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An experimental investigation

Mahmoudi Nezhad, Sajjad; Rezaniakolaei, Alireza; Ranjbar, Ali Akbar; Rosendahl, Lasse Aistrup

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Transient behavior of the thermoelectric generators to the load change; an experimental investigation

Sajjad Mahmoudinezhad[a]*, Alireza Rezania[a], Ali A. Ranjbar[b], Lasse A. Rosendahl[a]

[a]*Department of Energy Technology, Aalborg University, Pontoppidanstræde 101, Aalborg ,DK-9220, Denmark*
[b]*Department of Mechanical Engineering, Babol University of Technology, Babol, P.O. Box 484, Iran*

Abstract

Thermoelectric generators (TEGs) are environmentally friendly and have become a promising technology for different waste heat recovery applications. An experimental study is carried out to examine the performance of four TEGs that are connected in series used for electric power generation over a range of different operating conditions and resistance loads. After obtaining I-V-P curves, the transient thermal response of the TEGs to a load change is investigated. The significance of the impact of volumetric flow rate in the hot and cold sides of the TEGs and the temperature in the constant temperature reservoir on power generation and transient behavior of the TEGs are determined and discussed in details. The results show the substantial effect of the volumetric flow rate and temperature in the power generation and transient thermal behavior of the TEGs.

Keywords: transient response; thermoelectric generator; experimental investigation; variable load

1. Introduction

   Having no moving parts and long lifetime, silent operation and low maintenance costs make thermoelectric generators (TEG) a promising technology for waste heat recovery. TEGs convert waste heat into electricity

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* Corresponding author. Tel.: +459-35-62-145; fax: +459-81-51-411.
  E-mail address: sma@et.aau.dk

directly [1–5]. Due to depletion of conventional energy resources, replacement of them by clean and renewable energies is very crucial. TEGs are small, robust and compact devices that make them an appropriate choice for different applications. There are a lot of studies that considered TEGs under transient conditions. Alata and Naji [6, 7] used an analytical model to investigate the transient performance of thermoelectric cooler (TEC). Generally, mathematical modeling of transient heat conduction problems involves a complex treatment. Due to thermoelectric multi-physics effect in the TEG, the condition is more challenging. Jia et al. [8] established a finite element model to investigate the transient response of linear-shaped TEGs. The results indicated reducing the time to reach steady condition, the entire generated electric power and conversion efficiency can be increased.

Savani et al. [9] studied the behavior of a Bi-Te based TEG under the transient condition of a silicon production plant. The results showed that by increasing the cooling capacity, it would be more advantageous to use the TEG with a higher fractional area and locate it as close as possible to the silicon melt. Blandino and Lawrence [10] investigated both numerically and experimentally transient response of a TEG exposed to spatially non-uniform heating, resulting in small temperature gradients across its thickness. They found that in such application it is crucial to use a highly efficient heat sink over the whole back area of the module.

To minimize the response time of the TEG and then higher working frequency, Fisac et al. [11] developed a TEG structure. The performance of the new TEG's structure is validated by comparing numerical simulation and experimental results. The finite-difference method is used by Nguyen and Pochiraju [12] to solve a transient TEG model subjected to an unsteady state heat source on the hot side. It has found that Thompson effect has a substantial impact on power generation by the TEG. The steady-state and transient models for a gas/liquid cylindrical TEG presented and validated by Crane et al. [13, 14]. The transient model can simulate a wide range of working circumstances.

One of the main advantages of the TEGs is that they are environmentally friendly and can recycle wasted heat energy and convert it into the reusable form of energy. There are many studies on different models and prototypes for different applications of waste heat recovery that have been established and validated with very promising outcomes. Most of them have been examined under steady-state conditions. However, in the real applications, we face unsteady situations, and this transient condition leads to substantial deviation in TEG performance. This experimental work presents an analysis of the transient electrical and thermal behavior of a TEG system to a load change. Moreover, mutual electrical and thermal response of the TEG system under transient condition will be discussed.

2. Experimental setup

Fig. 1 shows a view of the test rig. Power generation by the TEG system is obtained by data derived from experiments. Four 30 mm·30 mm·4.2 mm Bi-Te based TEGs are used in the experiments that electrically connected in series. Force convection cooling of the cold side of the TEG is provided by an axial fan. A DC power supply is used to apply different fan powers and different mass flow rates in the heat sink. For the hot side of the TEGs, a hot gas supplier and a constant temperature reservoir is used. The temperature and mass flow rate of the hot side of the TEG can be controlled by the constant temperature reservoir and hot gas supplier, respectively. Four T-type thermocouples are placed just behind of the TEGs. A programmable DC electronic load device is used for applying different loads to the TEGs. Temperatures in the different points, volumetric flow rates, and output voltage are the main parameters recorded during experiments. All experimental data are collected by LXI (34972A) data acquisition system.
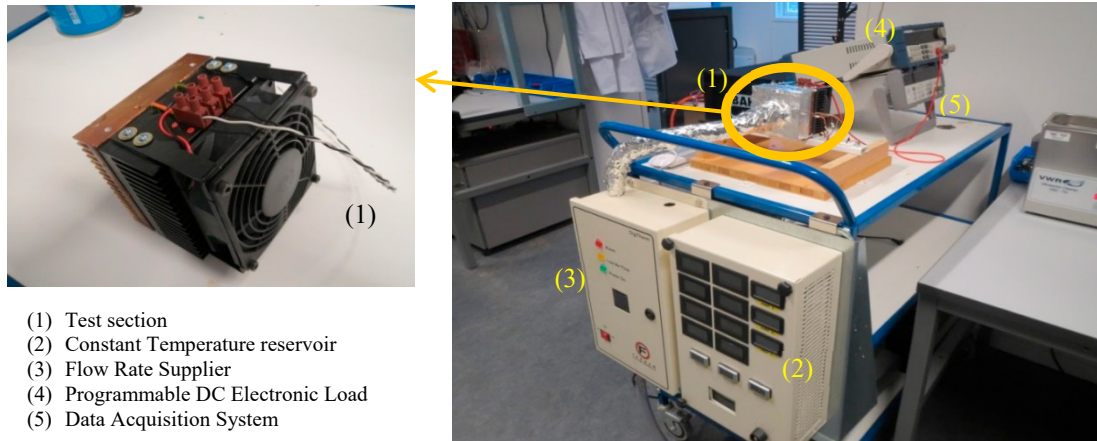
(1) Test section
(2) Constant Temperature reservoir
(3) Flow Rate Supplier
(4) Programmable DC Electronic Load
(5) Data Acquisition System

Fig. 1. A view of the TEG test rig.

2.1. Uncertainty analysis

Uncertainty analysis has been carried out using the method proposed in [15, 16]. To ascertain the accuracy of the equipment, they were calibrated before experiments. The measuring value and the resolutions of all the devices are presented in Table 1. The relative uncertainty of the devices is calculated by [15]:

Relative uncertainty = 0.5 · resolution · measuring value $^{-1}$ (1)

As it can be seen, the maximum relative uncertainty of the equipment is 2 %.

Table 1. List of equipment relative uncertainties.

Equipment	Measuring range	Resolution	Relative uncertainty
Hot gas supplier	30–90 L/min	0.1 L/min	0.17 %
Constant temperature reservoir	100–400 °C	0.1 °C	0.05 %
DC power supply (for voltage)	3–13 V	0.00125	0.02 %
Programmable DC electronic load (for electric current)	0.025–1.2 A	0.001 A	2.00 %

An error analysis of experiments also is carried out. For a typical test, results for temperature in the different points of the system, voltage, and current are shown in Table 3. The mean value ($\overline{X}$) and the standard deviation (S_X) of the data are defined by [16]:

$$\overline{X} = n^{-1} \sum_{i=1}^{n} X_i$$ (2)

$$S_X = \left[(n-1)^{-1} \sum_{i=1}^{n} X_i - \overline{X})^2 \right]^{\frac{1}{2}}$$ (3)

Then the uncertainty (S_J) is:

$$S_J = S_X \cdot (\overline{X})^{-1} \cdot 100$$ (4)

As it can be seen in Table 2, the maximum uncertainty is 1.98 % which is less than 6 %. It shows that the experiments are reliable.

Table 2. List of experiment uncertainties.

Variable	1st	2nd	3rd	Mean value	Sample standard deviation	Uncertainty
T_{HA} (°C)	215.1 °C	216.39 °C	217.84 °C	216.44 °C	1.37 °C	0.63 %
T_H (°C)	165.37 °C	166.52 °C	163.91 °C	165.26 °C	1.31 °C	0.79 %
T_C (°C)	65.86 °C	63.3 °C	64.46 °C	64.54 °C	1.28 °C	1.98 %
V_{OC} (V)	11.8747 V	11.9194 V	11.9326 V	11.9089 V	0.0303 V	0.25 %
V (V) (@P_{max})	5.7635 V	5.6979 V	5.7241 V	5.7285 V	0.0330 V	0.58 %
I (A) (@P_{max})	0.4513 A	0.4502 A	0.4489 A	0.4501 A	0.0012 A	0.27 %

3. Results and discussion

Four Bi-Te based TEGs are tested under different operating conditions. In the experiments, the volumetric flow rate of the fan in the heat sink and temperature, and volumetric flow rate of the air flow on the hot side are changing to provide different working circumstances. The volumetric flow rate of the fan (Q_c) and hot gas supplier (Q_h) are varied between 406.3 L/min to 1229 L/min and 30 L/min to 90 L/min, respectively.

The variations of the open circuit voltage with the temperature difference for different volumetric flow rates are obtained. Due to electrical resistance in the wires, switches, connections and other devices, the measured open circuit voltage is always less than the actual value, but if TEG produces high voltage and low current, this error is almost negligible [17]. The Seebeck coefficient of a material depends on the temperature [18, 19] but in this framework the open circuit graphs are linear, and it shows that in the tested temperature range, the magnitude of the Seebeck coefficient is approximately constant. From Eq. (5), the value of the Seebeck coefficient can be measured by using the open circuit voltage and the temperature difference between hot side and cold side of the TEGs.

$$V_{oc} = \alpha \Delta T = \alpha (T_h - T_c) \tag{5}$$

where

V_{oc}	the open circuit voltage;
α	the Seebeck coefficient;
T_h and T_c	the temperatures of the hot and cold side of the TEG, respectively.

Using Eq. (5) shows that the Seebeck coefficient values for tested material and in this temperature range are varied between 0.104 V/K and 0.121 V/K for four TEGs.

V-I, R-I and P-I curves for four TEGs at a specific temperature difference ($\Delta T = 107.8$ °C) and with $Q_c = 406.3$ L/min are illustrated in Fig. 2.
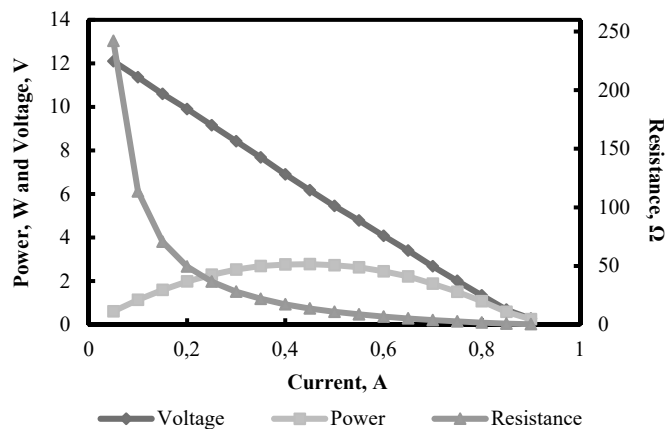

Fig. 2. V-I, R-I and P-I curves for ($\Delta T = 107.8$ °C), $Q_h = 90$ L/min and $Q_c = 406.3$ L/min.

The focus of this investigation is on the transient thermal response of the system to an electrical load change. After reaching the steady state condition, the I-V-P curves for all the operating conditions are obtained. Then the equivalent voltage for the maximum power can be achieved. The same operating condition is applied again to the system with open circuit voltage. This time the voltage suddenly drops to the equivalent voltage of the maximum power which is obtained before. Fig. 3 displays the thermal response of the TEGs to the load change for $Q_h = 30$ L/min and $Q_c = 406.3$ L/min and $T_{TSR} = 250$ °C, T_{TSR} is the temperature of the constant temperature reservoir.
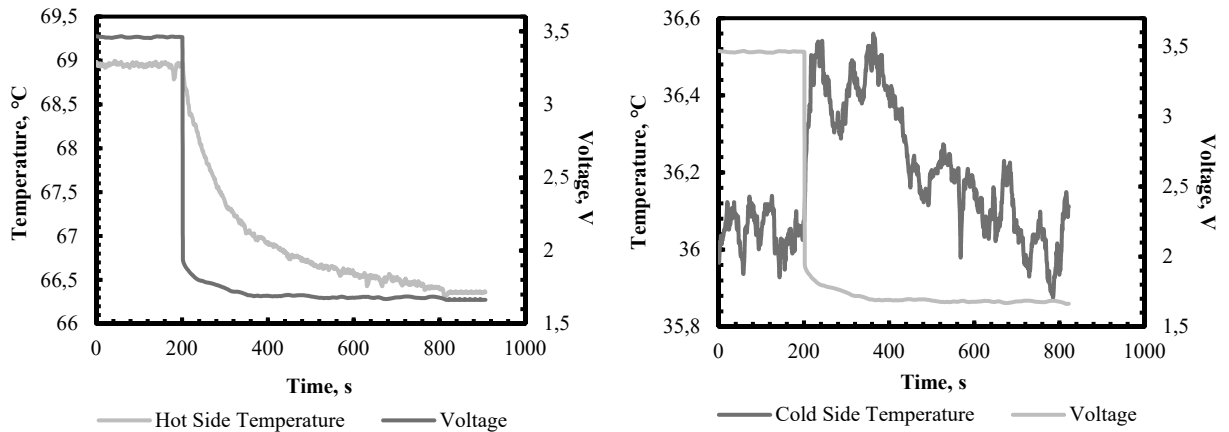

Fig. 3. Variation of the hot and cold side temperatures and voltage versus time for $Q_h = 30$ L/min and $Q_c = 406.3$ L/min and $T_{TSR} = 250$ °C.

As can be observed, the open circuit voltage is equal to $V_{oc} = 3.45$ V. By applying equivalent current for the maximum power $I_{@Pmax} = 0.175$ A, the equivalent voltage for the maximum power is $V_{@Pmax} = 1.66$ V. In this condition, the temperature of the hot side of the TEG drops around 2.5 °C, but the cold side temperature does not change a lot. This variation is owing to the Peltier effect that is working against power generation and deviates the peak working point from the generally known maximum power point (MPP). As a matter of fact, the heat transfer across the TEG from the hot to the cold side varies with the load current produced by the TEG according to the Peltier effect.

By increasing the volumetric flow rate in the hot and cold sides of the TEG, these variations are more sensible. Fig. 4 shows the same graphs for higher volumetric flow rates and the same temperature in the constant temperature reservoir. The open circuit voltage is $V_{oc} = 8.67$ V and equivalent current and voltage for maximum power are $I_{@Pmax} = 0.4$ A and $V_{@Pmax} = 3.98$ V, respectively. Fig. 4 indicates that the drop in the hot side temperatures is around 5 °C, while the cold side temperature enhances 1 °C.
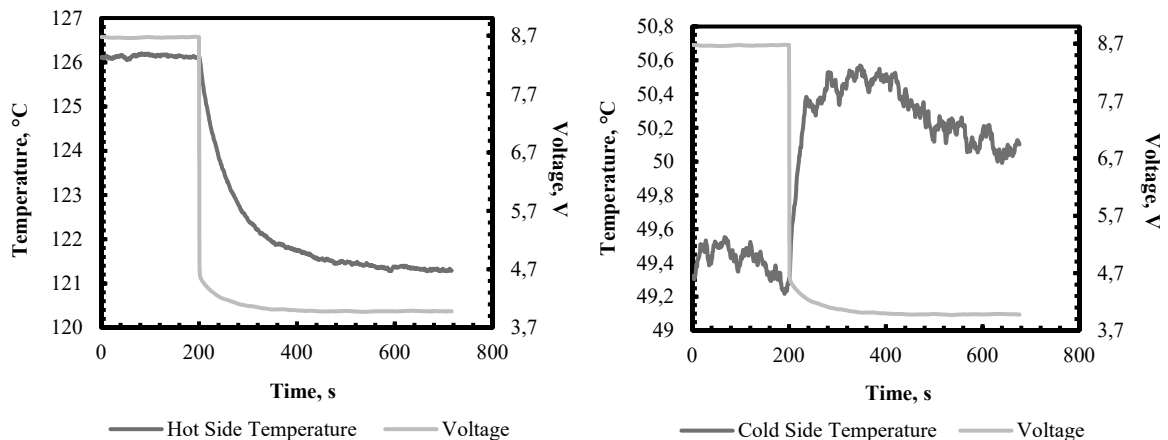

Fig. 4. Variation of hot and cold side temperatures and voltage versus time for $Q_h = 90$ L/min and $Q_c = 1015.7$ L/min and $T_{TSR} = 250$ °C.

Fig. 5 illustrates that increment in the value of the temperature of the constant temperature reservoir has a substantial effect on the characteristics of the TEGs. As can be seen, in this condition the open circuit voltage reaches $V_{oc} = 15.05$ V. When the current is increased to $I_{@Pmax} = 0.55$ A, the equivalent voltage for reaching the maximum power is $V_{@Pmax} = 7.42$ V. In this operating condition, the hot side temperature decreases more than 7.5 °C and the cold side temperature enhances around 2.5 °C.
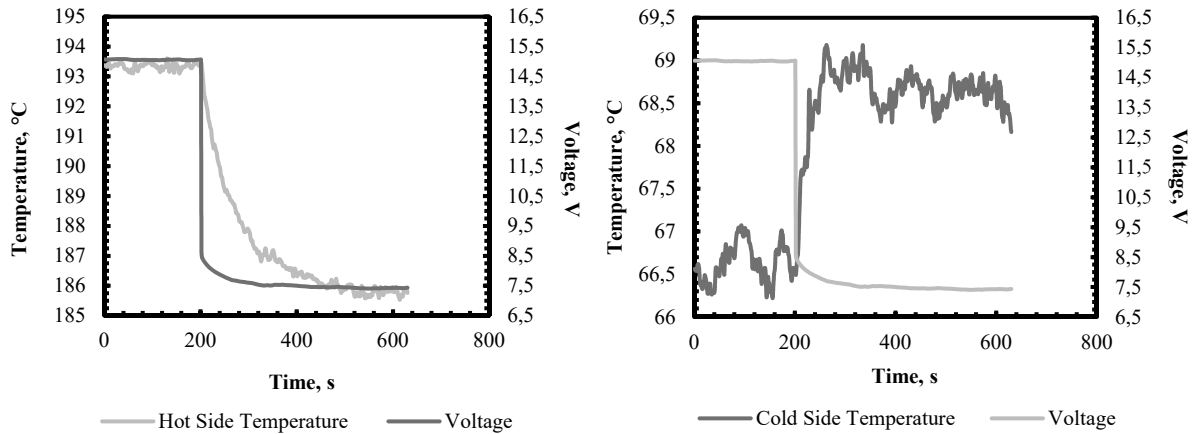
Fig. 5. Variation of hot and cold side temperatures and voltage versus time for $Q_h = 90$ L/min and $Q_c = 1015.7$ L/min and $T_{TSR} = 400$ °C.

The significant effect of volumetric flow rate in the heat source can be observed in Fig. 6. Identical condition with the Fig. 5 is considered except the volumetric flow rate in the hot side that is decreased to $Q_h = 30$ L/min. A huge drop in the open circuit voltage can be seen. In this working circumstance, by increasing the current from 0 to $I_{@Pmax} = 0.275$ A, the voltage drops from $V_{oc} = 5.70$ V to $V_{@Pmax} = 2.65$ V. The hot side temperature drop is around 4 °C and the variation of the temperature in the cold side is small.

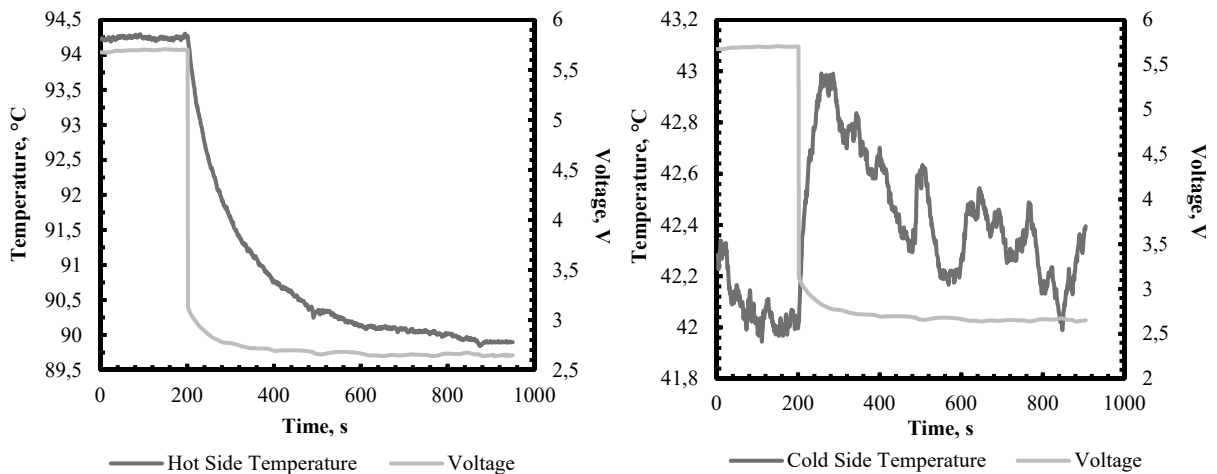Fig. 6. Variation of hot and cold side temperatures and voltage versus time for $Q_h = 30$ L/min, $Q_c = 1015.7$ L/min and $T_{TSR} = 400$ °C.

4. Conclusion

Four Bi-Te based TEGs are examined experimentally. I-V-P curves in different operating condition are obtained. The impact of different parameters has been considered. Thermal response of the system to a load change from the

open circuit voltage to the equivalent voltage for maximum power is discussed. The results indicate that in the low volumetric flow rate values of the heat source, the variation of the temperature of the cold side is small. With increasing the volumetric flow rate on both sides of the TEG, the temperature drop on the hot side and the enhancement of the temperature on the cold side is increased. The maximum variation in the temperatures is related to the higher temperature in the constant temperature reservoir and higher volumetric flow rate on both sides of the TEG.

Acknowledgements

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