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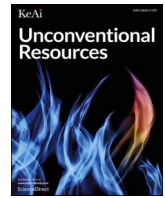
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Enhancing heat recovery efficiency in chimney exhaust systems using thermoelectric generators – Thermal modeling and parametric analysis

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ABSTRACT

The rising demand for sustainable energy solutions has made the utilization of waste heat from industrial processes a priority. Thermoelectric generators present an effective method for recovering and converting waste heat into useable electrical energy, therefore enhancing energy efficiency and sustainability. This study presents a parametric study of thermoelectric generators for waste heat recovery from heating chimney exhaust. In order to investigate the impact of placing the thermoelectric generators at different locations, simplified thermal resistance modeling was performed. Performance metrics demonstrate that the positioning of the thermoelectric generator site can bring about major improvements including thermal resistance, generated power, temperature of water heated, and energy conversion efficiency, which ranged from 0.57 % to 5.6 %, depending on thermoelectric generators configuration and operating parameters. By positioning thermoelectric generators on the exterior walls of the exhaust pipe, close to the heat source, a significant amount of electrical power—up to 37.67 W—could be produced. Additionally, a parametric analysis was conducted on important operating parameters: the mass flow rate and input temperatures of the exhaust gas and water. The application of 6 different cases showed that Case 5 of thermoelectric generator modules, with $\dot{m}_g = 0.25$ kg/s, $T_{g,i} = 390$ °C, $\dot{m}_w = 0.3$ kg/s and $T_{w,i} = 20$ °C, was the optimal condition, based on observations. The results demonstrate notable advancements in power production and energy recovery, and includes clear recommendations for future research that will bring about a shift in the direction of sustainable industrial operations.

1. Introduction

1.1. Problem statement

Energy is the foundation for various applications and is crucial in enabling daily activities [1–5]. Multiple reports showed a considerable growth rate in the world's energy demand due to an increase in population and use applications [6–12]. This increase in demand encourages creative ideas to address energy problems [13,14]. Researchers can improve sustainable energy solutions by combining academic investigations with practical applications, significantly impacting the future orientation of the energy landscape [15,16]. About 2.7 billion people, or 40 % of the world population, depend on wood and other biomass for domestic heating and cooking in conventional biomass cook

stoves [17]. However, with the improvement of living standards, people have higher requirements for electrical energy. These requirements are therefore increasing the energy demand, especially in refrigeration and lighting systems [16,18]. Meanwhile, pollution arises as a result of waste heat being released into the atmosphere through flue (exhaust) gas. Recovering this waste heat can lead to a large reduction in energy demand and greenhouse gas emissions [19,20]. The energy sector, which is accountable for 75 % of global greenhouse gas emissions, requires substantial changes in order to attain a net zero CO₂ emissions objective by 2050. Energy system research focuses on improving efficiency or developing new systems that utilize renewable sources more effectively [21].

Thermoelectric generators (TEGs) are considered to be a highly promising technology for mitigating gas emissions and addressing the

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challenges of global warming [22]. TEGs are devices that can generate electricity by utilizing temperature differences. Through the phenomenon known as the Seebeck effect, the heat flux is converted into electrical energy, which allows for the direct and environmentally friendly conversion of thermal energy into electrical energy [22,23]. TEG systems have gained significant attention in the recovery of waste heat due to their unique advantages in recent years [24,25]. TEGs provide an opportunity to generate electrical energy from heat energy without moving parts such as turbines, eliminating extra maintenance and replacement costs [26]. Nevertheless, cogeneration systems, which utilize waste heat sources, have become essential solutions for reducing energy consumption and mitigating CO₂ emissions in various industrial sectors [27]. Numerous studies have been dedicated to the development of innovative heat exchangers with the aim of enhancing heat transfer and optimizing output performance. Nevertheless, there has been limited research on the joint optimization of heat transfer enhancement and flow resistance in the TEG system [28]. However, TEG is vital in heat utilization, especially in the industrial and automotive fields [29]. There is a restricted supply of research available on the application of TEGs in waste heat recovery (WHR) across various fields. It is evident that the world is dealing with several pressing concerns, including the challenges caused by a growing population, rising energy expenses, and the issue of global warming. Researchers are currently working on enhancing energy harvesting efficiency [22].

WHR method is a highly effective approach to enhancing energy efficiency, reducing wasted energy released into the environment, and ultimately mitigating greenhouse gas emissions [30]. Typically, waste heat occurs as hot flue gas, vapor streams, exhaust cooling water, and heat emitted by convective and radiating hot surfaces [31]. Indeed, WHR systems are promising technologies that can efficiently harvest this energy lost to the environment [32,33]. Thermal energy (TE) is the main energy source utilized in different applications, although it disperses excess energy that could be committed to alternative objectives. WHR is an economical method to enhance the efficiency of a system and reduce energy usage [19].

1.2. Novelty of this study

Industrial waste heat recovery is a crucial approach for advancing the transition to a low-carbon economy and attaining climate objectives. Additionally, it is an essential measure for fostering sustainable development and preserving the ecological environment [34,35]. Using waste heat disposed from industries such as power generation, oil refining, and steelmaking is necessary for increasing energy utilization efficiency [36]. Nevertheless, it is worth noting that a substantial quantity of low-grade waste heat produced by conventional systems is simply released into surrounding environment, resulting in a low energy utilization rate for the system [37].

Current research in energy management within industrial settings often focuses on recovering waste heat from emissions, typically released through chimneys, and converting this thermal energy into useable electricity using thermoelectric modules [38].

This study distinguishes itself by presenting a comprehensive thermal modeling and parametric analysis of TEG integration within chimney exhaust systems. Unlike past work, this research.

1. Develops a simplified thermal resistance network to analyze heat transfer pathways across various TEG configurations.
2. Examines six distinct TEG placements (outer/inner walls of pipes and tanks) to determine their impact on energy recovery performance.
3. Investigates parametric variations, including gas and water mass flow rates, exhaust gas temperatures, and water inlet temperatures, to identify optimal operating conditions.
4. Demonstrates a novel approach to enhancing the simultaneous generation of electricity and hot water, providing insights for sustainable industrial operations.

The findings from this study present actionable recommendations for improving energy recovery systems and advancing the use of TEGs in real-world applications. By bridging gaps in current research, this work contributes to ongoing efforts to reduce energy waste and minimize environmental impact.

2. Methodology

2.1. System overview

This research investigates the integration of TEGs into a chimney exhaust system for the purposes of waste heat recovery and energy conversion. The suggested system consists of the following fundamental components.

- Chimney with exhaust pipe: the principal source of heat.
- Water tank: Enclosing the exhaust pipe to improve heat transfer and facilitate water heating for secondary energy use.
- TEG modules: Strategically located at multiple points along the exhaust pipe and water tank to optimize thermal energy absorption and subsequent electrical energy production.
- Insulation material: Rockwool with a thermal conductivity of 0.043 W/mK, utilized to reduce heat loss and enhance system efficiency.

2.2. Thermal modeling methodology

Recent studies have utilized CFD analytical models and fluid-thermal electric interaction models to simulate TEG systems. A CFD based method that effectively captures localized temperature distributions and fluid flow dynamics offers comprehensive insights into the thermal and electrical performance of TEGs [39]. Likewise, a fluid-thermal electric coupling model is employed to examine multiphysics interactions, facilitating accurate estimations in dynamic operating configurations [40]. These advanced models provide excellent precision because they often involve complex configurations, long computation durations, and specialized software requirements. However, these characteristics may constrain their practical utilization in expedited parametric analyses and initial system designs. Therefore, this study employs a simplified thermal resistance model, offering several significant benefits.

- Implementation simplicity: The model necessitates minimal processing resources and can be executed with fundamental mathematical tools.
- Faster simulations: Facilitates rapid assessments of system performance, rendering it ideal for parametric analysis and design optimization.
- Practical application: The simplicity of the model makes it accessible for engineers and designers seeking to evaluate TEG performance without the need for complex simulations.

Therefore, a simplified thermal resistance network model was created to enhance the examination of heat transfer kinetics and energy conversion efficiency. The modeling methodology was based on the following assumptions.

- Constant-state thermal transfer conditions.
- Equations of governance.
- Thermal energy transfer rate from exhaust gas.
- Power output of a unit TEG module.

2.3. Parametric examination

The performance evaluation included a systematic parametric study, during which the subsequent operating variables were altered to evaluate their effects.

- Exhaust gas mass flow rate (\dot{m}_g): 0.05–0.25 kg/s.
- Inlet temperature of exhaust gas ($T_{g,i}$): 270–390 °C.
- Mass flow rate of water (\dot{m}_w): 0.1–1.2 kg/s.
- Inlet water temperature ($T_{w,i}$): 10–30 °C.

2.4. Analyzed TEG configurations

- Case 1: Baseline condition absent TEGs.
- Case 2–6: TEGs positioned at various locations, encompassing the exterior and inner surfaces of both the exhaust pipe and water tank.

2.5. Performance indicators

The assessment criteria comprised.

- Thermal resistance (R_{total}): A measure of the efficacy of heat transport routes.
- Electrical power output (P_{TEG}): Measures the energy conversion capability of the TEG modules.
- Water heating efficiency: Assesses the degree of temperature increase in the water tank.

3. Configurations and thermal modeling

3.1. TEG main configurations

The integration of TEGs into a Heat Recovery System (HRS) specifically engineered for the exhaust gas of a wood chimney. The study analyzes six cases (Fig. 1), beginning with a baseline scenario in which water heating is solely dependent on the HRS. Fig. 1 shows an upper cross section view of the heating chimney water tank, in which the placement of TEGs is specified in six different configurations.

These scenarios involve strategically placing TEGs within the HRS to enhance its efficiency. Accordingly, these cases, as presented in Fig. 1, are as follows.

1. Case 1: No TEG configuration.
2. Case 2: TEGs positioned at the outer wall of the water tank.
3. Case 3: TEGs positioned at the inner wall of the water tank.
4. Case 4: TEGs positioned at the outer wall of the exhaust pipe.
5. Case 5: TEGs positioned at the inner wall of the exhaust pipe.
6. Case 6: TEGs positioned at both the inner and outer walls of the pipe and the water tank walls.

3.2. Governing equations

With a specific focus on the thermal resistances of the different suggested scenarios, Fig. 2 offers a visual representation of the thermal

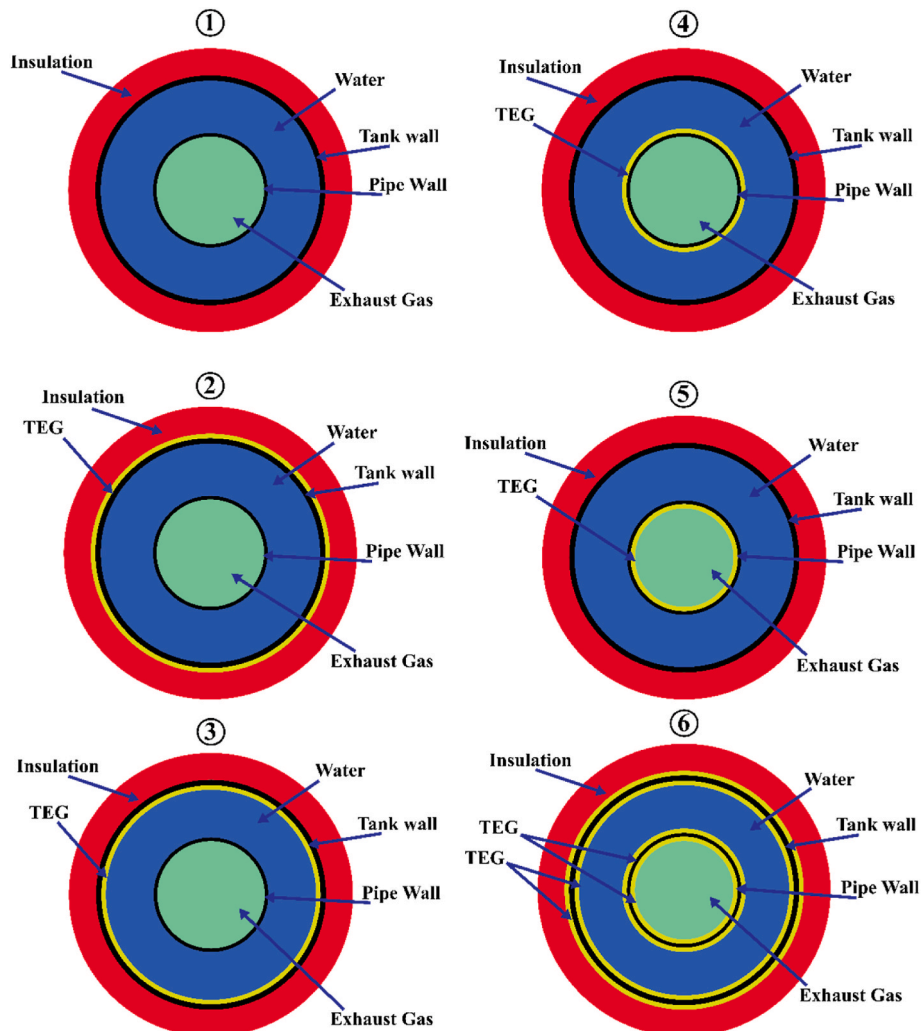


Fig. 1. The six studied cases for different placement of TEGs integrated with the chimney.

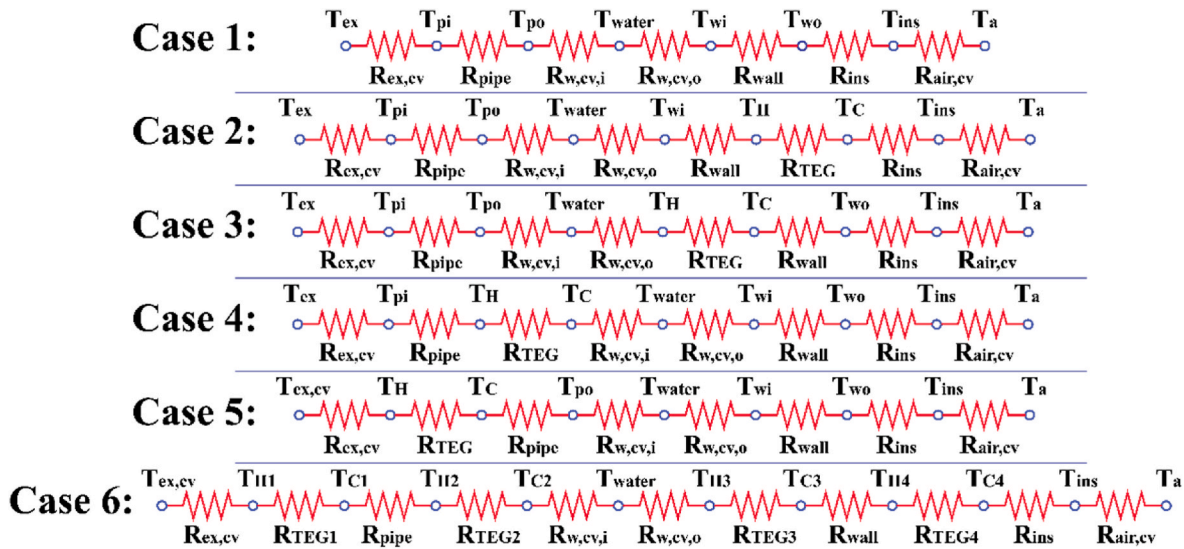


Fig. 2. Illustration of thermal modeling of scenarios in relation to thermal resistances.

analysis performed. This analysis investigates the distribution of heat in each situation. The temperatures are exhaust gas (T_{ex}), inner surface of the pipe (T_{pi}), outer surface of the pipe (T_{po}), water (T_{water}), inner surface of water tank wall (T_{wi}), outer surface of water tank wall (T_{wo}), insulation layer (T_{ins}), ambient (T_a), hot side of TEG (T_H), and cold side of TEG (T_C).

Tables 1 and 2 list the terms and equations used in the paper, respectively.

4. Performance results and analysis

The input parameters for exhaust gas temperature and mass flow rate which were derived from Ref. [41] are subjected to a thorough analytical analysis. A specific wood chimney was considered for the study. The essential variables required for this analytical investigation are measured and crossed through a parametric analysis in a previous study [42].

This investigation used a 56×56 mm TEG, model number is TEG1-12611-8.0 [43]. A 30-mm thick Rockwool layer with a thermal conductivity of 0.043 W/mK is employed as insulation [44].

The results of the configurational investigation are shown in Table 3. These values correspond with water's high mass flow rate (0.59 kg/s). Furthermore, the initial water temperature ($T_{w, in} = 20$ °C) equals the surrounding air temperature. This lowers the temperature gradient between the water and the surrounding air. As a result, the impact of insulation on the outer surface and TEG on the water tank's inner and outside surfaces is insignificant. In the second and third cases, the values

Table 1
Definition of terms and their corresponding symbols.

Symbol	Term Definition
$q_{exhaust}$	Exhaust heat flow rate
ΔT_{ex}	Differential temperature between water temperature and exhaust gas
R_{total1}	Computation of the total thermal resistance in a particular scenario
q_{water}	Water heat flow rate
$q_{water,out}$	Lost heat flow rate from water
$\Delta T_{water,out}$	Differential temperature between ambient temperature and water temperature
R_{total2}	Summation of thermal resistances in a specific case
$T_{(n)}$	Number of level gauged from the exhaust gas to the air
P_{1TEG}	Power produced by a single TEG
$\left(\frac{P}{\Delta T^2}\right)_{Ref}$	Provided by the supplier
ΔT	Differential temperature of TEG between heat source and sink

Table 2
Governing equations.

Number	Equation	Number	Equation
1	$q_{exhaust} = \frac{\Delta T_{ex}}{R_{total1}}$	5	$q_{water} = q_{exhaust} - q_{water,out}$
2	$\Delta T_{ex} = T_{ex} - T_w$	6	$T_{(n)} = T_{(n-1)} - qR_{(n)}$
3	$q_{water,out} = \frac{\Delta T_{water,out}}{R_{total2}}$	7	$\left(\frac{P}{\Delta T^2}\right)_{Ref} = \left(\frac{P_{1TEG}}{\Delta T^2}\right)$
4	$\Delta T_{water,out} = T_w - T_a$	8	$P_{1TEG} = \left(\frac{P}{\Delta T^2}\right)_{Ref} \Delta T^2$

Table 3
Key outcomes of all cases.

Case	Exhaust heat flow rate (W)	Water heat flow rate (W)	Number of TEGs	Total Power Generated (W)
1	6411	6407	-	No power generation
2	6411	6407	522	No power generation
3	6411	6407	497	No power generation
4	6054	6051	260	34.6
5	5563	5560	244	36.79
6	5245	5242	244	32.70
			260	26.02
			497	No power generation
			522	No power generation
				58.7

for $q_{exhaust}$ and q_{water} are approximately 6410 W, indicating their similarity. TEG production does not occur in either case, regardless of its positioning on the outer or inner water tank. The temperature difference in both cases is negligible. In Case 4, where TEGs are positioned on the external surface of the exhaust pipe, the heat transfer rates $q_{exhaust}$ and q_{water} achieve their optimal values at 6054 W, resulting in a power output of 34.67 W for the TEGs (P_{TEG}). However, in Case 5, there is a reduction of around 500 W in both $q_{exhaust}$ and q_{water} , but P_{TEG} rises to 36.79 W. TEGs have the highest efficiency level compared to all other configurations. In Case 6, TEGs are placed at 4 different sites, resulting in the maximum number of TEGs being used. In this scenario, the values for $q_{exhaust}$ and q_{water} are the lowest, measuring around 5245 W. However, the TEG production is much higher compared to earlier cases, with a P_{TEG} value of 58.7 W. Based on Equation (8), the power generated will increase with a greater temperature difference between the heat source

and heat sink, as indicated by the supplier's reading of $\left(\frac{P}{\Delta T^2}\right)_{Ref}$.

Another case demonstrates that the TEG's close proximity to the exhaust gas causes a significant temperature difference, leading to a notable boost in power output. Nevertheless, the temperature difference is at its lowest point in the case of TEG, as it is positioned further away from the exhaust gas. (Case 4). However, Case 6, which has the highest number of TEGs among all cases, generates the most power in total. Therefore, the fifth configuration is the most favorable choice for power generation. The third scenario is the most optimal option considering q_{water} , but Case 6 is the most effective regarding overall power output. Case 4, which involves placing TEGs on the outside surface of the exhaust gas pipe, is a suitable option that effectively balances heat recovery and power generation. When lower water flow rates are used and higher water temperatures are present, Cases 2 and 3 become more favorable. This is because it results in increased heat losses to the surrounding environment, eliminating the need for TEGs. TEGs, in this scenario, function as insulation and offer greater heat recovery capabilities. A best-suggested case for TEGs involves replacing insulation with TEGs for transferring heat between water and ambient air. Cases 4 to 6 have the potential to be more favorable if thinner and more thermally conductive TEGs are used. In this scenario, it is possible to recover a greater amount of heat while still maintaining a reasonable level of power output. These designs can be improved by utilizing TEGs with a higher power-to-temperature difference ratio. Furthermore, these arrangements can demonstrate their capabilities as the flow rates of the exhaust gas increase due to the elevated thermal resistance of the exhaust pipe wall.

The present study included integrating TEG modules with a chimney WHR system using Rockwool insulation. The research considered many factors, such as thermal resistance, power output, water temperature, and energy conversion efficiency. The findings display that in the comparison of cases, Cases 2 and 3 provide equivalent results for $q_{exhaust}$ and q_{water} , suggesting equal performance. Nevertheless, there is no observable creation of TEG in these cases. However, Cases 4, 5, and 6 show differences in $q_{exhaust}$ and q_{water} . Case 5 has lower values for both parameters than Case 4, while Case 6 has the lowest values. Finally, Case 6 has the greatest number of TEGs, which results in the highest TEG output. Regarding the effect of TEG location, installing TEGs in greater proximity to the exhaust gas (Case 5) leads to a higher temperature differential, which increases power production. Yet, placing TEGs farther from exhaust gas (Case 4) reduces the temperature difference but still achieves the best power production. On the other hand, Case 6, where TEGs are placed in several sites, delivers the most significant total power production.

Therefore, Case 5 is the optimal operating configuration. It is the ideal choice for power-generating efficiency due to its superior power output compared to the other examples. This case, with its respective results, will be used as a reference for upcoming analyses of parameter variation.

5. Parametric analysis of key operating variables

The main operating parameters that have a significant impact on the performance of the current system in terms of water heating and power generation are examined. The primary fluids used in the integration of TEGs into HRS are water and gas. This system is specifically designed to capture the waste heat from the exhaust gas of a wood chimney. Two crucial factors in this system which have a substantial impact on its overall efficiency when they change, are the mass flow rate and the inlet temperature. Next, this section will provide a comprehensive analysis of these parameters, including.

- Mass flow rate of gas.
- Inlet exhaust gas temperature.
- Mass flow rate of water.

- Inlet water temperature.

As mentioned in section 3, Case 5, with TEGs positioned at the internal wall of the exhaust pipe, will be the reference for the next parametric analyses.

5.1. Mass flow rate of gas

The mass flow rate of gas is a crucial parameter in fluid dynamics because it governs the behavior and interaction of gas inside the system. The variability of this factor has significant effects on factors such as heat transfer rates, pressure drops, and overall efficiency. By analyzing the gas mass flow rate, the complex equilibrium between energy input and system output, uncovering important insight for enhancing efficiency and maintaining stability is explored. This parameter is studied in this section. However, the TEG configuration (Case 5), which is chosen as a reference for the analysis in this section, showed $P_{total} = 58.7 \text{ W}$, and $q_{water} = 5560 \text{ W}$. In the current chimney study, the mass flow rate of gas presents the mass flow rate of exhaust gas passing through the chimney exhaust pipe. Five cases are considered, where $\dot{m}_g = 0.05, 0.1, 0.14, 0.2$ and 0.25 kg/s . While \dot{m}_g in the reference case was $\dot{m}_g = 0.14 \text{ kg/s}$. Therefore, two values are taken below the reference case and two other values above the reference case. Fig. 3 displays the variation of the heat convective coefficient of gas h_g as a function of gas mass flow rate \dot{m}_g .

Results show that as \dot{m}_g increases, h_g increases too, where h_g reaches maximum value $64.64 \text{ W/m}^2\text{K}$ at $\dot{m}_g = 0.25 \text{ kg/s}$. Fig. 4 and 5 show the variation of exhaust gas temperatures ($T_{g,in}$ and $T_{g,o}$) and water temperatures ($T_{w,in}$ and $T_{w,o}$) as a function of gas mass flow rate \dot{m}_g , respectively.

For Fig. 4, inlet exhaust gas temperature $T_{g,i}$ is constant at $330 \text{ }^\circ\text{C}$ for all cases, while $T_{g,o}$ increases as \dot{m}_g increases, to both reach maximum values $T_{g,o} = 302.15 \text{ }^\circ\text{C}$ at $\dot{m}_g = 0.25 \text{ kg/s}$. For Fig. 5, inlet water temperature $T_{w,i}$ is constant at $20 \text{ }^\circ\text{C}$ for all cases, while $T_{w,o}$ increases as \dot{m}_g increases, to both reach maximum values $T_{w,o} = 23.01 \text{ }^\circ\text{C}$ at $\dot{m}_g = 0.25 \text{ kg/s}$. Subsequently, the increase in the heat convective coefficient enhances heat transfer. This is because a higher coefficient leads to more efficient heat exchange between the surface and the fluid. Moreover, the increase in outlet water temperature shows that water is heated more thus more heat is captured from gas. Fig. 6 shows the variation of water heat flow rate q_{water} and (total power generated by TEG) P_{total} as a function of gas mass flow rate \dot{m}_g .

q_{water} increases to reach their maximum values with 9051 W , which

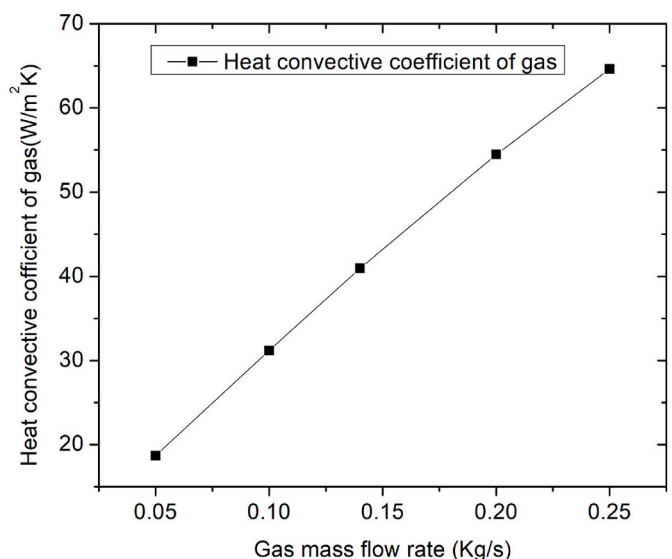


Fig. 3. Variation of h_g as a function of \dot{m}_g .

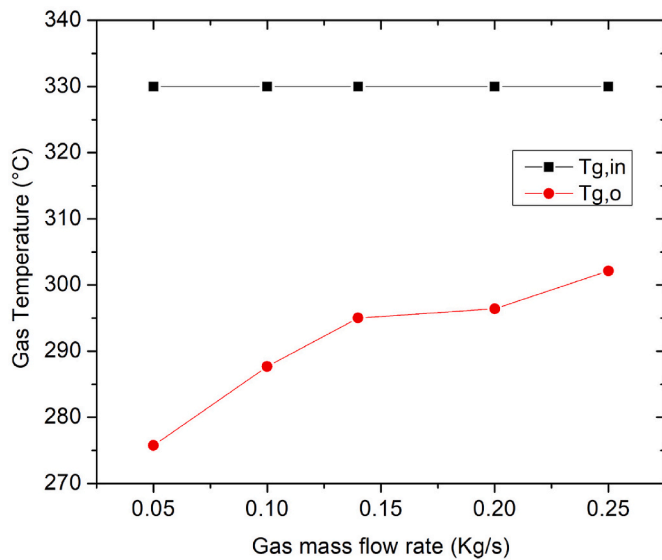


Fig. 4. Variation of $T_{g,in}$ and $T_{g,o}$ as a function of \dot{m}_g .

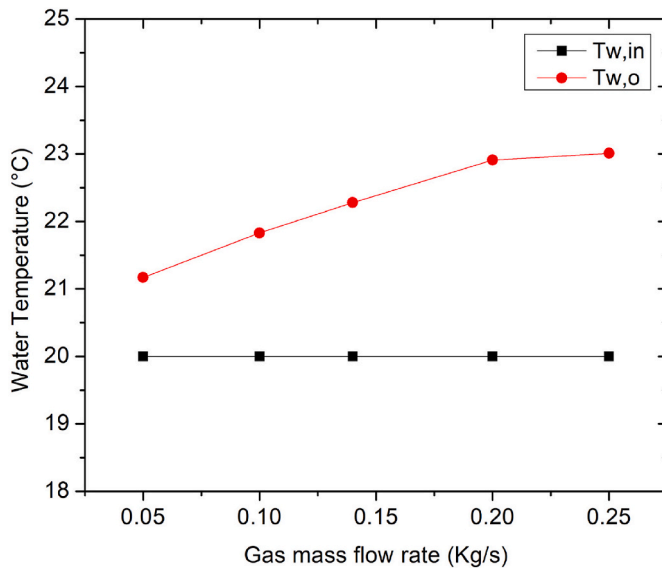


Fig. 5. Variation of $T_{w,in}$ and $T_{w,o}$ as a function of \dot{m}_g .

is triple the lowest value, and P_{total} increases to reach 97.48 W, which is 7.8 times greater than that with the lowest value. Both parameters rise with the gas mass flow rate increase. Compared to reference Case 5, with $P_{total} = 58.7$ W, and $q_{water} = 5560$ W, the new variation ($\dot{m}_g = 0.25$ kg/s) showed higher total power generation and water heat rate. Therefore, the best case to take as a reference for the next parametric study, is with the highest values, with $\dot{m}_g = 0.25$ kg/s, and upholding the thermal modeling for TEG positioning (Case 5).

5.2. Inlet exhaust gas temperature

The measurement of the inlet exhaust gas temperature is crucial for estimating the maximum amount of thermal energy that may be connected in heat recovery processes. It presents both a difficulty and an opportunity: a challenge due to the thermal stress it can generate and an opportunity because of the energy that can be utilized. Examining the variation of this phenomenon yields essential insight for enhancing heat transfer methods, enhancing energy recovery, and reducing heat losses, eventually improving the sustainability and effectiveness of thermal

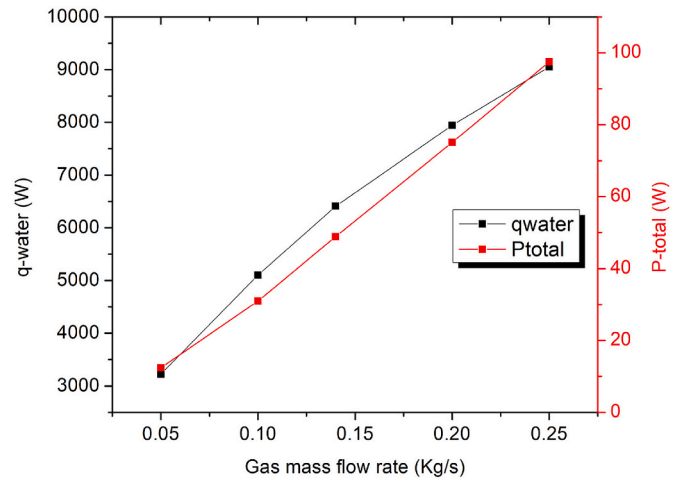


Fig. 6. Change of P_{total} and q_{water} as a function of \dot{m}_g .

systems. For this reason, this parameter is studied in this section.

In the ongoing chimney investigation, the inlet of the exhaust gas temperature represents the temperature of the exhaust gas as it flows through the chimney exhaust pipe and is released into surrounding. Five cases are considered, where $T_{g,i} = 270, 300, 330, 360$ and 390 °C. While $T_{g,i}$ in the reference case was $\dot{m}_g = 330$ °C. Therefore, two values are taken below the reference case and two other values above the reference case. Fig. 7 shows the variation of outlet water temperature $T_{w,o}$ and outlet gas temperature $T_{g,o}$ as a function of inlet gas temperature $T_{g,i}$.

For this case study, inlet water temperature is constant at $T_{w,i} = 20$ °C. Results show that as $T_{g,i}$ increases, $T_{g,o}$ increases too. In addition, $T_{w,o}$ maximum value 24.3 °C at $T_{g,i} = 390$ °C. Fig. 8 shows the change of heat flow rate of water q_{water} and (entire power generation by TEG) P_{total} as a function of inlet gas temperature $T_{g,i}$.

In Fig. 8, q_{water} increases to reach their maximum values with 10728 W at $T_g = 390$ °C, while P_{total} increases to reach 136.96 W, at maximum inlet gas temperature value. Results show that this range of changes showed good enhancements but were not effective in the previous modification (gas mass flow rate). This is justified by the factor of addition, which cannot be unified for all parameters (mass flow rate can be doubled, but inlet gas temperature is hard to double). However, current values at maximum inlet gas temperature $T_{g,i} = 390$ °C, showed values higher than that in Section 3.1. Finally, the best case to take as a reference for the next parametric study is with the highest values, with $\dot{m}_g = 0.25$ kg/s, and $T_{g,i} = 390$ °C, and upholding the thermal modeling

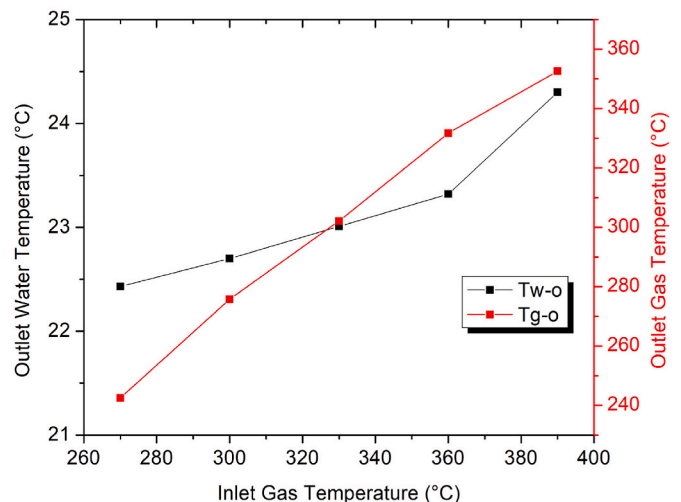


Fig. 7. Variation of $T_{w,o}$ and $T_{g,o}$ as a function of $T_{g,i}$.

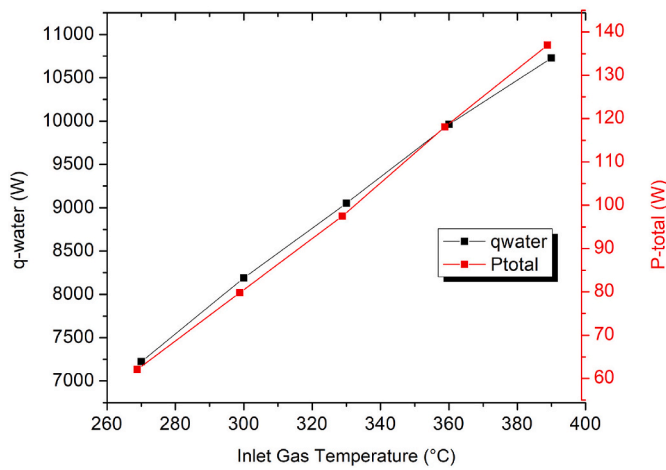


Fig. 8. Change of P_{total} and q_{water} and as a function of $T_{g,i}$.

for TEG positioning (Case 5).

5.3. Mass flow rate of water

Water, an important part of thermal systems, can absorb and release heat, making the rate at which water flows a critical characteristic to investigate. Variations in water flow rate may affect the process of transferring heat, consequently affecting the system's capacity to maintain desired temperatures. Gaining a comprehensive understanding of the complexities of water flow enables us to precisely influence the thermal efficiency, guaranteeing that systems function within their most efficient temperature range and improving their total energy preservation.

In the current chimney study, the mass flow rate of water presents the flow rate of water passing through the water tank placed on the chimney exhaust pipe. It is usually driven by a water pump. Five cases are considered, where mass flow rate of water $\dot{m}_w = 0.1, 0.3, 0.59, 0.9$ and 1.2 kg/s. While \dot{m}_w in the reference case was $\dot{m}_w = 0.59$ kg/s. Therefore, two values are taken below the reference case, and two other values above the reference case. Fig. 9 shows change of water heat convective coefficient h_w as a function of water mass flow rate \dot{m}_w .

Results show that as \dot{m}_w increases from 0.1 to 0.6 kg/s, h_w is constant at 242.19 W/m²K, while when \dot{m}_w increases from 0.6 to 1.2 kg/s, and h_w rises sharply from its initial value to reach maximum value at 1284.50

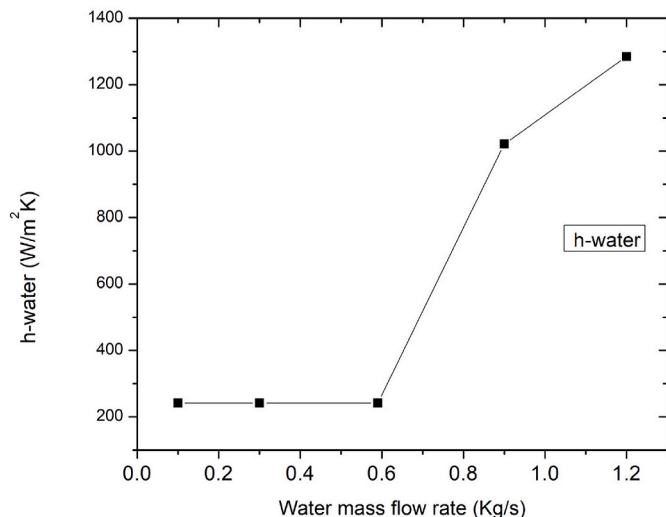


Fig. 9. Variation of h_w as a function of \dot{m}_w .

W/m²K. Analysis of these results shows that the heat convective coefficient of water is steady at the same value when the water flow rate is still laminar, where Nusselt number Nu (parameter used in calculating h_w) is considered constant throughout the calculations. However, when the flow turns turbulent, h_w increases rapidly with the water mass flow rate increase. Fig. 10 shows the variation of $T_{w,o}$ and $T_{g,o}$ as a function of \dot{m}_w .

In this case study, inlet water temperature is constant at $T_{w,i} = 20$ °C. Results show that as \dot{m}_w increases, $T_{w,o}$ decreases. In addition, $T_{g,o}$ decreases as \dot{m}_w increases. $T_{w,o}$ and $T_{g,o}$ reach their minimum values at 22.43 and 347.4 °C at $\dot{m}_w = 1.2$ kg/s. As the water mass flow rate increases, the output water and gas temperatures decrease due to the water's increased heat absorption capacity. Increasing the flow rate of water reduces the time it remains in contact with the heat source, such as gas. However, a higher volume of water can absorb more heat in total. Consequently, there is a decrease in the increase of water temperature and a greater extraction of heat from the gas, leading to reduced outlet temperatures for both the water and the exhaust gas. Fig. 11 shows the change of water heat flow rate and total generation of power by TEGs, as a function of \dot{m}_w .

For Fig. 11, q_{water} increase to reach their maximum values of 12244 W at $\dot{m}_w = 1.2$ kg/s. In addition, P_{total} increases to reach 178.32 W, at $\dot{m}_w = 1.2$ kg/s. Results show that this range of changes showed very high enrichments in terms of TEG power generation and water heat flow rate. Yet, the main aim is not to warm a huge volume of water but power generation. It is just heating the water in the chimney exhaust water tank. Therefore, an increase in water outlet temperature should be considered. To optimize the water mass flow rate, a balance should be done to achieve the higher water temperature and power generation levels simultaneously. Finally, case of $\dot{m}_w = 0.3$ kg/s is considered where $T_{w,o}$ is relatively high 28.5 °C, q_{water} is 10662 W and P_{total} is 135.41 W. However, current values at $\dot{m}_w = 0.3$ kg/s, showed values almost the same of that in section 3.2 but with higher water outlet temperature. Finally, the best case to take as a reference for the next parametric study, is with $\dot{m}_g = 0.25$ kg/s, $T_{g,i} = 390$ °C, $\dot{m}_w = 0.3$ kg/s and upholding the thermal modeling for TEG positioning (Case 5).

5.4. Inlet water temperature

Inlet water temperature represents the initial measurement of thermal energy in a system. It serves as the fundamental basis for heat exchange activities. Variations in this temperature not only affect the speeds at which heat is transferred, but also the thermal differences that push these processes. Through the exploration of the effect of water temperature at inlet initially, the power to regulate and influence the

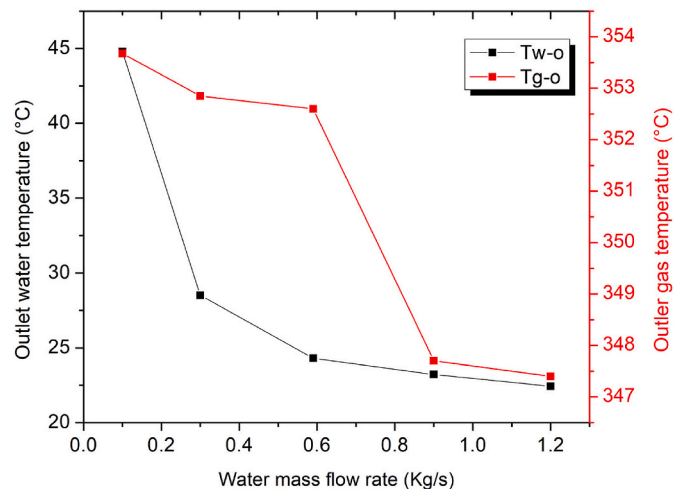


Fig. 10. Variation of $T_{w,o}$ and $T_{g,o}$ as a function of \dot{m}_w .

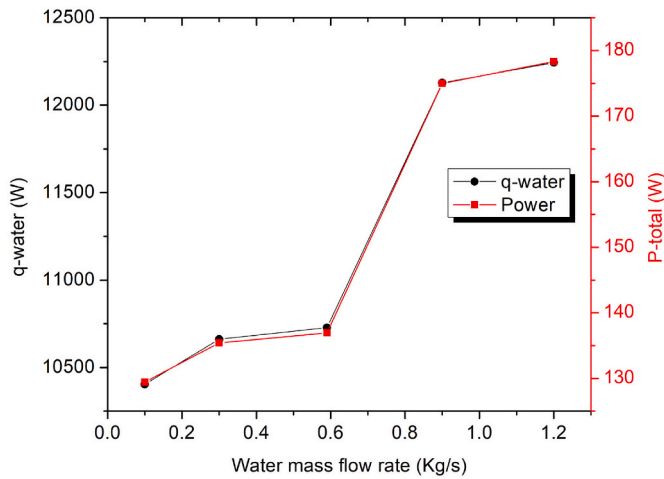


Fig. 11. Variation of q_{water} and P_{total} with change of \dot{m}_w .

thermal efficiency of the system is obtained, therefore creating opportunities for advancements in energy conservation and system reliability.

In the current chimney study, the inlet water temperature presents the temperature of water entering the water tank placed on the chimney exhaust pipe. It is usually driven by a water pump. Five cases are considered, where inlet water temperature rate $T_w = 10, 15, 20, 25,$ and $30\text{ }^\circ\text{C}$. While T_w in the reference case was $T_w = 20\text{ }^\circ\text{C}$. Therefore, two values are taken below the reference case and two other values above the reference case. Fig. 12 shows the change of water outlet temperature $T_{w,o}$ and gas outlet temperature $T_{g,o}$ as a function of inlet water temperature $T_{w,i}$.

Results show that as $T_{w,i}$ increases from 10 to $30\text{ }^\circ\text{C}$, $T_{w,o}$ increases from 18.73 to $38.6\text{ }^\circ\text{C}$. However, during this water temperature increase, $T_{g,o}$ is almost steady at $351\text{--}352\text{ }^\circ\text{C}$. Fig. 13 shows the change of P_{total} and q_{water} as a function of $T_{w,i}$.

For Fig. 13, q_{water} decrease to reach their minimum values with 10322 W at $T_{w,i} = 30\text{ }^\circ\text{C}$. In addition P_{total} decreases to reach 127.54 W , at $T_{w,i} = 30\text{ }^\circ\text{C}$. The decline in overall power generation can be attributed to the reduction in the temperature gradient between the high and low temperature sides of the TEG, which is induced by the rise in the temperature of the incoming water. Simultaneously, a decrease in the quantity of water is anticipated when there is a smaller disparity in temperature between water and gas. The system is less effective at transferring heat from the gas to the water, which could affect the overall thermal efficiency. However, the increase in outlet water

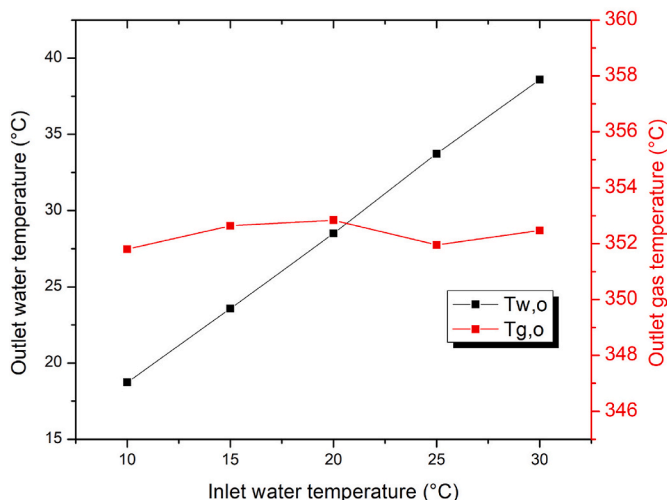


Fig. 12. Variation of $T_{w,o}$ and $T_{g,o}$ with change of $T_{w,i}$.

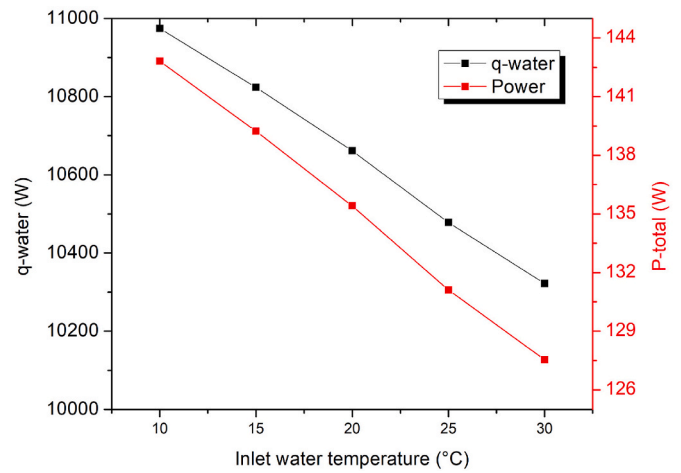


Fig. 13. Change of P_{total} and q_{water} as a function of $T_{w,i}$.

temperature is caused by the higher starting temperature. With the reduced heat transfer rate, the water absorbs less heat, but because it started at a higher temperature, the outlet temperature increases. The best case for balancing between water temperature, power generation, and water heat flow rate is the case with $T_{w,i} = 20\text{ }^\circ\text{C}$, which is initially the reference case, with $T_{w,o} = 28.5\text{ }^\circ\text{C}$, $q_{water} = 10662\text{ W}$ and $P_{total} = 135.41\text{ W}$. Finally, the best case that meets with all the main goals of the study: TEG power generation P_{total} , higher heat flow rate q_{water} and higher outlet water temperature is considering the following parameters: $\dot{m}_g = 0.25\text{ kg/s}$, $T_{g,i} = 390\text{ }^\circ\text{C}$, $\dot{m}_w = 0.3\text{ kg/s}$, $T_{w,i} = 20\text{ }^\circ\text{C}$ and upholding the thermal modeling for TEG positioning (Case 5).

5.5. Comparison with reference (case 5)

The variation of the four studied parameters in the current study and further analyses lead to significant improvements in the main outputs, which are: power generation by TEGs, water heat flow rate, and outlet water temperature. Fig. 14(a, b and c) show pie graphs for $T_{w,i}$, q_{water} , and P_{total} enhancement, respectively.

To calculate the percentage of improvements compared to reference values, the following equation is used:

$$\text{Percentage of Enhancement} = \frac{(\text{New Value} - \text{Reference Value})}{\text{Reference Value}} \times 100 \quad (1)$$

The leading enhancement percentage for total power generation by TEGs was 268 %, whereas, for water heat flow rate enhancement, the percentage was 91.7 %. However, the lowest percentage of enhancement was for outlet water temperature, at 23.68 %.

This study investigated the impact of different key parameters on a water heating and power generating system that utilizes TEGs in a heat recovery configuration from the exhaust of a wood chimney. Raising the gas mass flow rate to 0.25 kg/s greatly enhanced the efficiency of the system, resulting in power generation of 97.48 W and a peak water heat flow rate of 9051 W . By increasing the temperature of the incoming exhaust gas to $390\text{ }^\circ\text{C}$, the performance was improved, leading to a power output of 136.96 W from the TEG and a water heat flow rate of 10728 W . A water mass flow rate of 0.3 kg/s was determined to be best, as it effectively balances power generation at 135.41 W and achieves a target output water temperature of $28.5\text{ }^\circ\text{C}$. By increasing the temperature of the incoming water, the rate of heat transfer and power generation decreased. However, it resulted in an increase in the temperature of the outgoing water, which emphasizes the need to balance the system's efficiency. These findings provide useful insights for improving the efficiency of heat recovery and power generation in similar systems.

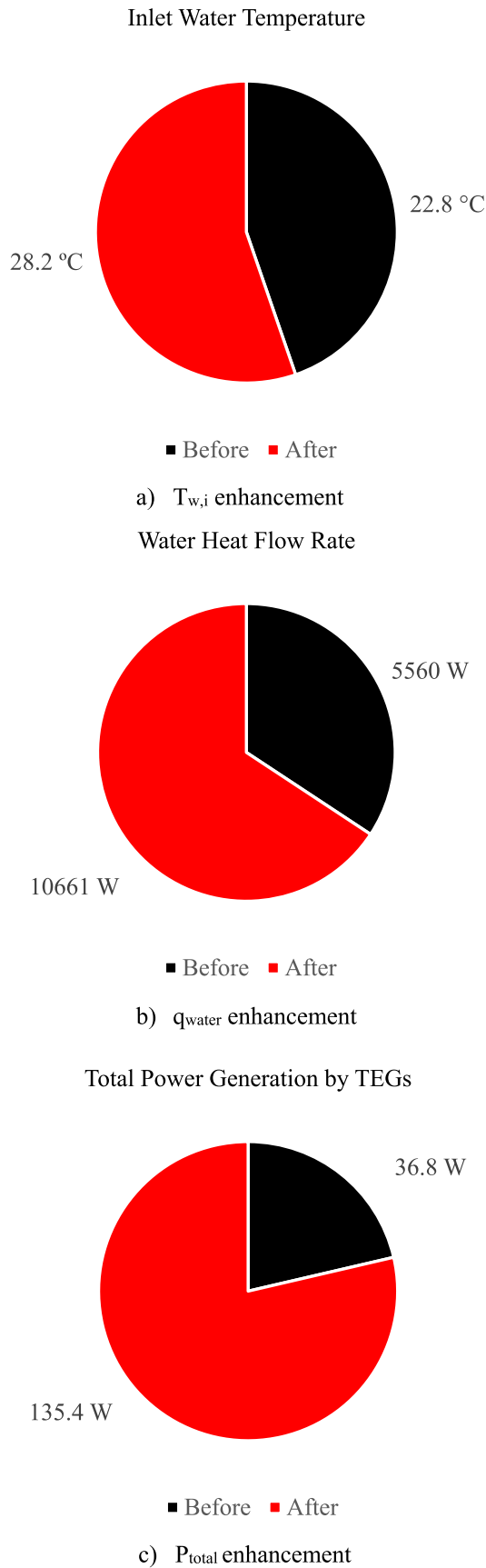


Fig. 14. Pie graphs for $T_{w,i}$, q_{water} , and P_{total} enhancement, respectively.

5.6. Energy conversion efficiency

The efficiency of the TEG system was evaluated based on the ratio of electrical power P_{TEG} generated to the total exhaust heat flow rate $q_{exhaust}$ supplied:

$$Efficiency_{TEG} = \frac{P_{TEG}}{q_{exhaust}} \times 100$$

The efficiency results are summarized in Table 4 as follows:

Case 6 demonstrated the highest efficiency (1.12 %) due to the use of multiple TEG units in different placements, optimizing energy recovery.

However, Efficiency values increased with higher gas mass flow rates and inlet gas temperatures, achieving up to 5.6 % under the optimal configuration with a gas mass flow rate of 0.25 kg/s and inlet temperature of 390 °C.

6. Conclusions and recommendations

This study examined the incorporation of TEGs into chimney exhaust systems to improve heat recovery efficiency. A thorough parametric and thermal modeling investigation was performed to assess the efficacy of various configurations and operating parameters.

• Quantitative analysis

1. Configuration analysis:

- Of the six configurations evaluated, Case 5 (TEGs positioned on the inside wall of the exhaust pipe) exhibited the greatest power generation efficiency, yielding 36.79 W under baseline conditions.
- Case 6, using TEGs positioned at various places, attained the most total power generation of 58.7 W, albeit with reduced heat transfer rates relative to Case 5.

2. Parametric analysis:

- Elevating the gas mass flow rate to 0.25 kg/s yielded a 268 % increase in total power generation (97.48 W) and a 91.7 % enhancement in water heat flow (9051 W).
- Increasing the input exhaust gas temperature to 390 °C enhanced power generation to 136.96 W and heat flow to 10728 W.
- Modifying the water mass flow rate to 0.3 kg/s resulted in a balanced performance, with a power output of 135.41 W and a water outlet temperature of 28.5 °C.
- Reducing the inlet water temperature to 20 °C produced ideal outcomes for heat transfer (10662 W) and electricity generation (135.41 W).

• Qualitative analysis

1. TEG placement effect:

- TEGs situated nearer to the heat source demonstrated elevated temperature gradients, leading to enhanced energy conversion efficiency.
- Configurations featuring several TEG locations yielded greater power outputs but diminished thermal efficiency owing to heightened thermal resistance.

2. System optimization:

- The parametric analysis revealed that modifying mass flow rates and intake temperatures can enhance performance according to particular application needs.

Slender and thermally conductive TEGs can further optimize system performance while preserving efficiency.

3. Practical consequences:

Table 4
Efficiency values for cases 4,5 and 6.

Case	$q_{exhaust}$ (W)	P_{TEG} (W)	Efficiency (%)
Case 4	6054	34.67	0.57
Case 5	5563	36.79	0.66
Case 6	5245	58.70	1.12

- The results present a scalable method for incorporating TEGs into industrial exhaust systems to concurrently produce power and reclaim waste heat.

This study emphasizes the capability of TEG-based systems as a dual-function solution for waste heat recovery and energy production. By optimizing essential parameters, this approach can substantially decrease energy usage and greenhouse gas emissions, thereby promoting sustainable industrial operations. Future research may focus on advanced materials for TEGs, system downsizing, and field-scale experimentation to validate laboratory results. These efforts aim to enhance efficiency and system performance by refining critical parameters and exploring innovative methods to improve both heat recovery and power generation. Furthermore, summary insights are provided to serve as guidelines for researchers in future studies.

For TEG modules integration.

- Subsequent research may enhance future framework by using CFD or coupled models for comprehensive performance validation and to augment the findings of future studies.
- Thinner and more thermally conductive TEGs might improve the efficiency of cases 4 to 6 by enabling better heat recovery without compromising power production levels.
- Using TEGs with better power-to-temperature difference ratios might significantly improve the efficiency of configurations from 4 to 6.

For parametric analysis of key operating variables.

- Optimization of gas mass flow rate: Future studies should focus on varying the gas mass flow rate to further enhance the heat transfer coefficient and maximize both power generation and heat recovery.
- Exploration of higher inlet gas temperatures: Investigate the potential benefits of further increasing the inlet exhaust gas temperature, while considering the thermal stress on the system components, to optimize energy recovery.
- Balancing water mass flow rate: Future research should explore the optimal water mass flow rate that balances between achieving higher power generation, heat flow rate, and an acceptable outlet water temperature, especially in systems where heating large volumes of water is not the primary goal.
- Inlet water temperature control: Further analysis on controlling the inlet water temperature to maintain an optimal balance between power generation efficiency and outlet water temperature, especially in systems with varying operational conditions.

CRediT authorship contribution statement

Obeida Farhat: Writing – original draft, Validation, Methodology, Investigation, Formal analysis, Data curation. **Mahmoud Khaled:** Writing – review & editing, Supervision, Project administration, Methodology, Investigation, Formal analysis, Conceptualization. **Jalal Faraj:** Writing – review & editing, Supervision, Project administration, Methodology, Investigation, Formal analysis, Conceptualization. **Khaled Chahine:** Writing – review & editing, Investigation, Formal analysis. **Farouk Hachem:** Writing – review & editing, Investigation, Formal analysis. **Cathy Castelain:** Writing – review & editing, Supervision, Project administration, Investigation, Formal analysis.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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