between the two flat surfaces. Extra care must be taken in the engineering design and the assembly protocol to create a maximum temperature difference between the two flat surfaces of the TEMs. Ideally, a vacuum on the edges of the modules would be maintained. This project uses special tolerance lapped modules that can be assembled in units of three TEMs. The assembled generator uses six TEMs. The current configuration has the TEMs wired in series.

The end result is a generator that is so effective that changes of airflow are immediately manifest by voltage fluctuations. For each 10°C of temperature change in the ambient temperature causes approximately 1 volt change in generated power. To maintain a more constant voltage and to create a power reservoir, a voltage regulator with trickle charge capability can recharge a battery.

Hot Block

The main function of the hot block (Figure 5) is to provide a curved surface to mount onto the exterior of a steam pipe, and a flat surface on which to mount thermoelectric modules without adding significant thermal resistance.

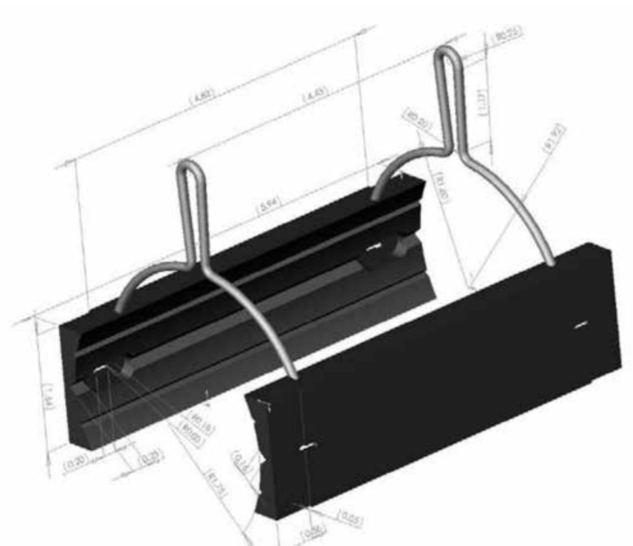

Figure 5: Solidworks rendering of a pair of hot blocks connected by 2 cradles.

Steel was chosen as the material for the hot block because the steam pipe is also steel. This choice eliminates any difference in the expansion and contraction rates, thus insuring no additional movement of the thermal interfaces that are coated with thermal grease. This solution also eliminates any potential galvanic reactions between the steam pipe and the hot block, and the thermal grease serves as an additional galvanic barrier. Prototype brass hot blocks for brass pipes have been fabricated and tested.

Parallel grooves were cut into the curved surface of the hot block. This helps to mitigate any difference in radius. It also minimizes any hot block warpage that could degrade the interface with the TEMs. These grooves serve a third function in providing a channel for the expulsion of any excess thermal grease.

The milled surface of the hot block was recessed to form a channel for the TEMS, which are oscillated into position with thermal grease between the surfaces. This enables precise control of the TEMs position while enhancing the unit's efficiency due to enhanced air circulation.

Two hot blocks are joined together, separated by an inverted stainless steel cradle system that is shaped to facilitate proper alignment on the steam pipe. This eliminates any possibility of steam pipe warpage due to an uneven pipe surface temperature. The cradle also serves as a spring that holds the unit in place during the clamping process. The top spring section serves the additional function of providing gripping points for the installation process, thus minimizing any unnecessary contact with the hot steam pipe.

All wiring of the TEMs can be completed before the installation, with the cradle serving as a mounting point for the wire harnesses.

Thermal Grease

Traditional thermal greases quickly dry at steam temperatures and are not recommended for these applications by the manufacturers. Arctic Silver has developed a high-temperature thermal grease, Ambrosia HT that was modified to our specifications for this project. This product is unique in that it contains nano particles that settle into any voids over a period of approximately 100 hours, thereby potentially creating an increase in system power generation after the unit is initially installed.

Cold Block

The main function of the cold block system is to provide a thermal channel between the cold plate of the thermoelectric module array and the ambient environment. Since the mode of heat transfer ultimately involves the convective/radiative transfer of heat from a solid to ambient air, the thermal goal is to provide a large exposed surface area of material as close to the cold plate temperature as possible.

The cold block system was fabricated by Noren Industries. The system's design consists of a copper mounting block (with one surface mounted on the thermoelectric module array), and a heat pipe onto which evenly spaced rectangular fins are mounted. There is a physical restriction in that the internal flow relies in part on gravity, and it performs poorly if placed horizontally. A mild angle (i.e. 15 degrees from horizontal) is sufficient for the heat pipe chosen. Rectangular fins are mounted onto the heat pipe. The system chosen relies primarily on natural convection, and a restriction on the fins is that they be nearly vertical to allow the flow to accelerate vertically between them. Also, the spacing must be sufficiently large that there is minimal interference between the thermal boundary layers of adjacent fins.

The system consists of two mirrored heat pipes that are splayed back along the steam pipe (Figure 6). This decreases the amount of heat pipe that protrudes into the workspace around the steam pipe. This geometry is important for safety concerns and it enables installation in a one square foot envelope around the steam pipe.

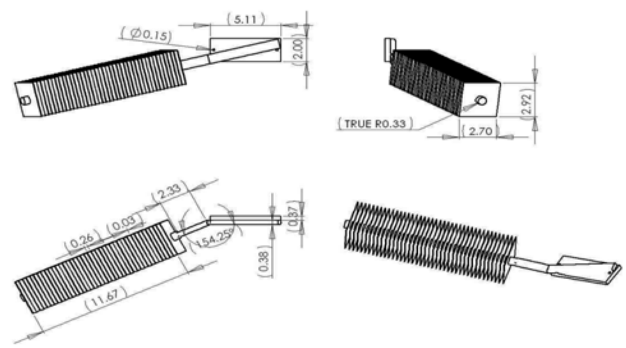

Figure 6: The cold block system.

RESULTS AND DISCUSSION

The first test bed (The Cooper Union's steam room at The Albert Nerken School of Engineering, 51 Astor Place) had a summer temperature of approximately 52°C at an elevation of 1 meter above the floor in the summer and 46°C in the winter. The 3 inch steam pipe had a surface temperature of 158°C. Temperatures were measured using a Linear Labs C-1600 non contact infrared thermometer, a Fluke 867B graphical multimeter with a temperature probe, and a Mikron 7200 thermal camera. Electrical measurements were taken with a Fluke 867B graphical multimeter, and a Fluke 87 multimeter.

The system output voltage and current were measured when the system was used to drive two different light bulbs. Figure 7 shows the experimental operating line of the system on a Voltage vs. Current plot. The point on the voltage axis (zero current) is the open circuit voltage of 17.2 V, and the point on the current axis (zero voltage) is the closed circuit current (0.63 Amps). The plot is linear between these two points, with a slope equal to 24.4 Ohms.

Figure 8 shows open circuit voltage (over a two hour period) and closed circuit current (over 10 minutes) obtained from the system as a function of time. The output is stable. An improved version of the generator produced 12.4 volts open circuit volts and 0.81 short circuit amps in steady state using only one half (one side) of the generator - 3 thermoelectric modules. The voltage would be doubled in a full unit (12 volts per side) because the modules are connected in series. Figure 9 shows the Iceland installation.

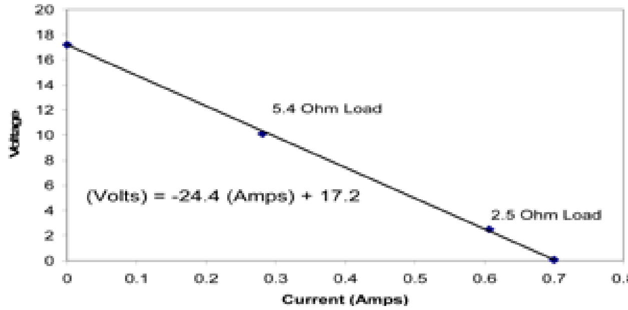

Figure 7: System voltage as a function of Current for various electrical loads.

To provide a backup, higher peak power and stable voltage, a battery cell that is charged by the generator under load a trickle charge system using a Xantrex 3-phase (bulk, absorption and float) unit was tested, as shown in Figure 10. A 12-volt 7 Ah (amp-hour) sealed lead acid rechargeable battery and a Manson SBC – 7112 PV charge controller was used.

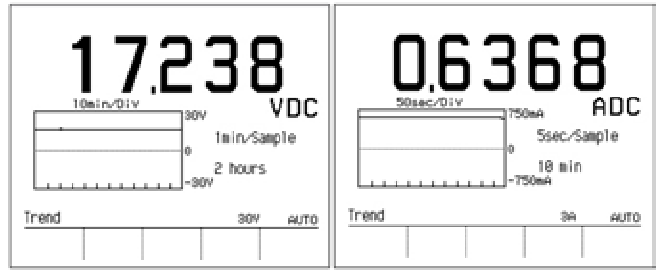

Figure 8: System voltage (open circuit) and current (short circuit) as a function of time.

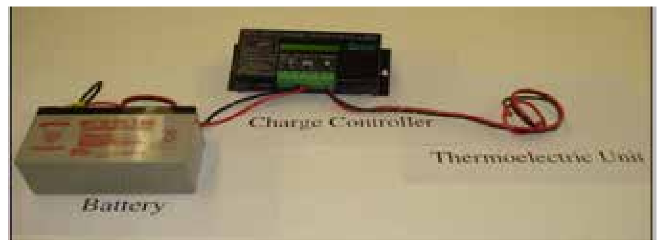

Figure10: The backup battery cell.

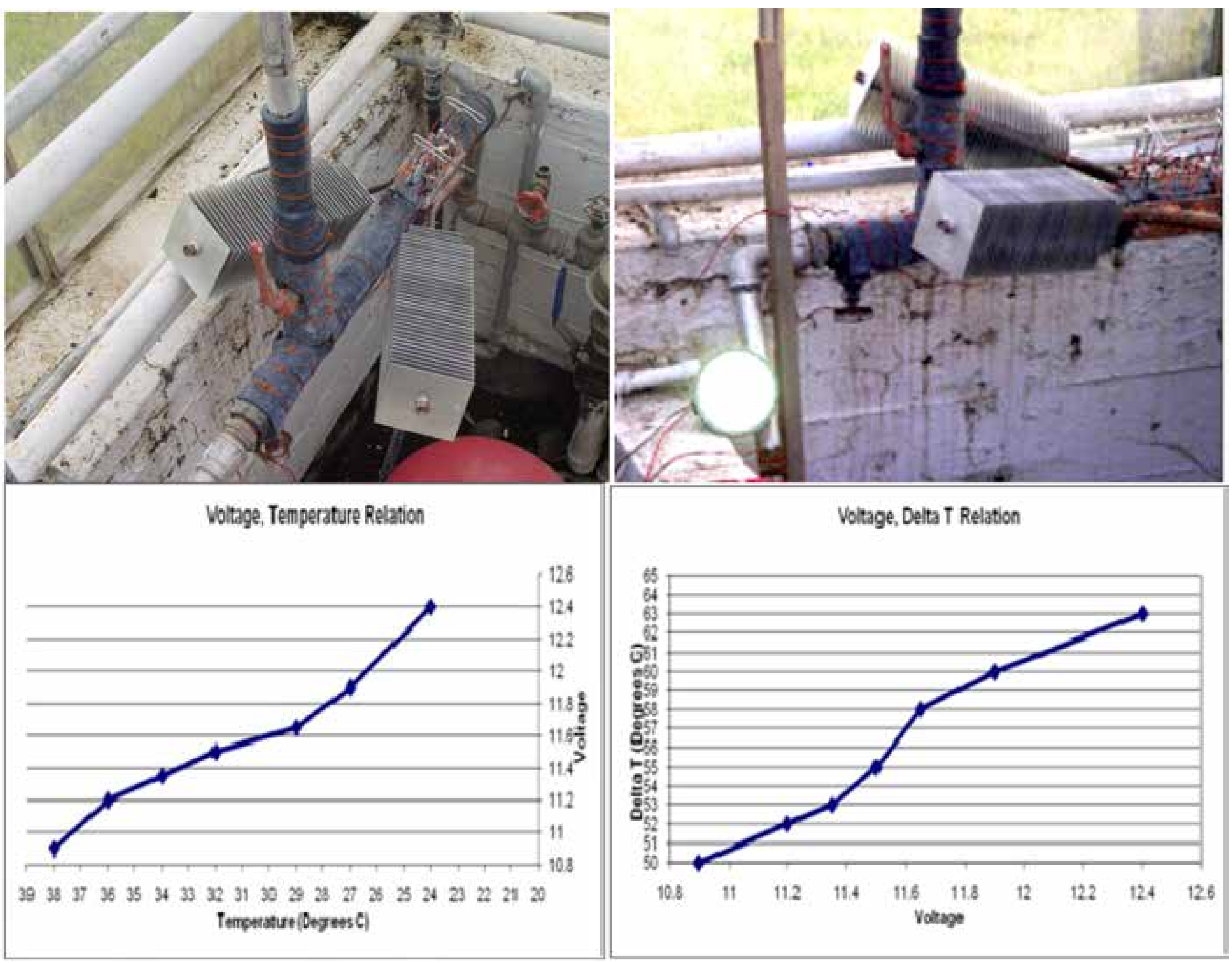

Figure 9: Iceland installation using geothermal steam and condensate mix at 100°C (top left), powering an LED light fixture (top right); temperature vs. voltage (bottom left); delta T vs. voltage (bottom right)

An improved unit was installed in another steam room with an ambient temperature of approximately 30°C at an elevation of 1.2 meters above the floor. The steam temperature was 160°C. It produced 31volts open circuit volts and 0.89 short circuit amps in steady state. The most recent configuration uses high amperage thermoelectric modules. At our new test bed, it produces 21.36 volts open circuit volts and 1.14 short circuit amps in steady state with similar temperature parameters (Figure 11).

Figure 11: Shows the system voltage (open circuit) and current (short circuit) for the improved unit.

The total watts produced by a thermoelectric generator can be approximated by multiplying the open circuit voltage by the short circuit amperage and then divide the product by 4. The improved unit produced 6.9 watts steady state and the higher amperage unit produces 6.1 watts steady state. For comparison purposes with other generators, our thermoelectric generator produces slightly more 1 watt per thermoelectric module.

As a demonstration of the generator's utility, a Y-cam Solutions Ltd. S-range Indoor IP security camera YK004 was connected to the system. The camera was successfully powered and transmitted surveillance images to an internet-enabled laptop computer.

CONCLUSIONS

A robust thermoelectric-based point of use power generation system with no moving parts that produces more than 6 watts of steady state power is now available. There are many potential locations for this system in the geothermal industry, including existing steam pipes and remote installations on municipal district heating pipes. The performance, low cost, and ease of installation of this generator enables the installation of reduced power telemetry and security camera systems.

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