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Hybridization of heat recovery from exhaust gas of boilers using thermoelectric generators

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Abstract. This study investigates the possibilities for energy recovery and environmental effect reduction of waste heat, a consequence of industrial activities. The main objective of the work is to integrate thermoelectric generators (TEGs) into industrial hybrid waste heat recovery system. The study consists of combining TEGs modules with a boiler waste heat recovery system with Rockwool insulation, taking into consideration variables like thermal resistance, power output, water temperature, and energy conversion efficiency. The results show that TEG placement has a major impact on system performance. One of the promising configuration is TEGs placed close to heat source, especially outside exhaust pipe outer walls, where electrical power up to 27 W can be generated and heat of 4215 W can be recovered from the exhaust gas.

Keywords: Hybridization, Heat Recovery, Exhaust Gas, Boiler, Thermoelectric Generator.

1. Introduction

Numerous research projects center on energy, with the main goal being to lower carbon emissions and energy consumption by using renewable energy sources and energy management [1–11]. The majority of energy produced today comes from non-renewable fossil fuels, which raises serious environmental issues and significant heat waste [12–17]. Global interest in tackling energy concerns is driven by high-energy costs, emissions, global warming, and regulatory demands [18–20]. In order to fulfill the increasing global demand, sustainable and renewable energy sources are urgent considerations [21–22]. The significance of energy and environmental challenges has grown due to increased industrialization, advancements in knowledge, and rising energy use [23–25]. Natural gas usage has increased because of regulatory pressure, highlighting the necessity for extremely efficient energy technologies [26]. With the global energy landscape shifting towards renewable sources [27], it is imperative that waste heat from industrial operations be addressed [28]. Following the International Energy Agency's recommendation for net-zero CO₂ emissions by 2050, it is imperative to address urgent concerns such as the demand for power, the depletion of fossil fuels, and global warming [29]. To address these issues, research efforts are mostly focused on improving energy efficiency and creating adaptable systems using renewable energy sources.

The need for high-performance components with contemporary traits like flexibility and reliability has arisen because of the transformation of energy systems brought about by the usage of low-intensity renewable sources like solar power and the advent of electricity-reliant technology. The thermoelectric generator (TEG) is one creative approach that has gained popularity recently [29]. Over the past 20 years, these little devices have become increasingly popular due to their effective conversion of thermal energy into electricity without the need for moving parts or noise. TE modules are regarded as a green technology with a broad variety of applications because of their adaptability and environmental friendliness [30]. The Seebeck effect was discovered in 1821, and thermoelectric generators (TEGs) are solid-state devices that use this phenomenon to directly convert heat into electricity [23]. TEGs are robust, silent, and pollution-free, and they do not have any moving components. Their dual purpose of acting as power sources and coolers in the presence of temperature gradients makes them adaptable. Because of their portability and dependability, TEGs are becoming more and more popular. They are being used in power production, waste heat recovery, microelectronics, and solar heat collecting [31-33] They are promising for a variety of commercial applications due to their simplicity and capacity to fully harness heat through the Seebeck effect. In order to address energy costs and environmental issues, waste heat recovery (WHR) technology [27] collects waste heat from exhaust gasses and turns it into usable energy. It provides lower energy expenditures, less pollutants, and better system performance. Heat recovery from exhaust gases is categorized according to several taxonomies that take into account variables such as temperature, energy source, equipment, and intended use [34]. Thermoelectric generators (TEGs) are important for WHR, particularly in automotive and industrial applications [20]. They can increase efficiency by more than 23%, especially when used in conjunction with solar cells. To save energy and cut emissions, creative ways to improve energy efficiency are essential [35].

In the context of the aforementioned targets and challenges, the focus of current research is on recovering waste heat from industrial exhaust gases (for instance those of boilers) and turning heat loss into power using thermoelectric modules. Combining these two methods is the current worldwide trend. Nevertheless, a number of thorough parametric studies with appropriate thermal modeling and thorough studies on exhaust gas sources are conspicuously lacking. In order to concurrently heat water and produce electricity, this study presents a novel idea: merging Waste Heat Recovery (WHR) from exhaust gas of boilers and Thermoelectric Generator (TEG) systems.

2. Configurations and governing equations

The present work intends to incorporate TEGs into a Heat Recovery System HRS applied to exhaust gas of a boiler. Six scenarios are included in the study, the first of which is a control case that heats water only with the HRS and the other instances that have TEGs positioned strategically within the HRS to increase efficiency. The six main configurations (Figure 1) are as follows:

- 1- Configuration 1: without TEG.
- 2- Configuration 2: TEGs at the water tank's outer wall.
- 3- Configuration 3: TEGs at the water tank's inner wall.
- 4- Configuration 4: TEGs at the exhaust pipe's outer wall.
- 5- Configuration 5: TEGs at the exhaust pipe's inner wall.
- 6- Configuration 6: TEGs at the inner and outer radii of the pipe and the walls of the water tank.

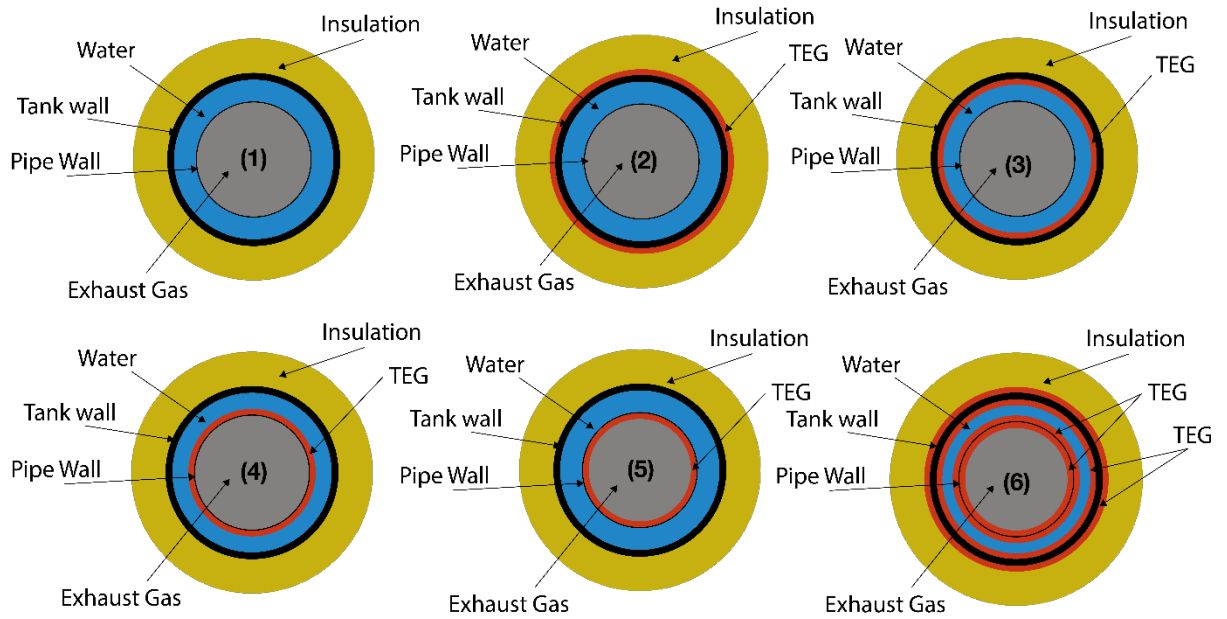


Figure 1. All studied configurations for TEGs placement.

Figure 2 shows the thermal modeling of all cases in terms of thermal resistances. T_{ex} , T_{pi} , T_{po} , T_{water} , T_{wi} , T_{wo} , T_{ins} , T_a , T_H and T_C are the temperatures for exhaust gases, inner pipe surface, outer pipe surface, water, inner water tank wall surface, outer water tank wall surface, insulation layer, ambient, hot side of TEG and cold side of TEG respectively.

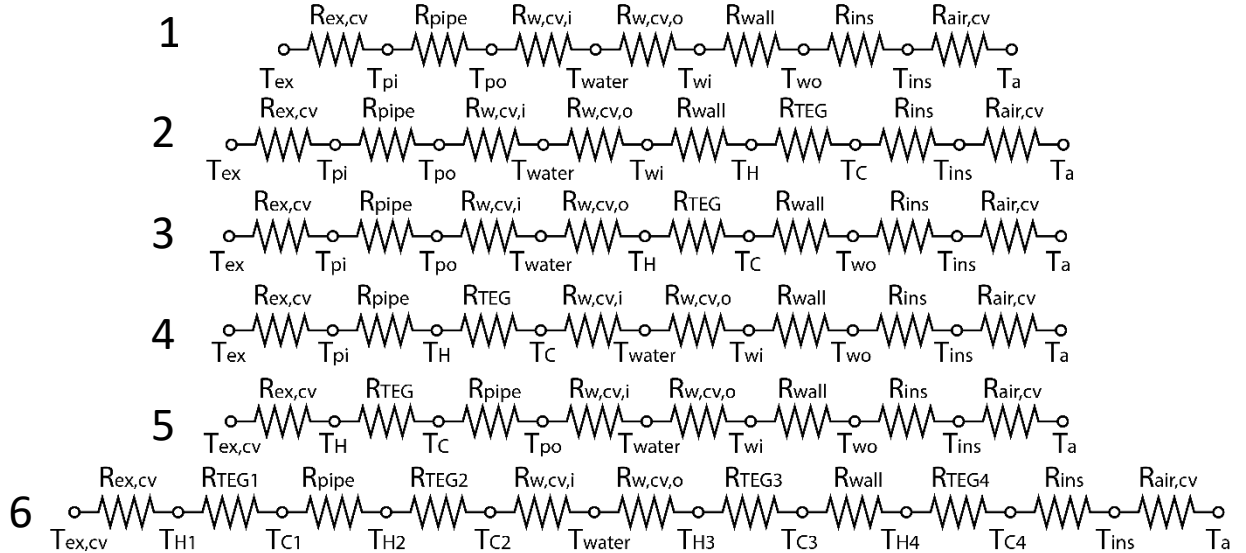


Figure 2. Thermal modeling for the six suggested configurations respectively.

The exhaust heat flow rate ($q_{exhaust}$) is calculated using the following equation:

$$q_{exhaust} = \frac{\Delta T_{ex}}{R_{total1}} \quad (1)$$

where ΔT_{ex} is the temperature difference between exhaust gases and water temperature

$$\Delta T = T_{ex} - T_w \quad (2)$$

and R_{total1} is the summation of thermal resistances in this case.

The lost heat flow rate from water ($q_{water,out}$) is calculated using the following equation:

$$q_{water,out} = \frac{\Delta T_{water,out}}{R_{total2}} \quad (3)$$

where $\Delta T_{water,out}$ is the temperature difference between water temperature and ambient temperature

$$\Delta T = T_w - T_a \quad (4)$$

and R_{total2} is the summation of thermal resistances in this case.

The water heat flow rate (q_{water}) is calculated using the following equation:

$$q_{water} = q_{exhaust} - q_{water,out} \quad (5)$$

The temperature at each point can be calculated:

$$T_{(n)} = T_{(n-1)} - qR_{(n)} \quad (6)$$

where “n” is the layer number measured from the exhaust gases to the air. The hot and cold temperatures at the sides of the TEG are estimated, this allows the calculation of the power output of one TEG:

$$\left(\frac{P}{\Delta T^2}\right)_{Ref} = \left(\frac{P_{1TEG}}{\Delta T^2}\right) \quad (7)$$

$$P_{1TEG} = \left(\frac{P}{\Delta T^2}\right)_{Ref} \Delta T^2 \quad (8)$$

where P_{1TEG} is the power generated by 1 TEG, $\left(\frac{P}{\Delta T^2}\right)_{Ref}$ is given by the manufacturer, and ΔT is the temperature difference between heat source and heat sink of the TEG.

3. Results and analysis

The analytical investigation is conducted based on experimental input data: exhaust gas temperature and mass flow rate. These data are taken from [36]. The required parameters for the analytical investigation are reported in Table 1.

Table 1. Input parameters for the calculations.

Parameter	Value	Unit	Parameter	Value	Unit
$r_{p,i}$	0.0498	m	k_p	50	W/mK
$r_{p,o}$	0.0508	m	k_w	50	W/mK
L	1.565	m	k_{TEG}	1.4	W/mK
$r_{w,i}$	0.0698	m	K_{ins}	0.043	W/mK
$r_{w,o}$	0.0758	m	$T_{ex,in}$	270	°C
h_g	91.4	W/m ² K	T_a	20	°C
h_w	103.00	W/m ² K	e	0.005	m
h_a	50	W/m ² K	$P/\Delta T^2$	0.0002	W/K ²
$r_{ins,i}$	0.0758	m	A_{TEG}	0.0031	m ²
$r_{ins,o}$	0.1058	m	$T_{w,in}$	20	°C

The thermoelectric generator employed in this investigation is a 56*56 mm (36") "TEG1-12611-8.0." [37]. However, the insulation used is Rockwool with 30 mm thickness, having a 0.043 W/mk thermal conductivity [38].

Table 2 presents the main findings of the configurationally study. These values of these findings are related directly to the relative high mass flow rate of water (0.59 kg/s). In addition, the low starting water temperature ($T_{w,in}=20$ °C) which is the same as the ambient air temperature. This causes lessening the temperature difference between water and ambient air. Therefore, the effect of insulation on outer surface and TEG's located at the inner and outer surface of water tank are almost negligible. In other words, cases 2 and 3 show similar $q_{exhaust}$ and q_{water} which is about 4610 W. Whereas, no TEG production in both cases, where it's located on the outer and inner water tank respectively. Temperature difference in both case is negligible. In case 4, where TEG's are located on exhaust pipe's outer wall, $q_{exhaust}$ and q_{water} exhibits it's optimum values with 4215 W and $P_{TEG}=26.6$ W. Yet, case 5 shows decrease in $q_{exhaust}$ and q_{water} by about 350 W; while P_{TEG} increases to 28.1 W. TEG's display the best efficiency among all cases. Case 6, with locating TEG's at 4 locations, the highest number of TEG's are involved, where $q_{exhaust}$ and q_{water} exhibit the lowest values with about 3600 W, with having the highest TEG production with a huge difference with other case, with $P_{TEG}=43.5$ W.

In light of Equation (8), since $\left(\frac{P}{\Delta T^2}\right)_{Ref}$ is provided by the manufacturer, the power generated also increases as the temperature differential between the heat source and heat sink rises. The TEG's proximity to the exhaust gases results in a larger temperature differential and corresponding increase in power generation (case 5). However, because TEG is located farthest from exhaust gasses, the temperature differential achieves its minimal value (case 4). Nevertheless, case 6, which has the most TEGs of any case, produces the most power overall. Thus, case 5 is the optimal option based on the power generation efficiency. Case 3 is the greatest option based on q_{water} , and Case 6 is the best option based on total power output. Finally taken into consideration the heat recovered and power generation together, case 4 (placing TEGs at the outer surface of the exhaust gas pipe) shows a promising solution compromising heat recovery and power generation.

Configurations 2 and 3 can be more promising if lower water flow rates are operated and higher water temperatures exist which increases the heat losses to the surrounding without TEGs. Using TEGs in this case plays the role of insulation and exhibits higher heat recovery potentials. One of the best configurations in using TEGs between water and ambient air is using TEGs in place of the insulation.

Configurations 4 to 6 can be more promising if one uses thinner and more thermally conductive TEGs. In this case, more heat can be recovered by keeping acceptable power generation. These configurations

can also be more promising by using TEGs with higher power to temperature difference ratio/potential. Finally, these configurations can also show potential when higher exhaust gas flow rates are operated and higher thermal resistance of the exhaust pipe wall are employed.

Table 2. Main results obtained analytically for the six configurations.

	q_{exhaust}	q_{water}	$P/\Delta T^2$	ΔT	P_{TEG}	N_{TEG}	$P_{\text{total}} \text{ (W)}$	
Case 1	4611	4610	0.0002	0.000	0.0000	0	0.00	
Case 2	4611	4610	0.0002	0.005	0.0000	240	0.00	
Case 3	4611	4609	0.0002	0.006	0.0000	221	0.00	
Case 4	4216	4215	0.0002	28.747	0.1653	161	26.61	
Case 5	3880	3879	0.0002	29.821	0.1779	158	28.10	
Case 6	3595	3595	0.0002	27.634	0.1527	158	24.13	43.5
			0.0002	24.519	0.1202	161	19.36	
			0.0002	0.005	0.0000	221	0.00	
			0.0002	0.004	0.0000	240	0.00	

4. Conclusions

The present study consisted of combining TEGs modules with a boiler waste heat recovery system, with Rockwool insulation, taking into consideration variables like thermal resistance, power output, water temperature, and energy conversion efficiency. The results show that:

1. **Heat Flow:** Heat flow from exhaust gases to the environment decreases as TEGs approach the exhaust gases; resistance is lowest when TEGs are situated farther away from the exhaust gases. In scenarios 2 and 3, the heat flow of water is the greatest.
2. **Power generated:** When a TEG is placed against the inner pipe wall (Case 5), it produces the most power and lowers the heat flow of water. TEG position affects water heat flow; instances 4 and 5 show lower values because of the TEGs' heat absorption.
3. **Effect of Insulation:** tiny effect of insulation is caused by the high water mass flow rate, and having starting water temperature similar to ambient air temperature.

This study constitute a first baseline study of testing the potential of hybridization of heat recovery from exhaust gas of boilers with thermoelectric generators. As future work, a parametric study that takes into consideration many important affecting parameters should be performed. This parametric study should mainly treat the effect of water flow rate and inlet temperature, exhaust gas flow rate and inlet temperature, TEG thickness and thermal conductivity, and TEG material (power to temperature difference ratio).

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