ISSN 2004-2965 Energy Proceedings, Vol. 18, 2021

International Conference on Applied Energy 2021
Nov. 29 - Dec. 2, 2021, Thailand/Virtual
Paper ID: 091

Solar Energy Conversion Using a Thermoelectric Generator with Conical Frustum Shaped Pins

Ramesh Kumar [1], Ravita Lamba [2*], Chika Maduabuchi [3*], Manish Vashishtha [1], Sushant Upadhyaya [1]

1 Department of Chemical Engineering, Malaviya National Institute of Technology Jaipur, India

2 Department of Electrical Engineering, Malaviya National Institute of Technology Jaipur, India

3 Department of Mechanical Engineering, University of Nigeria, Nsukka, Nigeria

ABSTRACT

Waste heat is inevitable in any human endeavour. Thus, the need to develop thermal energy conversion systems. Thermoelectric generators (TEGs) are solid-state devices that convert waste heat to useful electricity. They have found various applications in converting solar energy to electricity, harvesting exhaust waste heat in automobiles and power plants and providing power for spacecrafts by converting the heat released during radioactive decay to electricity. Despite these perks, they are characterised by very low efficiencies. Thus, several efficiency enhancement strategies such as material modification and leg geometry alteration have been introduced. Pertaining the latter, the trapezoidal shaped geometry has been studied extensively. Although it offers a higher efficiency compared to the conventional rectangular leg geometry, it still exhibits higher thermal stresses and consequently, a reduced lifespan. A conical frustum shaped TE pin has not been conceived yet. The investigation of this leg geometry is important since it might provide a higher efficiency and operating lifetime compared to the current trapezoidal leg. Thus, a thoroughly validated numerical model is used in evaluating the performance of three TEGs comprising rectangular, trapezoidal and conical frustum shaped TE legs. Results indicate that the proposed conical frustum leg TEG enhances the power density and exergy efficiency of the trapezoidal device by 20% and 23%, respectively. Also, the thermal stress and thermodynamic irreversibilities of the trapezoidal leg TEG are reduced by 2% and 0.5%, respectively.

Keywords: conical frustum, solar thermoelectric generator, heat transfer analysis, exergy efficiency, thermal stress, thermodynamic stability.

1. INTRODUCTION

Amongst all renewable energy sources, solar energy stands out as the mother source [1]. This is due to its global accessibility and inexhaustibility [2]. The two methods of converting solar energy to electricity is either through light (photovoltaics) [3] or heat (thermal-electric) [4]. Since the thermal energy component of the solar spectrum is very high [5], more potential abound in thermal-electric systems. However, solar power generation is dominated by photovoltaic. Thus, research targeted at exploring more efficient solar thermal-electric systems is greatly needed [6].

An example of a thermal-electric conversion device is a thermoelectric generator (TEG). TEGs are capable of converting thermal energy directly to electricity without requiring any intermediary electromechanical conversion system. This is made possible by the Seebeck effect [7]. They offer such lucrative merits compared to other renewable energy conversion devices such as: [8]. However, owing to material limitations, they are still limited by relatively low efficiencies of 5% [9]. In order for them to match up with the conventional fossil-fuel sources, much explorative studies on improving the device efficiency are needed. Over the years, various performance improvement methodologies have been proposed [10,11] and [12,13]. While these techniques were beneficial in slightly improving device performance, it was further shown that they were relatively expensive and increased system complexity [14,15].

* Corresponding author
Email addresses: chika.maduabuchi.191341@unn.edu.ng, ravitalamba.lamba247@gmail.com

Hence, in this paper, we seek to investigate the TE leg geometry configuration. This is a method that was thoroughly explored and has proven to be very effective, performance and cost wise [16,17].

The majority of literature shows that altering the geometry of traditional rectangular legs resulted in notable performance improvement. However, majority of these papers used isothermal boundary conditions and concluded that the trapezoidal TE leg provided the least thermal stresses [18]. However, few recent papers have shown that the constant heat flux boundary condition is more accurate in the analysis of trapezoidal leg TEGs [16,17]. The use of this boundary condition will definitely result in some modification in the previous results on the low thermal stresses of trapezoidal shaped TE legs. Furthermore, a conical frustum shaped TE leg has not been conceived. The study of this geometry becomes necessary since the optimum trapezoidal shaped TE pin might turn out to have a higher thermal stress relative to the rectangular leg geometry.

To answer these questions, a validated three-dimensional numerical model of a rectangular, trapezoidal and conical frustum shaped TE legs is developed. By doing this, we seek to investigate the thermal response of a trapezoidal shaped TE leg when exposed to constant heat instead of temperature boundary condition. We would also study the thermal stresses generated in the pins. True to our predictions, we found that the trapezoidal leg geometry generated a higher thermal stress than the conventional rectangular shaped TE pins. This means that it will have a short lifespan relative to the rectangular leg. However, we try to solve this problem by introducing a conical frustum TE leg which improves the thermodynamic and mechanical performance of the trapezoidal TE leg by 23% and 2%, respectively.

2. METHODOLOGY

2.1 Materials and Methods

To determine the magnitude of the performance enhancement provided by the conical frustum TE leg, three models are developed comprising the traditional rectangular, trapezoidal and conical frustum leg geometries. These are represented by models 1 to 3, as shown in Figs. 1a – c, respectively.

The thermoelectric pins are made of pure bismuth telluride. The temperature dependent properties of bismuth-telluride are obtained from refs. [19,20]. Additionally, the properties of other materials, such as the ceramic plates, copper electrodes and solder paste, are sourced from refs. [21,22].

The finite element solver used during the simulation was the commercial ANSYS 2020 R2 software. A three-dimensional computer aided design model was developed and imported to ANSYS workbench. A validated coupled thermal, electric and structural solver was incorporated. The boundary conditions applied to the developed model were gotten from refs. [23,24].

The results obtained are validated with the reports of ref. [25]. A relative error of ±1.3% was obtained. Thus, declaring the numerical model accurate.

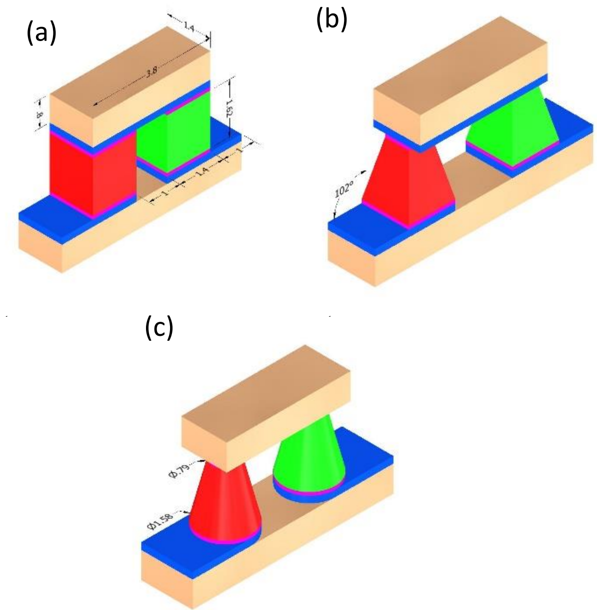

Fig. 1. Proposed Models. (a) Model 1 (b) Model 2 (c) Model 3.

2.2 Theory

A The steady-state coupled thermal-electric field equations used by ANSYS in determining the thermal and electrical distributions in the TE legs are [26,27]

$$\vec{\nabla}.\left(k\vec{\nabla}T\right)+J^2\rho-\tau\vec{J}.\vec{\nabla}T=0 \tag{1}$$

$$\vec{\nabla}.\left(\frac{1}{\rho}\vec{\nabla}\phi\right)+\vec{\nabla}.\left(\alpha\vec{\nabla}T\right)=0 \tag{2}$$

where α , ρ , k and τ are the temperature dependent Seebeck coefficient, electrical resistivity, thermal -conductivity and Thomson coefficient, respectively. $\vec{J}$ is the current density vector. ϕ is the scalar potential of the electric field.

$$P_{te}=I^2R \tag{3}$$

where P_{te} is TEG power output. R is the external load resistance.

Hence, the energy efficiency of the TEG becomes

$$\eta_{en} = \frac{P_{te}}{Q_f} \tag{4}$$

where Q_f is the concentrated solar flux incident on the TEG hot junction.

Finally, the exergy efficiency is evaluated using

$$\eta_{ex} = \frac{P_{te}}{Ex_f} \tag{5}$$

where Ex_f is the exergy inflow which is evaluated using the Petela's theory of solar radiation [28,29].

3. RESULTS AND DISCUSSION

3.1 Validation

The numerical model employed in this study is thoroughly validated by using it to reproduce the results of an experimental study on variable area thermoelectric generators. The results of this experimental validation are clearly portrayed in Fig. 2. A maximum error of 0.01% exists between the numerical and experimental results, hence, declaring the present numerical model accurate and reliable.

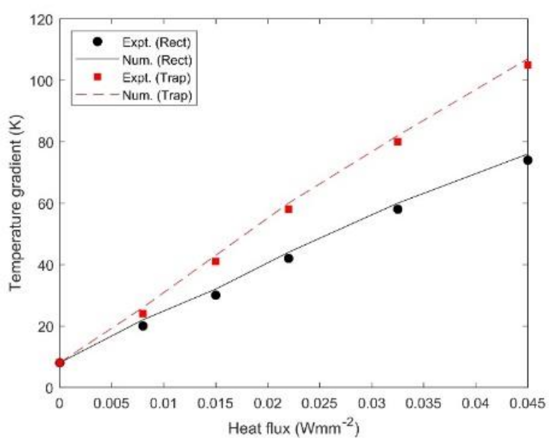

Fig. 2. Validation of TEG's numerical model using experimental data [30]

3.2 Effects of optical concentration ratio

The optical concentration of the solar concentrator affects the overall performance of the solar TEG (STEG). This is because an increased amount of solar radiation incident on the TEG hot junction implies a larger temperature gradient. Hence, a higher efficiency.

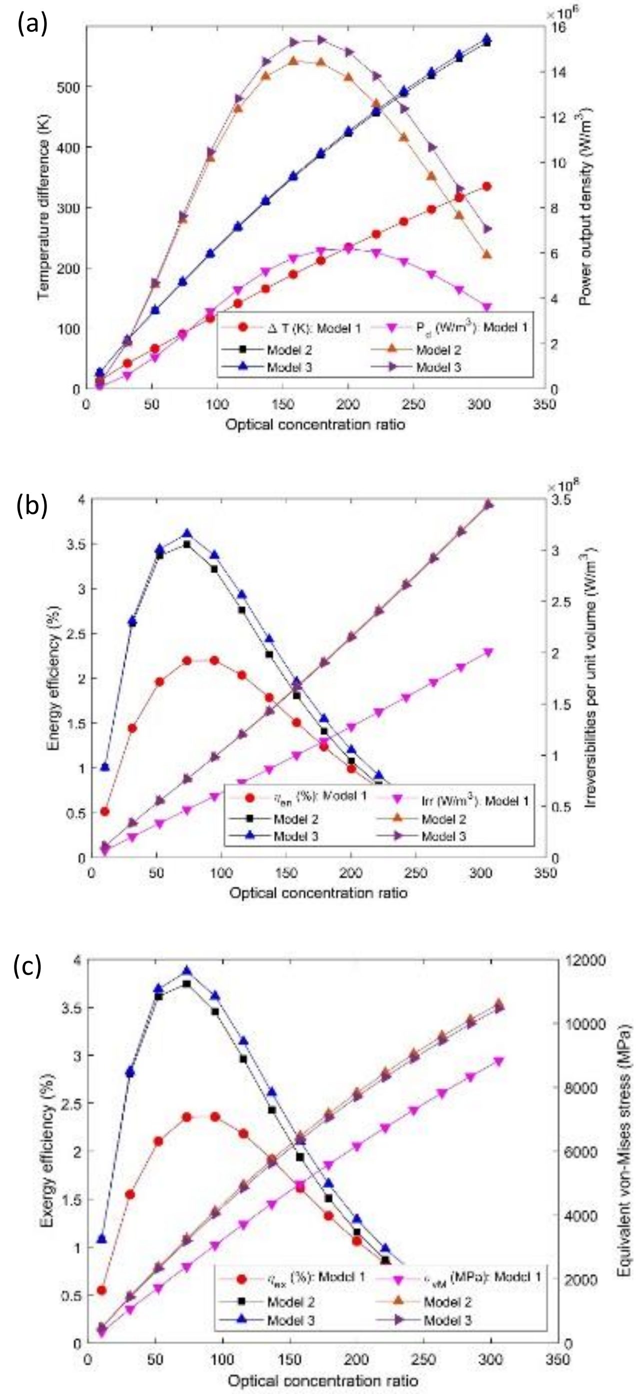

Fig. 3. Effect of optical concentration ratio on
(a) Temperature gradient and power output density
(b) Energy efficiency and irreversibilites per unit volume
(c) Exergy efficiency and equivalent von-Mises stress.

This relationship is clearly captured in Fig. 3a. The plot shows that the temperature gradient maintained across the TEG hot and cold junctions increases linearly with the optical concentration ratio. Also, for the same concentration ratio, model 3 generates the highest temperature gradient, with its increase relative to model

2 becoming more pronounced at high optical concertation. This is because of the higher thermal conductance offered by the conical frustum shaped TE legs relative to the trapezoidal shaped legs.

In addition, the behaviour of the power density and energy/exergy efficiencies is depicted in Figs. 3a, b and c. These parameters first increase with increasing optical concentration up to a certain maximum value, before decreasing with further increase in the concentration ratio. This is due to the decline in the properties of bismuth-telluride beyond the optimum temperature.

It is also seen that model 3 is more suitable for concentrated solar flux magnitudes. This is because, as the concentration ratio increases, it provides higher power densities and efficiencies relative to other models. Values show that model 3 increases the power density of model 2 by 20% under very high concentrated solar radiation.

Also, a solar concentrator with a relatively lower magnifying power, and consequently cost, will be needed in maximising the power densities and efficiencies of model 3 relative to model 1. This is due to the higher temperature gradients obtained in model 3.

In a nutshell, model 3 enhances the power density and energy/exergy efficiencies of model 2 by 20% and 23%, respectively.

The results of the STEG irreversibility analysis are portrayed in Figs. 3b and c. The plot shows that the irreversibilities generated in model 1 is the least. More striking is the fact that despite the relatively higher temperature gradients developed in models 3 relative to 2, the former still maintains approximately the same irreversibilities with the latter. This is due to the circular surface and edges in the conical frustum leg geometry which are very efficient in heat distribution. This is interesting since model 3 offers a higher overall performance than model 2 due to its unique leg geometry.

Finally, the thermal stresses in the TE leg cavity are shown in Fig. 3c. Model 2 provides higher stresses than model 1 because it generates higher temperatures. Thus, any effort in plummeting these stresses is a serious progress and reflects a much-expected development. Model 1 generates the least stresses owing to its uniform rectangular cross-section and relatively lower temperature gradients when compared to models 2 and 3 put together. Although model 3 develops a slightly higher temperature gradient than model 2, it still succeeds in reducing the thermal stresses of the trapezoidal leg geometry by 2%. This is because of the circular surface and edges in the conical frustum leg which are very efficient in spreading heat evenly throughout the leg. Thus, it can be model 3 will provide a higher device operation life than model 2.

4. CONCLUSIONS

This work conducted a performance comparison between a conical frustum TE leg and a traditional trapezoidal shaped TE leg used in solar power generation. The effect of the concentration ratio was studied.

Based on the results obtained, the proposed conical frustum shaped TE leg was found to be more efficient and stable than the trapezoidal TE leg. In fact, the former improved the exergy efficiency of the latter by 23% while reducing its thermal stresses by 2%. This will result in a longer operation lifespan.

The trapezoidal and conical frustum shaped TE legs were found to be less thermodynamically stable than the rectangular shaped TE leg. However, the conical shaped TE leg reduced the generation of irreversibilities in the trapezoidal TE leg by 0.5%.

The reason for the higher thermodynamic and mechanical performance reported in the conical frustum shaped TE leg was due to its circular surfaces and edges. These ensured a smooth distribution of heat in the TE cavity as opposed to the rectangular surface and edges in the trapezoidal leg geometry.

The mass production of trapezoidal TE legs should be stopped. Instead, conical frustum legs should replace trapezoidal legs due to the desirable perks they offer.

REFERENCE

1. C. G. Ozoegwu, Renew. Sustain. Energy Rev. **92**, 146 (2020).
2. S. Shittu, G. Li, X. Zhao, J. Zhou, X. Ma, and Y. G. Akhlaghi, Energy Convers. Manag. **207**, 112515 (2020).
3. R. Lamba and S. C. Kaushik, Energy Convers. Manag. **170**, 34 (2018).
4. A. A. Candadai, V. P. Kumar, and H. C. Barshilia, Sol. Energy Mater. Sol. Cells 1 (2015).
5. Y. Tanaka, World J. Dermatology **1**, 30 (2012).
6. C. Maduabuchi, R. Lamba, C. Ozoegwu, H. O. Njoku, M. Eke, Y. G. Gurevich, and E. C. Ejiogu, Heat Mass Transf. (2021).
7. D. Narducci, P. Bermel, B. Lorenzi, N. Wang, and K. Yazawa, *Hybrid and Fully Thermoelectric Solar Harvesting* (Springer International Publishing, Cham, 2018).
8. D. Champier, Energy Convers. Manag. **140**, 167 (2017).
9. H. Lee, *Thermoelectrics*, First Edit (John Wiley & Sons Ltd, West Sussex, UK, 2017).

10. C. Lundgaard and O. Sigmund, Appl. Energy **236**, 950 (2019).
11. A. Yusuf and S. Ballikaya, Appl. Sci. **10**, 408 (2020).
12. J. Chen, J. Yu, and M. Ma, Energy Convers. Manag. **98**, 28 (2015).
13. E. Kanimba, M. Pearson, J. Sharp, D. Stokes, S. Priya, and Z. Tian, J. Power Sources **365**, 266 (2017).
14. S. Asaadi, S. Khalilarya, and S. Jafarmadar, Appl. Therm. Eng. **156**, 371 (2019).
15. M. W. Tian, L. W. W. Mihardjo, H. Moria, S. Asaadi, H. Sadighi Dizaji, S. Khalilarya, and P. T. Nguyen, Appl. Therm. Eng. **181**, 115996 (2020).
16. H. Liu, S.-L. Wang, Y. Yang, W. Chen, and X. Wang, Energy **201**, 117660 (2020).
17. M. Ranjan and T. Maiti, J. Power Sources **480**, 228867 (2020).
18. A. S. Al-Merbati, B. S. S. Yilbas, and A. Z. Z. Sahin, Appl. Therm. Eng. **50**, 683 (2013).
19. C. Maduabuchi, H. Njoku, M. Eke, C. Mgbemene, R. Lamba, and J. S. Ibrahim, J. Power Sources **500**, 229989 (2021).
20. C. C. Maduabuchi, M. N. Eke, and C. A. Mgbemene, Int. J. Energy Res. **45**, 13163 (2021).
21. C. C. Maduabuchi and C. A. Mgbemene, in *2020 Sustain. Eng. Ind. Technol. Conf.* (Nsukka, Enugu, Nigeria, 2020), pp. 1–3.
22. C. Maduabuchi, S. Singh, C. Ozoegwu, H. Njoku, and M. Eke, J. Energy Resour. Technol. **144**, 1 (2022).
23. C. Maduabuchi, K. Ejenakevwe, I. Jacobs, and A. Ndukwe, in *2nd African Int. Conf. Ind. Eng. Oper. Manag.* (Harare, Zimbabwe, 2020), pp. 1–7.
24. C. Maduabuchi, K. Ejenakevwe, A. Ndukwe, and C. Mgbemene, E3S Web Conf. **239**, 00005 (2021).
25. G. Li, S. Shittu, X. Ma, and X. Zhao, Energy **171**, 599 (2019).
26. C. C. Maduabuchi and C. A. Mgbemene, J. Electron. Mater. **49**, 5917 (2020).
27. C. C. Maduabuchi, C. A. Mgbemene, and O. I. Ibeagwu, J. Electron. Mater. **49**, 6417 (2020).
28. R. Petela, J. Heat Transfer **86**, 187 (1964).
29. R. Petela, Sol. Energy **74**, 469 (2003).
30. A. Fabián-mijangos, G. Min, and J. Alvarez-quintana, Energy Convers. Manag. **148**, 1372 (2017).