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A New Test Rig for Accurate Nonparametric Measurement and Characterization of Thermoelectric Generators

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Thermoelectric generators (TEGs) are increasingly employed in large-scale applications, therefore accurate performance data are necessary to permit precise designs and simulations. However, there is still no standardized method to test the electrical and thermal performance of TEGs. This paper presents an innovative test system to assess device performance in the "real world." The fixture allows the hot temperature to be increased up to 800°C with minimal thermal losses and thermal shock; the clamping load can be adjusted up to 5 kN, and the temperatures are sensed by thermocouples placed directly on the TEG's surfaces. A computer program controls all the instruments in order to minimize errors and to aid accurate measurement and test repeatability. The test rig can measure four TEGs simultaneously, each one individually controlled and heated by a maximum electrical power of 2 kW. This allows testing of the effects of series and parallel connection of TEGs under mismatched conditions, e.g., dimensions, clamping force, temperature, etc. The test rig can be employed both as a performance evaluator and as a quality control unit, due to the ability to provide nonparametric testing of four TEGs concurrently. It can also be used to rapidly characterize devices of different dimensions at the same time.

Key words: Thermoelectric, characterization, test, measurement, rig

TEG Thermoelectric generator
MPP Maximum power point

INTRODUCTION

Thermoelectric devices are used in three different operating modes: cooling, heating, and power generating. They convert thermal energy into electrical energy, or the contrary, and they can increase or decrease the heat power flow rate through them.[1] Traditionally, heat power is more difficult to quantify compared with electrical power, because of various losses and ways of transferring heat energy from one body to another. This means that it is not easy to precisely determine the performance of thermoelectric devices; results often depend on how the tests are performed, and they are difficult to replicate on different measurement systems. When designing a thermoelectric system, the thermal/electrical engineer often relies on data provided by the manufacturer, therefore it is important to have precise knowledge of the performance of off-the-shelf thermoelectric devices. Even if other measurement systems have been developed in the past,[2–6] to date there is no standardized way of testing thermoelectric devices. The performance obtained by the user is often better or worse than that written in the datasheets; both cases are not suitable for the user, because the load/supply might not be able to cope with a higher or lower power produced or requested by the thermoelectric device. This problem is particularly acute when dealing with large-scale applications, in which it is more difficult to predict how the whole system

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will behave. However, large-scale applications of thermoelectric generators have recently come under focus in the search for technologies for waste heat recovery from other necessary processes, e.g., car exhaust systems [7,8] and power plants.[9] The designer of such large thermoelectric systems needs to select the modules most suitable to the application; hence having clear performance data for every module available on the market is desirable.

Depending on the cross-sectional area, thickness, and number of pellets contained in a module, its performance and current–voltage rating can change considerably. This paper presents an innovative measurement system to precisely analyze the performance of thermoelectric devices, also providing experimental results about commercial thermoelectric generators (TEGs).

TEST RIG

The proposed measurement system, shown in Fig. 1, is included in a standard 19-inch equipment rack and constitutes a standalone system, able to test four TEG modules at the same time.

The schematic in Fig. 2 helps to understand the architecture of the proposed system. A data logger unit is used to feed back temperature and mechanical pressure measures to the computer, where a completely automated program controls the amount of electrical power provided to the hot side, and the load connected to the TEG. A chiller unit is used to cool the cold side of the system. The main mechanical, electrical, and computer features of the system are described in the next subsections.

MECHANICAL SIDE

The mechanical side of the test rig is shown in Fig. 2. The general idea behind the test rig is to have a common and stationary cold side, while separate and independent mechanical fixtures can be vertically adjusted over a range of approximately 75 mm; as a consequence, each thermoelectric module, sitting on an individual hot block, is brought towards the cold block. The 300-mm-long cold block is made of copper and is supported by steel columns at a height of 18 cm. It is water-cooled by a chiller unit. A manual valve adjusts the quantity of water arriving into the inlet manifold from the chiller, and the fluid flow is measured by a mechanical flow meter; the incoming water temperature is sensed by a thermocouple. The water passes through 12 straight holes (3 for each TEG) in the cold-side block, and its temperature in several of the outgoing pipes is sensed by thermocouples before arriving at the outlet manifold. The chiller unit (Thermal Exchange CS-10) is capable of extracting 1 kW of heat power and controls the water temperature with a proportional–integral–derivative (PID) controller to an accuracy of ±0.1°C between 5°C and 25°C. Four thermocouples are placed inside the copper block, going out from the bottom side with an aperture of just 1 mm diameter, in order to measure the TEG cold-side temperature directly on its surface.

Each of the four TEGs is placed within a separate mechanical structure of fixed height, composed of two steel plates connected together by four columns. An M20 bolt runs through the top plate, and it is positioned over the top face of the cold block, touching a load sensor cell at a single point of contact. For mechanical compliance, a 1000 lb/inch (179 N/mm) spring with thrust bearings is added; it is locked on the M20 bolt by a pair of nuts. When turning the M20 bolt, the external structure climbs the bolt and the bottom steel plate is drawn towards the bottom face of the cold block.

Fig. 1. The complete measurement system used for the experiments.

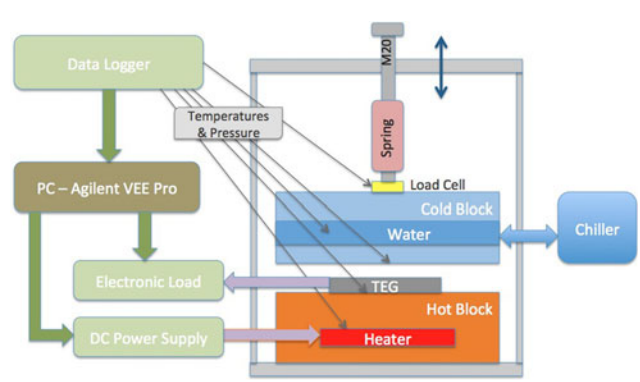

Fig. 2. Schematic representing the architecture of the proposed system.

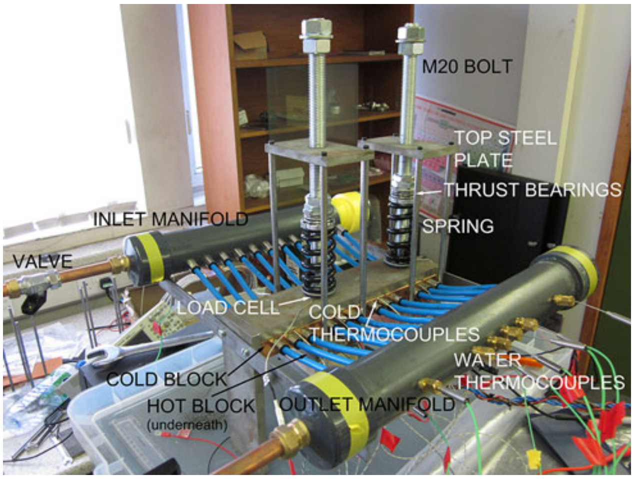

Fig. 3. Test rig, showing just two measurement structures.

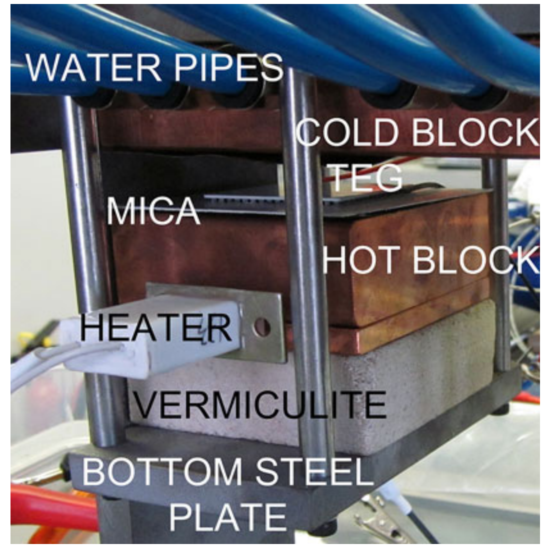

Fig. 4. One of the four hot-side mechanical fixtures.

A copper block serves as the hot side, as shown in Fig. 3; it contains a silicon nitride high-temperature high-power heater rated to 1200°C* and 500 W. Two thermocouples are fitted inside each hot-side block, one terminating on the TEG hot-side face with an aperture of just 1 mm diameter and another one sensing the heater temperature. The TEG is positioned on top of the hot-side block; hence when the bottom plate rises, the device under test is sandwiched between the hot and cold copper blocks.

If the device under test requires a thermal input power in excess of 500 W, alternative copper heater blocks are available to host two and four heaters, respectively, thus providing a rated maximum electrical power of 2 kW. The maximum temperature tested to date was 800°C for an oxide TEG. The absolute maximum temperature the test rig is capable of has not yet been measured.

All the copper blocks are custom designed and produced at the Mechanical Workshop of the University of Glasgow.

HEAT ISOLATION

The cold- and hot-side blocks are thermally decoupled. The only mechanical point of contact between the cold block and the hot block is the load cell onto which each individual structure is balanced. Between the hot copper block and the bottom steel plate there is a 2.5-cm-thick block of vermiculite, therefore the heat conducted through the four steel columns is minimized and can be readily calculated by means of a thermocouple placed on the underside of the vermiculite board.

A thin mica sheet on top of the hot block, with a cut in its center with the dimensions of the TEG module, is used to reduce thermal radiation losses from the hot to the cold side around the TEG module (Fig. 4). A thin graphite sheet (eGRAF HT-1205, not shown in Fig. 4) is used to reduce the thermal resistance between the hot block and the TEG hot face.

For studies of the thermal conductivity and efficiency of the TEG module, it is important to control the heat losses from the hot block and/or to quantify them. It is difficult to precisely calculate the heat dissipated to air through convection, thus the hot block was enclosed into a box (open on one side) made of a thin mica sheet and surrounded on the sides with glass fiber (Fig. 4).

Losses are calculated in the "Experimental Results" section.

ELECTRICAL AND CONTROL SIDE

The thermocouples and the pressure sensors are connected to a data logging unit. The outputs of the TEGs are connected to an electronic load with four independent channels, while four 750-W direct-current (DC) power supply units provide the power to the heaters. All the instruments are connected to a general-purpose interface bus (GPIB) computer interface and controlled by VEE Pro software by Agilent. All the experimental results presented in this paper were automatically generated by the VEE Pro program interfaced to Microsoft Excel. The program can independently control the temperature difference across each TEG and use any number of electronic load channels.

The main aim of the program is to obtain an electrical characterization of the device under test, recording all the temperatures and electrical parameters at every operating point. The program also brings the system to steady state at open cir-

*The heater is theoretically capable of melting the copper block, but in practice the thermal conductivity of the TEG is such that this does not happen.

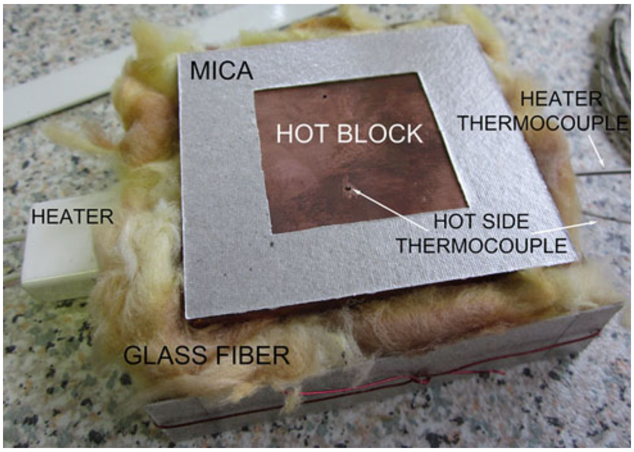

Fig. 5. Insulating box for the hot block with mica antiradiation screen.

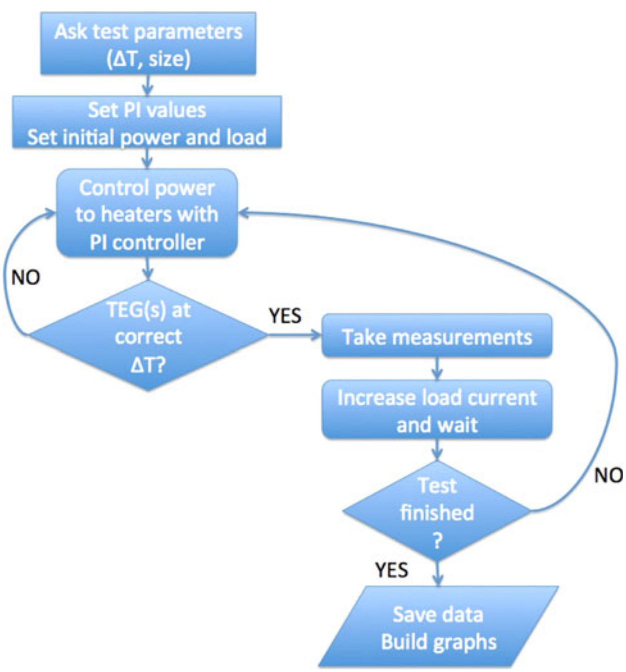

Fig. 6. Flow diagram of the Agilent VEE Pro control program.

cuit, at the maximum power point (MPP), and close to short-circuit, in order to calculate the efficiency and thermal conductivity of the device. User intervention is required to set the desired pressure on the module by turning the M20 bolt on top of the test rig. Future enhancements to the test fixture will include a stepper-motor-driven clamping mechanism, so that pressure variations due to thermal expansion and contraction within the test rig can be automatically compensated for. The flow diagram of the control program is shown in Fig. 5.

At the beginning of the execution, the program asks the user for the temperature difference required for each TEG, the current load step size, and the dimensions of each TEG. The latter parameter is needed to set the coefficients needed by the proportional–integral (PI) control for the power to the heater. The program can bring the system to the desired temperature difference starting from any initial temperature. The electronic load is initially set to open-circuit, and then the current is increased by the set step size.

Next, the program controls the electrical power to the heater necessary to establish the required temperature gradient across the device; when the error is less than ±0.25°C, the program takes readings from the data logger, the electronic load, and the power supply. Afterwards, the current load is increased by the set step size and the program waits for 10 s before controlling the temperature again, in order to let the thermal transient evolve. The program takes a steady-state measurement at the beginning (open-circuit), at the MPP, and at the end of the test (short-circuit); the MPP is passed when the sequent power is less than that of the previous operating point, hence the previous load is set again. For steady state, data are recorded only after waiting for 2 min with the temperature difference continuously within ±0.25°C of the desired temperature.

EXPERIMENTAL RESULTS

All the data provided were obtained using two TEG modules of the same model (ETdyn** GM250-127-14-10, 40 × 40 mm). Other tests have been done on seven additional (pairs of) TEG modules.

When designing a thermoelectric power generation system, the most important thing, from a practical point of view, is to understand how the power generated varies depending on the electrical load applied to the TEG and on the temperature difference across it. When connected to different loads, the TEG effective thermal conductivity changes; knowing how this happens is important to estimate the thermal energy that needs to be provided to and extracted from the system, and the change in temperature difference. In applications where electrical energy can be recovered from waste heat, the low conversion efficiency of TEGs places an upper limit on the amount of energy that can be scavenged. Steps must therefore be taken to understand other losses and ensure that the system is able to maximize the electrical energy produced.

ELECTRICAL CHARACTERIZATION

This section presents the data and graphs for the power produced at different temperature gradients, depending on the electric load applied. After gathering some experimental data, it is possible to calculate mathematical relations that allow the generation of correct electrical values at each operating point.

**http://www.etdyn.com

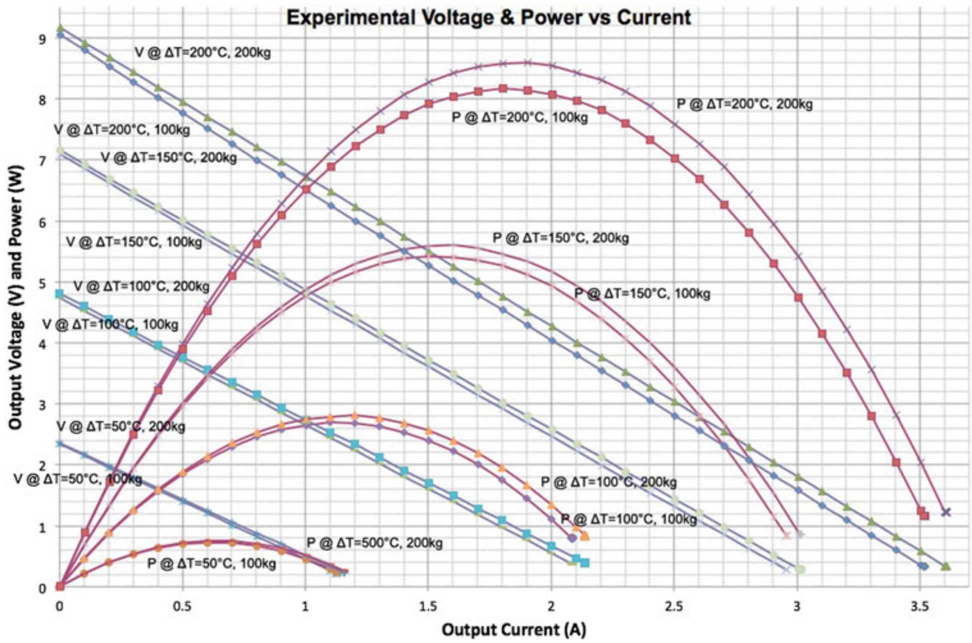

Fig. 7. Output power and voltage versus output current for GM250-127-14-10 #1. The module has been tested at temperature differences ΔT = 50°C, 100°C, 150°C, and 200°C, each time at two different values of pressure, 100 kg and 200 kg.

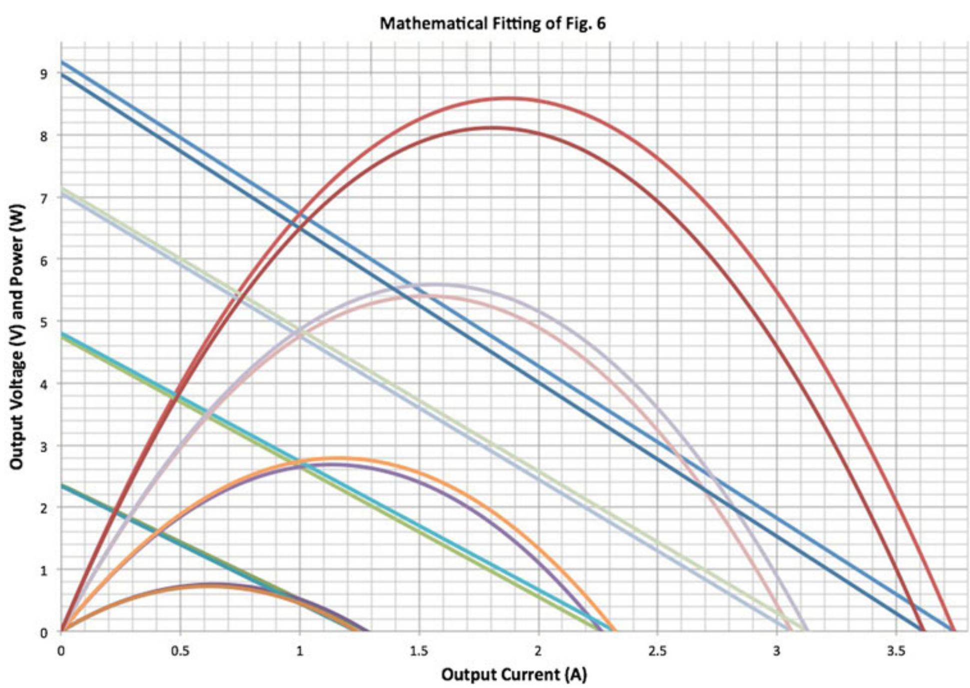

Fig. 8. Mathematical fitting of the graphs of Fig. 6. ΔT = 50°C, 100°C, 150°C, and 200°C, each at 100 kg and 200 kg.

Experimental Values

Custom Thermoelectric[†] suggests a maximum operating pressure of 1.275 MPa, which corresponds to 209 kg on a 40 mm × 40 mm TEG module. Tests were done at four temperature differences (50°C, 100°C, 150°C, and 200°C), each time at two different values of pressure (100 kg and 200 kg), to investigate the influence of contact pressure on thermal and electrical performance.

Figure 6 shows the experimental data obtained during the electrical characterization of one of the TEG modules. This shows that the maximum power is always produced at half of the open-circuit

[†]http://www.customthermoelectric.com

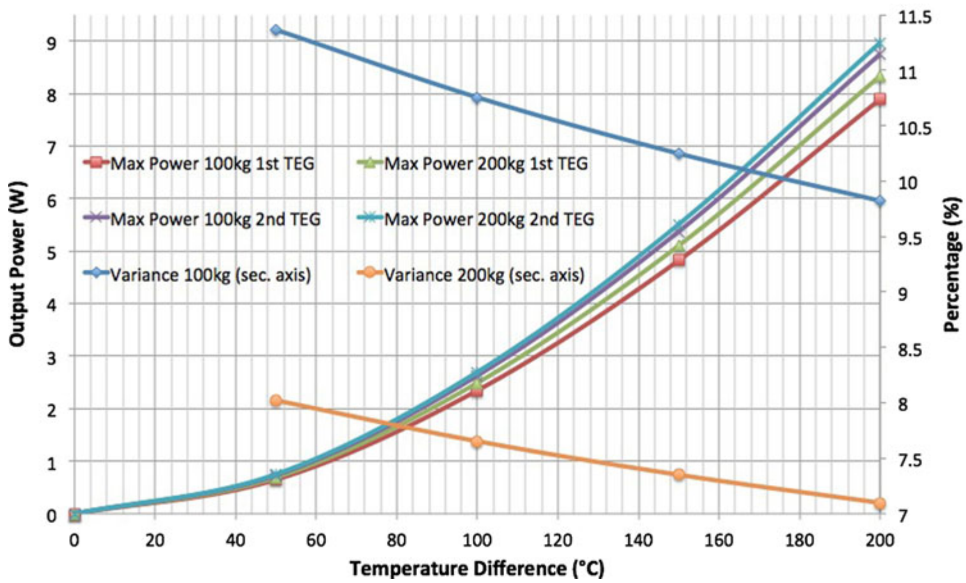

Fig. 9. Graph showing the maximum power versus temperature difference for both TEGs at 100 kg and 200 kg pressure (first y-axis) and the variance in power produced by the two TEGs for both values of pressure (second y-axis).

Table I. Coefficients and dimensions used to calculate the heat losses from the hot block

Name	Value (Dimension)
TEG dimensions	40 × 40 × 3 (mm)
Hot block dimension	75 × 70 × 25 (mm)
Glass fiber thickness	10 (mm)
Glass fiber therm. cond.	0.035 (W/mK)
Vermiculite thickness	25 (mm)
Vermiculite therm. cond.	0.15 (W/mK)
Air therm. cond.	0.024 (W/mK)

voltage. The power produced by the TEG is clearly reduced when the pressure is lower, which is logical because a higher pressure reduces the thermal contact resistances in the system.

Mathematical Fitting

As already explained in Ref. 10, the voltage of a TEG is related to its current as

$$V = -R_{\text{int}} I + V_{\text{OC}}. \qquad (1)$$

R_{int} and V_{OC} can either be measured directly at MPP and at open-circuit, respectively, or be calculated from any operating point achieved from the electrical characterization:

$$-R_{\text{int}} = (V_m - V_n)/(I_m - I_n) \text{ and}$$
$$V_{\text{OC}} = V_m + R_{\text{int}} I_m, \qquad (2)$$

where m and n are two operating points, at the same temperature difference and different load current, with $I_m > I_n$.

R_{int} and V_{OC} vary linearly with the temperature difference ΔT, and it is possible to calculate the slope and intercept of the line representing such variation in a similar way as done in Eq. 2. Hence, it is possible to write

$$V = -(m_{\text{Rint}} \Delta T + q_{\text{Rint}}) I + m_{\text{Voc}} \Delta T, \qquad (3)$$

where q_{Voc} is zero because the voltage produced at ΔT = 0°C is zero. From these results it is finally possible to draw the electrical characterization at any operating point, as shown in Fig. 7 for the first TEG; it can be seen that the values match the experimental data of Fig. 6.

Variance of Performance

A second TEG module (GM250-127-14-10 #2) was characterized to investigate the variance of performance between two modules of the same model and batch. Similar results to Fig. 6 were obtained, but the power produced is higher. Figure 8 shows the curves of the maximum power (at the MPP) over the temperature difference of the two TEGs, for both values of pressure. The variance is between 7% and 11.5%. Obviously, this difference might depend on how the devices are mounted in the test rig, but this is likely to happen anyway in a practical application, with further possible mismatches. The difference increases at lower pressures and decreases with higher temperatures.

The relation between the power produced and the mechanical pressure on the module was also studied. Results are presented in Fig. 9 for three different values of pressure (104 kg, 139 kg, and 200 kg) for the second TEG at 200°C temperature difference. The maximum power produced varies

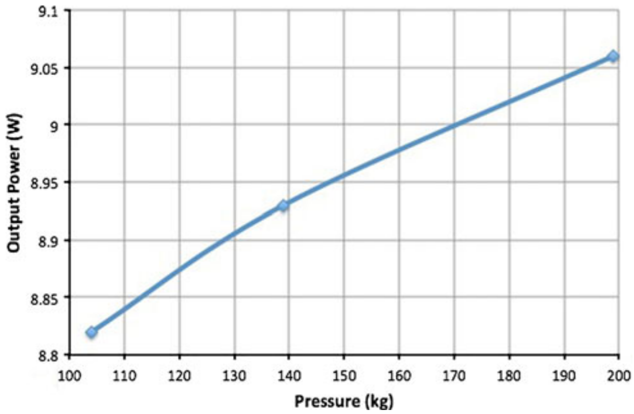

Fig. 10. Variation of the maximum power produced by the second TEG at ΔT = 200°C for different values of pressure: 104 kg, 139 kg, and 200 kg.

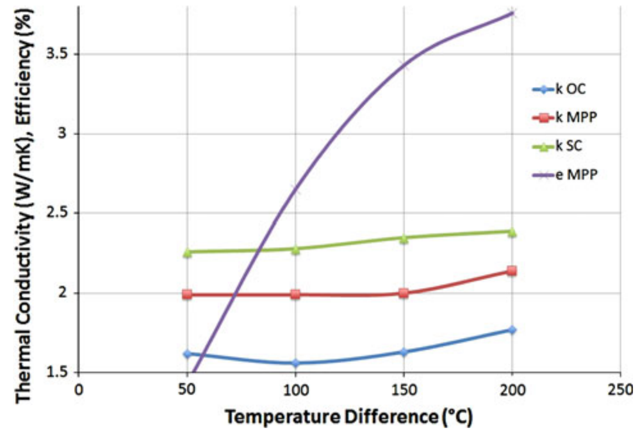

Fig. 11. Efficiency at MPP and thermal conductivity (at open-circuit OC, MPP, and short-circuit SC) of TEG #1 versus the temperature difference.

linearly with pressure, but it is expected that it will asymptotically approach a maximum value with increasing pressure. Once all other data have been collected, the TEG will be tested to destruction. The theoretical limit of the clamping force for Bi_2Te_3 modules is principally dependent on the compression strength of the thermoelectric materials and is thought to lie around 10 N/mm^2 or 1.6 metric tons for the 40 mm × 40 mm module.

Results for the performance and interactions of different TEGs connected together while under different operating thermal states will be presented in future work.

THERMAL CHARACTERIZATION

The data presented in this subsection are preliminary. Future work will focus on increasing the accuracy of the results and the calculation of losses. Reasonable values for the thermal conduction coefficient and the efficiency of the device under test can be estimated, likely reflecting a real system, which is usually not lossless. The thermal characterization presented considers the heat losses to ambient through the insulation of the hot copper block, using the classic equation of thermal conduction

$$P_{\text{loss}} = kA(T_{\text{H}} - T_{\text{C}})/x, \tag{4}$$

where k is the thermal conduction coefficient, A is the surface area of conduction, x is the thickness of the medium, and T_{H} and T_{C} are the temperatures of the two bodies.

The values used for the material properties and dimensions are listed in Table 1.

Future work will add a heat flux sensor on the cold side, and will use the adjustable fluid rate and the water pipe temperatures to precisely calculate the heat power being released to the water; this constitutes an invaluable way to compare the results obtained by calculating the heat losses from the hot block.

The data obtained in steady state (at open-circuit, MPP, and short-circuit) are used to calculate the variation of the effective thermal conductivity and efficiency of the device under test according to the output current. The total electrical power P_{in} provided to the heater is transformed into heat energy; this energy, minus the mentioned losses P_{loss} and the energy used to change the internal heat energy of the hot copper block, flows through the TEG module. However, in steady state, there is no change in the temperature of the hot block, therefore $P_{\text{in}} - P_{\text{loss}}$ flows through the TEG module. The efficiency η is calculated as the ratio between the output electrical power and the heat power flowing through the TEG:

$$\eta = P_{\text{out}}/(P_{\text{in}} - P_{\text{loss}}). \tag{5}$$

Figure 10 illustrates how the effective thermal conductivity and MPP efficiency of a TEG vary with the temperature difference. The efficiency at the MPP increases asymptotically. It is interesting to note the great change in effective thermal conduction between the three operating points selected (open-circuit, MPP and short-circuit); this happens because a higher load current increases the Peltier effect, which pumps more heat from the hot to the cold side (Fig. 11).[10]

CONCLUSIONS

This paper describes an innovative test rig that can be used to test the performance of commercial TEG modules in conditions similar to those that will be encountered in real-world applications. The system is controlled by a computer without much user interaction needed, and it can individually control the temperature difference across four separate TEG modules, and as many electronic loads. It can be used for performance evaluation, for quality control, or to investigate the effects between devices connected together under mismatched conditions. Several experimental results have been presented to demonstrate the capabilities of such measurement system. Although this paper has concentrated on thermoelectric power generation, the same test hardware and fixtures can be used to characterize heat pump performance.

Future work will include the addition of a variable-temperature cold side, a computer interface to measure and control the fluid flow rate, automatic compensation of thermal expansion/contraction effects, and improvements to the precision of the calculation of the heat flux through the device under test.

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