INTERNATIONAL JOURNAL of RENEWABLE ENERGY RESEARCH
P. Thanthong et al., Vol.12, No.1, March, 2022

Radiation-Based Thermoelectric Power Generation with Finned Heat Absorber

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Received: 16.09.2021 Accepted: 04.10.2021

Abstract- This paper reports experimental performance of a new concept of waste heat thermoelectric power generation using radiative heat transfer with horizontal finned heat absorber (TEG-RFA). To this end, a lab-scale experimental setup was built using a heated plate (297 mm length and 182 mm width), horizontal finned absorber, thermoelectric modules and air-cooled finned aluminum heat sink 119 mm wide and 200 mm length with two DC fans. Four sets of horizontal finned absorber 41 mm wide and 55 mm length with 40x40 mm thermoelectric module were assembled, the absorber assembly was well insulated on the lateral sides. The air gap space between the heated plate and finned absorber could be adjusted. In this paper, five air gaps (1, 2, 3, 4 and 5 cm) and five electrical powers supplied to the heater (1000, 1100, 1200, 1300 and 1400 watts) were considered. Temperatures at different positions and generated voltage and current were recorded. Experimental results showed that the electrical current generated increased with increasing the power supplied and decreased when increasing air gap. The maximum electrical power generated and the corresponding temperature difference between the hot and cool sides of thermoelectric modules were 1.20 Watt and 118°C at 1400 Watt and 1 cm air gap whereas the minimum measured parameters were 0.060 Watt and 14.90°C at 1000 Watt and 5 cm air gap. The maximum TEG-RFA efficiency is about 7.4%. Therefore, it is well demonstrated that the use of finned absorber is an interesting option for radiative waste heat thermoelectric power generation namely in industries.

Keywords Finned heat absorber, radiative heat exchange, thermoelectric power generation, waste heat recovery.

1. Introduction

Despite actual economic crisis due to COVID-19 and relative stabilization of energy consumption worldwide, demand for energy shall continue to increase due to the use of smart technologies, home automation, electrical vehicles and mass transportation while energy resources such as fossil fuel, coal, natural gas etc. are decreasing and may be depleted in the future. Today it is widely admitted that electrical power generation using renewable energy and waste heat recovery offer promising solutions for power generation. Efforts to increase the ratio of renewable energy part are seen in many countries worldwide. The Number of solar and wind farms have increased significantly due to reduced cost and technological advances. However, waste heat recovery has experienced slower development. This is due to several reasons that vary from one country to another such investment cost, installation difficulties, technical and practical problems etc. A complete review of this topic is out the scope of this paper.

Among the various alternatives to recover heat wasted from industrial plants, thermoelectric technology that can transform heat into electrical current directly based on Seebeck effect [1] seems to be the most attractive, figure (1). Thermoelectric generator (TEG) offers many advantages such as being highly reliable, having no moving parts, and being environmentally friendly [2]. Owing to these advantages, there have been considerable efforts at the end of the last decades on the development of small TEGs for a variety of applications using various heat sources including renewable energy especially flat and concentrating solar collectors [3-9], biomass [10-11] and waste heat sources [12-14]. Interesting reviews on thermoelectric renewable energy and principal parameters that affect their performance are reported in [15-16]. Thermoelectric generator sandwiched in a crossflow heat exchanger was also investigated in [17-18]. Research reported in [19] estimated that 20% of electrical energy used could be produced using waste heat from industrial sector. Moreover, due to the advances of nano technology in thermoelectricity [20], new materials [21], developement of design and enegineering softwares [22] and concepts improving conversion efficiency [23-28], it is expected that thermoelectric generators will experience accelerated development in the near future with improved conversion efficiency.

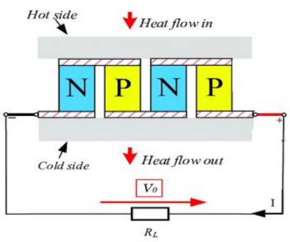


Fig. 1. eration.

It should be pointed out that most published research papers did consider the use of conductive and convective heat transfer mechanisms to collect heat due to simplicity and efficiency whereas the use of radiative heat exchange principle had received less attention. However, as there is no direct contact between the heat source and the TE modules, TEG design and system assembly seems to be more practical without the need for any modification of the industrial process in use. This concept for harvesting waste heat by using radiative heat exchange principle was initially investigated in [29] using a simple experimental setup with flat plates heat emitter and heat absorber. Results showed that using 10 thermoelectric modules, the maximum electrical power generated was 0.3132 watts at 0.5 cm air gap between the heat emitter and absorber and 35◦C temperature difference between hot and cold sides of thermoelectric module was recorded. In order to reach steady temperature difference between the hot and cold sides of TE modules and ensure constant current generation, authors used an open loop high flowrate of water. This may represent an important obstacle for the application in real systems as significant amount of water for cooling TEG is required. Also, in real systems waste heat generated by the industrial process may vary and fluctuate continuously. Obviously, this shall impact the current generated by the TEG especially when heat is absorbed radiatively.

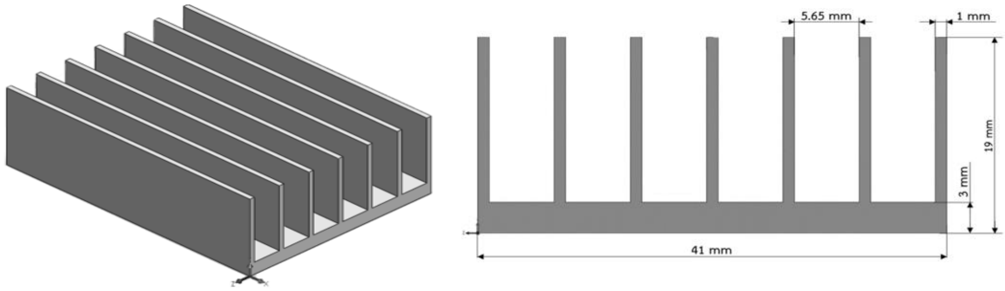
The objective of the paper is to propose a new concept to harvest waste heat emitted radiatively. The idea is to use finned absorber to absorb the incident heat instead of a flat absorber. The fins will play a role of a stabilizer of radiative heat emitted by the source as some the heat will be absorbed on the top of fins while remaining part, trapped between the fins, will be absorbed gradually from to the top of fins till their basis. This shall help minimize the impact of fluctuation of heat emitted and ensure relatively uniform temperature at the base in contact with the thermoelectric modules generating, therefore, relatively stable electrical current. For cooling, we use air for economic consideration.

2. Experimental Setup

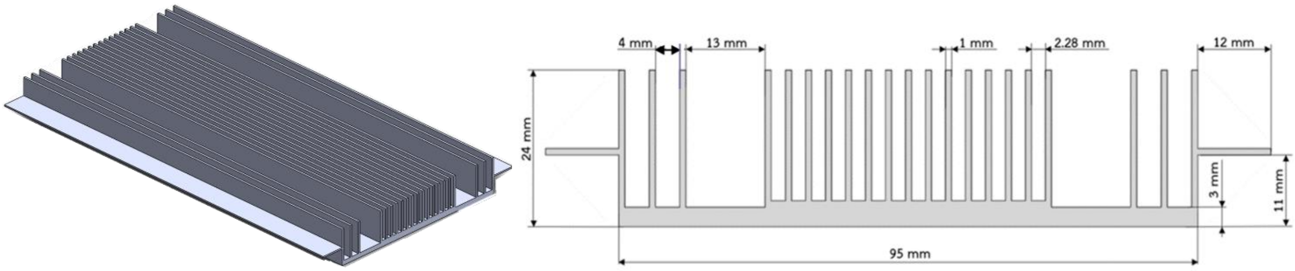
The new concept developed here is referred to as Thermoelectric Generator with Radiative Finned Absorber (TEG-RFA). To investigate our concept, we used four sets of commercial rectangular finned heat sinks 41 mm wide and 55 mm length (Fig.2.a) and 40 x 40 mm thermoelectric module (MT2-1,6-127) to absorb the radiative heat emitted by the heated plate. At the back side of thermoelectric modules, a finned aluminium heat sink (Fig.2.b) 119 mm wide and 200 mm length with two 12V, 0.20A DC fans (dimensions 80x80x25mm) was installed to cool the 4 thermoelectric modules. The absorber assembly was well insulated on the four lateral sides to protect heat transfer to the cooling heat sink. To simulate waste heat, we used an electrical heater fixed to an aluminium plate 297 mm length and 182 mm width. The power supplied to the heater can be adjusted using voltage transformer regulator (INPUT 0-220V/50-60Hz, OUTPUT 0-250V. The various components were assembled using screws located at appropriate positions. The air gap space between the heated plate and top of finned heat absorber could be adjusted manually. Figure (3) gives a schematic view and diagram of the experimental procedure and picture of the setup mounted on a metallic structure. Table (1) gives the specifications of thermoelectric modules used. Thermocouple type K (range from -270 to 1260 ˚C accuracy ±0.4%) were used to record temperature at different positions, electrical voltage and current were measured using Keithly DAQ 6510 data acquisition and multi-meter system. To limit the effect of varying ambient conditions, experiment was conducted in a laboratory room located at the 7th floor at the inner part of the building 63, College of Industrial Technology, King Mongkut's University of Technology North Bangkok.

3. Result and Analysis

In this paper, tests were conducted during 60 minutes for each case considered and all data were recorded continuously.



(a) Geometry and dimensions of finned heat absorber



(b) Geometry and dimensions of finned cooling heat sink

Fig. 2. Geometry and dimensions of (a) finned heat absorber and (b) cooling heat sink

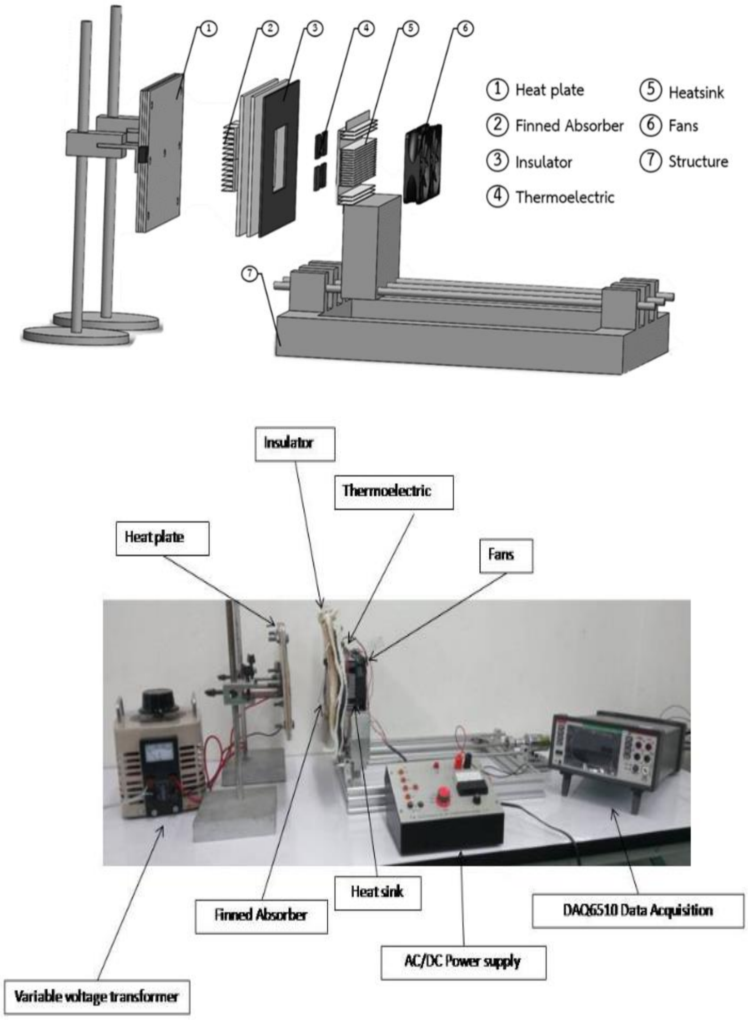
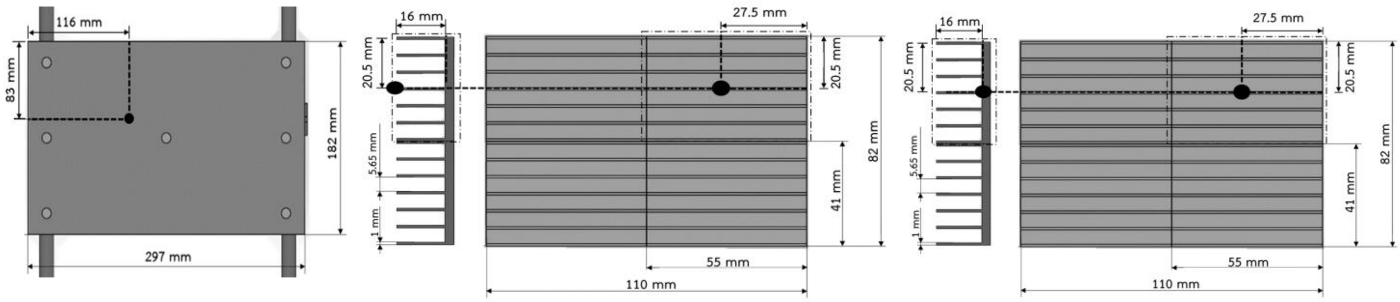


Fig. 3. Schematic of TEG-RFA (top) and experimental diagram and picture of the lab-sacle setup (bottom).

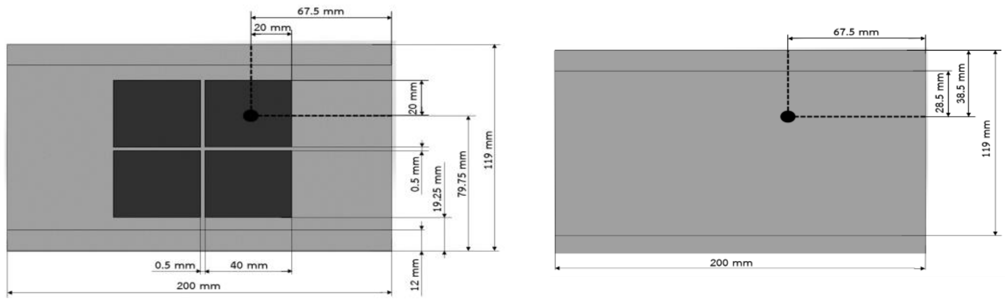


Top of fin

Base of fin

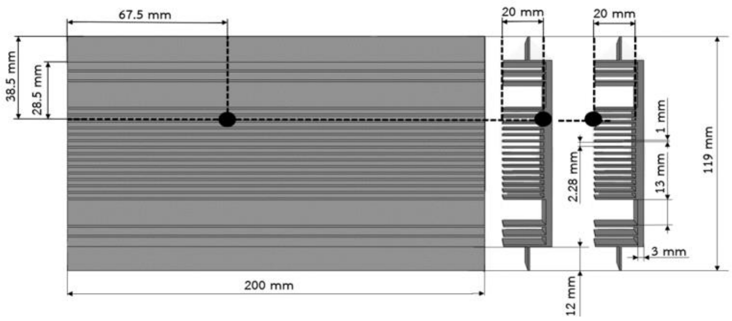
(a) Heated Plate

(b) Finned heat absorber



(c) Hot side of thermoelectric module

Cold side of thermoelectric module



(d) Top and base of fin of cooling heat sink

Fig.4. Positions of the temperature measurements: (a) Heated Plate (b) Finned heat absorber (c) Hot and cold sides of thermoelectric module (d) Top and base of fin of cooling heat sink.

Table 1. Specifications of Thermoelectric module MT2-1,6-127

Parameter	Cooling module
Leg height (mm)	1.2
Area of the thermoelement $(mm)^2$	1.96
Contact height (mm)	1.0
Insulator plate thickness (mm)	0.63
Module height (mm)	4
Area to length ratio	1.63
No. of couple (number)	127
Maximum operating hot side temperature (°C)	135

3.1 Temperatures Variations

Figure (5) shows the variations of measured temperature difference between (top) heated plate and top of fin of heat absorber, (middle) top and base of fin of heat absorber and (bottom) hot and cold sides of thermoelectric module versus time for the various electrical power supplied to the heater at 3 cm air gap.

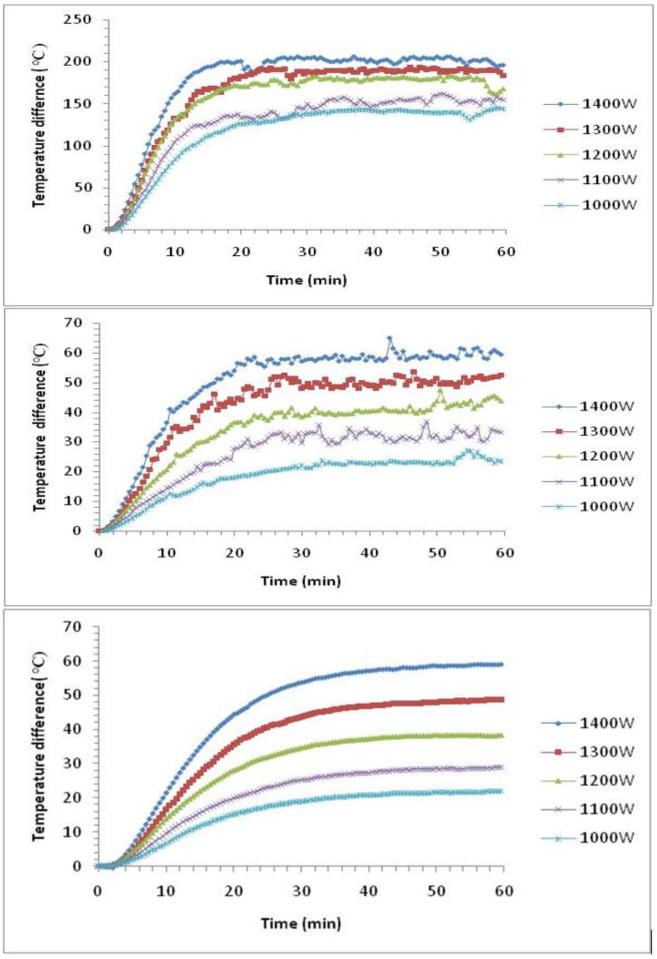


Fig.5. Variations of measured temperature difference between (top) heated plate and top of fin of heat absorber, (middle) top and base of fin of heat absorber and (bottom) hot and cold sides of thermoelectric module versus time for various electrical power supplied at 3 cm air gap.

It can be seen that the measured temperature differences increased continuously then reached a relatively steady state condition. Obviously, the higher the electrical power supplied to the heater, the higher is the temperature difference and the longer the time needed to reach steady condition. The measured temperature difference between heated plate and top of fin of heat absorber reached relatively steady condition within 10-20 minutes (Fig.5 top) whereas that between hot and cold sides of thermoelectric module needed longer time period about 30-40 minutes (Fig.5 bottom). It can be observed that the measured variations of measured temperature difference between (top) heated plate and top of fin of heat absorber, (middle) top and base of fin of heat absorber fluctuate continuously. These variations are due to the different heat transfer mechanisms taking place from the heated plate (radiative) through the finned absorber (radiative, conductive and conductive) and the thermoelectric modules till the cooling heat sink. However, the measured variations between the hot and cold sides of thermoelectric module (bottom) are more stable. This is due to the fact that there is only conductive heat transfer taking place through the base of absorber in contact with the TE module which reduced the heat fluctuation. Further detailed investigation of this matter is recommeneded. The longer the distance between the heated plate and the measured position, the longer is the time period needed to reach steady condition. Figure (6) shows the variations of measured temperatures of heated plate (Ts), base of fin of heat absorber (Tab), hot (Th) and cold (Tc) sides of thermoelectric module, and top of fin of cooling heat sink (Tsh) for different electrical power supplied to the heater at 3 cm air gap space at steady conditions. As mentioned earlier, the higher is the electrical power supplied the heater, the higher the measured temperature differences. Therefore, these results clearly demonstrate that our experimental setup as designed and tested is efficient as no overheating was observed without any damage to the thermoelectric modules.

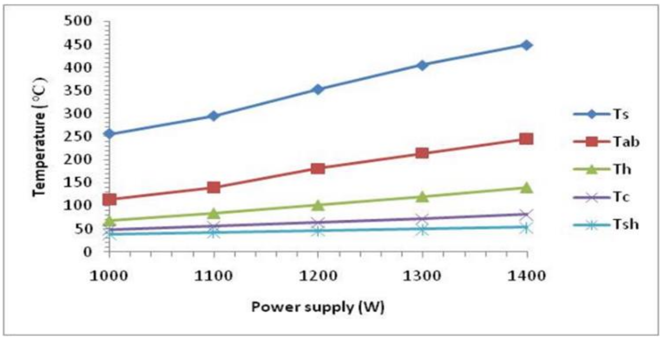


Fig. 6. Variations of measured temperatures of heated plate (Ts), base of fin of absorber (Tab), hot (Th) and cold (Tc) sides of thermoelectric module, and top of cooling heat sink (Tsh) for different electrical power supplied to the heater at 3 cm air gap space at steady conditions.

3.2 Electrical Current

Figure (7) shows the variations of measured electrical voltage, current and power generated by the TEG-RFA versus time for the different electrical power supplied to the heater at 3 cm air gap. It can be seen that the measured voltage (Fig.7 top) stabilized within relatively short time 5 to 15 minutes and was nearly close; it varied between 1.82-1.90 V. However, the measured current (Fig.7 middle) depended closely on the power supplied to the heater and took longer time about 20 to 30 minutes to reach relatively steady condition; the higher is the power the longer the time and the higher the current (varied between 0.098 to 0.41 Amp) and the power generated (Fig.7 bottom). These observations are typical for thermoelectric generators and depend closely on the specifications of thermoelectric modules used. When compared to results published in [29] where 10 thermoelectric cooling modules (TEC I-12706) and high amount of water for cooling were used at power supplies similar to ours, our TEG-RFA experimental setup could generate more electrical power varying between 0.17 to 0.78 Watt compared to 0.03 to 0.3 Watts as reported in [29]. That represents a significant improvement.

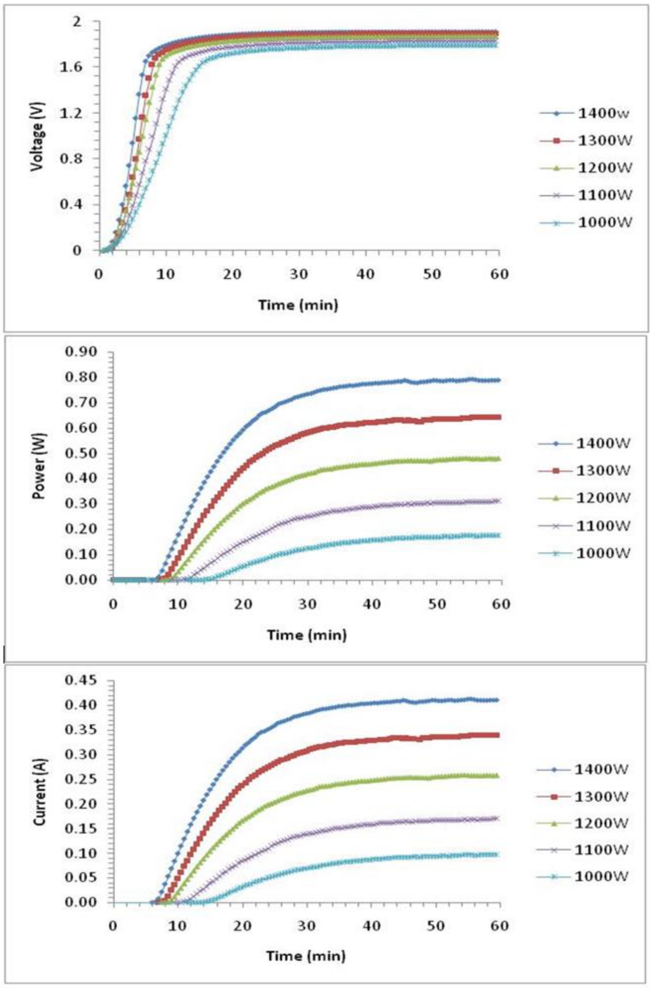


Fig. 7. Variations of measured voltage (top), electrical current (middle) and power generated (bottom) versus time for different electrical power supplied to the heater at 3 cm air gap.

3.3 Air Gap space

Figure (8) shows the measured variations of temperature difference between hot and cold sides of thermoelectric module and generated electrical voltage, current and power for the different air gap spaces and different power supplied to the heated plate considered at steady conditions. It can be observed that there is a close relationship between the electrical power supplied to the heated plate and air gap space. Increasing the electrical power supplied to the heated plate or decreasing the air gap space increases the power generated considerably.

We remind that our main motivation of this research is to develop a TEG that can absorb by means of radiative mechanism fluctuating waste heat generated by industrial processes to generate relatively constant electrical current. Varying the electrical power supplied to the heater can simulate the fluctuating waste heat and adjusting the air gap space by moving the TEG-RFA forward or backward according to the variation of temperature of the heat source can be adopted to generate constant electrical current. Using data from figure (8), the relationship between air gap space and power supplied to the heated plate to generate a constant 0.15 Amp electrical current can be illustrated in figure (9). Obviously, further investigation on this topic is recommended.

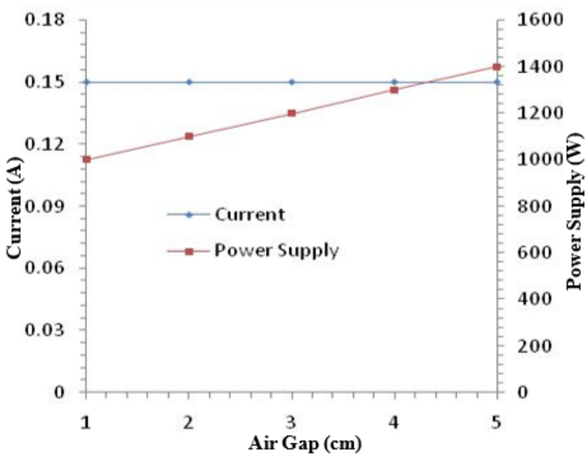


Fig. 9. Relationship between air gap space and power supplied to the heated plate to generate constant electrical current.

3.4 TEG-RFA Efficiency

To calculate the efficiency (η) of TEG-RFA, we followed the method adopted in [29] in order to make subjective comparison. It is defined as the ratio of generated power (*P*) and the radiative heat transferred from the heated plate to the fined absorber (*Q*) as given in below equation [29].

$$\eta = \frac{P}{Q} \qquad (1)$$

For simplicity, *Q* is expressed mathematically in the equation below [29].

$$Q = \frac{\sigma(T_1^4 - T_2^2)}{\frac{1-\varepsilon_1}{A_1\varepsilon_1} + \frac{1}{A_1F_{12}} + \frac{1-\varepsilon_2}{A_2\varepsilon_2}} \qquad (2)$$

Where,

σ = Stefan-Boltzmann constant (5.67x10^{-8} W.m^{-2}.K^{-4})

T_1 = Temperature of heated plate (K)

T_2 = Temperature of at the base of finned absorber (K)

ε_1 = Emissivity of heated steel plate [29,30]

ε_2 = Emissivity of aluminum finned absorber [29,30]

A_1 = Surface area of heated plate (m^2)

A_2 = Surface area of finned absorber plate (m^2)

F_{12} = View factor between the heated plate and finned absorber

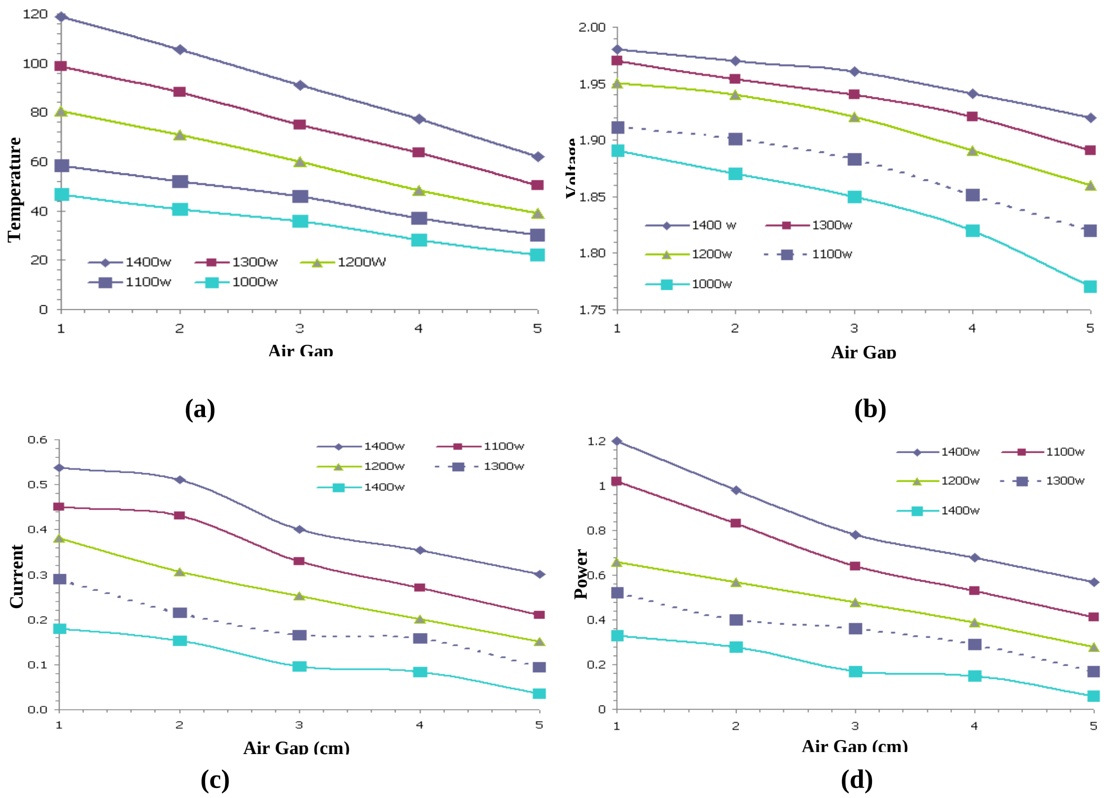


Fig. 8. Measured variations of (a) temperature difference between hot and cold sides of thermoelectric modules (b) generated electrical voltage (c) current (d) power for the different air gap spaces and different power supplied to the heated plate at steady conditions

Figure (10) shows the variation TEG-RFA for different power supply and at 3 cm air gap space. As discussed earlier, when the power supplied increases, the system efficiency increases and the shorter is the time needed to stabilize. At 1,400 watts, the maximum TEG-RFA efficiency is about 7.4%. Figure (11) shows the efficiency variation for the different air gap spaces considered at constant power supplied to the heater (1200 W). It can be seen that efficiency decreases significantly with increasing air gap and longer time period is need to reach steady condition. At an air gap of 1 cm, the maximum efficiency of the system is about 7.6 whereas at an air gap of 5 cm, the minimum efficiency of the system of 5% is observed. By comparing our results to data reported in [29] that indicated system efficiency varying between 0.1 to 1.1%, our efficiency is significantly higher that's satisfying.

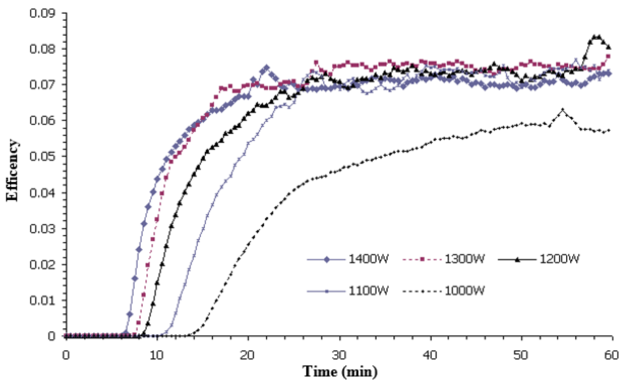


Fig. 10. TEG-RFA efficiency versus time for different power supply at 3 cm air gap.

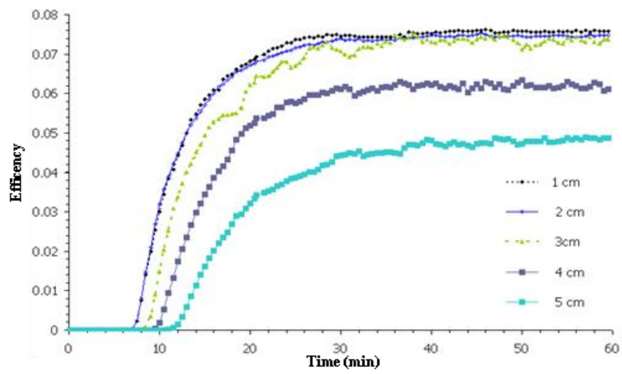


Fig. 11. TEG-RFA efficiency versus time for different air gap spaces and constant power supply (1200W).

4. Conclusion

A lab-scale experimental setup was built using a heated plate, finned absorber, thermoelectric modules and air-cooled heat sink to investigate the performance of a new concept of thermoelectric power generation using radiative heat transfer exchange with horizontal finned heat absorber (TEG-RFA). Four sets of horizontal finned sink 41 mm wide and 55 mm length with 40 x 40 mm thermoelectric module were assembled to absorb the radiative heat emitted by the heated plate. At the back side, a finned aluminium heat sink 119 mm wide and 200 mm length with two DC fans was installed to cool the 4 sets of TEG. Five air gaps (1, 2, 3, 4 and 5 cm) and five electrical powers (1000, 1100, 1200, 1300 and 1400 watts) supplied to the heater were considered.

Test results show that at a given power supply, the small the air gap, the higher is the generated electrical current. When the power supplied increases, the TEG-RFA efficiency increases and the shorter is the time needed to stabilize. At 1400 watt and 1 cm of air gap, the maximum measured electrical power is 1.20 watt. Whereas the minimum electrical power of 0.060 watt was generated at 1000 watts at 5 cm of air gap. The relationship between air gap space and power supplied to the heated plate to generate constant 0.15 Amp electrical current is also reported. When compared to data reported in [29], our TEG-RFA efficiency was significantly higher confirming, therefore, promising alternative to recover waste heat from industrial processes as there is no direct contact between the heat source and the thermoelectric generator. Numerical investigation of the effect of fins on the performance of TEG is necessary to determine the optimum configuration of heat absorber for radiative waste heat TEG. A sophisticated experimental setup with large surface area and automatic control of the air gap space depending on temperature of emitted heat source and required power generated needs to be elaborated and tested.

Declaration of Competing Interest

The authors declare that there is no conflict of interest.

CRediT authorship contribution statement Pisut Thanthong: Experimentation, Investigation, Writing, **Joseph Khedari:** Conceptualization, Methodology, Analysis, **Preeda Chantawong:** Analysis, Writing - review & editing.

Acknowledgment

The authors would like to express their appreciation to College of Industrial Technology, Graduate College, King Mongkut's University of Technology North Bangkok for providing area for this study.

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