JURNAL SAINS MATERI INDONESIA (JUSAMI)
ISSN: 1411-1098 (print), 2614-087X (online)
VOL. 24, ISSUE 2, 2023
DOI: 10.55981/jsmi.2023.761

ORIGINAL ARTICLE

Geometry Design-Based Thermoelectric Optimization Module

A. Prananca and I. Fatimah*

Department of Physics, Institut Teknologi Sepuluh Nopember, Kampus ITS Sukolilo, Surabaya 60111, Indonesia

ABSTRACT – One alternative energy source is thermoelectric, which is able to convert waste heat into electricity. However, study on thermoelectric still needs a lot of development, particularly in module design because there is still not many thermoelectric development in terms of the module geometry design when compared to the development in material structure. Therefore, research on thermoelectric optimization based on the module design was carried out using computer simulation. One of the parameters that can be used for analysis is the maximum output power which is thought to be increased through the cross-sectional area, length, shape, and type of pairs of legs. The thermoelectric properties used in the simulation are the Seebeck effect, resistivity, thermal conductivity, finite element analysis (FEA), and power output to understand the processing of simulation results. The research begins by making a design for each variation, entering the specifications, then the running process and calculations to obtain the maximum output power. From the simulation results, it is known that the thermoelectric design will be optimal for small leg lengths, large cross-sectional areas, and using similar materials (Unileg) which have good specifications with a maximum output power value of 3.713×10^{-8} W for blocks, 3.634×10^{-8} W for cylinders, and 8.617×10^{-8} W for Unileg N-N.

ARTICLE HISTORY

Received: 28 Oct 2022
Revised: 27 Jan 2023
Accepted: 13 April 2023

KEYWORDS

ANSYS
Finite element analysis
Power output
Thermoelectric

INTRODUCTION

The human need for energy is increasing. Therefore, many scientists are starting to develop alternative energy sources. Many alternative energy sources have been developed, some of which are steam, nuclear, solar cells, and so on. One alternative energy that has been widely studied is thermoelectric which is an alternative energy source which can convert waste heat into electrical energy. One of the related studies is optimization in terms of material improvement which has been carried out considerably. Other optimizations can be carried out by using a thermoelectric module geometry design which is easier and cheaper since this optimization can be done by simply forming a printed thermoelectric material. Thereof, a study will be carried out on thermoelectric optimization through the module geometry design.

A thermoelectric is a device which can convert energy between heat to electricity [1]. Thermoelectric requires materials which have high electrical conductivity and Seebeck coefficient, while the thermal conductivity is low [2]. Thermoelectric can convert a temperature difference to a potential difference thus it has a role as a generator (Thermoelectric Generator) as in Figure 1 or converts a potential difference into a temperature difference which can be used for cold temperatures thus it can act as a cooler (Thermoelectric Cooler).

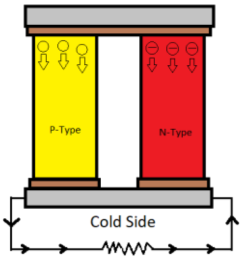


Figure 1. Energy conversion process in Unicouple thermoelectric module

The core of the thermoelectric material is a semiconductor, which is a material with a very small band gap between the conduction band and the valence band so that semiconductors have electrical conductivity between conductors and insulators. Based on the impurity (doping), semiconductors are divided into two, namely pure intrinsic semiconductors without any impurities and extrinsic semiconductors which have impurities such as N-type with impurity atoms with more electrons than the basic structure atoms and P-type with atoms with fewer electrons than structural atoms, basically [3].

One of the parameters related to see effectiveness of a semiconductor material used in thermoelectric devices is the figure of merit (zt). the higher the zt value, the better the thermoelectric performance. zt value of thermoelectric is

*CORRESPONDING AUTHOR | I. Fatimah | iimf@physics.its.ac.id

influenced by electrical conductivity (related to the ability of the material to flow electrons) [4], thermal conductivity (related to the ability of the material to conduct heat) [5], and seebeck coefficient (related to the ability to convert between heat and electricity) [6]. the relationship between these three factors can be seen in Equation (1).

$$zT = \frac{\sigma S^2 T}{\kappa} \tag{1}$$

Where σ is the electrical conductivity, κ is the thermal conductivity, S is Seebeck coefficient, and T temperature [7]. Finite element analysis (FEA) is an analytical method based on the finite element method. The method describes a complex system into a simple one by dividing it into elements and solving them partially. To get the results of computational analysis using the FEA method, several stages are needed, starting from the description of the actual system and modelling it. Furthermore, comparison of real models with physical phenomena (Physical Modelling). From the obtained physical phenomena, modelling of all the required formulas and equations (Mathematical Modelling) is carried out. After obtaining formulas and equations, the system is divided into small elements, the formula is applied to each element using computer calculations (computation). Eventually, after being processed by a computer, the results are compiled and analyzed in order that it become systematic data such as the distribution of heat, electricity, and so on [8],[9]. First, to describe a thermal electrical system, two main equations are needed, namely Equation (2) and Equation (3) (heat transfer and continuity of current density phenomena) for thermoelectric [9].

$$\rho c \frac{\partial T}{\partial t} + \vec{\nabla}.\vec{q} = Q \tag{2}$$

$$\vec{\nabla}.\left(\varepsilon \frac{\partial \vec{E}}{\partial t}\right) + \vec{\nabla}.\vec{J} = Q \tag{3}$$

T is temperature, $\vec{E}$ is electric field, $\vec{q}$ is heat flux, $\vec{J}$ is electrical current density, Q is internal heat generator, t is time, ρ is density, c is heat capacity, and ε is electric permittivity. Then, all the variables are described as in Equation (4) (Joule Heat), Equation (5) (Peltier Effect), and Equation (6) (Electric Field Relationship and Potential).

$$\vec{J} = \sigma\vec{E} - \sigma S \vec{\nabla} T \vec{J} \tag{4}$$

$$\vec{q} = \Pi \vec{J} - \kappa \vec{\nabla} T \tag{5}$$

$$\vec{E} = -\vec{\nabla}\phi \tag{6}$$

ϕ is electric potential. Next, the main variables (temperature T and Potential) are described into the interpolation function in Equation (7) to Equation (8).

$$T = [N]\{T_e\} \tag{7}$$

$$\phi = [N]\{\phi_e\} \tag{8}$$

T_e is vector of nodal temperature, ϕ_e is vector of nodal electrical potential, and N is element shape functions. Then, all the variables in Equation (2) and Equation (3) are replaced with all the described variables (Equation (4) to Eqeation (8)) and the FEA matrix equation like Equation (9) is made.

$$\begin{bmatrix} C_T & 0 \\ 0 & C_E \end{bmatrix} \begin{Bmatrix} \frac{\partial T^2}{\partial t} \\ \frac{\partial \phi^2}{\partial t} \end{Bmatrix} + \begin{bmatrix} K_T & 0 \\ K_{ET} & K_E \end{bmatrix} \begin{Bmatrix} T^e \\ \phi^e \end{Bmatrix} = \begin{Bmatrix} Q \\ I \end{Bmatrix} \tag{9}$$

C and K are element of matrix which describe coefficient in finite element equation. Equation (9) is what will be converted into computational form and used to process input data [9]. Every electronic device has a load (resistance/impedance) in it, therefore the device will always consume power when operated. Power itself is a measure of energy per unit of time thus power is related to the movement of energy. The energy in question can be anything such as chemical, heat, or electricity. One method to see the thermoelectric performance is to look at the output power of an electronic device (load). With the same temperature difference, it can be seen which thermoelectric module is better by comparing the maximum output power of the module. At the same temperature, the output power is also indirectly related to the thermoelectric conversion efficiency. The thermoelectric output power is related to the yield potential ($V_s = \alpha\,\Delta T = \alpha(T_H - T_C)$), the internal resistance of the material (foot resistance = R), and the load resistance (R_L). Mathematically shown by Equation (10).

$$P_0 = \alpha^2 (T_H - T_C)^2 \frac{R_L}{(R_L + R)^2} \tag{10}$$

Po is the output power, α is Seebeck coefficient, T_H is the hot side temperature, T_C is the cold temperature, R_L is the load resistance, and R is the internal resistance [10]. The output power will be maximum when $R_L = R$ [11]. Another parameter which can be used for thermoelectric analysis is its efficiency (η, conversion efficiency) which is the ratio of the input heat power (Qh) to the output power (Po). Mathematically the value can be written as in Equation (11).

$$\eta = \frac{Po}{K\Delta T + (|\alpha_P| + |\alpha_N|)T_h I + \frac{1}{2} I^2 R} \tag{11}$$

K is thermal conductance (W/K), α_P is P-type Seebeck coefficient (V/K), α_N is N-Type Seebeck coefficient (V/K), Th is temperature at hotspot (K), I is urrent (A) [11]. Many factors can hinder thermoelectric efficiency. Therefore, there are also many methods which can increase thermoelectric performance. Among the many methods are reducing the thickness of the thermoelectric leg, like Al-Fath reported [12], simulation results in this study show that the smallest thickness can reduce internal resistance but cannot explain the anomalies in some fabricated thicknesses where the internal resistance value is even greater, other is increase cross-section of the leg, like Ge did which result can increase induced EMF [13], changing the shape of the leg like Liu did can reduce thermal stress to increase performance of thermoelectric [10], and can also change modules into a single type (Unileg) like Aljaghtam did, which result can increase more efficiency if use single type semiconductor sincethat can reduce the risk due to the use of two different types [13]–[15].

Resistance (R) is related to the level of the material's ability to flow electrons (create current) with a certain voltage. Resistance is also related to the dimensions of the material. The basic property of resistance is related to resistivity (rho). Resistivity is a basic property of materials related to the material's ability to generate electric current regardless of dimensions. Therefore, if a material has a certain resistivity rho and volume dimensions V (V=l x A), then the relationship between resistivity can be seen in Equation (12).

$$R = \rho \frac{l}{A} \tag{12}$$

R is resistance (Ω), ρ is resistivity (Ω m), l is length of the material in the direction of the field from the potential difference (m), and *A* is the cross-sectional area of the material perpendicular to the direction of the field from the potential difference. From Equation (12), it is known that the resistance will increase if the material is long and will decrease if the material is wide [4].

EXPERIMENTAL METHODS

Materials and Instruments for Simulation

The physical materials and equipment used for the simulation are a PC (personal computer) with ANSYS 2021 R2 Software, Microsoft Excel 2019 installed in it, and MATLAB Online for making graphs. While the virtual materials and equipment needed are material models, such as $CaTiO_3$ with oxygen void (CTO +Vo) as a model material for P-type feet [16], SiC with a mixture of 30% AlN (SiC/AlN) as a model material for N-Type feet [17], alumina with a purity of 96% as a model material for insulators (electrically isolating the thermoelectric module), copper alloy as a model material for thermoelectric conductive parts (conducting output electricity), and a model material as a load test (Load) to determine the output power. Further specifications are as in Table 1 and Table 2.

Table 1. Materials specification

Materials Name	Specification			Source of Data
	Thermal Conductivity (W/mC)	*Seebeck* Coefficient (V/C)	Resistivity (Ωm)	
Alumina 96%	25	-	-	ANSYS Database (suhu 22-27)
Copper Alloy	401	-	1,69E-08	ANSYS Database (suhu 22-27)
Load	1	-	Depend on total internal resistance of leg	-
CTO(Tipe-N Leg)	4.806	-2.062 E-04	2.049E-04	Li, 2021
SiC (Tipe-P Leg)	13.348	1.169E-04	0.099	Besisa, 2018

Table 2. Other specification

	Value	Unit
Mesh Size	0.0005	m
Hot Temperature	27	°C
Cold Temperature	22	°C

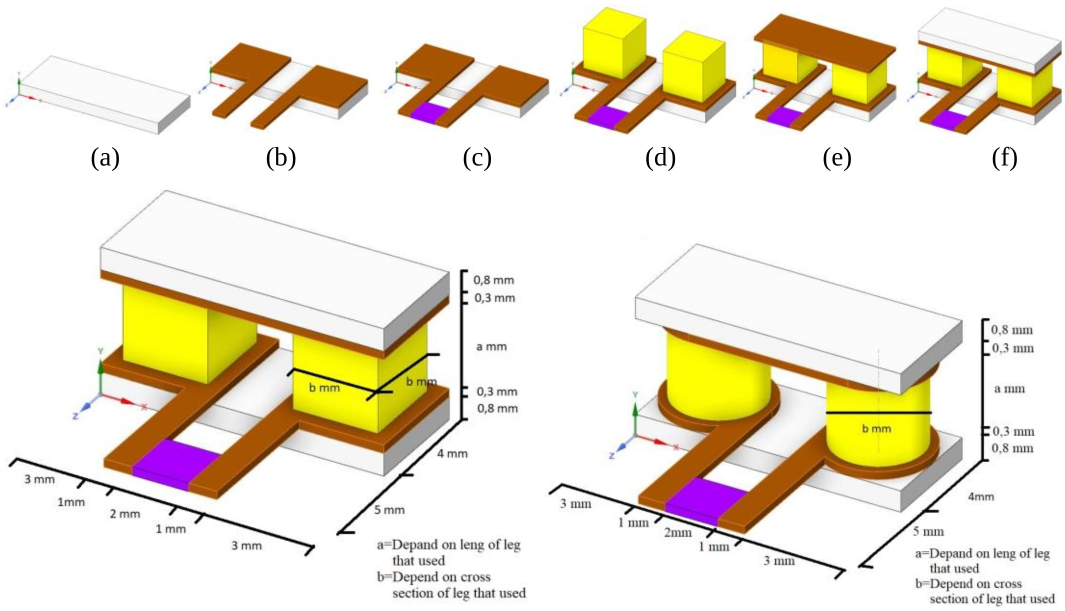
Simulation Conditions

The study started with the search for literature related to thermoelectrics, specifically in the module design section or the geometry of the thermoelectric. Next, several journals and books related to thermoelectricity were obtained, including two journals related to thermoelectric materials which use to model, CTO and SiC/AlN was chosen because journals which describe those materials are complete with the specification needed. After finding a journal which describes how to optimize thermoelectrically (like optimizing figure of merit, power output, etc), obtained four journals that focused on discussing variations which can optimize thermoelectric (cross-sectional area [13], leg length [12], shape [10], and types of pairs of legs [14]).

Table 3. Variation used

Variation Type	Variation		
Leg length/thickness	1 mm	2 mm	3 mm
Cross-section of leg	1X1 = 1 mm^2	2X2 = 4 mm^2	3X3 = 9 mm^2
Shape of leg	Block	Cylinder	
Type of pair of legs	Unileg P-P	Unicouple	*Unileg* N-N
Sum of sesign = [3 (Leg length/thickness) X 3 (Cross-Section) X 2 (Shape)]+1 (Type of pair of legs)=19 Design Type			
Sum of variation = 21 (Unicouple and Block 3x3x3 use the same design) (Unileg PP and NN use the same design)			

Variation of properties which was chosen to optimization, as described in Table 3, is length of leg, area or cross-section of leg, shape of leg, and type of leg pair, *unileg* which uses just one kind of semiconductor like P-P pair, and *unicouple* which uses one couple semiconductor like N-P pair. After obtaining the Variable Type, the value of the used variable is determined as in Table 3 and a design is carried out for each combination of variables (for those related to dimensions). The Design Step begins with the opening of the SpaceClaim 2021 R2 Software (including the ANSYS 2021 R2 Software family and included). Each step of making the design part in SpaceClaim starts with a 2D sketch and then drags it until a 3D shape (2D sketch > Pull > 3D shape) is obtained. The Design step begins by making the insulator plate, then the conductor plate, and Semiconductor Feet, then closing with the conductor plate and the insulator again as in Figure 2. Block shape are used because it is commonly used as well as for comparison, and cylinder shape is used because it is more effective, like described by Liu [10].



(g) (f)

Figure 2. Process of making thermoelectric module design: (a) bottom insulator plate; (b) bottom conductor plate (c) load; (d) thermoelectric leg; (e) top conductor plate; (f) top insulator plate; (g) size scale for block, and (h) size scale for cylinder

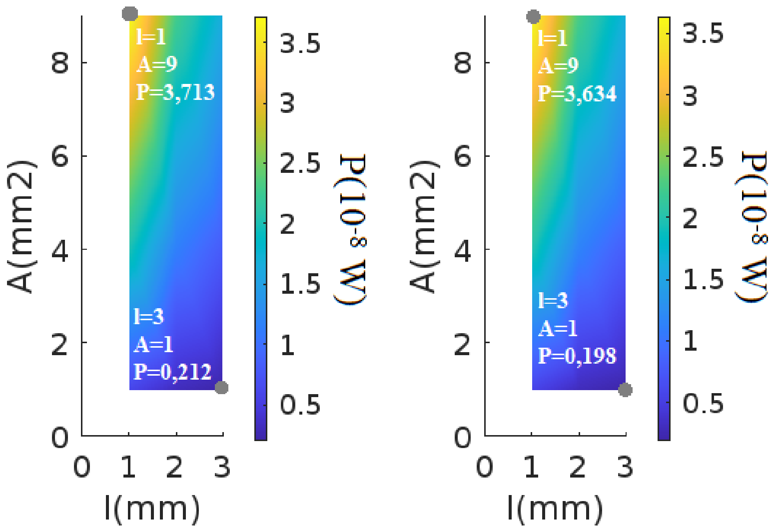
The next step is a simulation using Workbench Software (Includes Input Specifications and Running). The software used is ANSYS Workbench (ANSYS 2021 R2 Software Clump). The first step starts with the inclusion of specifications in the Engineering Data. Second, adjust the design parts with suitable materials and Mesh on the Model. Third, enter each probe used such as the temperature difference used and the Ground in Setup. Fourth, it is continued by entering the various desired results in the Solution menu and Fifth Running so that the results are obtained which will be recalculated to find the maximum output power and efficiency. Sixth, the maximum output power value graph is made using MATLAB and Excel.

Table 4. Experimental data

	l(mm)	A(mm^2)	Rpmax (Ω)	Vo (10^{-4} V)	P out max (10^{-9} W)	η (10^{-12})
Block	1	1	99.634	7.715	5.973	65.81
	2	1	199.268	7.899	3.131	17.25
	3	1	298.903	7.963	2.121	7.79
	1	4	24.909	7.101	20.25	892.2
	2	4	49.817	7.558	11.47	252.7
	3	4	74.726	7.727	7.99	117.4
	1	9	11.070	6.412	37.13	3682
	2	9	22.141	7.135	22.99	1140
	3	9	33.211	7.423	16.59	548.3
Cylinder	1	1	99.634	7.424	5.531	60.94
	2	1	199.268	7.624	2.917	16.07
	3	1	298.903	7.7	1.984	7.284
	1	4	24.909	7.066	20.05	883.3
	2	4	49.817	7.539	11.41	251.4
	3	4	74.726	7.715	7.966	117
	1	9	11.070	6.343	36.34	3603
	2	9	22.141	7.091	22.71	1126
	3	9	33.211	7.39	16.45	543.5
Type of pair	Unicouple N-P (3x3x3)		33.211	7.423	16.59	548.3
	Unileg P-P (3x3x3)		33.211	2.965	2.647	87.47
	Unileg N-N (3x3x3)		33.211	16.92	86.17	2848

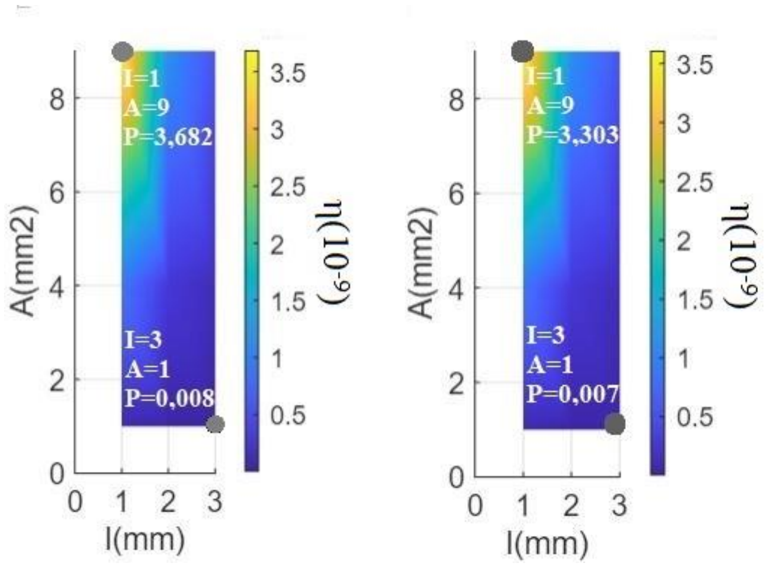
RESULTS AND DISCUSSION

After the simulation, the results of the potential output are obtained in Table 4. Then the calculations are carried out. After all the data has been calculated, the next step is to graph the maximum output power value in Table 4. Using MATLAB and Microsoft Excel, the data is processed to obtain results such as the color graphs in Figure 3, Figure 4, and Figure 5.



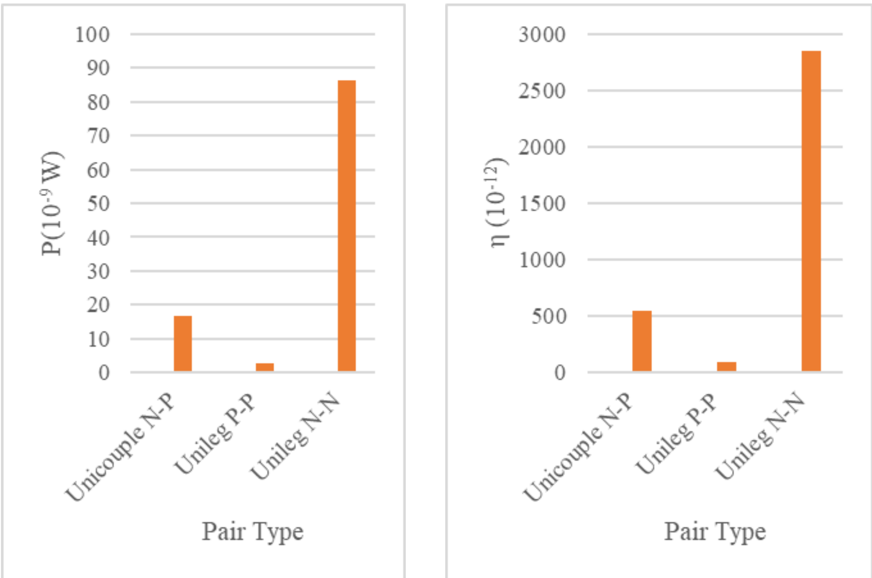
(a) (b)

Figure 3. Color grid graph Maximum output power: (a) block leg and (b) cylinder leg



(a) (b)

Figure 4. Color grid graph Conversion Efficiency: (a) block leg and (b) cylinder leg



(a) (b)

Figure 5. *Unicouple* and *Unileg Graphs*: (a) Maximum Output Power and (b) Conversion Efficiency

Dimension-related variables are the length/thickness of the foot and also the cross-sectional area related to its internal resistance. The shape of the foot is related to the distribution of thermal stress, as well as the deformation of the material. In addition, there are also variations in the types of pairs (Unileg and Unicouple) related to whether or not each material is used together or separately.

In this process, many design variations are made, the number of which corresponds to the product of the basic variables and form variables (3×3×2=18 variables) to ensure that each type of variable intersects with each other so that it can be analyzed thoroughly (Global, analyze just in one graphic). Especially for the Leg pairs variable, a special self-simulation was carried out to see the basic behavior (one stacked type) of the pair type.

In the temperature selection, a lower temperature equal to the base temperature/room temperature/default ambient temperature of ANSYS is selected. The temperature difference is kept small (5°C) to avoid changes in material characteristics due to temperature changes. The mesh used is 0.0005 m. This is the minimum Mesh size that the personal PC can do with minimal crashes on the simulation. After creating the mesh, the next step is running (Solve) Software and the results are obtained.

The cross-sectional area and length of the thermoelectric leg are the basic variables of the shape of the thermoelectric leg. The basic variable is related to the basic properties it has. In the color Grid Graph in Figure 3, it can be seen that both cylinders and blocks have a high maximum output power value with a large cross-sectional area. One of the properties, which affect it, is resistance like in Table 4. Resistance and Maximum Power Output has inversely relation like describe in Equation (10) if R_L=R. Resistance is inversely proportional to the cross-sectional area. The wider the cross-sectional area, the easier it is for electrons to pass through the material, so that the resistance is getting smaller and also the output power is getting bigger. This is because the reduced power wasted due to the internal resistance of the thermoelectric material [4]. It can also be seen in the color Grid Graph that the shorter leg length has the greater Maximum Power Output. Seen in This shows that there is an inverse relationship between power and the length or thickness of the foot. Likewise in the case of cross-sectional area. The length of the leg is also related to the maximum output power through resistance, where the resistance is directly proportional to the length of the leg like in Equation (12). Because the maximum output power also has a direct effect on efficiency, the graph form is not much different from the maximum output power, as shown in Figure 4. Thus, it is known the relationship between maximum output power and efficiency with the cross-sectional area and leg length, when the cross-sectional area is 9 mm^2 and the Leg length 1 mm. The maximum output power for the block is 3.713×10^{-8} W and the efficiency is 3.682×10^{-9}. For the cylinder, the maximum output power is 3.634×10^{-8} W and the efficiency is 3.603×10^{-9}.

For the shape of the legs analysis, in previous study about shape [10], it was stated that the shape of the cylindrical foot can reduce the deformation due to stress which occurs at the corners of the copper alloy plate on the thermoelectric block. However, it is not directly related to the output power. In this study, the relationship is seen through simulation. From Figure 3, both shapes (blocks and cylinders) have the maximum side (3.713×10^{-8} W for blocks and $3.634.10^{-8}$ W for cylinders), and minimum side (2.121×10^{-9} W for blocks and 1.984×10^{-9} W for the cylinder). The maximum Power Output value is dominating with Block, as well as for efficiency. It can be concluded that the reduction in deformation is not related to the maximum output power or it may be related to the less-than-optimal meshing process (either in terms of square meshing shape or mesh size).

For the type of pair of legs analysis, in previous studies about pair of leg [14], it was proven that Unileg had a better performance than Unicouple. However, this research shows that Unileg is not always better than Unicouple, depending on the type of material itself. In this study, it can be seen that the maximum output power or efficiency of the P-N Unicouple is lower than the Unileg N-N but still higher than the Unileg P-P, as shown in Figure 5. This can happen because the thermoelectric performance of N is superior to the P-type so that if it paired, the P-type hinders the performance of the N-type legs. Therefore, the function of Unileg's design is to make maximum use of single thermoelectric material (N only or P only) without using a partner which can actually hinder its performance.

CONCLUSION

Research on design-based thermoelectric optimization is carried out with several methods, including modifying the thickness of the legs, cross-sectional area, shape, and types of pairs of thermoelectric legs. Experiments were carried out using ANSYS software to obtain optimal results from these variables. From the simulation experiment, it is found that the Thermoelectric Module Design will be optimal when the leg length is small, the cross-sectional area is wide, the block shape, and also pairs of Unileg legs using good single material.

ACKNOWLEDGEMENT

This research is supported by Research Grants, Department of Physics Fund 2018 with a contract No: 2175/PKS/ITS/2018. The authors would like to thank the Instrumentation Laboratory, Department of Physics, Institut Teknologi Sepuluh Nopember for experimental equipment.

REFERENCES

[1] D. Dávila Pineda and A. Rezania, Eds. *Thermoelectric Energy Conversion: Basic Concepts and Device Applications, 1st ed*. Winheim: Wiley, 2017.

[2] M. Alawiyyah, A. Vora-Ud, S. Thaowankeaw, T. Seetawan, and M. S. Muntini, and I. Fatimah. "Pengaruh variasi temperatur uji ZEM-3 pada properti termoelektrik lapisan tipis Ti-doped ZnO." Jurnal Sains dan Seni ITS, vol. 9, no. 2, p. B1–B6, 2020.S

[3] W. Jiang. "Overview of semiconductor thermoelectric power generation technology." in *AIP Conference Proceedings*, 2020, vol. 2238, no. 1, p. 020003.

[4] C. K. Alexander and M. N. O. Sadiku. *Fundamentals of Electric Circuits, 5th ed*. New York: McGraw-Hill, 2013.

[5] D. Halliday and R. Resnick. *Fundamentals of Physics, 9th ed.* Ohio: John Wiley & Sons, Inc., 2011.

[6] B. I. Ismail and W. H. Ahmed. "Thermoelectric power generation using waste-heat energy as an alternative green technology." *Recent Patents on Electrical & Electronic Engineering (Formerly Recent Patents on Electrical Engineering)*, vol. 2, no. 1, pp. 27–39, 2009.

[7] T. M. Ashani, P. O. Adebambo, F. Ayedun, I. O. Osinuga, M. A. Idowu, and G. A. Adebayo. "The effective mass, fitness function and enhanced thermoelectric properties in CuSbS2 for p-type thermoelectric material applications: Density functional theory approach." *Materials Science and Engineering: B*, vol. 273, p. 115404, 2021.

[8] S. W. Lee and P. W. Chung. *Finite Element Method for Solids and Structures: A Concise Approach*. Cambridge University Press, 2021.

[9] T. Seetawan, U. Seetawan, A. Ratchasin, S. Srichai, K. Singsoog, W. Namhongsa, C. Ruttanapun, and S. Siridejachai. "Analysis of thermoelectric generator by finite element method." *Procedia Engineering*, vol. 32, pp. 1006–1011, 2012.

[10] L. Liu, X. Meng, Z. Miao, and S. Zhou. "Design of a novel thermoelectric module based on application stability and power generation." *Case Studies in Thermal Engineering*, vol. 31, p. 101836, 2022.

[11] M. M. Barry, K. A. Agbim, P. Rao, C. E. Clifford, B. V. K. Reddy, and M. K. Chyu, "Geometric optimization of thermoelectric elements for maximum efficiency and power output." *Energy*, vol. 112, pp. 388–407, 2016.

[12] F. N. F. Al-Fath. "Studi Eksperimen dan Simulasi Pengaruh Ketebalan Geometri Material Terhadap Kinerja Generator Termoelektrik." Tugas Akhir. Institut Teknologi Sepuluh Nopember, Indonesia, 2020.

[13] Y. Ge, K. He, L. Xiao, W. Yuan, and S.-M. Huang. "Geometric optimization for the thermoelectric generator with variable cross-section legs by coupling finite element method and optimization algorithm." *Renewable Energy*, vol. 183, pp. 294–303, 2022.

[14] M. Aljaghtham and E. Celik. "Design of cascade thermoelectric generation systems with improved thermal reliability." *Energy*, vol. 243, p. 123032, 2022.

[15] X. Wang, H. Wang, W. Su, T. Chen, C. Tan, M. A. Madre, A. Sotelo, and C. Wang. "U-type *unileg* thermoelectric module: A novel structure for high-temperature application with long lifespan," *Energy*, vol. 238, p. 121771, 2022.

[16] J. Li, Y. Wang, X. Yang, H. Kang, Z. Cao, X. Jiang, Z. Chen, E. Guo, and T. Wang. "Processing bulk insulating $CaTiO_3$ into a high-performance thermoelectric material." *Chemical Engineering Journal*, vol. 428, p. 131121, 2022.

[17] D. H. A. Besisa, E. M. M. Ewais, E. A. M. Shalaby, A. Usenko, and D. V. Kuznetsov. "Thermoelectric properties and thermal stress simulation of pressureless sintered SiC/AlN ceramic composites at high temperatures." *Solar Energy Materials and Solar Cells*, vol. 182, pp. 302–313, 2018.