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Effect of Exhaust Gases Temperature on the Performance of a Hybrid Heat Recovery System

Hassan Jaber [a,c], Mahmoud Khaled [a,b,*], Thierry Lemenand [c], Jallal Faraj [a], Hasan Bazzi [a] and Mohamad Ramadan[a,d]

[a] *School of Engineering, Lebanese International University LIU, PO Box 146404 Beirut, Lebanon.*
[b] *Univ Paris Diderot, Sorbonne Paris Cité, Interdisciplinary Energy Research Institute (PIERI), Paris, France*
[c] *LARIS EA 7315, University of Angers – ISTIA, Angers, France*
[d] *Associate member at FCLAB, CNRS, Univ. Bourgogne Franche-Comte , Belfort cedex, France.*

Abstract

The reuse or reduction of wasted heat supplies an excellent opportunity for cost saving in industrial and residential application. This paper deals with a Hybrid heat recovery system that reuses the thermal energy captured by exhaust gases to produce domestic hot water and generate electric power using thermoelectric generators (TEG). The heat recovery process is mainly affected by the temperature of exhaust gases. The effect of gases temperature on the performance of the system – water temperature and power generated – is studied including different residential applications. It shows that as the exhaust gases temperature increase the heat rate, water temperature, and power generated increases.

Keywords: Heat recovery; Thermoelectric generators; cogeneration; Thermal modeling; Domestic hot water;

* Corresponding author. Tel.;
E-mail address: mahmoud.khaled@liu.edu.lb

1. Introduction

Due to the rapid increase in demand and consumption of energy, scientists are forced to find solutions of what is called "Energy crisis". Fossil fuel remains still the main energy resource that feeds most industrial and residential applications. Renewable energy and energy management are certainly the most effective solutions of Energy crisis

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[1]. Renewable energy which is an alternative source of energy is mainly generated from solar, wind, biomass, geothermal, and hydropower [2-11].

Energy recovery consists in the reuse of energy dumped to the environment without taking advantage of it [12-17]. Because of the high dependence of fossil fuel which is burned to generate thermal energy, high amount of exhaust gases are generated which could be the highest energy loss in the system. Recovering heat from exhaust gases can be done directly or indirectly by a mean of heat exchanger or any energy transformation process. Jaber et al. [18] did a short review on heat recovery, classifying it into different configurations. The authors classified exhaust gas heat recovery systems within three classifications that are exhaust gas temperature, utilized equipment and proposed a new classification according to recovery purposes.

This paper deals with heat recovery from exhaust gases. A hybrid heat recovery system proposed is utilized to recover exhaust gases to produce simultaneously domestic hot water and generate electricity using thermoelectric generators (TEG). The concept of study is discussed in section 2. Section 3 presents the thermal modeling of the system, and section 4 studies the effect of changing exhaust gases temperature on the performance of the system. Finally a conclusion about the whole study is carried.

Nomenclature

A	Area $[m^2]$
h	Convection heat transfer coefficient $[W/m^2.K]$
HHRS	Hybrid heat recovery system
q	Heat transfer rate [W]
L	Length of the tank [m]
N	Number of items
P	Power produced [W]
r	Radius [m]
T_a	Temperature [°C]
k	Thermal conductivity [W/m.K]
R	Thermal resistance [K/W]
e	Thickness of the TEG [m]

2. Heat recovery concept

The relatively high amount of thermal energy lost through exhaust gases forced scientists to investigate how to get benefit of this energy. Variety of studies were made in the field of heat recovery including single or hybrid heat recovery systems. This paper proposes a hybrid heat recovery system in which hot water is produced and electric power is generated. The system is composed of water tank with a pipe passing through it. At the inner wall of the pipe a thermoelectric generators layer is attached allowing a direct contact of exhaust gases with TEGs. Part of the thermal energy hold by exhaust gases transfer through the TEGs layer in which this TEG layer dissipate heat to the water at the tank. The TEGs layer is sandwiched between the exhaust gases (heat source) and the inner wall of the tube (heat sink) [19]. As the TEGs are subjected to a temperature difference an electric power is generated. Figure 1 shows a schematic of the proposed hybrid heat recovery system. It shows a pipe crosses the tank in which exhaust gases passes through the pipe with a direct contact with the TEG layer (Red layer). TEG in its turn convert part of the absorbed thermal energy to electrical energy and dissipate the other part to water. The quantity and quality of exhaust gases plays a crucial role in the recovery process. The effect of exhaust gases temperature on water temperature and power generated is examined in this paper. To proceed, a thermal modelling of the system will be carried in order to obtain the behaviour of the hybrid heat recovery system while changing the temperature of exhaust gases

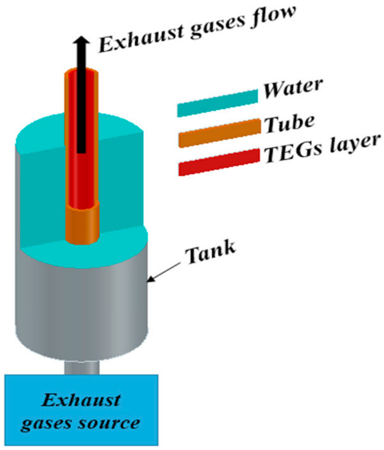

Fig. 1. Hybrid heat recovery system.

3. Thermal modeling

In order to estimate the water temperature and the power generated by water a thermal modelling of the system is carried out. Some assumptions are used to simplify the calculation: the study is done at steady state, one dimensional heat flow and constant gases temperature along the tank length. Figure 2 shows the steps required to obtain the water temperature and the power generated.

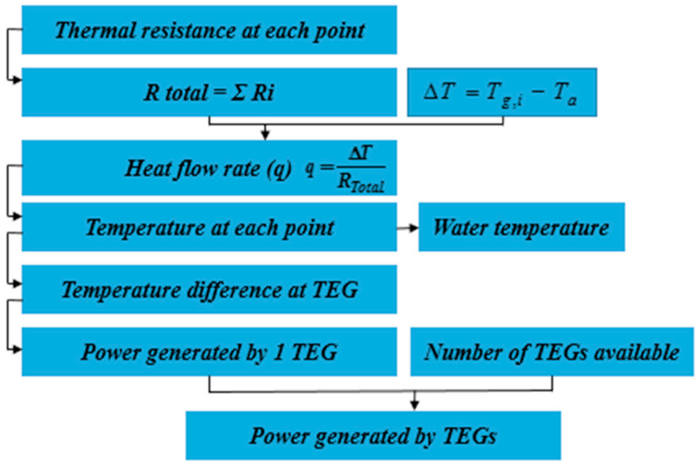

Fig. 2. Thermal modelling steps.

As shown in figure 2, in order to obtain the heat flow rate the total resistance of the HHRS should be calculated. Knowing the gases temperature and ambient air temperature, the temperature at each layer could be calculated in which the heat flow rate (q) is constant over the system. To obtain the total power, the power generated by one TEG should be estimated and multiplied by the number of TEGs available. The power generated by one TEG is estimated by a direct relation with the temperature difference at the TEG.

Figure 3 shows the thermal resistance diagram of the system. The thermal energy captured by exhaust gases undergoes convection heat transfer with the surface of the TEG (R_g). At the TEG the energy transfer by conduction through the layers of TEG and pipe to water (R_{TEG}, R_p). Due to the change in density of water, water will undergoes natural convection with the walls of the pipe and the tank ($R_{conv,w-p}$, $R_{conv,w-w}$). At the tanks' wall energy transfer through the wall by conduction (R_{wall}) and with the air through convection heat transfer (R_{air}).

Fig. 3. Thermal resistance of the system.

where $T_{g,i}$, T_H, T_C, $T_{p,o}$, T_w, $T_{wall,i}$, $T_{wall,o}$ and T_a are the temperature of exhaust gases, hot, cold, outer pipe wall, water, inner tank wall, outer tank wall, and ambient air temperature respectively. And R_g, R_{TEG}, R_p, $R_{conv,w-p}$, $R_{conv,w-w}$, R_{wall}, and R_{air}, are the thermal resistance of internal convection of gases in pipe, conduction in thermoelectric generator, conduction in the pipe wall, convection between water and pipe , convection between water and cylindrical tank wall, conduction in the cylindrical tank wall and convection of tank with air respectively. The thermal resistances are calculated using the following equations [20]:

$$R_g = \frac{1}{h_g\left(2\pi\left(r_{t,i}-e\right)L\right)} \tag{1}$$

$$R_{TEG} = \frac{ln\left[\dfrac{r_{t,i}}{r_{t,i}-e}\right]}{2\pi k_{TEG}\ L} \tag{2}$$

$$R_p = \frac{ln\left[\dfrac{r_{t,o}}{r_{t,i}}\right]}{2\pi k_t\ L} \tag{3}$$

$$R_{conv,w-p} = \frac{1}{h_w\left(2\pi r_{t,o}\ L\right)} \tag{4}$$

$$R_{conv,w-w} = \frac{1}{h_w\left(2\pi r_{w,i}\ L\right)} \tag{5}$$

$$R_{wall} = \frac{ln\left[\dfrac{r_{w,o}}{r_{w,i}}\right]}{2\pi k_w\ L} \tag{6}$$

$$R_{air} = \frac{1}{h_a\left(2\pi r_{w,o}\ L\right)} \tag{7}$$

where h_g, h_w and h_a are the convection heat coefficient of exhaust gases, water and air respectively. k_{TEG}, k_t and k_w are the conduction coefficient of the TEG, tube wall and tank wall respectively. And $r_{t,i}$, $r_{t,o}$, $r_{w,i}$, $r_{w,o}$ and L are the inner, outer radius of the tube and inner, outer radius of the water tank, and length of the tank respectively. e is the thickness of the thermoelectric generator.

Knowing that heat flow rate is constant over the system then the temperature at each point can be estimated by the following equation:

$$T_{(n)} = T_{(n-1)} - q.\,R_{(n)} \tag{8}$$

where q is the heat flow rate in "W" and n is an increment of the layers of the HHRS starting from exhaust gases to air.

By calculating the hot and cold temperature at the TEG surface the power produced by one TEG is calculated as follows:

$$P_{1TEG} = \left(\frac{P}{\Delta T^2}\right)_{ref} \Delta T^2 \tag{9}$$

where P_{1TEG} is the output power of one TEG, ΔT is the temperature difference between the hot and cold sides of TEG, and $\left(\frac{P}{\Delta T^2}\right)_{ref}$ is given by the manufacturer of the TEG. Then the total power produced by TEGs P_{Total} is estimated by equation below knowing that N_{TEG} is the number of TEGs available on the system:

$$P_{Total} = N_{TEG} P_{1\,TEG} \tag{10}$$

4. Results

One of the main parameters that affects the performance of heat recovery process is the gases temperature. Variety of applications that can be utilized as exhaust gases source of the system can be found. For a residential level: generators, chimney, boilers and furnaces are the main applications found. Table 1 shows the dimensions of the system used and the main parameters required for the thermal modeling. In order to simplify the study the heat convection coefficient of the exhaust gases is set as constant. It should be noted that a specific type of TEG is utilized and its main parameters are listed in Table 1 [21].

Table 1. Heat recovery system main parameters.

Parameter	Value	Unit
$r_{t,,i}$	0.049	m
$r_{t,o}$	0.050	m
L	1	m
$r_{w,i}$	0.158	m
$r_{w,o}$	0.160	m
h_w	300	W/m^{2}K
h_a	50	W/m^{2}K
H_g	80	W/m^{2}K
k_t	401	W/mK
k_{wall}	80	W/mK
k_{TEG}	1.4	W/mK
N_{TEG}	99	Piece
T_a	25	°C
e	0.005	m
$P/\Delta T^2$	0.0002	W/K^2
A_{TEG}	0.0031	m^2

Using the table and equations above the effect of changing exhaust gases temperature on the heat rate, temperature variation, temperature difference at the TEG and power produced by TEGs is studied. Figure 4 shows the variation of heat flow by varying the exhaust gases temperature.

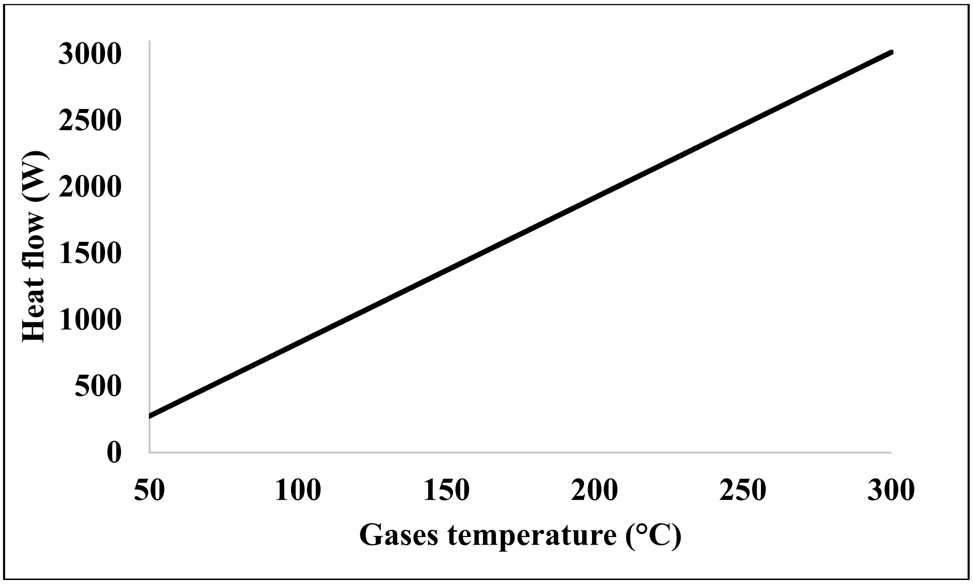

Figure 4. Effect of exhaust gases temperature on heat rate.

The heat transfer rate increases linearly with the increase in exhaust gases temperature. This is directly reflected by the following equation:

$$q(T_g) = \frac{1}{R_{total}} T_g - \frac{T_a}{R_{total}} \tag{11}$$

Figure 5 shows the temperature distribution on different layers on the system.

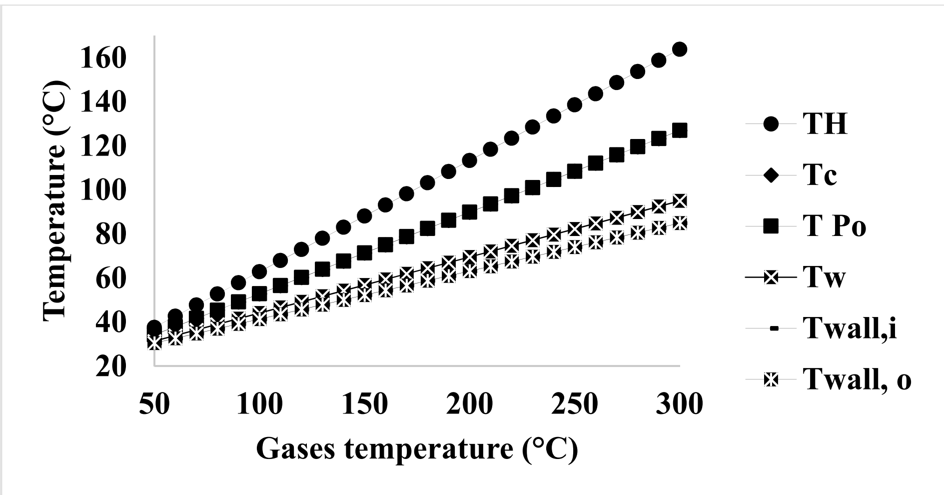

Figure 5. Variation in temperature distribution of the system.

The temperature at any layer in the system increased linearly with the increase in exhaust gases temperature. It should be noted that cold side temperature of the TEG T_C and the outer tube wall have a relatively equal temperature which is due to the small tube thickness and high thermal conductivity which reflect the invisibility of Tc on the graph.. Also $T_{wall,i}$ and $T_{wall,o}$ are approximately equal due to the low thickness of the tanks' wall.

Figure 6 shows the power generated by one TEG and the corresponding temperature difference at the two sides of the TEG.

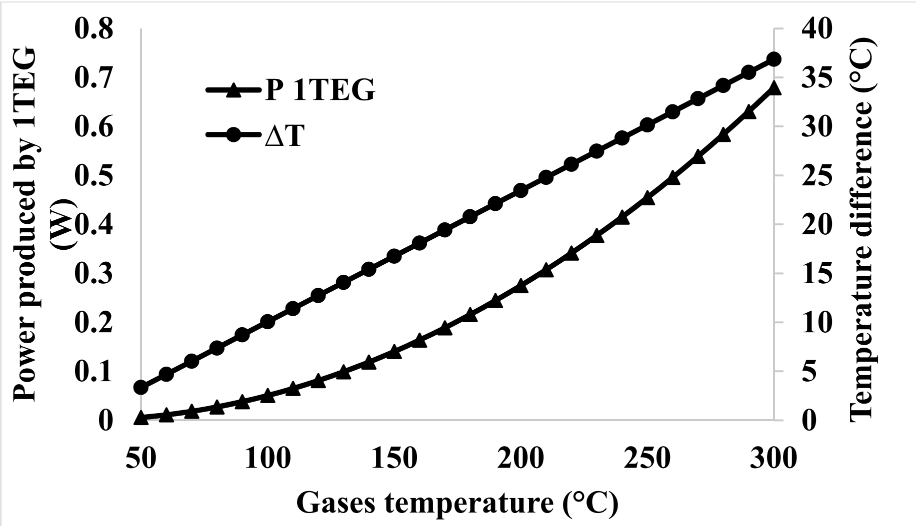

Figure 6. Temperature difference and power generated by one TEG.

It shows that the power generated by one TEG is continuously increasing with the increase in exhaust gases temperature. For a 300°C exhaust gases, 0.68 W of electricity is being produced at a 36.8°C temperature difference between the hot and cold sides of the TEG. While for 100°C, 0.14 W electric power is produced at a 17°C temperature difference.

Figure 7 shows the effect of changing the exhaust gases temperature on the total power produced by the TEGs layer.

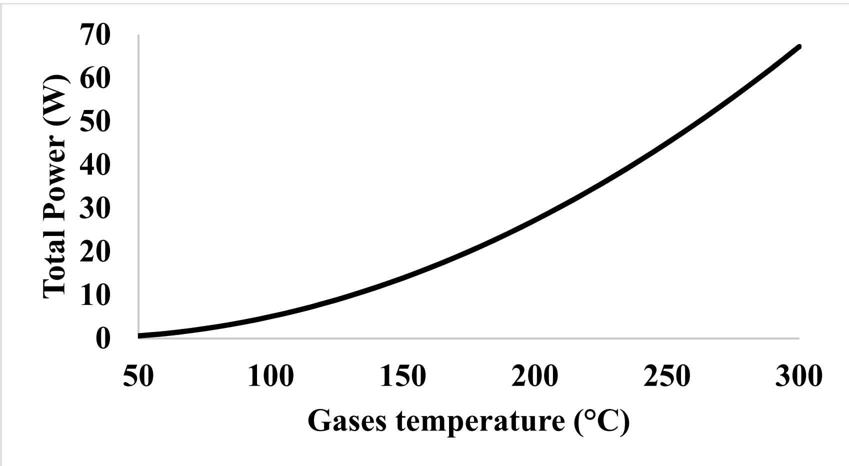

Figure 7. Total power produced by TEGs.

When the temperature of exhaust gases was 150°C the total power is total power produced is 14 W, when the exhaust gases temperature is doubled (300°C) the total power is 67 W. This indicates that the relation between power and exhaust gases is not linear and when the temperature of gases doubled the power increased 5 times from what it was.

5. Conclusion

Heat recovery offers an excellent opportunity for cost and energy saving in industrial and residential applications. The heat recovery process is mainly affected by the quality and quantity of thermal energy lost. In other words, heat recovery from exhaust gases is affected by the exhaust gases temperature and flow rate. The effect of exhaust gases on a proposed hybrid heat recovery system is studied. A domestic thermoelectric cogeneration heat recovery system is utilized in this study. The results shows that by increasing the gases temperature, the heat rate and temperatures at each layer increase linearly. The power generated by TEG progressively increases with the increase on exhaust gases temperature. Also it was shown that for the utilized configuration of HHRS, when doubling the gases temperature the power produced increases about 5 times more.

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