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Published in:
Energy Procedia

DOI (link to publication from Publisher):
[10.1016/j.egypro.2017.12.087](https://doi.org/10.1016/j.egypro.2017.12.087)

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Publication date:
2017

Document Version
Publisher's PDF, also known as Version of record

[Link to publication from Aalborg University](#)

Citation for published version (APA):
Mahmoudi Nezhad, S., Rezaniakolaei, A., & Rosendahl, L. A. (2017). Experimental Study on Effect of Operating Conditions on Thermoelectric Power Generation. *Energy Procedia*, 142, 558-563. Article 498.
<https://doi.org/10.1016/j.egypro.2017.12.087>

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9th International Conference on Applied Energy, ICAE2017, 21-24 August 2017, Cardiff, UK

Experimental Study on Effect of Operating Conditions on Thermoelectric Power Generation

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Abstract

Effect of boundary conditions of thermal reservoirs on power generation of thermoelectric modules (TEMs) is examined experimentally. To realize the characteristics of the power generation by the TEMs, the system performance is studied over various volumetric flow rates and flow temperatures of the hot gas and in the heat sink over a wide range of electrical load. The results show a significant influence of forced convection produced by an axial fan in the heat sink in comparison with natural convection. Also, both of the temperature and volumetric flow rate of the hot gas have a substantial effect on power generation by the TEMs. Lower volumetric flow rate in the heat sink is suggested to save fan power because it is found that higher volumetric flow rates on the cold side after the optimal flow rate does not have much effect on the power generation by TEMs. The maximum power produced by tested TEMs is 4.59 W at temperature difference equal to 133.78°C.

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Peer-review under responsibility of the scientific committee of the 9th International Conference on Applied Energy.

Keywords: Forced and Natural Convection; Thermoelectric Module; Experimental Study; Power Generation.

1. Introduction

Some special features like having no moving parts, having long life time, being highly reliable, silent operation and being environmentally friendly make TEMs a good alternative energy technology to decrease dependency on fossil fuels. As TEMs do not need fuel supply and also their low maintenance requirements they can be a good choice for energy harvesting via the direct recovery of waste heat and conversion into useful electrical energy. Applying TEMs to improve the efficiency of waste heat recovery by using different heat sources such as geothermal

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energy, power plants, automobiles and other industrial heat-generating process is an interesting subject in studies [1–4]. Hsiao et al [5] developed a mathematic model of TEM to comprehend the characteristics of thermoelectric generator (TEG), and the effects of engine speed and coolant temperature of radiator on the TEM. Output power and thermal efficiency of TEG at different coolant temperatures were presented. Commercially available Bi_2Te_3 thermoelectric cells were examined by Ding et al [6] in different operating conditions. Performance and reliability of TEGs for power generation were presented. Performance of these TEGs when subjected to thermal cycling and continuous operation at hot side temperature of about 160°C was also investigated. The results showed that commercially available TEG tested is reliable to be used under thermally cycled hot side temperature $<90^\circ\text{C}$ and cooled at ambient temperature, for at least 500 cycles as tested. An experimental and numerical study on low-temperature waste heat harvesting with 24 TEGs to convert heat from the exhaust pipe of an automobile to electrical energy was carried out by Hsu et al [7]. Open circuit voltage and output power of the system were presented for variant temperature differences. The performances of TEMs at different operating conditions were investigated by Chen et al [8]. Flow patterns, heating temperatures, flow rates of water and numbers of modules were examined experimentally. They found that heating temperature is the most important parameter in the performance of the TEMs and the effect of the other factors are not significant. Rezania et al [9] studied and optimized a micro plate-fin heat exchanger applied to a TEG to maximize the output power and the cost performance of generic TEG systems. They showed that there is a unique pumping power that delivers the maximum cost performance for the TEG systems. To study the effect of complex vehicle driving conditions on the TEG performance, a numerical model of TEG based on vehicle waste heat recovery was developed by Yu et al [10]. They found that the performance variation of TEGs becomes more remarkable with faster acceleration or deceleration. Meanwhile in deceleration the transient response of the hot and cold side temperatures, voltage and power is less significant in comparison with acceleration.

This experimental study aims to find TEMs electrical response to variation of thermal boundary conditions. The effect of volumetric flow rate and the temperature of the exhaust gas, and the effect of variation of the volumetric flow rate in the cold side of the TEMs are tested. Furthermore, in the cold side a comparison between natural and force convection has been studied.

2. Experimental setup

The schematic diagram of the experiment setup is shown in Fig. 1(a). An axial fan with variable power supply is used for cooling the cold side and a hybrid system including a hot gas supplier and a constant temperature reservoir is applied for heating the hot side of TEMs. T-type thermocouples are used for measuring temperatures of the hot and cold sides and also the ambient temperature. Four thermocouples are located on each side of the finned plates just behind of the modules. All the temperatures are monitored continuously in a PC by a data acquisition system. A programmable DC electronic load device is used for applying load to the TEMs. The test section consists of a thermoelectric generator made of four TEMs connected electrically in series. The commercially available Bi_2Te_3 based thermoelectric modules with a module size $30\text{mm}\times 30\text{mm}\times 4.2\text{mm}$ is used for the experiments. As it is shown in Fig. 1(b), TEMs are inserted between two finned plates as conventional heat sink and heat source with the same areas ($100\times 100\text{ mm}$). The finned surface consists of 17 fins with thickness 2 mm and height 30 mm. The gap between the fins is 2 mm.

3. Results and discussion

Corresponding to equation 1, for obtaining the absolute value of the internal resistance of the TEG, the slope of the V-I linear lines should be calculated. Fig. 2(a) shows the V-I curves in different temperature differences.

$$V = RI \tag{1}$$

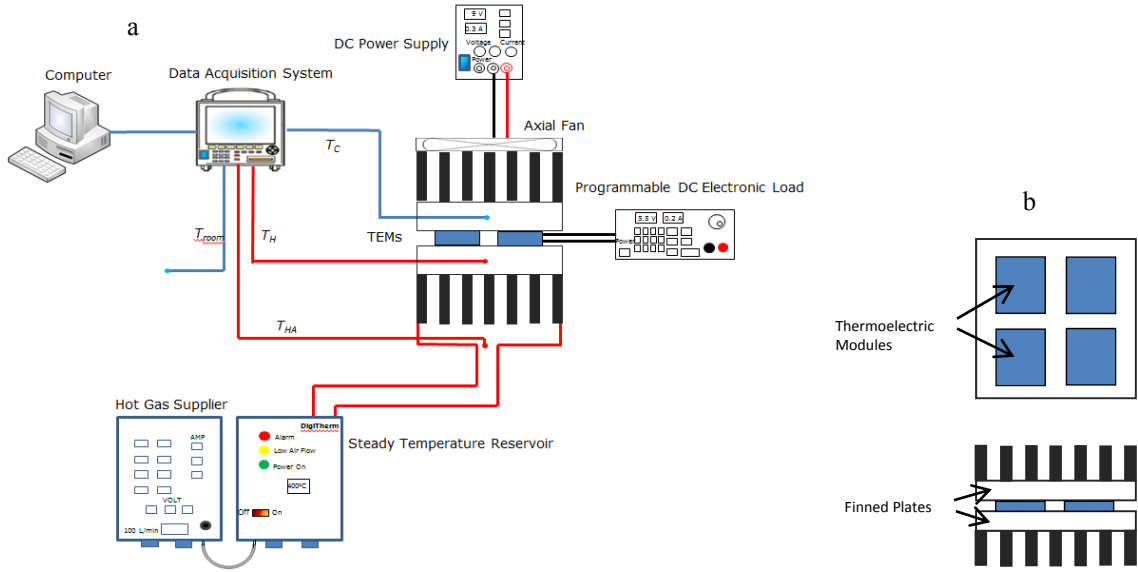


Fig. 1. (a) Schematic diagram of the experiment setup; (b) Schematic diagram of the test section.

It can be seen that the internal resistance for four TEMs is varied between 10.29Ω to 14.54Ω . Subsequently the maximum power should occur when the electric load resistance is approximately equal to 12.41Ω . As it can be seen, the V-I curve slope is slightly increases with increasing the temperature difference. As it is mentioned before, the gradient of the V-I curve is equal to the electrical resistance of the TEG and as the electrical conductance of a material changes with temperature [11-12], thus with increasing the average temperature of the TEG, the electrical resistance of the TEG also should increases.

The variation of output power against current for different ΔT is presented in fig. 2(b). As it can be seen, there is a maximum electrical power output for every value of ΔT . These maximum values are used to create Fig. 3(a). The maximum power produced by the TEG for a given ΔT is:

$$P_{max} = \frac{V_{oc}I_{sc}}{4} = (\alpha\Delta T)^2 / 4R \tag{2}$$

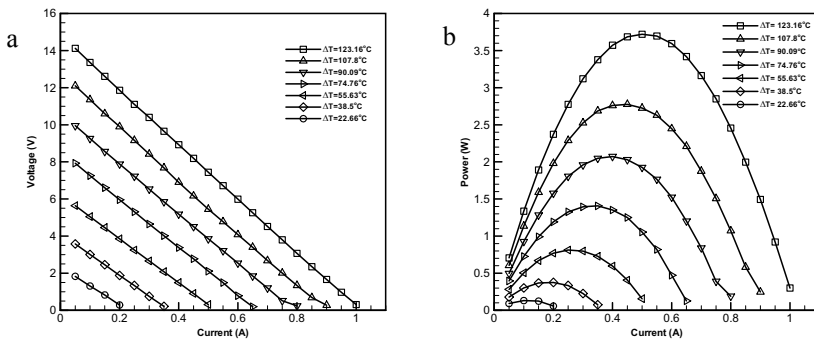


Fig. 2. (a) V-I curves; (b) P-I curves for different temperature differences and with $Q_h=90$ Lit/min and $Q_c=406.3$ Lit/min.

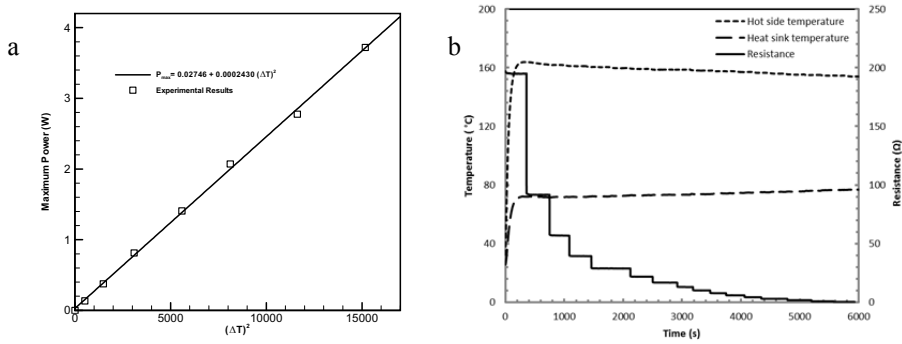


Fig. 3. (a) Maximum power versus ΔT^2 ; (b) Hot and cold side temperatures and resistance of TEG for $Q_h=90$ Lit/min and $Q_c=406.3$ Lit/min.

Where, V_{OC} and I_{SC} are the open circuit voltage and short circuit current. Then based on the equation (2) the power-current relation should have a parabolic form. Fig. 3(a) shows the variation of maximum power of TEMs versus ΔT^2 . By using equation 2, the slope of the $P_{max}-\Delta T^2$ curve is equal to $\alpha^2/4R$. As it can be seen in the fig. 3(a) the slope of the line is 0.0002430, then by considering the internal resistance 12.41 Ω , the value of Seebeck coefficient will be 0.1098 V/K. As it can be seen in fig. 3(b), with increasing the current, the resistance decreases by the time. Joule heating effect can be seen in the variation of the hot and cold side temperatures. With passing the time, hot side temperature decreases slightly and in the opposite, cold side temperature is increased gradually.

3.1. Effect of the natural and force convection in the cold side

As it can be seen the temperatures of the hot side of TEG and surface of CPV are almost the same and the temperature of the cold side of TEG is also varied in a same manner but by a time delay. This delay is because of the time which heat passes through the CPV and the components of TEG. All of the temperatures are changed by variation of sun radiation which presented in fig. 2(a). Obviously by increasing the sun radiation during the time, all temperatures are increased and vice versa. One another important point in the fig. 2(b) is related to the low sun radiations. As it can be seen, in the small sun radiations, all the temperatures are very close to each other. It is clearly due to low amount of heat transfer through the hybrid system.

Fig. 4(a) and 4(b) show the V-I and P-I curves for different volumetric flow rates of the fan in the cold side, respectively. To observe the substantial effect of the fan and force convection cooling on the power generation by TEMs, figs 4(a) and 4(b) can be compared with figs 5(a) and 5(b). The voltage and power output by the TEMs when natural convection is used for cooling the cold side are illustrated in figs 5(a) and 5(b).

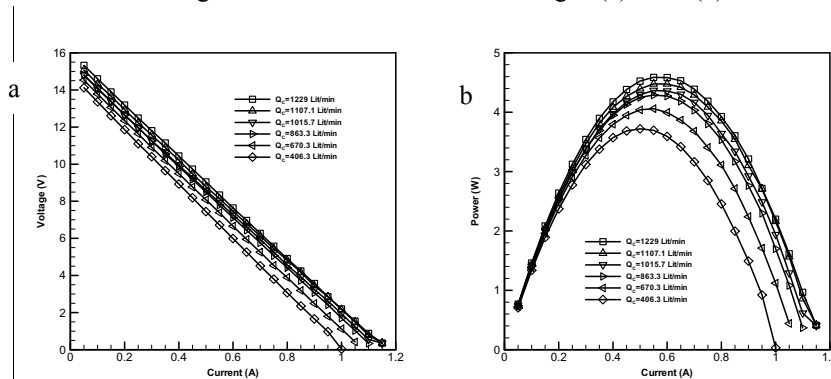


Fig. 4. (a) V-I; (b) P-I curves, both for different volumetric flow rates of the fan in the cold side.

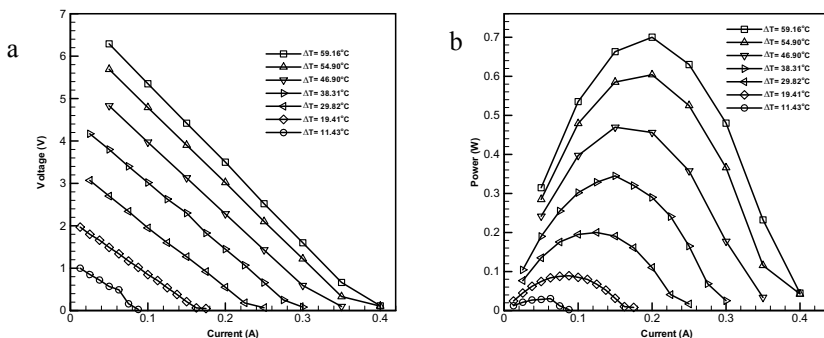


Fig. 5. (a) V-I; (b) P-I curves, both for different temperature differences and $Q_h=90$ Lit/min (natural convection cooling).

As it can be seen, when there is no fan and thus natural convection heat transfer exists in the cold side, the value of the output voltage and also output power are very small. By running the axial fan, the force convection cooling leads to increasing in the value of the voltage and power significantly. As it can be seen in both figures 4(b) and 5(b) maximum power produced by TEMs increases while temperature difference is increasing. As it is illustrated in figures 4(a) and 4(b) the variation of volumetric flow rate of the fan has not much effect on output voltage and power. So, lower value of the volumetric flow rates is suggested for cooling the cold side. Because, in this way more power could be save.

Table 1 shows the values of the temperatures at different points of the set up for natural and force cooling conditions when the temperature of steady temperature reservoir is 300°C . It can be seen that with increasing of the volumetric flow rate produced by the fan, the temperatures of the cold side and hot side are decreased. But totally the temperature difference ΔT will increases and it leads to increment of voltage and power output.

Table 1. Temperatures at different points in the system for constant $T_{STR} = 300^{\circ}\text{C}$.

	$T_{HA} (^{\circ}\text{C})$	$T_H (^{\circ}\text{C})$	$T_C (^{\circ}\text{C})$	$\Delta T (^{\circ}\text{C})$	$V_{OC} (V)$	$P_{max} (W)$
Natural convection	267.22	236.9	177.74	59.16	7.2	0.7
$Q_c=406.3$ Lit/min	266.51	211.6	88.44	123.16	14.96	3.72
$Q_c=670.3$ Lit/min	263.82	202.14	74.33	127.81	15.35	4.06
$Q_c=863.3$ Lit/min	262.38	198.97	68.66	130.31	15.55	4.29
$Q_c=1015.7$ Lit/min	261.07	197.61	66.17	131.44	15.61	4.37
$Q_c=1107.1$ Lit/min	260.22	196.47	63.65	132.82	15.86	4.48
$Q_c=1229$ Lit/min	259.6	195.31	61.53	133.78	16.10	4.59

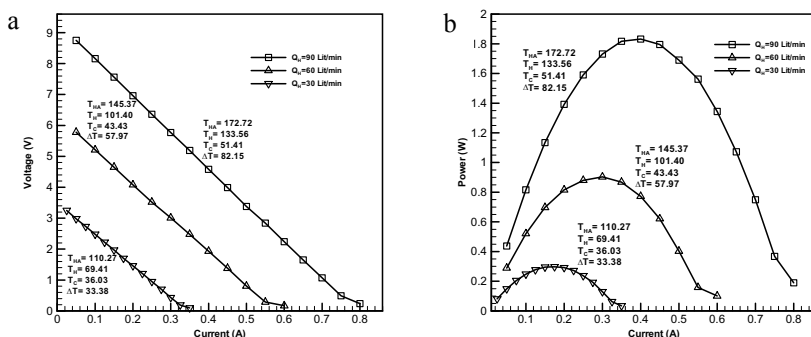


Fig. 6. (a) V-I; (b) P-I curves, both for different volumetric flow in the hot side and $Q_c=1015.7$ Lit/min.

3.2. Effect of volumetric flow rate of the hot gas

Figs 6(a) and 6(b) show V-I and P-I curves at a constant temperature ($T_{STR}=200^{\circ}\text{C}$) and for different volumetric flow rates provided by hot gas supplier. As it can be seen, because of the heat loss during the path of the hot gas, the temperature in the hot side is decreased. This falling in temperature value is very depended on the volumetric flow rate applied by hot gas supplier. With increasing the volumetric flow rate, higher force convection heat transfer is produced in the hot side and it leads to having higher temperature in the hot side. The value of temperatures in different points of setup is presented in figs 6(a) and 6(b). It can be seen the volumetric flow rate has a very significant effect on the temperature difference in the hot and cold sides of TEMs and obviously on the voltage and power generated by the TEMs.

4. Conclusions

The effect of different parameters such as temperature and volumetric flow rate in the cold and hot reservoirs, on power generation by four TEMs is investigated experimentally. A comparison between power generation for natural and force convection heat transfer in the cold side is also accomplished. The results show significant influence of using forced convection cooling on the power generation. Variation of the fan power or volumetric flow rate in the cold side at high fan speed does not affect the power generation by TEMs. Therefore, a lower fan speed and volumetric flow rate is recommended to net power. Average Seebeck coefficient of the is obtained by using $P_{max}-(\Delta T)^2$ curve. Finally, the significant effect of the volumetric flow rate of the hot gas on power generation by the TEMs is also studied. It is found that by increment in hot gas flow rate, the temperature difference across the TEMs enhances, and therefore the power generation increases noticeably.

Acknowledgements

The authors would like to acknowledge Center for Thermoelectric Energy Conversion funded in part by the Danish Council for Strategic Research, Programme Commission on Energy and Environment, under Grant No. 63607.

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