Heat Transfer Analysis and Performance Investigation of Generator Thermoelectric Applied in LPG Stove Waste Heat Recovery

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Abstract- A thermoelectric generator (TEG) can convert heat from LPG gas stoves into electricity. The application of this conversion technology consists of three major components: a hot side heat exchanger, a TEG, and a cold side heat exchanger. This study investigates the effects of TEG cold surface cooling system variations on heat transfer and the thermoelectric generator module's electric performance when applied to convert liquefied petroleum gas (LPG) stove waste heat. Four thermoelectric generator modules are placed outside the plate and connected in series to take advantage of the waste heat. Three different cooling systems are used to cool the thermoelectric generator module's cold surface: a heatsink, a heatsink with a fan, and a water block cooling system. Measurement and data retrieval are performed using the temperature and electrical output from the TEG module. Temperature and electrical output from the thermoelectric generator module are measured and data retrieved, while the heat transfer that occurs in the cooling system is calculated using the formulation. The results indicate that the cooling system's heat absorption capacity increases by more than 300% when the heatsink with a fan is used. When compared to a heatsink with a fan cooling system (i.e., 47.09 J/s), using a water block as a cooling system can increase heat absorption by 27% or a value of 60.00 J/s. Based on the performance of the thermoelectric generator module in generating electricity, it is clear that when comparing an air-cooling system to a water block-based cooler, the water block-based cooler produces more power. Water cooling is the optimal method for obtaining a high-power output from the TEG module when this conversion technology is applied to convert LPG stove waste heat to electrical energy.

Keywords Waste heat, LPG stove, TEG, cooling system, heat transfer.

1. Introduction

The majority of the energy produced on the planet today comes from fossil fuels. However, using fossil fuels contributes to pollution, exacerbates the greenhouse gas effect, and runs out within the next few decades [1]. In particular, the fossil fuel in the form of LPG gas from the stove used can produce certain pollutants, such as particulate matter, which can increase the risk of respiratory disease for its users [2]. Future generations must reduce their reliance on nonrenewable energy sources, which can be accomplished by implementing and developing new renewable energy conversion technologies such as solar panels, hydropower, and other renewable energy sources [3].

Thermoelectric generators are a promising future energy conversion technology [4]. Compared to energy conversion from fossil fuels, water and wind utilize mechanical energy before converting it to electrical energy without requiring another energy transfer process [5]. Electrical energy from thermoelectric is generated by converting the temperature difference on the module's surface to electrical energy throughout the Seebeck effect [6]. Thermoelectric energy can also generate hot and cold temperatures throughout the Peltier effect [1].

Nomenclatures:

Symbols:

A	Surface area, m^2
c	Distance between fin, m
C_p	Specific heat, kJ/kg.K
D	Diameter, m
F_{s-surr}	Total view factor
h	Heat transfer coefficient, W/m^2.K
I_e	Electric current, A
K	Thermal conductivity, W/m.K
l	Fin length, m
$\dot{m}$	Mass velocity of water,
N	Number of
P	Power output, W
Q_{ch}	Radiation heat transfer rate from U-shaped channel, W
Q_{Fire}	Sensible heat in the burned, W
Q_{HS}	Heat absorbed to heatsink, J/s
Q_{WB}	Heat absorbed to water block, J/s
t	Fin thickness, mm
TEG	Thermoelectric generator
T_a	Ambient temperature, K
T_C	Cold surface TEG temperature, K
T_H	Hot surface TEG temperature, K
$T_{w.in}$	Input water temperature to water block, K
$T_{w.out}$	Output water temperature from water block, K
V	Voltage, V
w	Width, m
X_{fin}	Fin high, m

Greek Letters:

a	*Seebeck coefficient, V/K*
e	Emissivity
σ	Stefman Boltzman constant, 5,67 x 10^{-8} W/m^{2}K^4
ρ_f	Water density,
ΔT	*Different Temperature, K*
η_{fin}	Fin heatsink efficiency, %

Subscripts:

a	Ambient
cc	Close circuit
rad	Radiation
conv	Convection
fin	Fin
Hs	Heatsink
i	Internal
in	Input
L	Load
o	External
oc	Open circuit
out	output
rad	Radiation
s	Surface

This technology has several advantages if compared with other energy conversion technologies, such as long operating life, environmental resistance, soundness, no moving parts, no lubricant, and maintenance free [7, 8]. The thermoelectric module's energy conversion technology has been widely applied in the aerospace industry [9], combined photovoltaic systems [10, 11], automotive heat recovery [12, 13], and stove-powered generators [14, 15]. Thermoelectric technology can use waste heat generated by LPG gas stoves in small-scale industries. However, it should be noted that the efficiency of heat energy used for cooking on conventional LPG gas stoves is approximately 66.27% of the total heat energy supplied by gas stoves, with the remainder being wasted heat energy [16].

Utilizing thermoelectric generator module technology to convert heat energy into electrical energy allows the reuse of waste heat energy on LPG gas stoves. With the use of thermoelectric generator module technology to convert heat energy to electricity, it is possible to reuse waste heat energy on LPG gas stoves. The thermoelectric module application consists of three major components: the thermoelectric module (TEM), a hot-side heat exchanger (HHX), and a cold-side heat exchanger (CHX). CHX is used in the thermoelectric system to conduct heat energy away from the TEG's cold surface and into the surrounding environment. Effective heat exchanger design is critical in this study's energy conversion system [17]. To maximize the power and efficiency of the thermoelectric generator module, the temperature difference between the hot and cold surfaces should be as large as possible [18, 19]. The cooling process is critical for thermoelectric conversion systems, supplying a constant and stable heat source. The most used thermoelectric cooling methods in various thermoelectric power generation modules are air and water medium [20].

Therefore, researchers are trying to maintain the difference in TEG surface temperature by conducting experiments on the cooling system, which contributes to the temperature difference, using various methods of cooling the TEG surface. The paper's objective is to propose the most optimal TEG surface cooling system when applied to convert waste heat from LPG stoves to electrical energy.

1.1 Mathematical Modelling of Air-Cooling System

Refer to previous research [21, 22, 23], heat transfer that occurs in the air-cooling system can occur by convection ($Q_{Hs,conv}$) and radiation ($Q_{Hs,rad}$). The heat transfer in the air-cooling system is shown in Fig. 1.

$$Q_{Hs} = Q_{Hs,conv} + Q_{Hs,rad} \tag{1}$$

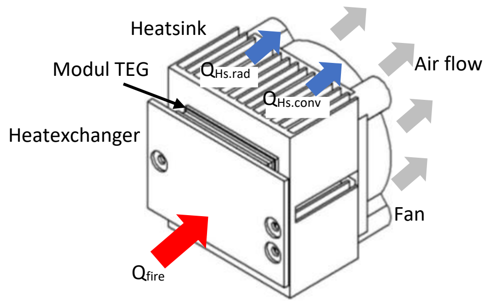

Fig. 1. Schematic of heat transfer in air conditioning systems.

The dimensions of the heatsink used in the experiment are shown in Fig. 2. The bottom plate in contact with the TEG surface is a flat plate with dimensions of 60 mm in length (L), 53.5 mm in width (w), and 2.5 mm in thickness ($t_{.fb}$). The heatsink has 13 fins and is made of aluminum, and the fin size of the heatsink is 27.5 mm in height ($X_{.fin}$), 1 mm in width ($t_{.fin}$), and 3.75 mm in the distance between fins (c).

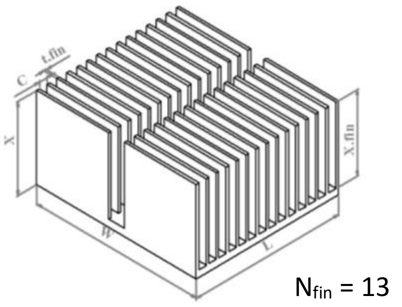

Fig. 2. Dimensions of heatsink.

The heat transfer by convection on the heatsink is calculated using the following formula [22]:

$$Q_{Hs,conv} = A_{unfin}.h_o.(T_{HS} - T_a) + \eta_{fin}.A_{fin}.h_o.(T_{HS} - T_a) \quad (2)$$

Where h_o is the coefficient heat transfer, T_{HS} and T_a are the fin heatsink temperatures and ambient temperature, respectively. The exposed surface area calculation using eq. (3) [22]:

$$A_{unfin} = (N_{fin} - 1).c.l \quad (3)$$

Total fin area including both sides of the heatsink cooling system is defined in eq. (4) [22]:

$$A_{fin} = N_{fin}(2.x_{fin}.l) \quad (4)$$

The efficiency of a heatsink fin can be calculated using the formula below, by assuming that the condition at the fin's tip is adiabatic [23]:

$$\eta_{fin} = \frac{tanh_o(m_{fin}.X_{fin})}{(m_{fin}.X_{fin})} \quad (5)$$

With,

$$m_{fin} = \sqrt{\frac{2(l + t_{fin})h_o}{l.t_{fin}.K}} \quad (6)$$

In the meantime, the formula below to calculate radiant heat transfer in the heatsink [24, 25]:

$$Q_{Hs,rad} = (N_{fin} - 1)Q_{ch} + [N_{fin}.t_{fin}.(l + 2x_{fin}) + 2.x_{fin}.l + 2t_{fb}(l + w)]\sigma\varepsilon({T_{HS}}^4 - {T_a}^4) \quad (7)$$

Heat transfer area of the U-Shape channel on the heatsink (Q_{ch}) [24]:

$$Q_{ch} = \frac{\sigma(c + 2.x_{fin})l({T_{HS}}^4 - {T_a}^4)}{(1 - \varepsilon/\varepsilon) + (1/F_{s-surr})} \quad (8)$$

View factor between fin and fin based on heatsink (F_{s-surr}) [24]:

$$F_{s-surr} = 1 - \frac{2.\overline{x_{fin}}.[(1 + \bar{l}^2)^{0.5} - 1]}{2.\overline{x_{fin}}.\bar{l} + (1 + \bar{l}^2)^{0.5} - 1} \quad (9)$$

Normally fin heatsink high [24]:

$$\overline{x_{fin}} = x_{fin}/c \quad (10)$$

Normally fin heatsink length [24]:

$$\bar{l} = l/c \quad (11)$$

The height of the fin base (t_{fb}) is defined using the Eq. (12) [24]:

$$t_{fb} = x - x_{fin} \quad (12)$$

1.2 Mathematical Modelling of Water-Cooling System

A thermoelectric generator, heat waste from an LPG stove, a cooling water circuit, and a DC water pump are schematically shown in Fig. 3(a) for waste heat utilization using a thermoelectric with a fluid cooler. Fig. 3(b) depicts the geometry of the cooling system used in this experiment. Inside the water block, there are fins with t.fin=1 mm, X.fin= 8 mm, and c=2.25 mm that will be fed with cooling water.

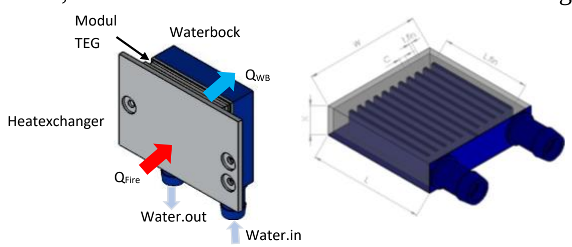

Fig. 3. a) Schematic of heat transfer in water cooling system, b) Geometry of water block.

The total heat energy from the cold side of TEG is absorbed by the water in the water block using the following formulation [26]:

$$Q_{wb} = \dot{m}.C_p(T_{w.out} - T_{w.in}) \quad (13)$$

Where $\dot{m}$ is the mass velocity of the water can be calculated used Eq. (14) [26]:

$$\dot{m} = \rho_f u_f D^2 \quad (14)$$

2. Experimental Setup

This study implemented the conversion system for utilizing the waste heat energy from the gas stove by modifying the LPG gas stove, as illustrated in Fig.4. Modification is done by adding a plate made of stainless steel around the gas stove fire source. The modification aims to use the heat generated by the plate around the fire as a source of wasted heat that can be converted into electricity using the TEG module. The modification of the gas stove is carried out without affecting the gas stove's primary function, ensuring that the stove function is preserved. Four thermoelectric modules are connected in series and placed on the plate's outer side. In this study, the teg used is of type SP1848-SA. Table 1 shows the specifications and dimensions of the SP1848-SA type TEG module. Three cooling methods are used in the TEG cold surface cooling system: a heatsink, a heatsink with a fan, and a water block. In the heatsink with fan cooling system, a DC fan with a power of 0.48 W use dissipates heat, whereas, in the water block cooling system, a DC water pump circulates 5 liters of cooling water and using a 300 L/h water flow rate measured with a water flow meter instrument, which has specifications listed in Table 2. The data collection process in this study was done at the system's working temperature and the thermoelectric module's electrical output in the form of voltage, current, and power.

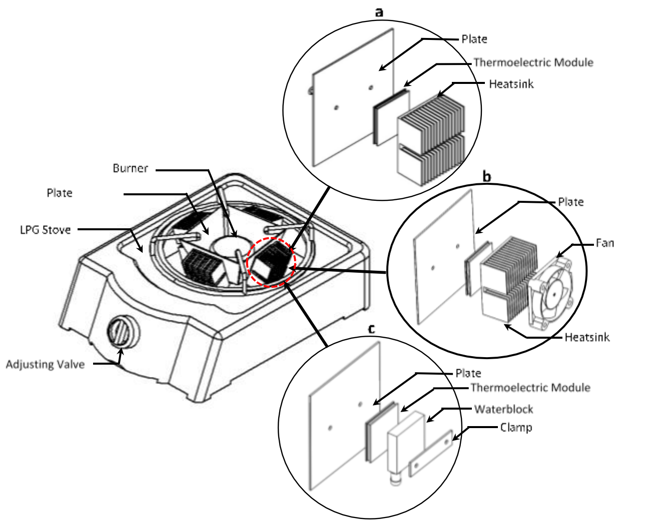

Fig. 4. TEG installation on LPG gas stoves with three different cooling systems: (a) heatsink, (b) heatsink with fan, and (c) water block.

Table 1. Specifications of Thermoelectric Generator Module Type SP1848-SA [27][28]

No	Parameters	Specifications
1	Dimension:	
	a. Width (mm)	40
	b. Length (mm)	40
	c. Total area (mm^2)	160
	d. Thickness (mm)	3.8
	e. Weight of module (gr)	25
	f. Thickness of ceramic layer (mm)	1
2	Materials:	
	a. P-leg	Bi2Te3
	b. N-leg	Bi2Te3
	c. Surface of TEG materials	Ceramic
3	Physical:	
	a. Maximum temperature (°C)	~300
	b. Thermal conductivity (W/K)	1/0.85 [22]
	c. Semiconductors pairs	12
	d. Electrical conductivity (W/m.K)	0.6
	e. Seebeck coefficient (V/K)	0.054 [29]
4	Manufacturing	SRT Co., Ltd

Fig. 5 shows that the thermocouple's position takes the temperature in this system. There are four temperature positions taken on the use of the air conditioning system, including the hot surface temperature of TEG (TH), the cold surface temperature of TEG (TC), the temperature of the fin-heatsink (THS), and ambient temperature (Ta). On the other hand, If the cooling system is water-cooled, the temperatures measured are the hot surface temperature of TEG (TH), the cold surface temperature of TEG (TC), the water temperature entering the water block (TW.in), and the temperature of the water leaving the water block (TW.out). Fig. 2 (b) shows the thermocouple's position using the cooling system water block. In this research, a thermocouple is connected to the Max 6675 sensor, and Arduino MEGA 2560 microcontroller is used to collect temperature data. Electrical output in the form of voltage, current, and power is measured by connecting the output data from the TEG module to a USB multimeter integrated with a laptop. The electrical output is in the form of voltage, current, and power. The measurement instrument's specifications are listed in Table 2.

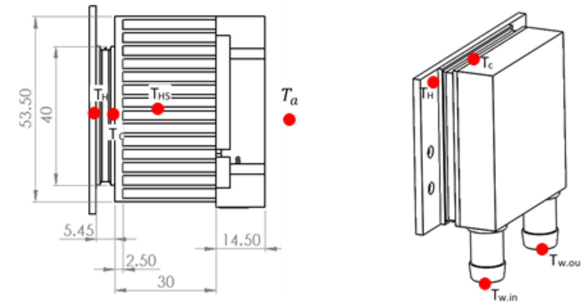

Fig. 5. Temperature measurement: (a) Heatsink with fan and (b) Water block.

3. Result and Analysis

3.1. *Temperature Profile on Surface of TEG*

Before analyzing the impact of cooling system changes on the heat absorbed by the cooler and the TEG module's electrical output performance, temperature at the TEG module's hot surface (T_H) and cold surface (T_C) were collected. The results of temperature measurements taken on the surface TEG module with cooling system variations are shown in Fig. 6.

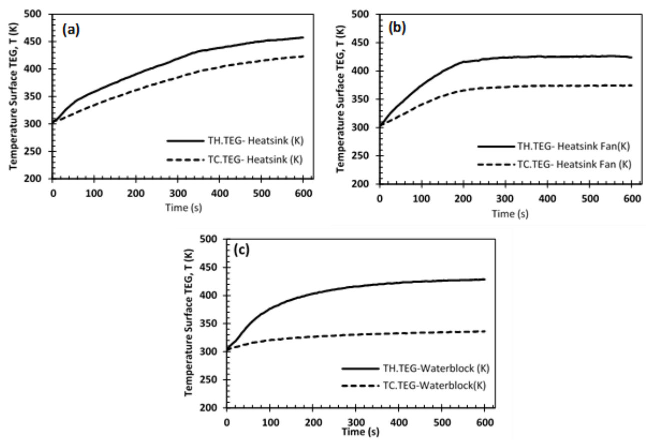

Fig. 6. Temperature profile on the surface of TEG with variations in the cooling system: (a) Heatsink, (b) heatsink with fan, and (c) water block.

Figure 7 shows the results of a temperature difference measurement between the hot and cold surfaces of the TEG module. The highest temperature difference was discovered in the TEG cooling system equipped with a water block. On the other hand, cooling the TEG module with air, either naturally (heatsink) or artificially (heatsink with fan), results in a lower surface temperature difference.

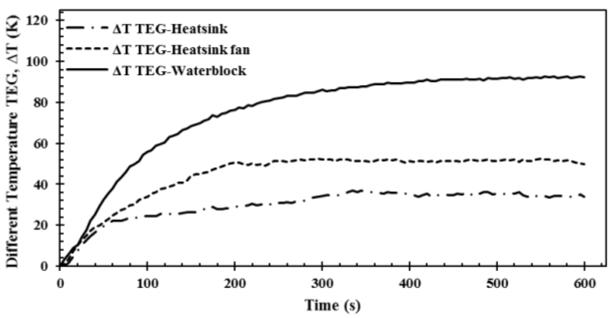

Fig. 7. Different temperature profiles on hot and cold surface TEG module.

3.2. Heat Absorbed by the Cooling System

Table 3 shows the measurement temperature at the T.hot (T_H), T.cold (T_c), T.water in ($T_{w.in}$), T.water out ($T_{w.out}$), and the calculation of heat absorbed by the cooling system. The system's average temperature is determined when the temperature is considered a steady state, and the heat absorbed by the cooling system is calculated using the formulas (2-14). The temperature on the hot surface of the TEG can be affected by differences in cooling systems. As a result, the more heat absorbed by the cooling system, the higher the surface temperature. This occurs due to the conduction heat transfer within the TEG module due to the cooling system's effectiveness. The heat absorbed by the heatsink from the hot to the cold surface of the TEG is still relatively low at 10.92 W. However, the heat absorbed increases by more than 300% with the heatsink with a fan cooling system. On the other hand, using a water block compared with a heatsink with a fan cooling system can increase heat absorbed by 27%.

Table 3. Heat absorbed calculation.

No	Cooling Method	Hot Surface TEG (K)	Cold Surface TEG (K)	Water In (K)	Water Out (K)	Heat absorbed by cooling system, Q (J/s)
1	Heatsink	365.50 ± 4.5	340.25 ± 4.1	-	-	10.92
2	Heatsink with fan	410.50 ± 4.75	362.50 ± 4.5	-	-	47.09
3	Water block	426.50 ± 7.12	334.75 ± 3.25	309.75 ± 1.75	311.25 ± 2.12	60.00

Fig. 8 compares the heat absorbed from cold surface TEG with the different cooling systems, demonstrating that the most effective cooling system employs a water block. Previously, research on using simple natural air convection to increase the temperature difference was conducted [30]. However, when compared to water, heatsink or heatsink with a fan is highly efficient, according to Murinková's research [31].

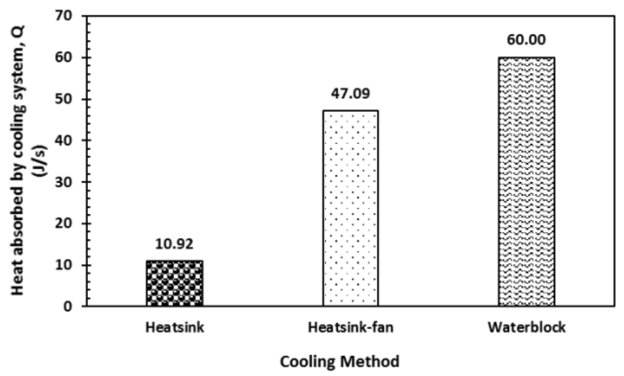

Fig. 8. Heat absorbed by cooling systems.

3.3. Performance of TEG Module

This experiment was intended to determine the effect of cooling system variations on a cold TEG surface on the performance of a TEG module heated by waste heat from an LPG gas stove. Output performance in the form of current and electric power. The results of the electrical output measurement in the form of an electric current are shown in Fig. 9. The results show that using a different cooling system will affect the current output generated by the TEG module. When a heatsink cooling system is used to cool the TEG surface, the electric current produced is low, whereas when a water block cooling system is used, the electric current produced is higher.

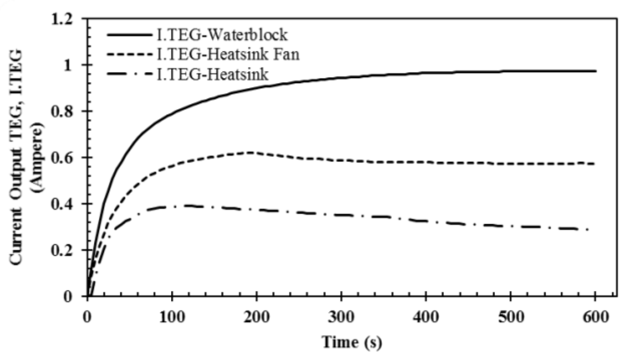

Fig. 9. Electrical current generated by TEG.

Fig. 10 displays the contours of the power output from the TEG module with various system cooling. We find that a heatsink with a fan cooling system produces more power than in the case of a heatsink cooling system, which is due to the higher heat transfer coefficient in the case of a heatsink with fan cooling compared to a heatsink cooling system [29]. We confirm it with the heat absorbed calculation on the TEG cold surface at their different cooling systems, as shown in Fig. 8. However, If the air-cooling system is compared to a water block-based cooler, the water block-based cooler will produce more power output as found based on previous research by T. Ishiyama [32]. When getting a high-power output from a TEG module, water block cooling should be the method of choice, and this research is in line with a study held by B. Pfeiffelmann [33].

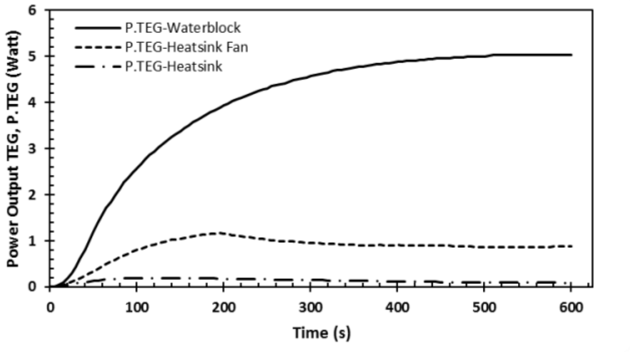

Fig. 10. Electrical power generated by TEG.

4. Conclusion

According to the heat transfer calculation in the cooling system, the heat absorbed is most excellent from the cold surface TEG when using a water block cooling system which is 60 J/s or 27% greater when compared to a heatsink-fan cooling system which can only absorb heat energy on the TEG surface of 47.09 J/s. While the module's performance in generating electricity by the experimental method, it can be concluded that when compared to a water block-based cooler, the water block-based cooler produces more power. When getting a high-power output from a TEG module, water block cooling should be the method of choice for the cooling system on the TEG surface when this conversion technology is applied to convert LPG stove waste heat to electrical energy.

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