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Optimizing Thermoelectric Generator Efficiency Through Geometric Management

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Abstract- This article is devoted to the analysis of the complex relationship between the spatial arrangement of thermoelectric generators and their efficiency in the conversion of waste heat into electricity. Using a complete 3D digital model consisting of 127 thermocouples, we conduct a thorough analysis of the mechanisms of heat transfer and electrical conduction within these generators. We explore critical parameters such as open circuit voltage and output power, which we then compare with empirical data. More precisely, we examine the impact of variable distances between generators, by imposing constraints on convection heat transfer. Our quantitative results show a significant increase in output power of about 35.5% when the distance between the TEG ranges from 2 cm to 30 cm. At a distance of 30 cm, the maximum output power reaches 5,077 W, marking a significant improvement over previous configuration. Beyond this range, gains become marginal. In particular, the analysis of power per unit area as a function of length reveals intriguing trends, with an initial increase in power as the length increases, culminating at 18 cm with a value of 59.8256 W/m². Our findings have considerable implications for various applications, including the use of TEG on external facades of buildings, where thermal energy recovery is crucial. This study highlights the pivotal role of the distance between generators in optimizing the efficiency of thermoelectric generators, Emphasizing the importance of a specific range of distances to maximize output power while delineating limits beyond that range.

Keywords Thermoelectric generator, Heat recovery, Distance between generators, System performance, Numerical simulation.

1. Introduction

Heat is an abundant resource around the world, and its conversion to electricity plays a crucial role in meeting the growing electrical energy needs of our societies, as it reached 28 642 TWh in 2022 according to International Energy Agency (IEA). However, traditional methods of producing electricity from heat face problems such as greenhouse gas emissions [1], air pollution [2] and relatively low efficiency. In parallel, although solar thermal power plants have advantages in terms of using solar energy to produce electricity [3,4,5], they also have some disadvantages such as a high upfront cost, the use of large tracts of land and limited efficiency at high temperatures [6]. Nevertheless, improving the efficiency of heat-to-power conversion globally is essential to reduce our reliance on fossil fuels and encourage more sustainable energy sources, such as thermoelectricity, emerging as a promising new technology.

Thermoelectric generators (TEG) are devices that, thanks to the Seebeck effect, convert heat into electricity. They are used to recover waste heat in various applications [7,8], ranging from motor vehicles to power plants, contributing to a more efficient use of energy and the reduction of thermal waste. The TEG offers advantages such as reliability, extended service life, operation without moving parts, and find their use in various environments [9,10]. The research aims to improve their efficiency, by developing more efficient thermoelectric materials and integrated systems, this makes it a promising technology for sustainable applications and energy recovery from renewable thermal sources [11]. The growing interest in this innovative approach to heat recovery electricity generation highlights the innovative operation of the thermoelectric generator (TEG) [12,13]. It is particularly valuable for capturing energy where heat is usually dissipated into the atmosphere. Through a temperature gradient, the TEG produces an electrical voltage, making this technology one of the most promising advances in energy.

For more than four decades, research has focused on thermoelectric effects, mobilizing many researchers to refine the thermoelectric properties of materials [14,15]. In addition, the improvement of the structural composition of thermoelectric devices by rigorous thermal analyses represents a crucial avenue to improve the performance of TEGs [16,17]. To maximize the effectiveness of TEG, it is crucial to clearly define the mechanism of thermoelectric coupling within these components and to carefully consider the effects of various factors on the resulting indicators [18].

So far, it has been possible to determine the performance of a thermoelectric generator (TEG) by solving temperature and electrical potential distribution problems and using computer tools to build heat transfer models [19]. It seems that the model can be used to evaluate the performance of the TEG because the difference between calculations and measurements is acceptable.

With regard mainly to the simultaneous operation of several heat transfer systems inside the TEG, it can be difficult to correctly predict electricity generation. Early attempts used inexpensive thermocouples to parallelize numerical results. This demonstrated the need to take into account the characteristics of materials as a function of temperature in the calculations and the need to take into account the resistance to thermal contact. The merit factor ZT is a feature that is often present in thermoelectric materials of type p and type n. As a result, it is simpler to combine elements of the types p and n with equal geometric dimensions. However, similar ZT values may not always correspond to the same material characteristics, such as thermal conductivity and electrical resistivity. The differences in thermal behavior between P-type and N-type elements were thus highlighted by examining them in two distinct parts [20].

The effects of the dimension on the generation of electrical and thermal stresses were then studied using a model consisting of two thermocouples. The results showed that element size and spacing had an impact on output power and efficiency [21]. A commercial TEG module in practice often includes a number of these components. The number of thermocouples has a considerable effect on the ability of TEG devices to cool [22]. They also noted that the power depends on the number of thermoelectric components.

Thermoelectric generators (TEG) represent a promising technology for converting heat into electricity, with a range of potential applications ranging from motor vehicles to buildings. However, the efficiency of these generators is strongly influenced by the spatial arrangement of thermoelectric elements and the distance between them. In this study, we examine the complex relationship between the distance between thermoelectric generators and their efficiency in the exploitation of electricity from waste heat. Our main objective is to answer several key questions and challenges, including:

How does the spatial layout of thermoelectric generators influence the output power and efficiency of heat to electricity conversion?

Is there an optimal range of distances between generators that maximizes output power?

How can these findings be applied in concrete contexts, such as the use of TEG on the external facades of buildings to recover thermal energy?

By exploring these questions, our study aims to provide crucial information to optimize the performance of thermoelectric generators, thus contributing to the development of more efficient and sustainable technologies in the field of heat to electricity conversion.

This study introduces an innovative model, the Global Scale Thermocouple, comprising 127 thermocouples, and focuses via numerical simulations on the open circuit voltage and the maximum output power of the device. The TEG offers a promising opportunity for the conversion of heat into electrical energy [23,24,25]. The simulations analyze the generation of open circuit voltage, illuminating its ability to produce electricity with temperature variations, as well as determining the maximum power to guide its operational efficiency.

In this approach, the types p and n are understood as two distinct entities, relying on parameters subject to thermal dependence to define their properties. In addition, the performance of the TEG was analyzed in a closed-circuit context, different from previous open circuit approaches. This made it possible to study the influence of the distance between the TEG on the overall performance, especially in the conditions of heat transfer limited by convection. The model was built using COMSOL Multiphasic simulation software.

The rest of this document is structured as follows. Section 2 discusses the overall theoretical model of a thermoelectric generator. Section 3 presents the performance of TEG. Section 4 presents the simulation module of a thermoelectric generator on COMSOL Multiphasic. Section 5, Numerical Model Validation. Finally, Section 6 presents the simulation results and discussions.

2. Theoretical Model

The theoretical model presented aims to answer the main purpose of the study, which is to explore the influence of the distance between thermoelectric generators (TEG) on their overall performance, especially under conditions of limited heat transfer by convection. The equations and concepts presented in the theoretical model serve to shed light on this fundamental relationship. The equations are chosen to represent the thermal and electrical processes that occur within the TEG. They describe how parameters, such as temperature, electrical resistance and thermal conductivity, interact to influence the output power of the TEG. In particular, these equations highlight the Peltier effect, which is crucial in the context of thermoelectric.

The theoretical model makes it possible to link these equations to the purpose of the study by showing how the distance between the TEG affects the temperature gradients, the heat transfers and therefore on the performance of the TEG. It provides a conceptual framework for understanding how parameters vary with distance and how these variations impact output power. Ultimately, this theoretical model is essential to interpret and explain experimental results, thus contributing to the understanding of the relationship between the distance between TEG and their overall performance.

Equations (1) and (2) describe the fundamental interactions within the thermoelectric element (TEG). Equation (1) describes the current density $\vec{J}$, while equation (2) governs the heat flux $\vec{q}$ through the thermoelectric element [13]:

$$\vec{J} = \frac{1}{\rho}\left(\vec{E} + \alpha \nabla T\right) \quad (1)$$

$$\vec{q} = \alpha \nabla T \vec{J} - k \nabla T \quad (2)$$

With $\vec{E}$ represents the intensity of the electric field; $\vec{J}$ is the current density; $\vec{q}$ is the heat flux; T is the temperature; α, ρ and k are respectively the Seebeck coefficient, the electrical resistivity and the thermal conductivity of a thermoelectric element.

The Thomson effect and thermal transport along thermoelectric components are disregarded. We may formulate the equation of heat transfer at equilibrium state by taking into consideration the thermal dependence of the characteristics of the materials, and k. [14]:

$$\nabla^2 k(x,y,z,T) - J.T.\alpha(x,y,z,T) + J^2.\rho(x,y,z,T) = 0 \quad (3)$$

The equation of electrical potential can be written [14]:

$$\nabla^2 \phi(x,y,z) = -\alpha \nabla^2 T \quad (4)$$

Where ϕ is the scalar electric potential.

Stationary three-dimensional thermal conduction in solids is governed by the equation [26]:

$$\frac{\partial}{\partial x}\left(k\frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(k\frac{\partial T}{\partial y}\right) + \frac{\partial}{\partial z}\left(k\frac{\partial T}{\partial z}\right) = 0 \quad (5)$$

Thermal convection by circulating water in the cooling pipes plays an essential role in keeping the thermoelectric generators at an optimal operating temperature. It is a heat transfer mechanism that occurs when a fluid, such as air or water, is in contact with a hot or cold surface. This process involves the movement of the fluid, which results in the transfer of heat from the hot surface to the surrounding fluid, is governed by the law of mass conservation and the law of momentum conservation.

The law of mass conservation in three dimensions [27]:

$$\frac{\partial \rho u}{\partial x} + \frac{\partial \rho v}{\partial y} + \frac{\partial \rho w}{\partial z} = 0 \quad (6)$$

The law of conservation of momentum translated by the equation of Navier Stokes in three-dimensional simply expresses the fundamental law of dynamics to a Newtonian fluid [27]:

$$\rho\left(u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} + w\frac{\partial u}{\partial z}\right) = -\frac{\partial P}{\partial x} + \rho g_x + \mu\left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} + \frac{\partial^2 u}{\partial z^2}\right) \quad (7)$$

$$\rho\left(u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} + w\frac{\partial v}{\partial z}\right) = -\frac{\partial P}{\partial y} + \rho g_y + \mu\left(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2} + \frac{\partial^2 v}{\partial z^2}\right) \quad (8)$$

$$\rho\left(u\frac{\partial w}{\partial x} + v\frac{\partial w}{\partial y} + w\frac{\partial w}{\partial z}\right) = -\frac{\partial P}{\partial z} + \rho g_z + \mu\left(\frac{\partial^2 w}{\partial x^2} + \frac{\partial^2 w}{\partial y^2} + \frac{\partial^2 w}{\partial z^2}\right) \quad (9)$$

3. TEG Performance

The electrical model is used to study the electrical behavior of a module, and an elementary electrical diagram for this purpose is presented in Figure 1. This model integrates the internal resistance and the voltage source of the TEG module, while load resistance is taken into account due to its impact on optimal operation.

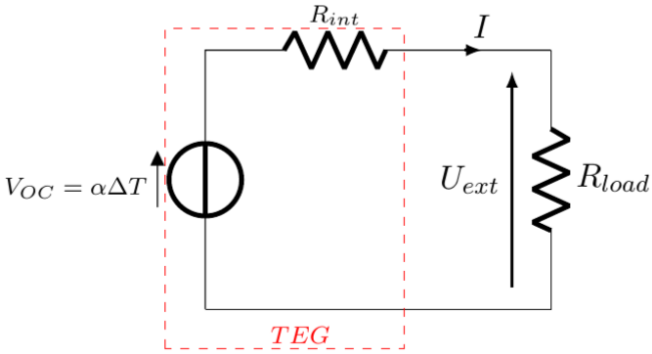


Fig. 1. Electrical equivalent circuit of the TEG

The external circuit voltage U_{ext} is calculated as follows:

$$U_{ext} = n.\alpha_{pn}\Delta T.\left(\frac{R_{load}}{R_{int}+R_{load}}\right) \quad (10)$$

In this equation, n represents the number of thermocouples present in the TEG module. α_{pn} is the Seebeck coefficient of the thermoelectric material P and N, which measures the material's ability to generate a voltage difference in response to a temperature difference. The temperature difference between the hot side (T_h) and the cold side (T_c) of the TEG module is represented by $\Delta T = (T_h - T_c)$, R_{int} is the electrical resistance of the thermocouples, and R_L represents the load resistance.

The voltage in open circuit $V_{oc} = U(R_{load} \to \infty)$ [23]:

$$V_{oc} = n.\alpha_{pn}\Delta T \quad (11)$$

The output power obtained is maximum P_{max} for a value of R_{load} load resistance is equal to the internal resistance R_{int}.

$$P_{max} = \frac{(n.\alpha_{pn}.\Delta T)^2}{4\,R_{int}} \quad (12)$$

The output of thermoelectric generator [27]:

$$\eta = \frac{P}{Q_h} = \frac{Q_h - Q_c}{Q_h} = 1 - \frac{Q_c}{Q_h} \quad (13)$$

With Q_h corresponds to the amount of heat absorbed by the hot side, while Q_c represents the amount of heat rejected by the cold side with water circulation.

4. Numerical Model

Our study, based on COMSOL simulation, requires special attention. First, simulation models are based on simplifying assumptions that may not fully reflect the complexity of reality. The results are also influenced by the input data, and any uncertainty associated with that data must be considered. The increasing complexity of our models can lead to significant demands in terms of computing resources and computational time. In addition, simulation results should be interpreted with caution, as they are not always directly comparable to experimental data. Finally, the generalization of our results to other contexts must be approached with caution, because our models are specific to certain configurations. Despite these limitations, our study provides crucial information to guide future research and provides valuable insight into the performance of thermoelectric generators under convection-limited heat transfer conditions.

In the COMSOL Multiphasic program [28], a three-dimensional model of a TEG TEG1-12710 module is created (Figure 2). In conjunction with boundary conditions, the governing equations described above are solved.

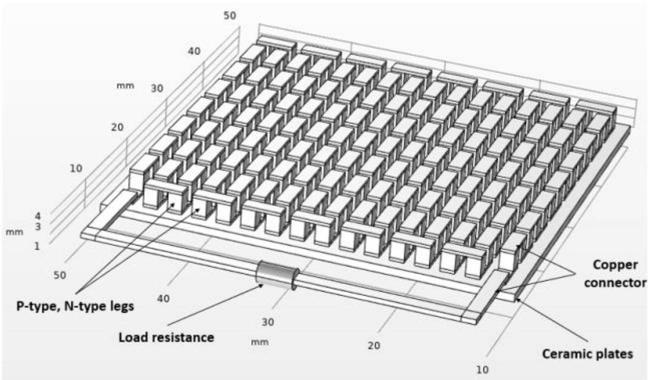


Fig. 2. Three-dimensional geometry of the TEG

The TEG module has the following measurements: 40 mm 40 mm 3.8 mm (width depth length). The module is made up of 127 pairs of thermocouples, each of which has a grain size of 1.4 mm, 1.4 mm, and 1.6 mm. Copper strips are used to make the electrical connection. Ceramic plates are also present to ensure electrical insulation and thermal conduction. In addition, to improve heat absorption, a copper plate was added as a heat absorber on the hot side of the TEG module. On the other side of the module, a water circulation line is installed to provide cooling of 45 mm wide and 10 mm deep, as a heat changer [29], as shown in Figure 3. The electrodes of the TEG module are also electrically connected to an external load resistor in the suggested form.

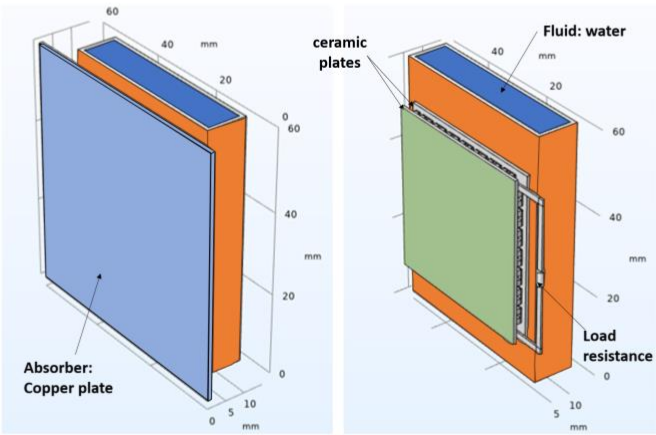


Fig. 3. Structure du module TEG proposer

However, the optimization of the spatial layout of thermoelectric generators in the context of solar heat recovery has been largely neglected in previous studies. The numerical model gap by examining the effect of the distance between thermoelectric modules, as shown in Figure 4.

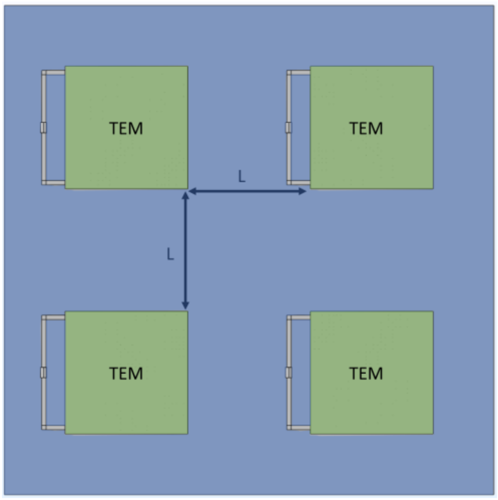


Fig. 4. Positioning structure of TEGs modules

Figure 5 depicts the TEG's mesh systems and geometric structures. To discover a good grid system, three distinct grids, each with a total of I=1057081, II=561883, and III=312947 components, are evaluated and compared. A hot side temperature of 200°C and a cold side temperature of 30°C are used to compute the output power for each of the four grid systems.

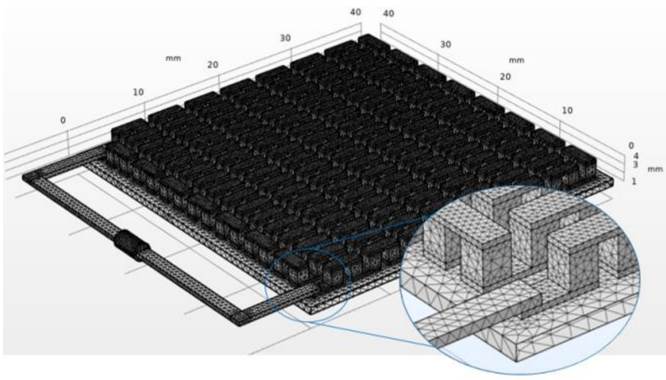


Fig. 5. Geometric structure and TEG grid system

The output power values for grids I, II and III are 4.9844W, 4.9645W and 4.7352W, respectively. These results highlight the magnitude of the differences between the values of the different grids. Grid II, composed of 561,883 elements, is ideal for simulation, because the greatest divergence between its results and those of grid III is less than 0.4%. However, the results of Grid I differ significantly from those of the other grids. As a result, Grid II is the most suitable for reducing the design load without compromising accuracy.

To fully understand the functioning of thermoelectric generators (TEG) in our study, it is essential to closely examine the temperature-dependent properties of the materials involved. The thermal conductivity (k) of the materials plays a crucial role. High thermal conductivity allows more efficient heat dissipation from the hot side to the cold side of the TEG, which improves the efficiency of thermoelectric energy conversion. Similarly, the Seebeck coefficient (α) is essential because it measures the ability of a material to generate an electrical voltage in response to a temperature gradient. Materials with a high α produce a higher voltage for the same gradient, thus increasing the output power. As for the electrical resistance (ρ) of materials, it directly influences the energy losses in the form of heat during the passage of electric current. Materials with low electrical resistance are preferred to maximize the output power. Integrating these properties into our theoretical model is essential to explain how the distance between TEG influences the variation of these parameters, and therefore, how it affects the overall performance of the device.

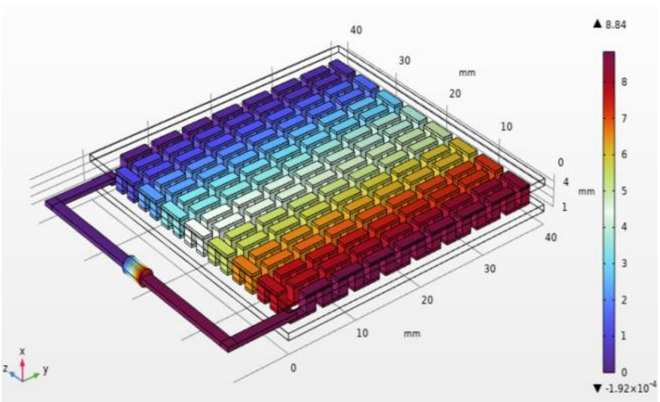
Table 1 provides a summary of the characteristics of materials that change with temperature.

Table 1. Material Properties [16]

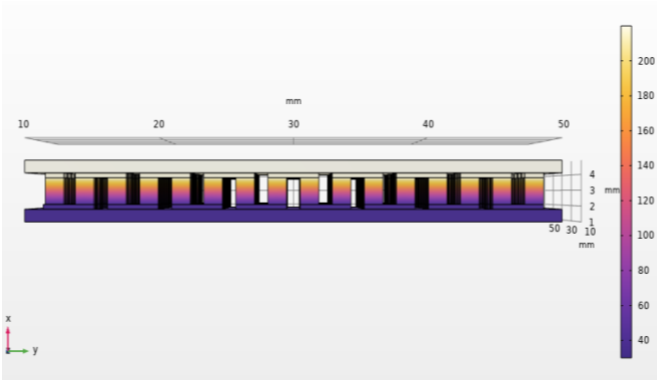
Name	Thermal conductivity (W/m K)	Seebeck coefficient (μV/k)	Electric resistivity ($10^{-5}\Omega$ m)
Ceramic plate	22	-	-
Copper	385	-	$1.78\ 10^{-3}$
P-type	$4.8482.10^{-5}\,T^2 - 0.0332\,T + 6.949$	$-4.5312 \times 10^{-6}\,T^3 + 0.0012\,T^2 + 0.8712\,T - 27.09$	$-1.3348\ 10^{-5}\,T^2 + 0.01748\,T - 2.95643$
N-type	$3.07 \times 10^{-5}\,T^2 - 0.02031\,T + 4.72174$	$-1.6797 \times 10^{-5}\,T^3 + 0.02219\,T^2 - 9.356\,T + 1054.78$	$-1.63839\ 10^{-5}T^2 + 0.01681\,T - 2.61014$
Solder	20	-	1.285

5. Results and Discussions

In this study, we adopted a rigorous validation method by comparing the results of our numerical simulations with experimental data, including open circuit voltage and output power, as presented in Article [16]. This experimental data comes from an earlier study where a similar system was used, comprising a TEG module attached to the outer surface of an aluminum heat absorber. The dimensions and parameters of the experimental system closely matched those of our numerical model.



(a)



(b)

Fig. 6. Voltage contour (V) (a) and temperature contour (b) for TH=200°C and TC=30°C

The potential distributions are shown in Figure 6(a) when the hot side is kept at 220°C and the cold side is kept at 30°C. The order of the thermoelements determines the direction of the potential rise, as may be seen visually. The positive and negative voltages recorded at the TEG electrodes are equal to the voltage flowing through the load resistor. The temperature distributions for the respective circumstances are shown in Figure 6(b). The thermoelements in the TEG model are where the temperature drops the most inside, as seen in this picture.

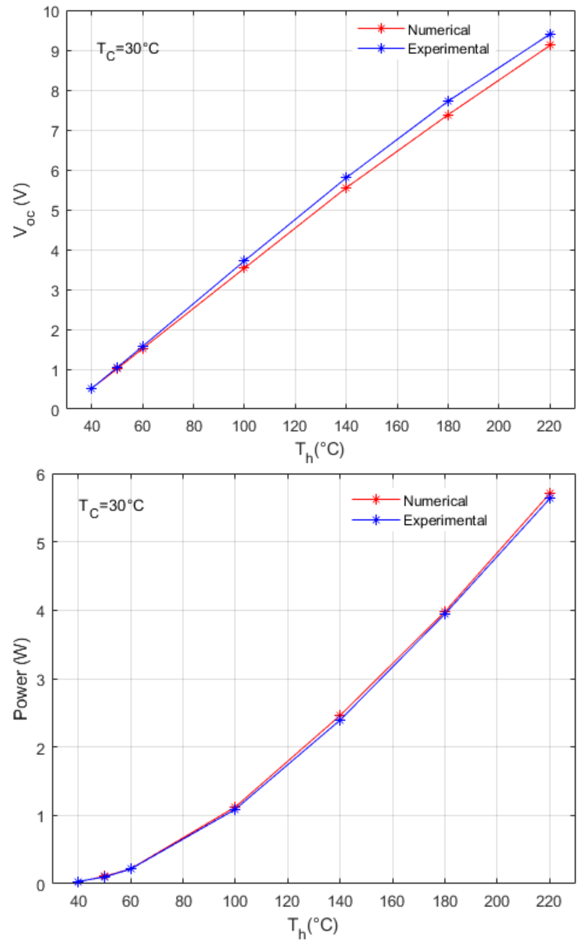


Fig. 7. Comparison between numerical and experimental performance curves-open circuit voltage and output power

The experimental results obtained by article [16] were compared with the results of the numerical simulation based on the proposed model. The measured quantities, such as hot side temperature, open circuit voltage and output power, were compared to the values predicted by the numerical model. Figure 7 shows the experimental and simulated measured open circuit voltage and the TEG output power. Comparisons between experimental results of article [16] and simulation results showed satisfactory agreement, confirming the validity of the numerical model.

Table 2. Comparison of open circuit voltage and output power between the design model and experimental data

Paramètres	T_C (°C)	T_h (°C)	Déviation (%)
Open-circuit voltage, U_0 (V)	30	40-220	4.5
Output power, P (W)	30	40-220	4.1

The differences between the experimental results of article [16] and the values predicted by the model were less than 5% (Table 2), which demonstrates a good correlation between the simulation and the actual measurements. This experimental validation strengthens confidence in the proposed numerical model and ensures its ability to accurately predict the performance of the thermoelectric generation system with an aluminium heat absorber and a water circulation pipe.

These encouraging results pave the way for the future use of the digital model for further studies and design optimizations in the field of solar heat recovery using thermoelectric generators. We have carefully defined the essential input parameters to accurately reproduce the conditions of our model. The incident heat flux on the absorber surface was set at 1000 W/m², representing the amount of heat absorbed by our system. In addition, a constant water flow rate of 300 litres per hour (300 l/h) was taken into account to simulate the flow of water through the device with an input speed of U=0.2 m/s. Finally, the initial inlet water temperature was established at 25°C.

The digital model includes a TEG model and the distances between the thermoelectric modules L are respectively 2cm up to 30cm (Fig. 4).

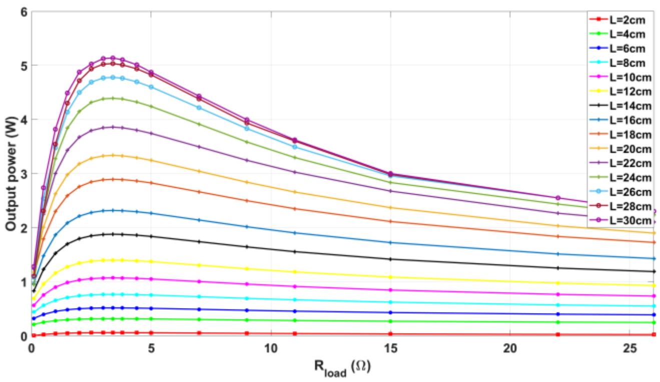


Fig. 8. Variation of output power with load resistance

As illustrated in Figure 8, the variations in output power, is closely related to the load resistance for different distances between thermoelectric generators, when convective heat transfer conditions are maintained constant. The open circuit voltage was determined by simulating the operation of our TEG generators under zero load conditions. This means that the load resistance in the circuit was adjusted so that no current was flowing. By measuring the voltage under these conditions, we obtained the value of the open circuit voltage. To quantify the output power, we followed the classical method using the relation P = VI, where P is the power, V is the voltage, and I is the current. In our simulations, the power was calculated by multiplying the voltage (V) by the corresponding current (I) under the determined load. We performed these measurements over a load resistor range of 0-26Ω to obtain the maximum output power.

Due to the effects of Peltier, the temperature on the hot side is forced down, resulting in a reduction in output power compared to previous cases. At the same time, the increase in load resistance causes a decrease in current, thus weakening the Peltier effect and contributing to a corresponding increase in temperature difference.

The results obtained also reveal that, compared to the absence of distance between thermoelectric generators, the distance of L = 30cm generates a significant improvement in the effective temperature difference of the order of 35,5°C and an increase in the maximum output power to 5.077W. However, it should be noted that a substantial performance improvement is observed only in a specific range of distances between thermoelectric generators, beyond which this improvement is restricted. The maximum recorded power, 5.137W at a length of 30cm, stands out as a highlight of this study, demonstrating the significant impact of the length on the performance of the device. Based on the findings presented, when moving from 2cm to 30cm (L), the output power increases. On the other hand, when the distance increases from 28cm to 30cm, the increase in output power is only 1%.

In the continuation of our analysis, we closely examine the power-voltage characteristic of thermoelectric generators (TEG) over a range of lengths from 2 to 30 cm, as shown in Figure 9. Output power data is of critical importance in assessing TEG performance in this length range. It is important to note that the results show a characteristic nonlinear relationship between the voltage and power of the TEG. The power generated highlights a general increase with the increase in length, until reaching a maximum power point. This point of maximum power is crucial because it represents the point where the TEG produces the highest electrical power for a given length. The set of maximum power points for all lengths forms a data series which, when represented graphically, creates a distinctive curve. This curve highlights how the output power evolves with the length of the TEG, providing essential information for optimizing the distance between thermoelectric generators to achieve optimal performance.

In this graphic representation, the points corresponding to the maximum power obtained at each specific length are highlighted using the red color (Figure 9). Thus, this red curve highlights the evolution of the maximum power according to the variation of the length, thus offering a visual overview of the performance of the system at different length scales.

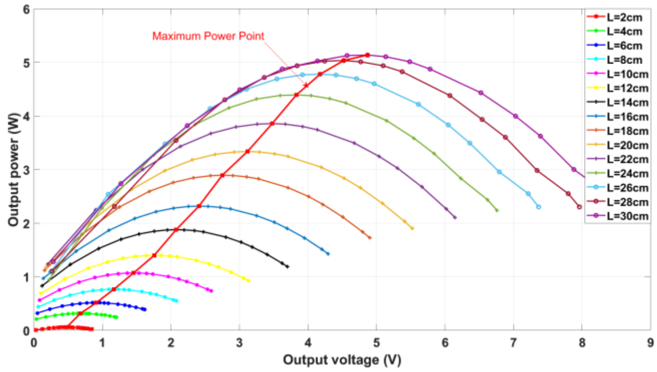


Fig. 9. Electric characteristic power-voltage of thermoelectric generator

We now discuss the analysis of the current-voltage characteristic of thermoelectric generators over the same length range. This step will detail the electrical behavior of the generator over this range of lengths and better understand its response in terms of current and voltage applied. This characteristic is in the form of a linear curve as shown in Figure 10.

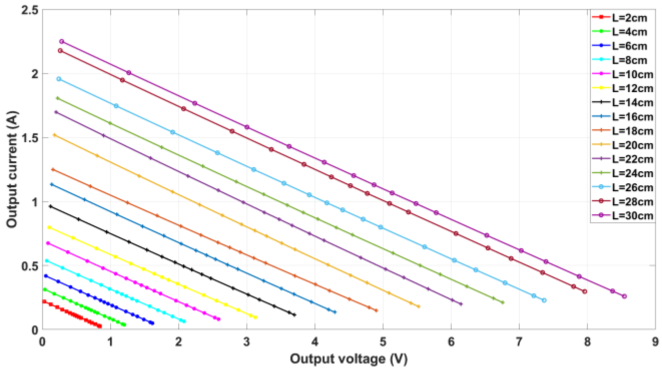


Fig. 10. Electric characteristic current-voltage of thermoelectric generator

The results of the power per unit area (expressed in W/m²) as a function of the length L (expressed in cm) show intriguing trends and information on the relationship between these two parameters.

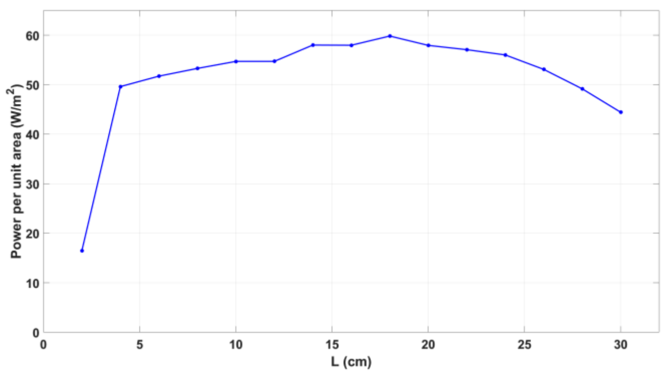


Fig. 11. Power per unit area with distance between TEG

The data clearly illustrate a gradual increase in power as the length L increases (Figure 11). Initially, at a length of 2cm, the power is recorded at 16.50 W/m², this value grows rapidly as the length L increases, reaching 54.71 W/m² for both 10cm and 12cm lengths.

However, from this point, apparent stability is observed, where the P/S power values remain at 5.471 W/m² for lengths up to 12cm and beyond, up to 16cm. This plateau is followed by a new progressive climb, reaching a maximum of 59.83 W/m² at a length of 18cm. Subsequently, a slight fluctuation in power values is observed in the length range between 20cm and 30cm, with values oscillating between 57.94 W/m² and 44.43 W/m².

This distribution of results highlights a nonlinear relationship between the length L and the power. Initially, the increase in length L seems to generate a significant increase in power. However, once a certain threshold is reached, the power seems to stabilize, suggesting a yield limit in this specific context. Thereafter, the power reaches another peak at a slightly longer length, before showing some variability as the length L continues to increase. This analysis highlights the importance of length L in the determination of power, while emphasizing the complexity of the relationship between these two variables. The fluctuations and levels observed underline the need for a thorough understanding of the underlying mechanisms to correctly interpret these results and guide future investigations in this area.

In sum, the section concludes by highlighting the complexity of the relationships between thermoelectric generator (TEG) length and output power. This complexity results from several factors. At short lengths, the temperature gradient is limited, reducing the power generation capacity of the TEG. As the length increases, this temperature gradient increases, increasing the power. However, beyond a certain length, the increased electrical resistance due to a longer section of the TEG can compensate for this positive effect, resulting in a stabilization of power.

In addition, the effects of Peltier play an essential role. As the length increases, the Peltier effect becomes more pronounced, contributing to an increase in the temperature difference between the hot and cold sides. This improves the output power up to a point, where Peltier's effects reach a balance. The complexity of these interactions creates an intrinsic non-linearity of the results.

These results encourage future research to refine models and explore innovative materials to optimize TEG performance. A promising example of future research will be the application of the results of our study to a thermoelectric generator (TEG) associated with a parabolic concentrator and cooled by water circulation, and we are working on this project as shown in Figure 12.

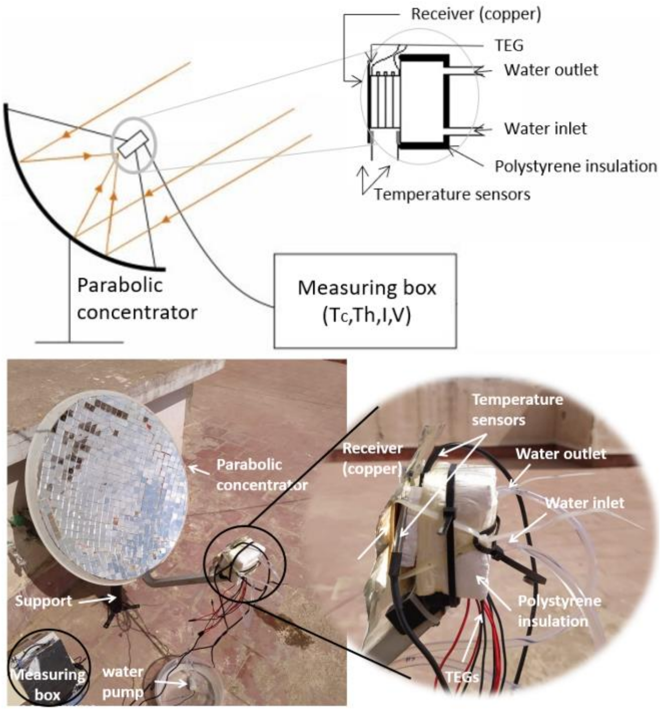


Fig. 12. Diagram and realization of a thermoelectric generator with parabolic concentrator and cooling by water circulation

This configuration can be particularly interesting for applications in concentrated solar energy, as TEG cooling is necessary to maintain its efficiency. By understanding how optimal spacing of TEG generators can improve their performance in such a context, we can help improve innovative and sustainable energy systems. This research area would also be an opportunity to explore more efficient solutions to convert thermal energy into electricity, contributing to more efficient and sustainable energy applications.

6. Conclusions

Our comprehensive study examined in depth the impact of the distance between thermoelectric generators on their ability to generate electricity from waste heat. Using a 3D digital model comprising 127 thermocouples, we examined the mechanisms of heat transfer and electrical conduction within thermoelectric generators. Our numerical simulations explored critical parameters, including open circuit voltage and output power, which we carefully compared with experimental data. Our study quantitatively revealed the crucial importance of the distance between generators in their performance. By imposing constraints on convection heat transfer and varying the distance between generators from 2 cm to 30 cm, we observed a significant improvement in output power. Specifically, our results show an increase in output power of about 35.5% when the distance varies from 2 cm to 30 cm. The maximum output power reaches 5.077 W at a distance of 30 cm, this represents a significant increase over previous configurations. However, it is crucial to note that this substantial performance improvement is observed only in a specific range of distances between thermoelectric generators. Beyond this optimal range, the output power improvement decreases. These quantitative results provide valuable information for the design and optimization of thermoelectric systems for the generation of electricity from waste heat. The complexity of the relationships between these variables underlines the need for a thorough understanding of the underlying mechanisms to guide future developments in this area. Ultimately, our study contributes quantitatively to the ongoing search for more efficient and sustainable energy conversion technologies.

References

[1] I. Jebabli, A. Lahiani, end S. Mefteh-Wali, “Quantile connectedness between CO2 emissions and economic growth in G7 countries”, Resources Policy, vol. 81, pp. 103348, 2023.

[2] Y. Wang, J. Fan, D. Liu, J. Fu, L. Ding, end J. Zhang, “Air pollution outcomes, land misallocation, and the transmission through urban sprawl”, Journal of Environmental Management, vol. 345, pp. 118730, 2023.

[3] U. K. Pata, M. T. Kartal, T. S. Adebayo, end S. Ullah, Enhancing environmental quality in the United States by linking biomass energy consumption and load capacity factor. Geoscience Frontiers, vol. 14(3), pp. 101531, 2023.

[4] P. P. Kumar, R. S. Nuvvuls, M. Venkatesh, end M. V. Kumar, “A Review On The Estimate Solar PV Cell Variables For Efficient Photovoltaic Systems”, International Journal of Smart Grid-ijSmartGrid, vol. 7(3), pp. 154-159, 2023.

[5] W.F. MBASSO, R.J.J. MOLU, S.R.D. NAOUSSI and S.K. TSOBZE, “A Technical Analysis of a Grid-Connected Hybrid Renewable Energy System under Meteorological Constraints for a Timely Energy Management”, International Journal of Smart Grid-ijSmartGrid, vol. 7(2), pp.53-60, 2023.

[6] F. Javed, “Impact of Temperature & Illumination for Improvement in Photovoltaic System Efficiency”, International Journal of Smart Grid-ijSmartGrid, vol. 6(1), pp.20-29, 2022.

[7] M. Jabri, S. Masoumi, F. Sajadirad, R. P. West, end A. Pakdel, “Thermoelectric Energy Conversion in Buildings”, Materials Today Energy, 101257, 2023.

[8] S. Shoeibi, H. Kargarsharifabad, M. Sadi, A. Arabkoohsar, end S. A. A. Mirjalily, “A review on using thermoelectric cooling, heating, and electricity generators in solar energy applications”, Sustainable Energy Technologies and Assessments, vol. 52, pp.102105, 2022.

[9] G.Y. Huang, C.T. Hsu, C.J. Fang, D.J. Yao, “Optimization of a waste heat recovery system with thermoelectric generators by three-dimensional thermal resistance analysis”, Energy Convers. Manage, vol.126, pp. 581–594, 2016.

[10] J.Y. Jang, Y.C. Tsai, “Optimization of thermoelectric generator module spacing and spreader thickness used in a waste heat recovery system”, Appl. Therm. Eng., vol. 51, pp. 677–689, 2013.

[11] A. Ramkumar, end M. Ramakrishnan, “Performance improvement of thermoelectric generator by drooping the cool side temperature with thermacool 0.3 M coating”, Case Studies in Thermal Engineering, vol. 39, pp. 102418, 2022.

[12] Y. Özcan, end E. Deniz, “Solar thermal waste heat energy recovery in solar distillation systems by using thermoelectric generators”. Engineering Science and Technology, an International Journal, vol. 40, pp.101362, 2023.

[13] Z. Sun, D. Luo, R. Wang, Y. Li, Y. Yan, Z. Cheng, end J. Chen, “Evaluation of energy recovery potential of solar thermoelectric generators using a three-dimensional transient numerical model”, Energy, vol. 256, pp.124667, Oct 2022.

[14] Z. Zhang, C. Zhang, Q. Liao, L. Qin, Y. Deng, end L. Liang, “Optimizing electrical and thermal transport properties of Ca3Co4O9 based thermoelectric materials by Ag and Fe co-addition”, Materials Today Communications, Vol. 33, pp. 104866, 2022.

[15] X. Bao, S. Hou, Z. Wu, X. Wang, L. Yin, Y. Liu, H. Hea, S. Duana, B. Wangc, J. Maoa, F. Caoc, end Q. Zhang, “Mechanical properties of thermoelectric generators”, Journal of Materials Science & Technology, 2023.

[16] M. Liao, He, Z., Jiang, C., Li, Y., & Qi, F, “A three-dimensional model for thermoelectric generator and the influence of Peltier effect on the performance and heat transfer”, Applied Thermal Engineering, vol. 133, pp. 493-500, 2018.

[17] T. Li, Y. Fu, C. Dong, D. Li, H. Gu, end Y. Ye, “Factors influencing the thermoelectric characteristics of a thermoelectric generator with cold-side micro heat pipe arrays”, Journal of Power Sources, vol. 557, 232493, 2023.

[18] J. Y. Jang, end Y. C Tsai, “Optimization of thermoelectric generator module spacing and spreader thickness used in a waste heat recovery system”, Applied thermal engineering, vol. 51(1-2), pp. 677-689, 2013.

[19] D. N. Kossyvakis, C. G. Vossou, C. G. Provatidis, end E. V. Hristoforou, “Computational and experimental analysis of a commercially available Seebeck module”, Renewable Energy, vol.74, pp. 1-10, 2015.

[20] W. H., Chen, C. Y., Liao, end C. I. Hung, “A numerical study on the performance of miniature thermoelectric cooler affected by Thomson effect”, Applied Energy, vol. 89, No. 1, pp. 464-473, 2012.

[21] U. Erturun, K. Erermis, end K. Mossi, “Influence of leg sizing and spacing on power generation and thermal stresses of thermoelectric devices”, Applied Energy, vol. 159, pp. 19-27, 2015.

[22] L. Chen, F. Meng, end F. Sun, “Effect of heat transfer on the performance of thermoelectric generator driven thermoelectric refrigerator system”, Cryogenics, vol. 52, No. 1, pp. 58-65, 2012.

[23] M. Mejdal, A. Abouhilal, E. Chahid, and A. Malaoui, “Effects of temperature in the performance of the thermoelectric devises: Power generation”, In 2016 International Renewable and Sustainable Energy Conference (IRSEC), Marrakech, Morocco, pp. 338-343, IEEE, November 2016.

[24] L. Ouhmad, A. Malaoui, “Study and Simulation of a Thermoelectric Generator for the Intel-ligent Agricultural System”, 1st International Conference on Sol, Water and Environment challenges and Solution (SWECS), High school of technology of Fkih Ben Saleh, Sultan Moulay Slimane University, Morocco, 29,03,2022.

[25] A. Malaoui, K. Ouotb, M. Ankrim, end M. Benhayoun, “Accurate temperature control of a ultrasonic cell using a microcontroller”. In 2004 IEEE International Symposium on Industrial Electronics, Vol. 1, pp. 213-215, May 2004.

[26] Z. Sun, D. Luo, R. Wang, Y. Li, Y. Yan, Z. Cheng, end J. Chen, “Evaluation of energy recovery potential of solar thermoelectric generators using a three-dimensional transient numerical model”, Energy, vol. 256, pp. 124667, 2022.

[27] D. Luo, R. Wang, Y. Yan, W. Yu, and W. Zhou, “Transient numerical modelling of a thermoelectric generator system used for automotive exhaust waste heat recovery”, Applied Energy, vol. 297, pp.117151, 2021.

[28] H. M. Haq, B. Martinkauppi, E. Hiltunen and T. Sivula, “Simulated thermal response test for ground heat storage: Numerical and analytical modeling of borehole”, In 2016 IEEE International Conference on Renewable Energy Research and Applications (ICRERA), pp. 291-296, November 2016.

[29] M.M. Ozturk, B. Doğan, and L.B. Erbay. “Thermohydraulic performance assessment of a compact heat exchanger by varying plate fins”, in 2017 IEEE 6th International Conference on Renewable Energy Research and Applications (ICRERA), 2017.