Waste Heat Recovery by Thermoelectric Generator from Thermal Oil Heater Exhaust

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***Abstract*—Thermoelectric power generation by recovering waste heat is a worthy choice to improve the system efficiency. In this study, we reports a method to estimate the amount of power produced by Thermoelectric Generator (TEG) module, placed between flue gas duct and fresh air duct of an industrial thermal oil heater. Plate fin heat sink on hot and cold side of the TEG module was inserted into the flue gas and fresh air duct respectively. The effect of various design parameters, flow parameters were investigated in order to maximize the power generation. Bi_2Te_3 based commercial TEG module (HZ-2) is considered in evaluation process and 3.7W could be generated from each module. Estimated annual power generation from this proposed system could be around 152,380kWh. Thermal efficiency of the TEG modules could be enhanced up to 7%. The specifications of plate fin heat sinks have substantial impact on the performance of TEG module.**

***Index Terms*—waste heat recovery, thermoelectric power generation, thermal oil heater, TEG**

I. Introduction

Waste heat recovery is now pressing demand of time due to increasing price of fossil fuels and environment protection regulations. Thermoelectric technology is one of the latest technology and getting more attention for applying in waste heat recovery application because of its favourable characteristics, such as no moving parts, compact, quiet, highly reliable. The primary challenge is its relatively low heat to electricity conversion efficiency, which is not the major issue when TEG is used for waste heat recovery because of the costless thermal energy input [1]. The performance of the thermoelectric generator depends on module properties as well as system configuration [2]-[4]. It has been reported that the technology for capturing waste heat has enormous effect on the performance of TEG [5]. Different types of heat exchangers for TEG application are also investigated by the researchers [6], [7]. Gaowei Liang *et al.* [8] investigated the effect of contact resistance on output power and current. Rowe and Gao [9] developed a method to assess the potential of commercially available. The effect of convective heat transfer coefficient is investigated in both automobile [3] and industrial application [5]. Zhiqiang Niu *et al.* [7] investigated various transport phenomena, and suggest that the TEG design should be optimized in exhaust-based thermoelectric generator system. Previous studies were done on the available commercial TEG module on various applications. This paper represents the method of estimation of power generation by recovering waste heat from moderately high temperature Thermal Oil Heater (TOH) exhaust with commercial TEG module HZ-2. Total power generation from the proposed system is calculated based on the output power of the module at best suited condition.

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II. Mathematical Modelling

The main function of a TEG is Seebeck effect, which is induction of current by temperature difference in an electrical conductor. Typically, *n*-type/*p*-type semiconductor blocks are attached to electrical conductors and followed by electrical insulator and ceramic substrates on both sides in a TEG module. Fig. 1 shows the working principle of TEG. Supply heat (Q_H) and removal heat (Q_C) can be expressed by (1) and (2) respectively.

$$Q_H = \alpha I T_H + K(T_H - T_L) - \frac{1}{2} I^2 R_G \quad (1)$$

$$Q_C = \alpha I T_L + K(T_H - T_L) + \frac{1}{2} I^2 R_G \quad (2)$$

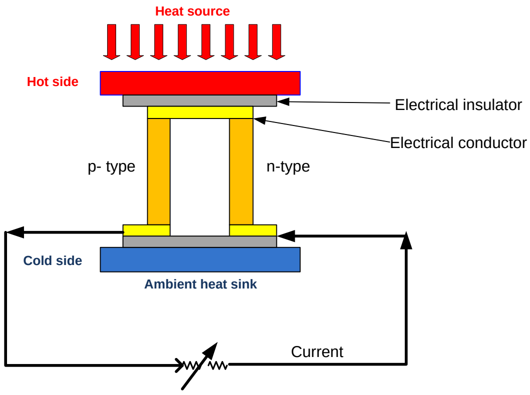

Figure 1. Schematic of a working TEG.

A. Performance of TEG

Power generation by TEG module depends on Seebeck coefficient (α), internal electrical resistance (R_G) and thermal conductance (K). Generated output power can be quantified in two ways, by multiplying output voltage and current or by subtracting removal heat from supply heat.

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Using expression of Q_H and Q_C, the output power can be written as follows:

$$P_O = V_O I_O = Q_H - Q_C = \alpha I(T_H - T_L) - I^2 R_G \quad (3)$$

If the condition of power generation is open circuit (*I=0*), (3) can be represented by (4) and The Seebeck coefficient (α) can be written by (5).

$$V_O = \alpha(T_H - T_L) \quad (4)$$

$$\alpha = \frac{V_O}{(T_H - T_L)} \quad (5)$$

The value of R_G can be obtained by combining (3) and (5). Consequently, the value of *K* can be obtained by substituting α and R_G into (1). Taking the 1st order partial derivatives of (3) with respect to *I* and assuming the result on the left hand side of equation is zero [10], the output current I_O can be expressed by following (6). By using the (7), the thermal efficiency of TEG can be obtained.

$$I_O = \frac{\alpha(T_H - T_L)}{2R_G} \quad (6)$$

$$\eta_G = \frac{P_O}{Q_H} \quad (7)$$

B. Thermal Resistance Model of the Waste Heat Recovery

In this study the source of heat is the high temperature flue gas of Thermal Oil Heater (TOH). Fig. 2 illustrates a thermal resistance model, which recovers waste heat from the flue gas duct. Thermal resistance on both sides is composed of interface thermal resistance (R_i), material thermal resistance (R_m), and convectional thermal resistance (R_{conv}). Thermal resitances were calculated using equations stated in [11]. Overall heat transfer coefficient can be obtained from the (8), (9).

$$U_H = \frac{1}{R_{overall,H} A_H} \quad (8)$$

$$U_C = \frac{1}{R_{overall,L} A_L} \quad (9)$$

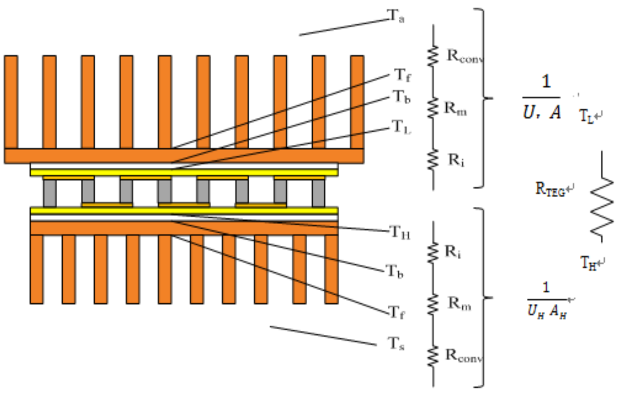

Figure 2. Incorporated thermal resistances of waste heat recovery TEG module.

The supply heat (Q_H) to the hot junction and removal heat (Q_C) from the cold junction can be expressed as following equations:

$$Q_H = U_H A_H (T_S - T_H) \quad (10)$$

$$Q_C = U_C A_L (T_L - T_C) \quad (11)$$

By combining (1) with (10) and (2) with (11), TH and TL can be expressed as equations are given below:

$$T_H = \frac{U_H A_H T_S + K T_L + \frac{1}{2} I^2 R_G}{\alpha I + K + U_H A_H} \quad (12)$$

$$T_L = \frac{U_C A_L T_C + K T_H + \frac{1}{2} I^2 R_G}{U_C A_L + K - \alpha I} \quad (13)$$

The values of T_H and T_L are derived by the iterative method for different source temperatures and other variations. Consequently, T_H, T_L, α and R_G are Substituted into (6) to derive I_O. Then T_H, T_L, α, R_G, K and I_O are replaced into (1), (2), and (3) to find out the values of Q_H, Q_C, and *Pout*.

III. TEG Application in Thermal Oil Heater

The scope of waste heat recovery from a biomass fired Thermal oil heater has been investigated. Average flue gas temperature was around 573K. To generate electricity from heat energy of moderately high temperature exhaust, TEG modules are proposed to place before APH and WPH on the flue gas duct. Plate fin heat sinks were considered to enhance the performance of TEG. Hot and cold side plate fin heat sinks were inserted in the flue gas duct and fresh air duct respectively. Dimension of the duct where thermoelectric modules are placed and fin parameters are presented in Table I.

TABLE I. Duct and Fin Parameters

Parameter	Unit	Value
Duct width	m	2.3
Duct height	m	1.3
Duct length	m	2
Number of TEG row	No	33
Number of module per row	No	78
Fin width	mm	60
Fin thickness	mm	1.5
Fin height	mm	40
Base width of heat sink (for 8 fin)	mm	29.50
Fin Spacing	mm	2.50

IV. Results and Discussion

A. Effect of Convection Heat Transfer Coefficient

The variation of output power and heat input with convection heat transfer coefficient has been calculated and shown in Fig. 3. When other parameters are constant, heat input and output power increases with the increased convection heat transfer coefficient. The reason is increased convection heat transfers coefficient reduces the thermal resistance between fluid and solid surface. This increases the temperature difference between two sides of TEG module. Gou *et al.* experimentally studied effect of natural and forced convection cooling on cold side and concluded that forced convection cooling produce more power than that of natural convection [12]. So, the value of h can be enhanced by using water or other coolant. In this case, the value of h can be varied by varying the inlet velocity of flue gas and fresh air. Velocity of flue gas and fresh air can be increased by reducing the flow area of the duct. Thus h=100W/m^{2}K can be the optimal value of convection heat transfer coefficient for this system.

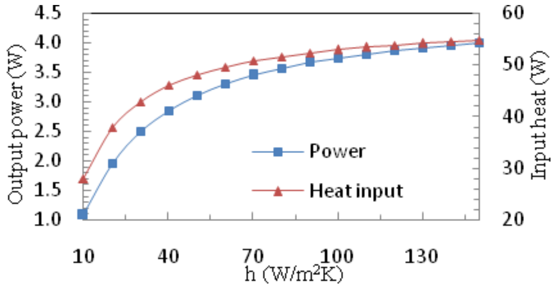

Figure 3. Effect of convection heat transfer coefficient on power and heat input.

B. *Effect of Number of Fin*

Variation of output power and heat supplied to the TEG module with number of fins have been calculated and displayed in Fig. 4. Heat transfer area on both sides can be increased to boost the heat transfer rate by increasing the number of fins which results the improved output power of TEG module due to the enhanced temperature difference.

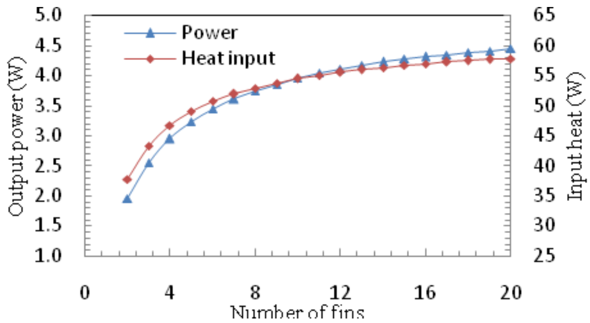

Figure 4. Output power and heat input variation with number of fins.

In this study, the fin specifications are kept fixed. So, the total number of fins accommodated within the duct is restricted by the duct width. With an increment of number of fins per module, the output power and heat flow through the TEG module increase noticeably when the number of fin is below 8. While the number of fin is less than 8, heat absorption by plate fin heat sink is insufficient for the TEG module, thus the output power is low. Increment of number of fins per module, gradually increase the output power, but noticeably decrease the total output power per row. Hence, total power generation capacity decreases with an increment of allocated number of fins per module as shown in Fig. 5. To supply sufficient amount of heat to TEG module and install maximum number of modules on the flue gas duct, we need to use optimal number of fins to get maximum power. In this particular condition, each module with 8 fins gives the maximum power per row though the output power of a single module is still increasing with the addition of number of fins.

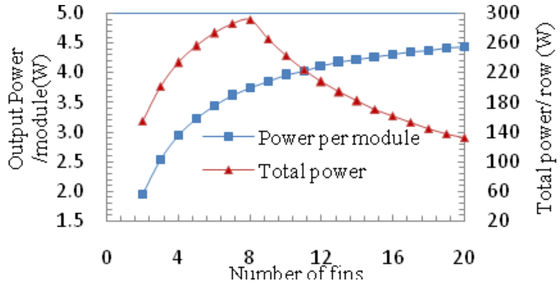

Figure 5. The variation of total power per row and output power per module with number of fins per module.

C. *Effect of Fin Height*

The effect of fin height on output power and efficiency have been calculated and shown in Fig. 6. Both the output power and efficiency increase with the fin height. The temperature difference between two sides of the TEG module increase with the enhancement of fin height and according to (7), the output power increases with the rise of temperature difference. Therefore, the increment of fin height promotes the output power of the TEG module. When the fin height is below 40mm, the change in output power and efficiency almost the same, growing rapidly. But, with the fin height 40mm or more, the output power and efficiency is not changing remarkably. Thus, it can be chosen 40mm is the economical fin height for this system.

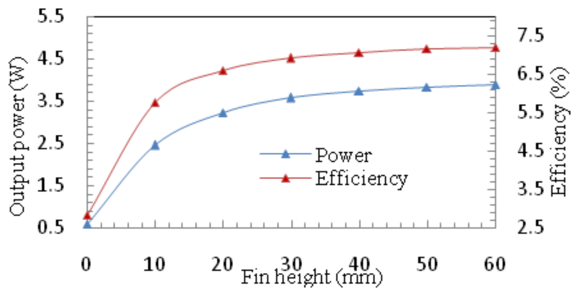

Figure 6. Variation of output power and efficiency with fin height.

D. *Power Generation*

Maximum output power per module has been determined using the data of HZ-2 module. The considered portion of flue gas duct where TEG has been proposed to be applied is 2.3m wide×2m length. The thermoelectric modules could be placed on both upper and lower side of the flue gas duct. In this situation maximum output power per module is 3.7W. If the operating time duration is 8,000 hours per year, then from the configuration stated in Table I, the annual power generation could be152,380kWh.

V. CONCLUSION

Maximum power generation by applying TEG with plate fin heat sink is the main focus of this study. For this, effect of number of fin, fin height of plate fin heat sink and convection heat transfer coefficient have been investigated for the commercial module (HZ-2). The following points can be drawn from this study

- The number of fins 8, heat transfer coefficient 100W/m^{2}K, fin height 40mm are considered as best suited conditions for this type of TE module.
- The maximum power could be produced form each commercial module HZ-2 is 3.7W.
- The estimated annual power generation is 152,380kWh using commercial TEG module HZ-2.
- Developing TE materials with better TE properties energy can be recovered more efficiently in future.

APPENDIX NOMENCLATURE

A	Area (m^2)	*U*	Overall heat transfer coefficient (W/m^{2}K)
APH	Air preheater	*V*	Voltage (V)
h	Convection heat transfer coefficient (W/m^{2}K)	*W*	
I	Current (A)	*WPH*	Water preheater
K	Thermal conductance (W/K)	Greek symbols	
P	Power (W)	α	Seebeck coefficient (V/C)
Q	Heat transfer rate (W)	η	Efficiency (%)
R	Electrical resistance (Ω)	ρ	Electrical resistivity (Ω.m)
T	Temperature (K)	Subscript	
T_C	Fresh air temperature (K)	*b*	Base
TE	Thermoelectric	*C*	
T_S	Flue gas temperature (K)	*G*	Thermoelectric Generator
TEG	Thermoelectric generator	*H*	Hot side

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