Numerical analysis of optimized flower-shaped metamaterial thermal concentrator application as a heat concentrator in thermal to electrical energy conversion using the thermoelectric device

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Abstract. Nowadays, the research about the harvesting of renewable energy sources is more interesting on being able to do the conversion and conservation of thermal energy source, which is very abundant in our environment especially in form of waste heat. The abundance of waste heat energy in our daily life is needed to be converted to become something useful like electrical energy. The research about a material called metamaterial in the form of thermal concentrator has shown the capacity for focusing heat flux into a specific area. Optimized flower-shaped metamaterial thermal concentrator design is successful to concentrated the heat flux from any direction to specific area efficiently. This research is about numerical analysis of harvesting thermal energy to become DC electrical energy by using a design of metamaterial thermal concentrator, especially the design of optimized flower-shaped metamaterial concentrator by using the thermoelectric device. The result showed that with using optimized metamaterial thermal concentrator can increase the output voltage of thermoelectric device become 4.1 volt, compare than without using the concentrator that just gets output voltage 3.3 volt.

1. Introduction

Energy needs are increasing in line with the rapid advances in technology that vary in the modern era today and in the future. Energy sources that are widely used to date are non-renewable sources such as oil, coal and natural gas. Because energy needs increase, human efforts to exploit the energy sources also increase [1]. Given the limited supply of energy sources, it has motivated conservation efforts and the conversion of other energy sources such as solar energy, wave energy, wind energy and heat energy to be converted into electrical energy.

The amount of wasted heat energy from industrial processes is unavoidable, facilities can reduce this loss by increasing equipment efficiency or installing waste heat recovery technology. To harvest heat energy from waste heat, media that can be used as heat collectors from the flow of heat flux are needed [2]. A heat concentrator can theoretically be more efficient for harvesting heat energy each time the heat flux from changing directions can be concentrated to certain nuclei or locations. The thermoelectric device is one of the device that can convert heat energy in form of waste heat energy become electrical DC energy source by using Seebeck effect. The use of thermoelectrics is
limited to low efficiency. This happens because materials that have good electrical conductor properties tend to be good heat conductors. This means that at the same time the temperature difference produces a voltage, the temperature difference also decreases, thus weakening the current. Materials that have high electrical conductivity and high thermal conductivity behave badly in changing temperature differences into voltage sources.

Harvesting of heat energy through manipulation of heat and focused heat fluxes has been proposed by researchers as a practical extension of the work on thermal metamaterials and has practical applications for autonomously driven sensors or self-activated devices [3]. In research of thermal metamaterials conducted by Liu et al [4], the metamaterial design as a concentrator has been analyzed numerically and experimentally and provides excellent concentration efficiency with an increase in satisfactory energy density and temperature gradients intensifying into the target core, while the temperature profile remains undisturbed.

The basic concept of design which was developed by Liu et al. [4] and then optimized again by Muslimin et al. [5]. The concept of this metamaterial design by directing heat flux is well explained by Bandaru et al. [6] with the heat flux angle equation below.

$$\varphi = \tan^{-1} \left( \frac{(-1 + c) \sin(\theta) \cos(\theta)}{\cos^2(\theta) + c \sin^2(\theta)} \right), \text{ with } c = \frac{1 + \left( \frac{k_1}{k_2} \right)^2}{4 \cdot \frac{k_1}{k_2}}$$

The equation then becomes the basis of the flower-shaped configuration using several metamaterial configurations that have been arranged to obtain the angle of heat flux that can lead to the design center area to make a thermal concentrator.

Based on the design carried out by Muslimin et al. [5], this study aims to determine the performance of the application of the optimized flower-shaped metamaterial thermal concentrator design for thermal to electrical energy conversion systems using numerically designed thermoelectric devices.

2. Optimized flower-shaped thermal concentrator design

![Figure 1](image)

**Figure 1. Design Of Optimized Flower-Shaped Thermal Concentrator [3]**

Numerical transient thermal analysis has been carried out by Muslimin et al [5] to analyze the design of flower-shaped metamaterials that have been optimized with profiles as seen in Figure 1.
Figure 2. The zone temperature profile of the metamaterial thermal concentrator [5]

Muslimin et al [5] divided the temperature profile zone into five parts, namely number 1 is the background zone, from the hot side edge to the outer circle of the concentrate. Number 2 is the petal part from the outer circle of concentrator to the circle boundary in the concentrator. Number 3 along the core diameter, number 4 is from the right side of the inner core boundary to the right side of the outer circle boundary, and number 5 is from the outer circle to the edge of the cold side material as seen in figure 2.

Figure 3. Temperature distribution [5]

The results of this design show that a thermal concentrator can direct heat to the center of the material as seen in figure 3, and harvest heat flux from an area wider than the heat source and then concentrate it well on the core part of the concentrator as shown in figure 4. This is indicated by the highest temperature indicators and the highest total heat flux collected (red scale) which can narrow to the core with more areas on the core surface with the highest total heat flux that can be collected in the nucleus is 1.1 W / mm2. The efficiency of the concentrator metamaterial designed by Muslimin et al [5] was 89.62%
3. Application of optimized flower-shaped metamaterial concentrator for thermoelectric

3.1. Application Design

Metamaterial concentrators are used on various heat surfaces of equipment that produce waste heat. The metamaterial thermal concentrator is arranged in an array on the heat source and serves to direct the heat flux to the core of the concentrator which will be attached to the generator thermoelectric device and then the heat source will be generated as a voltage source. More and more metamaterial concentrators are used due to the large amount of thermal energy that can be collected and the greater the amount of stress that can be generated from the heat energy wasted from a hot surface. For more details, a description of the design of the application of a thermoelectric metamaterial concentrator can be seen in figure 5.
phenomenon, the authors just designed 1 pair of thermoelectric semiconductors in this research. The picture of the thermoelectric design of this research can be seen in Figure 6.

![Figure 6. Single element thermoelectric simulation design](image)

3.2. Comparison of Thermoelectric Simulations Using Metamaterial Thermal Concentrator and Without Thermal Concentrator

In this simulation, the analysis is carried out by using 2 temperature variations, namely Metamaterial with $T_h = 134.54 \degree C$ on the core section, and the temperature of a cross-section with a distance or temperature sample point which is the same as the point where thermal concentrator is used without the concentrator being used. $T_h = 122.58 \degree C$ and the condition of cold temperature section is $T_c = 70 \degree C$. This value of $T_c = 70 \degree C$ is assumed to be the value of environmental temperature where if the application of a combination of thermal concentrator material as shown in figure 6 where the condition of the average temperature of the environment around the tool can increase from the average air temperature to normal. The results of the simulation are shown in Figure 7.

![Figure 7. The results of a thermoelectric simulation](image)

The results of the single element simulation of semiconductor pairs show that the voltage that can be produced by the design concentrator metamaterial is 0.0324 volts and without using a thermal concentrator the resulting voltage is 0.0269 Volt. From these results, for a thermoelectric generator with a total of 127 pairs of semiconductor elements, it can be estimated that the voltage value obtained is 4.1 Volt for a thermoelectric device use metamaterial thermal concentrator and without using a thermal concentrator the resulting voltage is 3.30 Volt. This shows that using a metamaterial thermal concentrator on a thermoelectric device can increase the voltage value compared without using a concentrator.

4. Conclusion

From the results of this research, it was found that the application of metamaterials especially the design of the Optimized Flower-Shaped design by Muslimin et al [5] can concentrate or collect heat energy well. This increases the amount of power produced by increasing the voltage value by the device heat-converting to electrical energy, namely the thermoelectric device placed at the center of the metamaterial design with the same current value.
The ability to combine metamaterial thermal concentrator with this thermoelectric device in the future in the application is expected to be a consideration for designing heat energy harvesting devices, especially harvesting waste heat energy derived from thermal machines so as to increase the efficiency of energy use in various fields. should be avoided whenever possible. If required they should be used only for brief notes that do not fit conveniently into the text.

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