PERFORMANCE ANALYSIS OF A THERMOELECTRIC POWER GENERATOR UNDER VOLUMETRIC CONSTRAINT

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ABSTRACT

The efficiency of a thermoelectric power generator can be optimized through proper sizing of the device geometric configurations. In the present study, pin length optimization of the thermoelectric generator for a fixed total pin volume is carried out and the pin length maximizing the device efficiency is formulated. The influences of temperature ratio, defined as the upper junction temperature divided by the lower junction temperature, and the figure of merit, defined as $Z = \alpha^2/KR$, on the device efficiency and output power operating at the optimum pin length are examined. It is found that a unique temperature ratio exists which maximizes the efficiency of the thermoelectric device with the optimum pin length.

Keywords: thermoelectric generator; pin length; efficiency; power generation; volumetric constraint.

ANALYSE DU RENDEMENT DE PUISSANCE D'UN GÉNÉRATEUR D'ÉNERGIE THERMOÉLECTRIQUE SOUS CONTRAINTE VOLUMÉTRIQUE

RÉSUMÉ

L'efficacité d'un générateur d'énergie thermoélectrique peut être optimisée par le dimensionnement approprié des configurations géométriques du dispositif. Dans la présente étude, l'optimisation de la longueur de broche du générateur thermoélectrique pour un volume total fixe de broche et la longueur de la goupille sont mis en ouvre afin de maximiser l'efficacité du dispositif. Les effets du quotient de la température, définie comme la température de jonction supérieure divisée par la température de jonction inférieure, et le facteur de mérite, définis comme $Z = \alpha^2/KR$, sur l'efficacité de dispositif et la puissance de sortie fonctionnant à la longueur de la broche optimale, sont examinés. On constate qu'il existe un rapport unique de température qui maximise l'efficacité du dispositif thermoélectrique avec une longueur de broche optimale bien définie.

Mots-clés : générateur thermoélectrique; longueur de la broche; efficacité; production d'énergie; contrainte volumétrique.

NOMENCLATURE

A	area (m^2)
I	electrical current (A)
k	thermal conductivity (W/mK)
k_e	electrical conductivity (S/m)
K	overall thermal conductance of the thermoelectric generator (W/K)
L	length (height) of leg (m)
R	overall electrical resistance of the thermoelectric generator (Ω)
R_L	external load resistance (Ω)
T	temperature (K)
V	volume (m^3)
W	power output (W)
Z	figure of merit (1/K)
Greek symbols	
α	Seebeck coefficient
λ	dimensionless leg length (Eq. 12)
η	efficiency
θ	temperature ratio, T_2/T_1
Subscripts	
0	reference
1	high temperature side
2	low temperature side
n	n-type thermoelectric material
opt	optimum
p	p-type thermoelectric material

1. INTRODUCTION

Energy is extremely important for the industrial development and the daily activities of human on the earth. Because of the adverse consequences of the fossil fuel based systems on the environment, renewable energy systems have become increasingly attractive alternatives to conventional fossil fuel energy systems because they provide less harm to environment and better energy security [1]. Regardless of the source of the energy being renewable or non-renewable, it is important to utilize energy efficiently and reduce the waste heat as much as possible for long-term sustainability. Thermoelectric power generation systems are mainly used for waste heat recovery to improve the sustainability of the energy resources.

Thermoelectric power generation is one of the potential renewable energy resources for commercial applications. The thermoelectric conversion requires high and low temperature sources which are easily available in the domestic environment. However, the low efficiency of the device makes it unable to be used widely in domestic applications. The thermal efficiency of a thermoelectric generator is directly proportional to the figure of merit of the thermoelectric material which is defined as equal to the seebeck coefficient square divided by the thermal conductivity and the electrical resistivity of the material, $Z = \alpha^2/KR$, that has the unit $1/K$.

A thermoelectric power generator consists of p-n-type semiconductor pins and its efficiency depends on the dimensionless figure of merit (ZT_{ave}) associated with materials used in p and n-types of pins, operating temperatures, and geometric configurations of the pins. Considerable research studies were carried out to improve the figure of merit of the device [2–5]. Although progresses are substantial, still further improvement in the device figure of merit is necessary for the efficient operation. However, study into optimization of the device geometry is limited [6–8] and further analysis in this direction is necessary. Consequently, the optimum length of thermoelectric device pins for various operating temperatures and type of thermoelectric material (i.e. the figure of merit) is the subject of the present study.

A considerable research study was carried out to examine thermodynamics aspects of the thermoelectric devices. A thermoelectric generator with multiple-irreversibilities was investigated by Meng et al. [9]. They analyzed the effects of external irreversibilities on the performance of the thermoelectric generator through comparing irreversible model with the exo-reversible model. Constructal design of a thermoelectric device was carried out by Pramanic and Das [10]. They indicated that the choice of constancy of total conductance was not only a natural constraint but also a purely realistic design criterion for thermoelectric devices. Investigation into topping cycle including the thermoelectric generator was carried out by Sahin et al. [11]. They showed that for a certain combination of operating and thermoelectric device parameters, thermal efficiency of the topping cycle became slightly higher than that of the same system without the presence of the thermoelectric generators. Thermoelectric device and optimum external load parameter and slenderness ratio were studied by Yilbas and Sahin [12]. The findings revealed that for a fixed thermal conductivity ratio, the external load parameter increased with increasing slenderness ratio while the electrical conductivity ratio of the p and n pins in the device reduced. An integrated assessment of energy conversion processes was carried out by Tonon et al. [13]. They developed suitable performance indicators for the thermoelectric devices. The optimization study on low-temperature waste heat thermoelectric generator system was carried out by Guo et al. [14]. They indicated that in addition to increasing waste heat temperature and thermoelectric modules in series, expanding the heat sink surface area in a proper range and enhancing the cold side heat transfer capacity could enhance the performance of the thermoelectric system. The analytical model for parallel thermoelectric generators was introduced by Liang et al. [15]. Their findings revealed that the existence of contact resistance contributed to thermoelectric module's internal resistance loading to decrease the device output power. Performance optimization for two-stage thermoelectric refrigerator system driven by two-stage thermoelectric generator was carried out by Meng et al. [16]. They presented the analytical formulae for the stable working electrical current and the coefficient of performance (COP). A solar thermoelectric generator for micro-power applications was investigated by Amatya et al. [17]. A thermodynamic analysis was presented for predicting the thermal-to-electrical conversion efficiency for the generator. High energy density thermoelectric generators were studied by Miodushevsky [18]. He demonstrated the characteristics of two-stage converter consisting of thermoelectric device and the combustor. A thermoelectric analysis of a thermoelectric device was carried out by Kassas [19]. The findings revealed that the second law efficiency increased with emitter to collector temperature ratio and reduced with increasing collector temperature owing to increase in collector current flow. Energy transport in one-dimensional thermoelectric systems was presented by Chao and Larsson [20]. They indicated that a one-dimensional approach was not sufficient to design a complete thermoelectric device. The evaluation of system configurations for thermoelectric power generation was carried out by De Bock et al. [21]. They showed that device performance could be expressed as a function of the figure of merit and thermal system performance metrics such as efficiency and power output.

Thermoelectric generators are one of the potential candidates for direct energy conversion from waste heat sources to electricity. Although the device size is small, due to the low power output of a single device, multiple devices in series or parallel are used to generate sufficient energy meeting the requirements in some of the practical applications [6–8]. This implies the minimization of the device size while meeting the power requirements. One of the challenges in such a consideration is to introduce the device volumetric constraint in the thermodynamics analysis identifying the device performance in terms of the maximum efficiency and the device output power. Although thermodynamic fundamentals of thermoelectric generators are well stated in the open literature [10–19], the volumetric constraint associated with the device configuration such as device pin geometry was not adequately addressed in details earlier. Therefore, in the present study, the

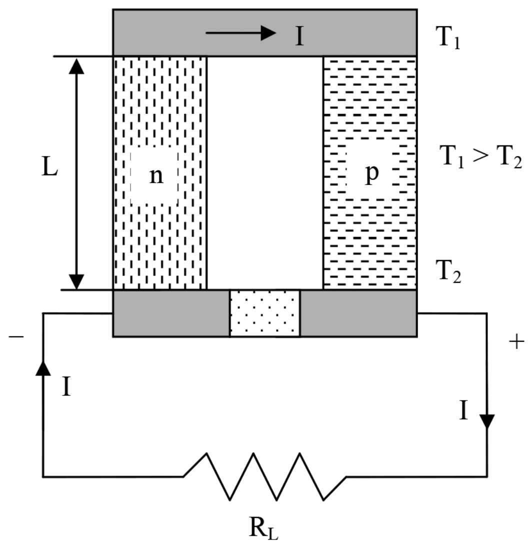

Fig. 1. Schematic view of thermoelectric power generator.

performance of thermoelectric power generator under volumetric constraint is examined. Thermodynamic analysis in relation to the optimum dimensionless pin length maximizing the device efficiency is presented. The present study focuses on thermodynamics aspects of the thermoelectric power generator.

2. THERMODYNAMIC ANALYSIS

A typical thermoelectric generator is shown in Fig. 1. The efficiency of a thermoelectric power generator with geometrically identical legs shown in Fig. 1 is given as [12]

$$\eta = \frac{I^2 R_L}{\alpha I T_1 + K(T_1 - T_2) - \frac{1}{2} I^2 R}, \tag{1}$$

where

$$K = \frac{A}{L}(k_p + k_n) \tag{2}$$

is the thermal conductivity and

$$R = \frac{L}{A}\left(\frac{1}{k_{e,p}} + \frac{1}{k_{e,n}}\right) \tag{3}$$

is the electrical resistivity of the thermoelectric generator.

In many engineering applications, the volume constraints may need to be taken into consideration in order to limit the size, the weight, or even the cost of the thermoelectric device. Thus, let us consider the volume constraint such that the total volume of the thermoelectric material used in the thermoelectric generator is constant, i.e.

$$AL = V_0 = \text{ const.} \tag{4}$$

Then the thermal conductivity and the electrical resistivity can be written as, respectively,

$$K = \frac{V_0}{L^2}(k_p + k_n) \tag{5}$$

and

$$R = \frac{L^2}{V_0}\left(\frac{1}{k_{e,p}} + \frac{1}{k_{e,n}}\right). \tag{6}$$

On the other hand, the current I is a function of the Seebeck coefficient $\alpha = \alpha_p - \alpha_n$, the upper and lower junction temperatures (T_1 and T_2), the electrical resistance R and the external load resistance R_l as

$$I = \frac{\alpha(T_1 - T_2)}{R_L + R}, \tag{7}$$

Substituting Eq. (7) into Eq. (1) the efficiency becomes

$$\eta = \frac{\alpha^2(T_1 - T_2)R_L}{K(R_L + R)^2 + \alpha^2 T_1(R_L + R) - \frac{1}{2}\alpha^2(T_1 - T_2)R}. \tag{8}$$

The terms in Eq. (8) can be written in dimensionless form as

$$\eta = \frac{ZT_2(\theta - 1)\lambda^2}{(1+\lambda^2)^2 + ZT_2\left[\lambda^2\theta + \lambda^4\left(\frac{\theta+1}{2}\right)\right]}, \tag{9}$$

where the dimensionless figure of merit ZT_2 is defined in terms of the seebeck coefficient, thermal conductivity, the electrical resistivity and lower junction temperature as

$$ZT_2 = \frac{\alpha^2}{KR}T_2 = \frac{\alpha^2}{(k_p + k_n)\left[\frac{1}{k_{e,p}} + \frac{1}{k_{e,n}}\right]}T_2 \tag{10}$$

the dimensionless temperature θ is

$$\theta = \frac{T_1}{T_2} \tag{11}$$

and the dimensionless leg length of the thermoelectric device λ is defined as

$$\lambda = \frac{L}{L_o} = \sqrt{\frac{R}{R_L}} \tag{12}$$

in which the characteristic length L_o is given by

$$L_o = \sqrt{\frac{V_o R_L}{\left(\frac{1}{k_{e,p}} + \frac{1}{k_{e,n}}\right)}}. \tag{13}$$

On the other hand, the power generation from the thermoelectric power generator is given as

$$\dot{W} = I^2 R_L = \frac{\alpha^2(T_1 - T_2)^2}{(R_L + R)^2}R_L. \tag{14}$$

Using the same dimensionless parameters as defined above, the power generation given in Eq. (14) can be written in dimensionless form as

$$\frac{\dot{W}}{\left(\frac{RK}{R_L}\right)T_2} = \frac{(\theta - 1)^2 ZT_2}{(1+\lambda^2)^2}. \tag{15}$$

It should be noted that RK in Eq. (15) is independent of the length L.

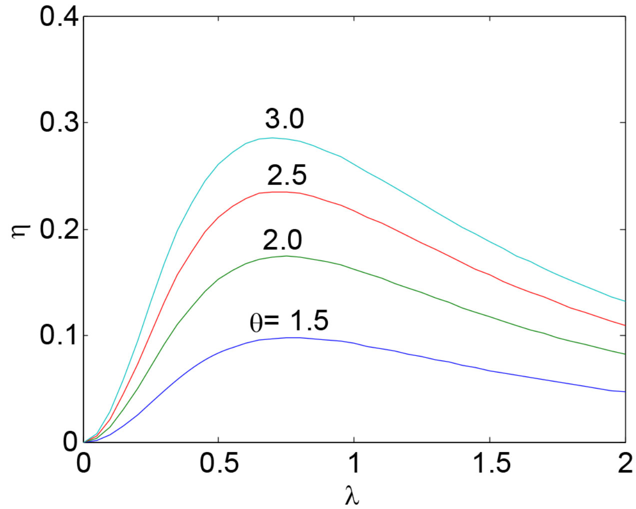

Fig. 2. Efficiency of thermoelectric generator as function of dimensionless length of legs for various dimensionless temperatures ($ZT_2 = 1.5$).

The optimum length that maximizes the efficiency given in Eq. (9) under the volumetric constraint given in Eq. (4) can be obtained by differentiating Eq. (9) with respect to λ and setting equal to zero, i.e.

$$\frac{\partial \eta}{\partial \lambda} = 0. \tag{16}$$

Performing this differentiation, it can be shown that the optimum dimensionless length that optimizes (maximizes) the efficiency is obtained to be

$$\lambda_{\text{opt}} = \left[\frac{2}{ZT_2(\theta+1)+2}\right]^{0.25}. \tag{17}$$

This optimum length of the thermoelectric power generator leg provides the maximum thermal efficiency under the volumetric constraint given in Eq. (4). The maximum thermal efficiency corresponding to this optimum dimensionless length becomes

$$\eta_{\max} = \frac{ZT_2(\theta-1)}{2\sqrt{ZT_2\left(\frac{\theta+1}{2}\right)+1} + ZT_2\theta + 2}. \tag{18}$$

3. RESULTS AND DISCUSSION

The performance analysis of thermoelectric device is carried out under volumetric constraint. The device efficiency maximizing the output power is presented and the optimum pin length maximizing the device efficiency is formulated.

Figure 2 shows thermoelectric efficiency with dimensionless pin length (λ) for different dimensionless temperature ratios. Thermoelectric efficiency increases with increasing λ for $0 \leq \lambda \leq 0.6$ and reaches its peak value at around $0.55 \leq \lambda \leq 0.65$ depending on the temperature ratio. The maximum efficiency occurs at $\lambda \cong 0.5$ for the temperature ratio $\theta = 0.2$. This is associated with Eq. (9), where the efficiency is a non-linear function of the parameters θ and λ.

The efficiency behavior indicates that reducing the pin length and temperature ratio, the efficiency increases and becomes the maximum at which the pin length becomes optimum. Since the optimum pin length

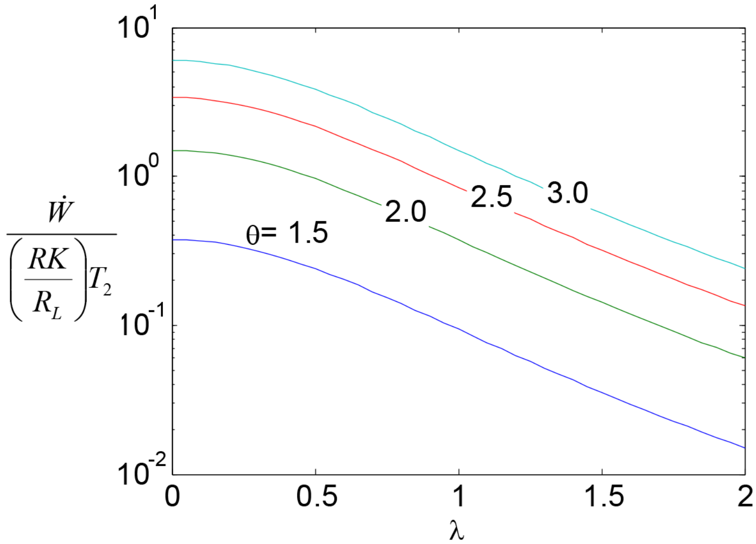

Fig. 3. The variation of the power generation as a function of dimensionless length of legs for various dimensionless temperatures ($ZT_2 = 1.5$).

maximizing the efficiency changes with temperature ratio, operating parameters of the thermoelectric device such as temperature ratio influences the optimum design parameters of the device. Consequently, a unique optimum design is not possible for the pin length, which maximizes the efficiency, since the optimum length of pins depends on the operating temperatures and the figure of merit of the thermoelectric material used. Moreover, increasing the pin length from its optimum value reduces the efficiency for all temperature ratios. This suggests that pin length should be kept around the optimum values, regardless of temperature ratio, when designing the device. Although changing the operating conditions of the device, such as temperature ratio, influences the efficiency, the selection of $0.55 \leq \lambda \leq 0.65$ results in higher efficiency than other pin lengths.

Figure 3 shows dimensionless device output power with dimensionless pin length for different temperature ratios. The output power increases with reducing pin length, which is more pronounced for low values of temperature ratio. This is because of the inverse relation between the output power and the pin length (Eq. 15). This indicates that smaller the pin length higher the output power of the device. However, device efficiency, possibly, may not be kept at maximum for all the time. Consequently, operating the device at its maximum output power does not satisfy the maximum efficiency of the device always. In addition, the operating conditions such as temperature ratio influences significantly the device output power. Therefore, the operating small pin length thermoelectric device at a low temperature ratio provides an improved output power with a reasonably high efficiency.

Figure 4 shows a variation of maximum device efficiency and the optimum pin length with temperature ratio for various temperature ratios. It should be noted that the maximum efficiency is obtained through maximizing the efficiency with temperature ratio while the optimum pin length corresponds to the maximum efficiency, which changes with temperature ratio. The maximum efficiency reduces with increasing temperature ratio; however, the optimum pin length increases with an increasing temperature ratio. The increase in the optimum pin length at low temperature ratios $0.2 \leq \theta$ is sharp resulting in a large change in the optimum length. As the temperature ratio increases further, the change in the optimum length becomes small. Consequently, the maximum efficiency of the thermoelectric device optimizing the pin length is sensitive to operating temperature ratio for devices with small optimal pin lengths. In addition, the max-

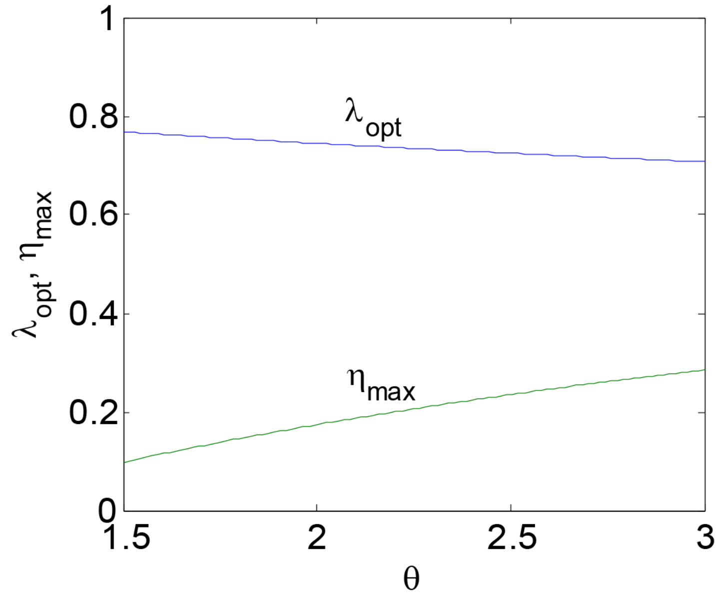

Fig. 4. The optimum length and the corresponding maximum efficiency as function of the dimensionless temperature ($ZT_2 = 1.5$).

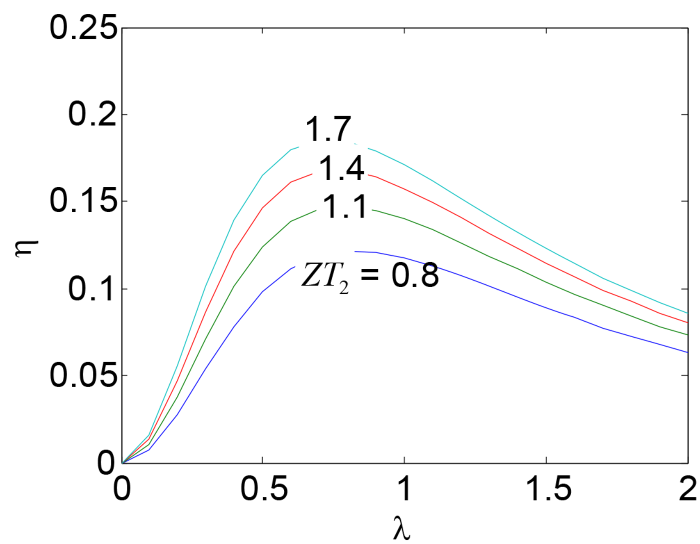

Fig. 5. Efficiency of thermoelectric generator as function of dimensionless length of legs for various values of figure of merit ($\theta = 2$).

imum efficiency of the device reduces almost at a same rate with increasing temperature ratio. Therefore, operating the device at a low temperature ratio improves the maximum efficiency, which is particularly true for small optimal pin length devices. Moreover, there is a point where the maximum efficiency and the optimum pin length co-existed. Consequently, the thermoelectric device designed for optimum pin-length can operate at a unique temperature ratio at which the efficiency of the device is maximum. Therefore, operational conditions for the thermoelectric device plays an important role in the attainment of the maximum efficiency.

Table 1. The optimum length and the maximum efficiency for various values of figure of merit ($\theta = 2$).

ZT_2	λ_{opt}	η_{max}
0.8000	0.8211	0.1218
0.9000	0.8077	0.1311
1.0000	0.7953	0.1396
1.1000	0.7838	0.1475
1.2000	0.7731	0.1549
1.3000	0.7630	0.1618
1.4000	0.7536	0.1682
1.5000	0.7448	0.1743
1.6000	0.7364	0.1800
1.7000	0.7285	0.1854
1.8000	0.7210	0.1905

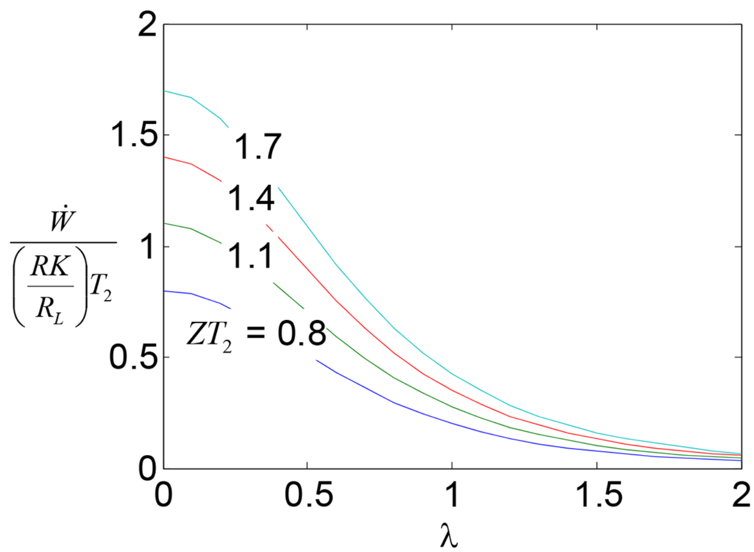

Fig. 6. The variation of the dimensionless power generation as function of dimensionless length of legs for various values of figure of merit ($\theta = 2$).

Figure 5 shows variation of efficiency with dimensionless pin length for different values of the figure of merit while Table 1 gives maximum efficiency and the optimum pin length for various values of figure of merit. The efficiency is maximum for the values of dimensionless pin length $\lambda < 1$. This indicates that the external load resistance (RL) must be less than the overall resistance of the device (R) for improved efficiency. This is true for all values of the figure of merit considered. Increase in the efficiency with the dimensionless pin length is sharper for the values $\lambda < 1$ as compared to those values corresponding to $\lambda > 1$. This suggests that the small change in the pin length results in large change in the efficiency for $\lambda < 1$. However, this change becomes gradual for $\lambda > 1$. Increasing the figure of merit enhances the efficiency of the device, which is more pronounced for the dimensionless pin length $0.5 \leq \lambda \leq 1.5$. Consequently, the influence of the figure of merit becomes most significant on the efficiency for the device designed to operate at the optimum dimensionless pin length.

Figure 6 shows dimensionless power generation with the dimensionless pin length for different figure of merit. The influence of figure of merit on the dimensionless power generation becomes significant for small

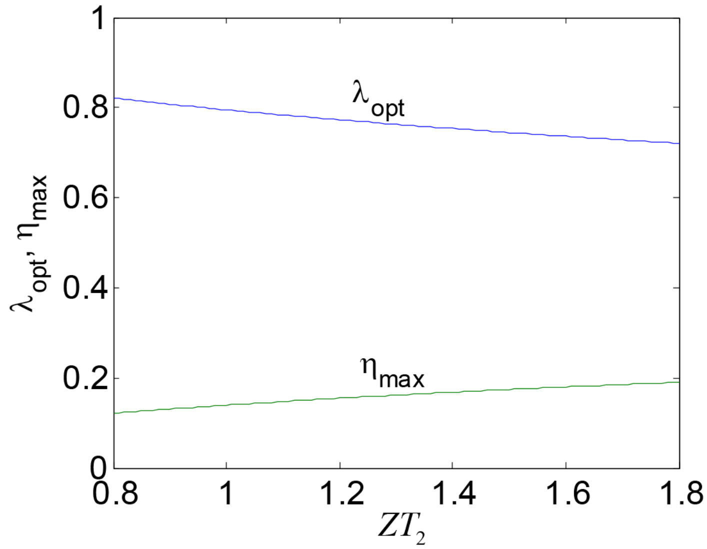

Fig. 7. The optimum length and the corresponding maximum efficiency as function of the figure of merit ($\theta = 2$).

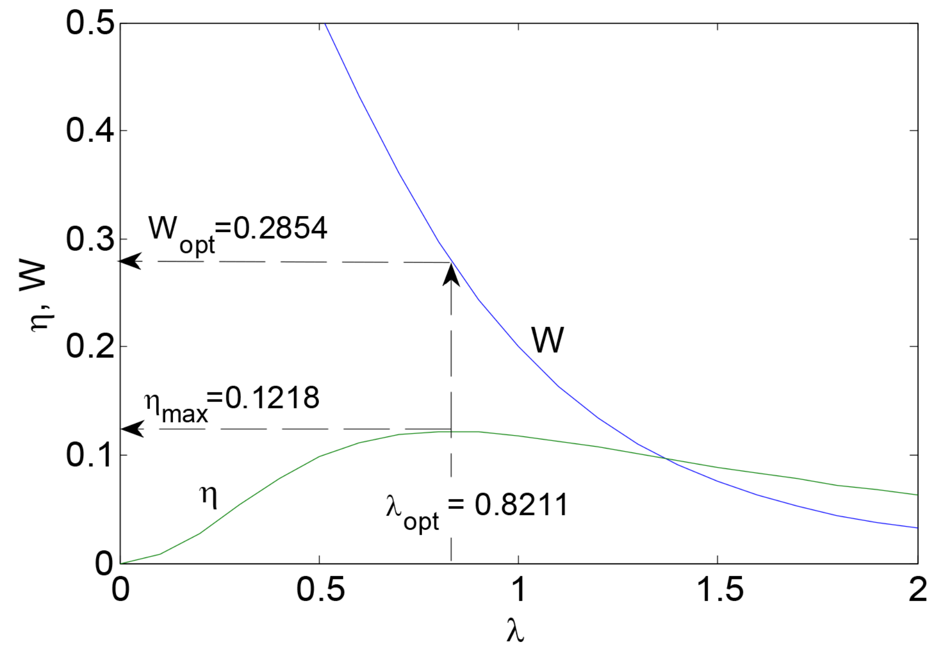

Fig. 8. Optimum dimensionless length of legs of Bi_2Te_3 ($ZT_2 = 0.8$) thermoelectric generator and the corresponding values of the efficiency and the dimensionless power generation for dimensionless temperature of $\theta = 2$. W in this figure stands for the dimensionless power output given as $\frac{\dot{W}}{\left(\frac{RK}{R_L}\right)T_2}$.

dimensionless pin length. This indicates that the maximum efficiency based on the optimum dimensionless pin length does not result in the maximum device power generation. Moreover, the device dimensionless output power reduces notably when the dimensionless pin length approaches to 1 at which the device efficiency reaches almost its peak value. This situation is also seen from Fig. 7, in which the optimum dimensionless pin length and the maximum efficiency are plotted with the figure of merit. It is evident that

Table 2. Values of thermoelectric properties for Bi_2Te_3 from literature.

Fabrication method	Seebeck	Resistivity	Figure of Merit (ZT)
	(μV/°C)	(μΩm)	300 K
Co-evaporation [22]	–189	7.7	0.93
Co-Sputtering [23]	–160	16.3	0.31
Metalorganic Chemical Vapor Deposition (MOCVD) [24]	–210	9.0	0.98
Co-evaporation [25]	–228	13	0.80
Electrochemical Deposition (ECD) [26]	–60	10	0.07
Flash evaporation [27]	–200	15	0.53
Cu I added (patent) [28]	–220	8.3	0.69

increasing figure of merit results in increasing maximum efficiency. In this case, optimum dimensionless pin length reduces. Moreover, the reduction in the pin length and increase in the maximum efficiency with increasing figure of merit are not significantly large.

Figure 8 shows variation of efficiency and the power out of the thermoelectric generator with dimensionless length of legs (λ). The average values of the data presented in Table 2 are used to plot Fig. 8. Since the maximum efficiency and the maximum power output do not correspond to the same value of "λ", the optimum value of "λ" maximizing the efficiency is considered as the λ_{opt}. It is evident that using the data from Table 2 for Bi_2Te_3 thermoelectric generator, the optimum dimensionless length of legs λ_{opt} is 0.8212; in which case, the maximum thermal efficiency of the device $\eta_{max} = 0.1218$ and the corresponding optimum output power is $W_{opt} = 0.2854$. It should be noted that increasing λ beyond its optimum value, efficiency and the device power output reduces. Thermoelectric power generator can operate up to the maximum hot junction temperature, which is 523 K for Bi_2Te_3.

4. CONCLUSIONS

Thermal analysis of thermoelectric device is carried out and pin length maximizing the device efficiency under volumetric constraint is formulated. The influence of temperature ratio on the maximum efficiency and the thermoelectric power output are examined. It is found that the device efficiency increases for certain values of pin length (λ) and becomes the maximum for $0.55 \leq \lambda \leq 0.65$ depending on the temperature ratio (θ). Further increase in the pin length lowers the efficiency, which is more pronounced for high temperature ratios. Thermoelectric device output power increases with reducing pin length, which is particularly true for high temperature ratios. However, further reduction in pin length lowers the thermal efficiency of the device. There exists a unique temperature ratio for the optimum pin length at which the device operate at the maximum efficiency. Consequently, operating the device with optimum pin length at certain temperature ratio, device output power as well as the efficiency improves considerably.

The dimensionless power generation is influenced by the figure of merit significantly for small dimensionless pin length. This means that the optimum dimensionless pin length that yields maximum efficiency does not result in the maximum device power generation. On the other hand, the device dimensionless output power decreases considerably when the dimensionless pin length approaches to 1 for which the device efficiency reaches almost its maximum. Increasing figure of merit results in increasing maximum efficiency and, in this case, optimum dimensionless pin length decreases.

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REFERENCES

1. Dincer, I. and Zamfirencu, C., *Advanced Power Generation Systems*, Elsevier, MA, USA, 2014.
2. Müller, K.H., "Thermoelectric figure of merit of a hybrid material", in *Proceedings of ICT'07 – 26th International Conference on Thermoelectrics*, pp. 353–356, 2007.
3. Wang, C.H., Chen, Y. and Huang, J., "Thermal and electrical mechanism of thermoelectric generation chip and its performances in solar energy thermal power system", *Energy Education Science and Technology Part A: Energy Science and Research*, Vol. 28, No. 1, pp. 331–338, 2011.
4. Ren, Z.F., Poudel, B., Ma, Y., Hao, Q., Lan, Y.C. and Minnich, A., "Enhancement of thermoelectric figure-of-merit by a nanostructure approach", *Materials Research Society Symposium Proceedings*, Vol. 1166, pp. 83–93, 2009.
5. Takeuchi, T., "Conditions of electronic structure to obtain large dimensionless figure of merit for developing practical thermoelectric materials", *Materials Transactions*, Vol. 50, No. 10, pp. 2359–2365, 2009.
6. Hodes, M., "Optimal pellet geometries for thermoelectric power generation", *IEEE Transactions on Components and Packaging Technologies*, Vol. 33, No. 2, pp. 307–318, 2010.
7. Lavric, E.D., "Sensitivity analysis of thermoelectric module performance with respect to geometry", *Chemical Engineering Transactions*, Vol. 21, pp. 133–138, 2010.
8. Fujii, T., Fukuda, S., Emoto, M., Osada, K., Kawahara, T. and Hamabe, M., "Thermoelectric property dependence and geometry optimization of peltier current leads using highly electrically conductive thermoelectric materials", *Journal of Electronic Materials*, Vol. 40, No. 5, pp. 691–695, 2011.
9. Riffat, S.B. and Ma, X., "Improving the coefficient of performance of thermoelectric cooling systems: a review", *International Journal of Energy Research*, Vol. 28, No. 9, pp. 753–768, 2004.
10. Pramanick, A.K. and Das, P.K., "Constructal design of a thermoelectric device", *International Journal of Heat and Mass Transfer*, Vol. 49, No. 7–8, pp. 1420–1429, 2006.
11. Sahin, A.Z., Yilbas, B.S., Shuja, S.Z. and Momin, O., "Investigation into topping cycle: Thermal efficiency with and without presence of thermoelectric generator", *Energy*, Vol. 36, No. 7, pp. 4048–4054, 2011.
12. Sahin, A.Z. and Yilbas, B.S., "The influence of operating and device parameters on the maximum efficiency and the maximum output power of thermoelectric generator", *International Journal of Energy Research*, Vol. 36, pp. 111–119, 2012.
13. Yilbas, B.S. and Sahin, A.Z., "Thermoelectric device and optimum external load parameter and slenderness ratio", *Energy*, Vol. 35, pp. 5380–5384, 2010.
14. Guo, X., Xiao, H. and Yang, S., "Modeling, experimental study and optimization on low-temperature waste heat thermoelectric generator system", *Applied Energy*, Vol. 87, pp. 3131–3136, 2010.
15. Liang, G., Zhou, J. and Huang, X., "Analytical model of parallel thermoelectric generator", *Applied Energy*, Vol. 88, No. 12, pp. 5193–5199, 2011.
16. Meng, F., Chen, L. and Sun, F., "A numerical model and comparative investigation of a thermoelectric generator with multi-irreversibilities", *Energy*, Vol. 36, No. 5, pp. 3513–3522, 2011.
17. Amatya, R. and Ram R.J., "Solar thermoelectric generator for micropower applications", *Journal of Electronic Materials*, Vol. 39, pp. 1735–1740, 2010.
18. Miodushevsky, P., "High energy density thermoelectric generators", in *Proceedings 6th International Energy Conversion Engineering Conference, IECEC 2008*.
19. Kassas, M., "Thermodynamic analysis of a thermoelectric device", *International Journal of Exergy*, Vol. 4, No. 2, pp. 168–179, 2007.
20. Chao, K.A. and Larsson, M., "Energy transport in one-dimensional thermoelectric systems", *Solid State Communications*, Vol. 139, No. 9, pp. 490–492, 2006.
21. De Bock, H., Peter, J. and Novak, V., "Evaluation of system configurations for thermoelectric power generation", in *Proceedings 11th IEEE Intersociety Conference on Thermal and Thermomechanical Phenomena in Electronic Systems, I-THERM 2008*, pp. 1276–1282, 2008.
22. Goncalves, L.M., Couto, C., Alpuim, P., Rowe, D.M. and Correia, J.H., "Thermoelectric Properties of Bi_2Te_3/Sb_2Te_3 Thin Films", *Materials Science Forum*, Vol. 514–516, pp. 156–160, 2006.

23. Böttner, H., Nurnus, J., Gavrikov, A., Kühner, G., Jägle, M., Künzel, C., Eberhard, D., Plescher, G., Schubert, A. and Schlereth, K.H., "New Thermoelectric Components Using Microsystem Technologies", *Journal of Microelectromechanical Systems*, Vol. 3, p. 414, 2004.
24. Giani, A., Boulouz, A., Pascal-Delannoy, F., Foucaran, A., Charles, E. and Boyer, A., "Growth of Bi_2Te_3 and Sb_2Te_3 thin films by MOCVD", *Materials Science and Engineering*, Vol. B64, pp. 19–24, 1999.
25. Zou, H., Rowe, D.M. and Williams, S.G.K., "Peltier effect in a co-evaporated Sb_2Te_3(P)– Bi_2Te_3(N) thin film thermocouple", *Thin Solid Films*, Vol. 408, p. 270, 2002.
26. Lim, J.R., Snyder, G.J., Huang, C.K., Herman, J.A., Ryanand, M.A. and Fleurial, J.P. "Thermoelectric microdevice fabrication process and evaluation at the Jet Propulsion Laboratory", in *Proceedings ICT2002*, 2002.
27. Foucaran, A., "Flash evaporated layers of (Bi_2Te_3-Bi_2Se_3)(N) and (Bi_2Te_3-Sb_2Te_3)(P)", *Materials Science and Engineering*, Vol. B52, pp. 154–161, 1998.
28. Sclar, N., "Thermoelectric infrared detector array", US Patent No. 4,558,342, 1985.