Harvesting Power from Saturated Steam: Utilizing TEG Systems for Waste Heat Recovery

M.A.Mahmoud [a,b*]
[a] Department of Mechanical Engineering, Benha Faculty of Engineering, Benha University, Benha,, Egypt
[b] Department of Energy Resources Engineering *Egypt-Japan University of Science and Technology, New Borg El-Arab City, Alexandria, Egypt*
mohammed.mahmoud@ejust.edu.eg
*Corresponding author

Sameh Nada [a,b]
[a] Department of Mechanical Engineering, Benha Faculty of Engineering, Benha University, Benha, , Egypt
[b] Department of Energy Resources Engineering *Egypt-Japan University of Science and Technology, New Borg El-Arab City, Alexandria, Egypt*
sameh.nada@ejust.edu.eg

Hidetoshi Sekiguchi[b,c]
[b] Department of Energy Resources Engineering, Egypt-Japan University of Science and Technology, Alexandria, Egypt
[c] Department of Chemical Science and Engineering, Tokyo Institute of Technology, Tokyo, Japan
hsekiguc@chemeng.titech.ac.jp

Hamdy Hassan [b,d]
[b]Department of Energy Resources Engineering, *Egypt-Japan University of Science and Technology, New Borg El-Arab City, Alexandria, Egypt*
[d]*Mechanical Engineering Department, Faculty of Engineering, Assiut University, Assiut, Egypt*
hamdy.aboali@ejust.edu.eg

Abstract— **Due to the substantial latent heat content found in the saturated steam exiting steam turbines in steam power plants characterized by high mass flow rates and velocities, our mathematical model addresses a group of thermoelectric generators arranged inside a heat exchanger. The saturated steam inlet to the heat exchanger serves as the heat carrier, complemented by cooling water for efficient heat management. Calculations demonstrate that the system's performance can be optimized by adjusting specific parameters.**

Initially, calculations are based on a proposed steam mass flow rate of 20 kg/sec and water mass flow rate of 20 kg/sec, with inlet temperatures of 100°C and 10°C, respectively. The key driver is the vapor amount with a quality of 0.97 in the hot source, providing significant latent energy depending on the convection heat transfer coefficient. The study investigates the variation of steam mass flow rate from 5 to 20 kg/sec across one heat exchanger and the distribution of steam mass flow rate across multiple heat exchangers. Results demonstrate that with water and steam mass flow rates both at 20 kg/sec, the system generates 2094.141 watts using 1254 thermoelectric generator, with an overall efficiency of 4.786%. Conversely, when the steam mass flow rate is 5 kg/sec and the water flow rate is 20 kg/sec across four heat exchangers, the system produces 2096.25 watts with an efficiency of 4.793%. This is attributed to heat transfer efficiency between hot and cold fluids in each heat exchanger, with each unit employing 313 TEGs. Additionally, variations in water inlet temperature significantly affect system performance in terms of power generation and efficiency.

Keywords—saturated steam, waste heat recovery, TEG

I. INTRODUCTION

Approximately 70% of the energy utilized in industrial processes is lost as low-grade heat, typically at temperatures below 100°C [1]. This represents a massive untapped resource that, if harnessed, could significantly contribute to sustainable development. Traditional energy sources like fossil fuels not only generate most of this waste heat but also lead to resource depletion and contribute to environmental issues. To address these challenges, we need a multi-faceted approach that focuses on both energy conservation and innovative energy conversion technologies. Thermoelectric generators (TEGs) offer a promising solution for converting waste heat into electricity [2]. Unlike conventional methods such as the Organic Rankine Cycle, Kalina Cycle, or Uehara Cycle, TEGs rely on the Seebeck effect to convert heat directly into electricity [3]. This method has several advantages: TEGs have no moving parts, do not require refrigerants, and do not emit carbon dioxide. Additionally, they operate silently and are simple in structure, which makes them suitable for a wide range of applications. However, the main limitation of TEGs is their relatively low conversion efficiency, typically around 5% [4], [5].Despite this, TEGs remain appealing because they make use of waste heat, a resource that is effectively free [5]. TEGs contribute significantly to overall energy efficiency. Their efficiency hinges on effective heat transfer between the hot and cold fluids. To optimize heat transfer in thermoelectric generator (TEG) systems, two primary factors require careful consideration: design strategies and operational parameters. Design strategies focus on selecting heat exchanger wall materials with high thermal conductivity, as this promotes efficient heat transfer. Additionally, optimizing the dimensions, geometry, and configuration of internal channels can significantly impact fluid dynamics and heat transfer rates. Techniques such as using fins or microchannels can increase the effective surface area, thereby

enhancing heat exchange. Operational parameters, on the other hand, involve controlling the flow rate of working fluids to achieve a balance between efficient heat transfer and reduced pumping power. The temperature differential between the hot and cold fluids is also crucial; a greater temperature differential can theoretically improve efficiency. However, practical constraints such as the availability of heat sources and the properties of working fluids must be taken into account. Various studies have examined these aspects to improve TEG system efficiency and more effectively harness waste heat. Numerous studies have explored various strategies to improve the performance of thermoelectric generator (TEG) systems, focusing on factors such as fluid inlet temperature, flow rate, thermal and electrical contact resistance, and heat exchanger design. Niu et al. [6] emphasized that higher hot fluid inlet temperatures and optimized flow rates can significantly boost system output power. Similarly, Sasaki et al. [7] demonstrated the scalability of TEG systems by constructing a water-based TEG with over 2,500 modules, achieving a peak output of around 900 W using spring water at temperatures between 82-96°C. Ahiska et al. [8] found that increasing flow rates for both hot and cold fluids led to higher output power and increased temperature differentials across the TEG. Kumar et al. [9] showed that a counterflow configuration in fluid flow provides superior performance compared to a co-flow design. Thermal and electrical contact resistance are crucial for efficient TEG operation. Liu et al. [10] proposed using silicone grease to mitigate thermal resistance, while Chen et al. [11] added concave grooves on heat exchangers to reduce thermal resistance, both of which enhanced TEG output. Electrical contact resistance, however, can hinder output power. Introducing an interface barrier between electrodes and thermoelectric materials, as suggested by W. Liu et al. [12], and R.He et al. [13], is one solution to this problem. Lesage et al. [14] explored vortex generator designs and found that the slotted flat plate type yielded the highest power output, despite its increased flow resistance. Rezania et al. [15] integrated microchannel heat exchangers into TEG systems, which significantly improved net output power. Wang et al. [16] utilized specific material to enhance heat transfer efficiency within TEGs, leading to notable performance improvements. Yang et al. [17] optimized heat transfer efficiency using flat fins and a variable cross-section area header, achieving high output power and effective pressure drop management. Different cooling methods have also been explored. Lv et al. [18] demonstrated the effectiveness of heat pipe heat exchangers in enhancing TEG output, while Li et al. [19], [20] designed a five-layer TEG system for low-grade geothermal water recovery, showcasing its potential for on-site geothermal energy harnessing. Lee et al. [21] suggest a mesh arrangement within

heat exchangers to enhance heat transfer. In a comprehensive study, Xiangrong Ma et al. [22] examined the effects of varying inlet saturation steam temperature and mass flow rate, as well as the use of turbulators and vapor gas concentration, on TEG performance. The study revealed that a combination of high inlet temperature and specific vapor concentrations yielded optimal net efficiency. Research by Zhao et al. [23], [24], [25] focused on the role of condensation in optimizing TEG performance, particularly when using natural gas boiler exhaust. Their studies demonstrated that humidification and condensation significantly increase output power and exergy efficiencies, by utilizing both sensible and latent heat from waste streams. Zhao et al. [26] introduced an innovative approach involving intermediate fluid TEGs to enhance power generation from automobile exhaust, achieving a 32.6% increase in maximum output power and reducing optimal TEG module area by 73.8%. Overall, these studies demonstrate a wide range of approaches to enhancing TEG system performance, from optimizing fluid flow and thermal resistance to exploring innovative heat exchanger designs and operational configurations.

In this paper, we explore a new approach to harness low-grade waste heat from the steam exits from turbines in small power plants. Our method focuses on the latent heat contained in steam as it exits the turbine and enters the condenser. By utilizing a specifically engineered heat exchanger, we capture the heat released during the condensation process and transfer it to TEG modules made from Bismuth Telluride (Bi2Te3). The heat is converted into electricity as the steam transitions from a quality of 0.97 to a fully saturated state at 100°C. This transition allows us to reclaim a significant amount of energy that would otherwise be lost.

The proposed approach offers a practical solution for enhancing electricity generation in small power plants. By capturing and converting waste heat into electricity, this method not only improves overall energy efficiency but also aligns with sustainable energy practices. This innovative use of TEGs could pave the way for broader applications, helping to turn waste heat into a valuable resource and contributing to a more sustainable energy future.

II. MATHEMATICAL MODELING

A mathematical model will be created to estimate the power generation potential from low-grade waste heat in wet steam that exits steam turbines. This model will be implemented and solved using MATLAB, taking into account critical factors such as heat transfer within the system and the properties of the thermoelectric generator (TEG) materials. The system used for this analysis features a specialized heat exchanger designed to facilitate the transfer of heat from the steam as it exits the turbine (the hot stream) to thermoelectric generator (TEG) modules made of Bismuth Telluride (Bi2Te3). These modules are

strategically placed within the heat exchanger to maximize heat transfer. The efficiency of electricity generation depends on the characteristics of the TEG materials, specifically their Seebeck coefficient, electrical conductivity, and thermal conductivity.

A. Properties of TEG module material

Power generation in thermoelectric generator modules is driven by a combination of phenomena, including the Seebeck effect, the Peltier effect, thermal conduction, and Joule heating, as previously mentioned. The Seebeck effect, which is the core mechanism, creates an electric current when there is a temperature gradient across an electrical conductor. TEG modules typically consist of a series of n-type and p-type semiconductor blocks arranged between electrical conductors, as shown in Fig. 1. These are encapsulated by insulating layers and ceramic substrates on both sides, creating a structured design that supports the generation of electricity as shown in Fig. 1b. The modules operate based on the principle of temperature differentials commonly referred to as ΔT where a greater temperature difference between the hot and cold sides leads to a higher electrical power output. The following equations describe the heat transfer dynamics within a thermoelectric generator (TEG) module, where heat is supplied to the hot side (Qh) and removed from the cold side (Qc) of the TEG:

$$Q_h = n\ [\alpha_{pn}* I*T_h + K_{pn}* (T_h - T_c) - 0.5*I^2*R_{pn}] \quad (1)$$
$$Q_c = n\ [\alpha_{pn}* I*T_c + K_{pn}* (T_h - T_c) + 0.5*I^2*R_{pn}] \quad (2)$$

where α_{pn}, Seebeck coefficient, K_{pn} thermal conductance, and R_{pn} internal resistance of the module. I denote the current generated by the module when the hot stream temperature is (T_h) and the cold stream temperature is (T_c). Equations (3) through (6) define $\alpha_{pn}, K_{pn}, R_{pn}$, and the generated current I, considering the dimensions and properties of the TEG module:

$$\alpha_{pn} = \alpha_p - \alpha_n \quad (3)$$
$$K_{pn} = (k_p + k_n)\ *A_{leg}\ /L_{leg} \quad (4)$$
$$R_{pn} = (\rho_p + \rho_n)\ * L_{leg}\ /A_{leg} \quad (5)$$
$$I = (\alpha_{pn}*(T_h - T_c))/\ R_{pn} + R_{load} \quad (6)$$

Each property, including the Seebeck coefficients (α_p and α_n), thermal conductance (k_p and k_n), and electric resistances (ρ_p and ρ_n), of both positive and negative legs material, is temperature-dependent. Their values can vary depending on the temperature limit, typically start from 300 K to 518 K [27], and can calculated using the following equations (7) to (12).

$$\alpha_{p\ (T)} = (5.921376*10^{-13}\ T^3 - 3.274207*10^{-9}\ T^3 - \quad (7)$$
$$3.274207*10^{-9}\ T^2 + 2.422355*10^{-6}\ T - 2.743842*10^{-4})$$
$$\alpha_{n\ (T)} = (1.291689*10^{-13}\ T^3 + 1.074408*10^{-9}\ T^2 - \quad (8)$$
$$9.271759*10^{-7}\ T + 8.9588882*10^{-6})$$
$$\sigma_{p\ (T)} = (2.248899*10^{-14}\ T^3 - 1.250867*10^{-10}\ T^2 + \quad (9)$$
$$1.388189*10^{-7}\ T - 2.244786*10^{-5})^{-1}$$
$$\sigma_{n\ (T)} = (-1.24614*10^{-14}\ T^3 - 6.429015*10^{-11}\ T^2 \quad (10)$$
$$+9.103036*10^{-8}\ T - 1.049646*10^{-5})^{-1}$$

$$k_{p(T)} = (1.251606*10^{-7}\ T^3 - 1.242845*10^{-4}\ T^2 \quad (11)$$
$$+3.873788*10^{-2}\ T - 2.362707)$$
$$k_{n(T)} = (-1.592653*10^{-8}\ *T^3 + 2.905845*10^{-5}\ T^2 - \quad (12)$$
$$1.58323*10^{-2}\ T + 3.727526)$$

B. Performance of TEG

Thermoelectric generators (TEGs) convert waste heat into electricity through the Seebeck effect, which occurs when a temperature gradient between two ends of a conductive material creates a voltage difference. TEGs leverage this effect by arranging p-type and n-type semiconductor materials to form thermoelectric modules. The Seebeck coefficient is crucial to TEG performance as it determines the voltage produced by a given temperature difference. However, internal resistance can reduce power output by impeding current flow. Thermal conductance also plays a key role in heat transfer; lower conductance allows for larger temperature gradients, leading to more efficient electricity generation. The electrical output power (P_o) of a TEG module is influenced by the heat transfer from the hot source (Q_h) to the hot side and from the cooling fluid (Q_c) to the cold side. To understand these relationships, it is important to examine the structural dimensions of the module's p-type and n-type legs, as they greatly affect both electrical resistance and thermal conductance. Table I provides a detailed overview of these dimensions, which is essential for accurate calculations. This information is critical for evaluating the efficiency and power output of thermoelectric generators. Certain assumptions are used to simplify calculations: PN couples are connected in series and remain in a steady state, contact thermal resistance and copper's impact are disregarded, all p-type and n-type materials have identical dimensions and heat conduction along the heat exchanger is negligible. The Thomson effect is also ignored. Accurate calculation based on these assumptions is key to assessing a TEG's efficiency and power generation potential. The combination of structural factors, thermoelectric properties, and these simplifying assumptions sets the stage for accurate calculation of TEG power output and efficiency. Thus, the combination of structural factors, thermoelectric properties, and calculated assumptions lays the groundwork for calculating TEG power output (P_o) and efficiency (η_{teg}), offering insights into how these generators can be optimized for better performance.

$$P_o = Q_h - Q_c = I^2.\ R_{load} \quad (13)$$
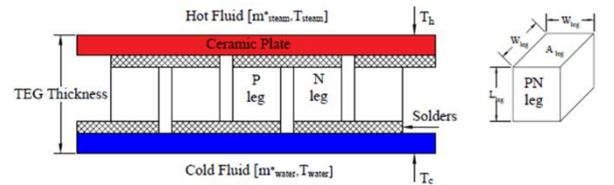$$\eta_{teg} = P_o / Q_h \quad (14)$$

Fig. 1. Thermocouples' layout structure

TABLE I.   BASIC PARAMETER TEG MODULE [28].

Parameter	unit	Value
TEG model		SP184827145
Parameter of PN couple		
PN thermocouples		127 thermocouples
Dimension of PN couple (length * width* height)	mm	1.4*1.4*1.6
Dimension of ceramic chip (length * width* height)	mm	40*40*0.8
TEG model dimension (width * length* thickness)	mm	40*40*3.9

III.   WASTE HEAT RECOVERY SYSTEM

A. Thermal resistance model of the TEG model

To maximize efficiency, the system employs aluminum plate-fin heat sinks on both the hot and cold heat exchanger of TEGs module as shown in Fig.2. a, featuring a thermal conductivity of 235 W/m.K. The hot side heat sink ensures a sufficient supply of heat and maintains a high temperature at the hot surface of the TEG module, which is essential for generating electricity. The cold side heat sink effectively dissipates heat, maintaining a low temperature at the cold junction. This arrangement maximizes the temperature differential between two sides, a critical factor for efficient TEG operation.

Fig.2. b illustrates a thermal resistance model for the recovery of waste heat, outlining the system's key segments: the hot side (saturated steam), the cold side (cooling fluid), and the TEG module itself. The heat transfer process on both the hot and cold sides is influenced by three primary types of thermal resistance: Contact Thermal Resistance (R_c): This arises from imperfect contact between various interfaces within the system. Base Material Thermal Resistance (R_b): This reflects the inherent resistance to heat flow through the base material of the plate-fin heat sinks. Convection Thermal Resistance (R_{conv}): This accounts for the resistance to heat transfer between the fluid and solid surfaces.

The following table provides the geometrical dimensions of the aluminum plate-fin heat sinks used in this system [27]. These dimensions are crucial for ensuring the heat sinks' efficiency in maximizing the temperature difference across the TEG module. The design and positioning of the heat sinks, as shown in Table II, play a significant role in optimizing heat transfer and TEG performance. The thermal resistances for the contact TEG surface and the base of the heat sink can be expressed by the equation stated below

$$R_c = R''_{t,c}/A_{base} \tag{15}$$

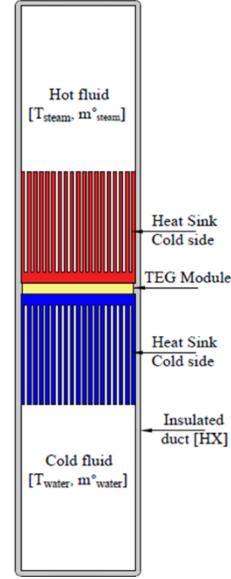Where $R''_{t,c}$ is the value of Thermal resistance of representative solid/solid interfaces [30]

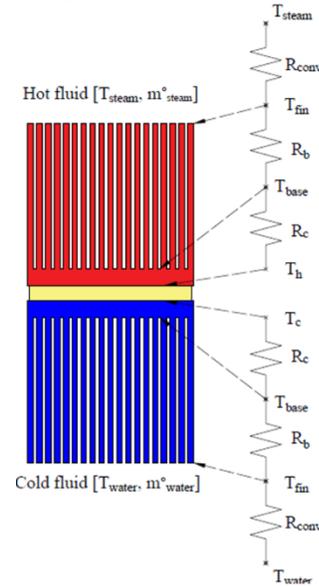Fig. 2. a. Thermoelectric generator model with a heat sink

Fig. 2. b Thermal resistance model

The thermal resistance for the base Rb of the plate-fin heat sink can be written by the following equation

$$Rb = L_b/K_b \, A_{base} \tag{16}$$

where K_b is the thermal conductivity of the base material.

TABLE II.   GEOMETRICAL DIMENSIONS OF THE ALUMINUM PLATE-FIN HEAT SINK [27]

Parameter	Variable	Units	Value
Heat sink width	W	mm	41
Heat sink length	L	mm	40.5
Fin height	Lfin	mm	36
Fin width	Wfin	mm	41
Base height	Lb	mm	4
Fin thickness	tfin	mm	1.3
Fin- to- fin distance	d	mm	0.9
Number of fins	n		19

In accordance with Newton's law of cooling, heat transfer between fluid and solid surface gives rise to a convection thermal resistance (R_{conv}). This resistance (R_{conv}) can be quantified in relation to the convective heat transfer coefficient (h) and the effective heat transfer area (A_{eff}), as demonstrated in the equation below.

$$R_{conv}=1/hA_{eff} \tag{17}$$

Plate fin heat sink's effective heat transfer area (A_{eff}) and fin efficiency (η_f) can be determined utilizing equations [18] through [20]. Here, n denotes the number of fins, while L_{fin}, W_{fin}, t_{fin}, and d represent the fin height, width, thickness, and fin-to-fin distance, respectively.

$$A_{eff}= (2n\times W_{fin} \times L_{fin}) \times \eta_f +(n-1)\times W_{fin}\times t_{fin} \tag{18}$$

$$\eta_f= (\tanh m. L_{fin})/ m. L_{fin} \tag{19}$$

$$m=\sqrt{2}\ h_{conv}/(K_{fin}\ t_{fin}) \tag{20}$$

Thermal resistance R_{teg} between two sides of the TEG module can be written by following the equation

$$R_{TEG}= (T_h-T_c)/ (Q_h-Q_c) \tag{21}$$

B. Basic equations for heat transfer in cold and hot fluid

To estimate the convection heat transfer coefficient for both the hot and cold sides as shown in Figure 2.a of a thermoelectric generator (TEG) system, specific methods are applied based on the unique conditions in each section (as outlined in Table III, which provides a detailed overview of the system's operational parameters and flow characteristics).

On the hot side, where steam quality decreases as it passes through the TEG module, the convection heat transfer coefficient must reflect the changing state of the steam. As steam condenses and its quality approaches zero as shown in Figure 4, the associated heat transfer characteristics require careful consideration to ensure accurate calculations. A widely used method for this is the general correlation for heat transfer during film condensation in pipes, as outlined by Shah [31]

$$h_{conv, steam}=h_{conv, liq}\times [1+3.8/Z^{0.95}] \tag{22}$$

$$h_{conv, liq}= 0.023J_m (1-X_{inlet}) D_h)/\mu_{liq}{}^{0.8} (Pr_{liq}{}^{0.4} K_{liq}) /D_h \tag{23}$$

$$Z= [(1- X_{inlet})/ X_{inlet}]^{0.8} P_r{}^{0.4} \tag{24}$$

$$J_m=m°_{steam}/D_h \tag{25}$$

Where is Pr is reduced pressure, and J_m is the mass velocity [kg/m^2. sec].

TABLE III.   SYSTEM'S OPERATIONAL PARAMETERS AND FLOW CHARACTERISTICS

Parameter	Variable	Units	Value
Duct width	Wduct	mm	41
Duct height	Hduct	mm	100
Parameters of saturated steam			
Inlet temperature	Tsteam	°C	100
Inlet pressure	Psat	Kpa	101.35
Mass flow rate	m°steam	Kg/Sec	20
Inlet quality	X	-	0.97
Parameters of cooling fluid			
Inlet temperature	Twater	°C	10
Inlet pressure	P	Kpa	101.35
Mass flow rate	m°water	Kg/Sec	20

For the cold side, the Dittus-Boelter equation is a commonly used method for calculating the convection heat transfer coefficient, especially in turbulent flow within pipes. This empirical equation relates the heat transfer coefficient to fluid properties and flow conditions. It is defined as:

$$Nu=0.023\times Re^{0.8}\times Pr^{0.4} \tag{26}$$

$$h_{conv, water}=(Nu \times K_{water})/D_h \tag{27}$$

where Re is the Reynolds number, and Pr is the Prandtl number.

The previous formula accounts for factors such as flow velocity, fluid viscosity, and thermal conductivity, providing a reliable means to estimate the heat transfer coefficient on the cold and hot side.

The convective heat transfer equation of hot fluid is given by

$$Q_h=h_{conv,steam}\times A_{teg}\times(T_{steam}-T_h)$$
$$Q_h= (T_{steam}-T_h)/R_{th, total, hot} \tag{28}$$

The convective heat transfer equation of cold fluid is given by

$$Q_c=h_{conv, water}\times A_{teg}\times(T_c-T_{water}$$
$$Q_c =(T_c-T_{water})/R_{th, total, cold}) \tag{29}$$

Where $R_{th,total}$ is the total thermal resistance on each side

$$R_{th, total}=R_c+ R_b+ R_{conv} \tag{30}$$

The energy change when a cold fluid flows through a thermoelectric generator (TEG) module is a critical aspect of its operation. It is generally expressed in terms of heat transfer, which can then be related to the generated electrical energy. To calculate this energy change, you consider the heat removed from the cold side of the TEG module. This change in energy can be determined by examining the enthalpy difference between the fluid's inlet and outlet temperatures.

$$Q_c=m°_{water}\times Cp\times (T_{e, water} - T_{i, water}) \tag{31}$$

To compute the required values for T_h, T_c, and I, an iterative approach is used. This involves substituting T_h, T_c, and I into the appropriate equations to derive the corresponding results. Specifically, T_h, T_c, and I are input into equation (1), which corresponds to equation (28), representing the heat transfer equation for the hot fluid.

Similarly, by substituting T_h, T_c, and I into equation (2), which aligns with equation (29), you can determine the heat transfer for the cold fluid. Additionally, power equation (13) is used, as it addresses heat transfer on both the hot and cold sides. Using an iterative method with MATLAB, we can obtain precise values for T_h, T_c, and I by integrating these equations. This iterative approach, which accommodates various initial conditions and diverse input data, leads to accurate estimates for temperature and current, providing a solid basis for analyzing heat transfer and electrical efficiency within the system.

IV. RESULTS AND DISCUSSION

A. Effect of change mass flow rate on the output performance

To understand how variations in steam mass flow rate affect the output performance of the thermoelectric generator (TEG) module and system, a study is conducted using different steam mass flow rates while keeping other parameters constant. Specifically, the steam temperature remains at 100°C, the water flow rate is 20 kg/sec, and the water temperature is 10°C.

a) Effect of change steam mass flow rate on the output performance of TEG system

Fig.3. a presents four curves representing the steam mass flow rates entering a thermoelectric generator (TEG) system: 5 kg/sec, 6.67 kg/sec, 10 kg/sec, and 20 kg/sec. As the steam contacts the heat sink in the TEG module, it begins to condense, releasing latent heat. This released heat drives the TEG system by generating electricity due to the temperature difference between the hot steam and the cooler heat sink. However, the power output from the TEGs varies as the steam mass flow rate changes. As condensation progresses, and latent heat is released, the power output from the TEG system tends to decrease.
Interestingly, the power output decline differs among the curves. Notably, the curve corresponding to the 20 kg/sec steam mass flow rate shows a steeper drop in output compared to other curves, indicating a higher loss of latent heat and reduced efficiency as shown in Fig.3. c. This decrease is primarily due to a larger number of TEG units used with higher mass flow rates to maintain stable power generation.

Maintaining consistent power output requires scaling the number of TEG units proportionate to the steam mass flow rate. For example, as shown in Fig.3. b, a steam mass flow rate of 5 kg/sec utilizes 313 TEG units to generate 524.1 watts of power.

In contrast, a steam mass flow rate of 20 kg/sec requires a much higher number of TEG units 1254 to generate 2094.12 watts. This observation underscores the direct correlation between steam flow rate and the number of TEG units needed to capture and convert waste heat into electrical energy. These findings demonstrate that while higher mass flow rates might theoretically suggest greater power output, the need for additional TEG modules to maintain efficiency presents a practical limitation. This leads to a more complex balance between increased energy generation and the resources required to achieve it.

Fig.3. c provides additional insights into the relationship between steam mass flow rate and thermoelectric generator (TEG) system efficiency. The Figure shows that the curves representing different steam mass flow rates intersect at various points, indicating that there may be an optimal range of steam quality where the TEG system achieves maximum efficiency for each flow rate. Initially, all four curves demonstrate a relatively high efficiency, approximately 4.79%, under the specific input conditions for each curve. However, as steam condenses and the system loses latent heat, the efficiency generally decreases, leading to points of intersection among the curves. These intersections represent critical thresholds where system behavior changes, suggesting that efficiency tends to drop as steam quality transitions from higher to lower levels.
The intersection point between the curve for a steam mass flow rate of 5 kg/sec and that for 20 kg/sec occurs at a steam quality of about 0.86. At this point, the higher flow rate system begins to experience a more pronounced drop in efficiency, while the lower flow rate system maintains relatively higher efficiency. This shift implies that beyond this intersection, a system with a lower steam mass flow rate of 5 kg/sec may operate more efficiently compared to one with a higher mass flow rate of 20 kg/sec. These findings are significant because they reveal that steam mass flow rates and steam quality levels can influence the efficiency of TEG systems. The results suggest that maintaining an optimal balance between these factors can lead to more sustainable and effective energy conversion, emphasizing the need for a careful examination of steam quality to maximize TEG system performance.
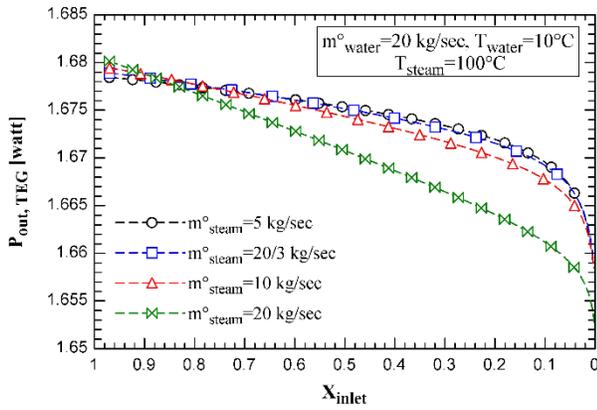
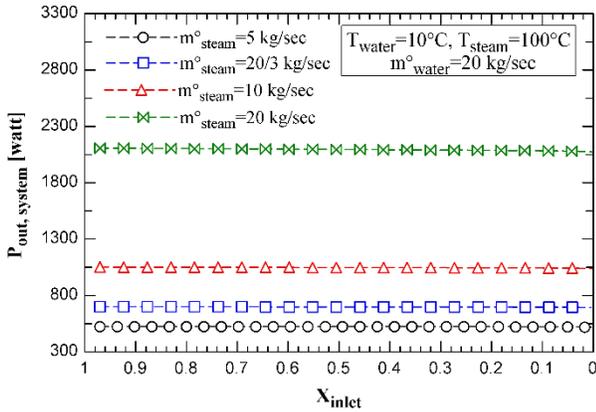Fig. 3.   a. Effect of change steam mass flow rate on the TEG output power

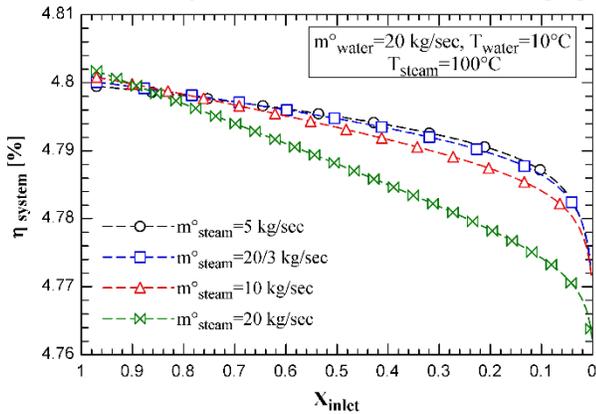Fig. 3.   b. Effect of change steam mass flow rate on the system output power

Fig. 3.   c. Effect of change steam mass flow rate on system efficiency

b) Effect of change water and steam mass flow rate on the output performance of TEG system

When both water and steam mass flow rates vary, the system's power output tends to decrease slightly compared to when the water mass flow rate is constant, as shown in Fig. 4. a. This reduction in power generation may be due to the changing conditions affecting heat transfer efficiency. For example, when both the water and steam flow rates are 5 kg/sec, the system generates 520.66 W, as depicted in Fig. 4. b, with an efficiency of 4.762%. Although the power output is slightly lower, the efficiency tends to increase as both water and steam mass flow

rates increase, peaking at 4.786% when the steam flow rate is 20 kg/sec and the water flow rate is also 20 kg/sec. This efficiency is higher compared to the 4.762% observed when both steam and water flow rates are 5 kg/sec, likely due to improved heat distribution and optimized steam quality, as shown in Fig 4. c.

Comparing the effects of varying water and steam mass flow rates, as opposed to constant water flow with varying steam flow, provides valuable insights into thermoelectric generator (TEG) system performance.

When both water and steam mass flow rates are 10 kg/sec, the system generates 1044.132 W, as shown in Fig. 4. b, with an overall efficiency of 4.776%. This setup, where both flow rates change, demonstrates a more stable efficiency trend, indicating that the system adapts well to varying conditions. Despite slightly lower power output compared to constant water flow scenarios, the efficiency remains relatively stable, suggesting better heat distribution and optimized steam quality, as depicted in Fig 4. c.

In contrast, when the water mass flow rate is constant at 20 kg/sec and the steam flow rate varies, the TEG system produces 1047.62 watts at a steam flow rate of 10 kg/sec, with an efficiency of 4.792%. Although the power output is similar, the constant water flow case generally has a higher efficiency, albeit with notable fluctuations as the steam mass flow rate increases. This comparison indicates that while a constant water mass flow rate can achieve higher efficiency, the varying steam flow can lead to a significant drop in efficiency at higher steam mass flow rates. As the steam flow rate increases to 20 kg/sec, the power output rises to 2094.141 watts, but the overall efficiency decreases to 4.786%. This decline could be due to increased thermal resistance and the greater number of TEG modules required to maintain power generation.

On the other hand, when both water and steam mass flow rates vary, the system's efficiency profile remains more consistent across different flow rates. Although the power output is slightly lower, as shown in Fig. 4. a, this approach provides a balanced thermal condition, suggesting that such configurations can be advantageous for maintaining efficiency while still generating substantial power.

Ultimately, these comparisons help identify the optimal setup for TEG systems, with a focus on achieving both high power output and consistent efficiency. The insights derived from this analysis can guide system design and operational decisions to optimize thermoelectric power generation.
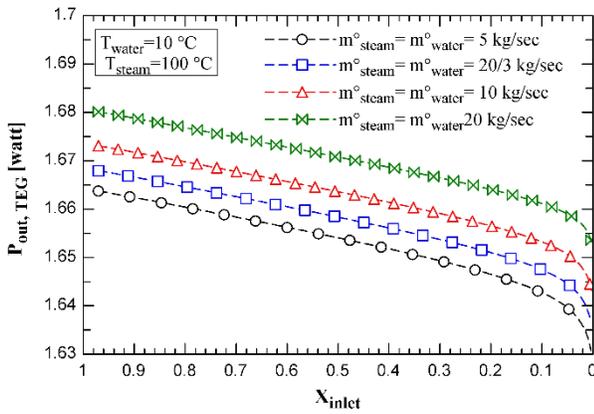
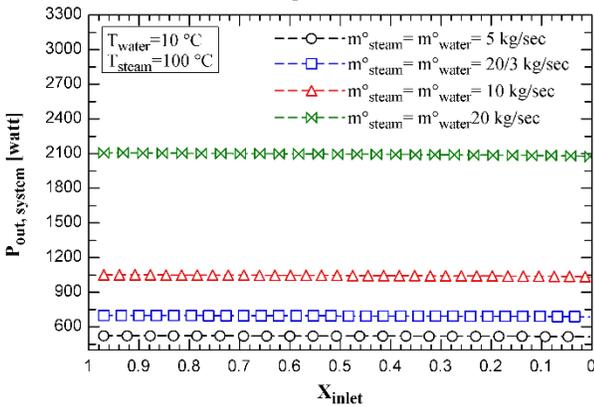Fig. 4.   a. Effect of change water and steam mass flow rate on TEG output power

Fig. 4.   b. Effect of change water and steam mass flow rate on system output power
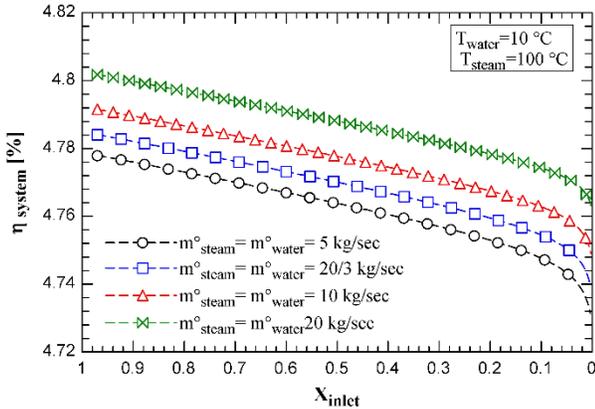

Fig. 4.   c. Effect of change water and steam mass flow rate on system efficiency

c) Effect of distributing steam flow across multiple heat exchangers on Teg system performance

Fig.5. a to 5. d illustrate the use of a different number of heat exchangers when distributing steam mass flow rates, while keeping the inlet conditions of both the cooling fluid and hot fluid constant. In these figures, each heat exchanger receives water as the cooling fluid at a constant flow rate of 20 kg/sec and a temperature of 10°C. The hot fluid, which is saturated steam, enters each heat exchanger with a consistent quality of x=0.97,

a temperature of 100°C, but varying steam flow rates. This setup provides a comparative view of how steam mass flow rates can be distributed across a different number of heat exchangers while maintaining the same inlet conditions for both hot and cold fluids.

Distributing steam mass flow rate across multiple heat exchangers has a significant impact on the overall power generation and efficiency of a thermoelectric generator (TEG) system. By analyzing the performance of configurations with different numbers of heat exchangers, it is possible to identify optimal setups for power output and efficiency. Comparing the effects of distributing steam mass flow among different numbers of heat exchangers, notable differences in power output and system efficiency emerge. When steam flow is divided among four heat exchangers, each generates 524.06 watts with 313 TEG modules, resulting in a total power output of 2096.25 watts as shown in Fig. 6. b and an efficiency of 4.793% as shown in Fig. 6. c. This configuration achieves consistent power generation thanks to the even distribution of steam.

In contrast, with three heat exchangers, each generates 698.2 watts using 417 TEG modules, yielding a combined output of 2094.5 watts and a slightly higher efficiency of 4.796%. Although the total power output is slightly lower than in the four-heat-exchanger setup, the efficiency improvement suggests that distributing steam across three units enhances heat transfer and reduces thermal resistance.

For two heat exchangers, each generates 1047.62 watts, contributing to a total power output of 2095.24 watts using 1252 TEG modules. The overall efficiency drops to 4.792%, potentially due to increased heat transfer resistance resulting from concentrating steam flow in fewer heat exchangers. This highlights the importance of balance in distributing steam to maintain efficiency and power generation.

In the final case, when the steam and water mass flow rates are both 20 kg/sec with one heat exchanger, the system produces power outputs similar to the cases with multiple heat exchangers. However, concentrating the steam flow in a single unit can increase the burden on that heat exchanger, potentially leading to greater heat transfer resistance and a slight drop in efficiency.

Another aspect to consider is that when using a single heat exchanger, the system initially generates more power than other configurations, but this trend reverses at an intersection point of approximately x = 0.58 as shown in Fig. 6. b, after which the power output from the single heat exchanger begins to decrease more rapidly than those with multiple heat exchangers. This is likely due to the inefficiencies caused by concentrating steam flow in one unit. Overall, these variations demonstrate that distributing steam mass flow across multiple heat exchangers can lead to more stable power output and efficiency.
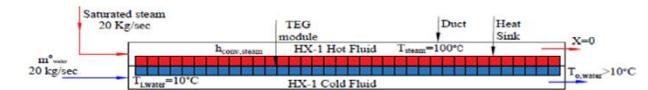
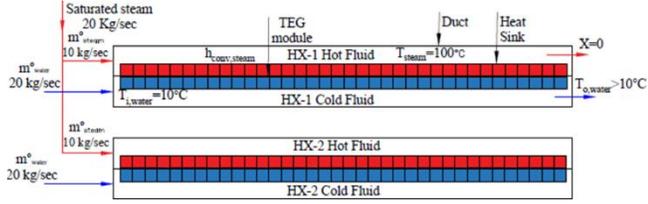Fig. 5.   a. Total Steam Mass Flow Rate Entering 1 Heat Exchanger.

Fig. 5.   b. Distribution of Steam Mass Flow Across 2 Heat Exchangers.
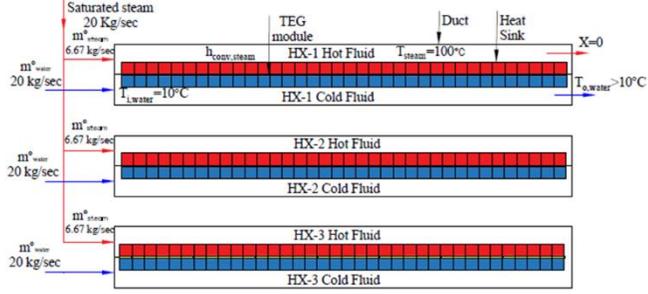

Fig. 5.   c. Distribution of Steam Mass Flow Across 3 Heat Exchangers.
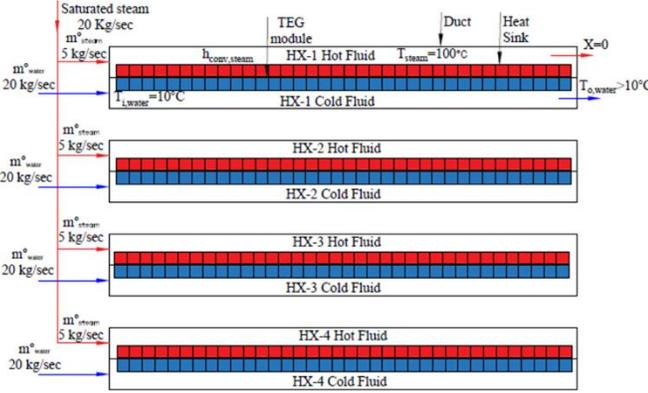

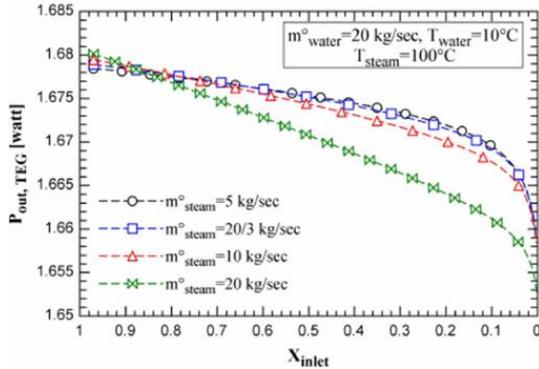Fig. 5.   d. Distribution of Steam Mass Flow Across 4 Heat Exchangers.

Fig. 6.   a. Effect of change steam mass flow rate on TEG output power

By optimizing the number of heat exchangers, the system can achieve a balance between power generation and thermal resistance, ensuring efficient operation. Configurations with three to four heat exchangers generally provide a good balance, while configurations with fewer heat exchangers might require additional considerations to maintain consistent performance.
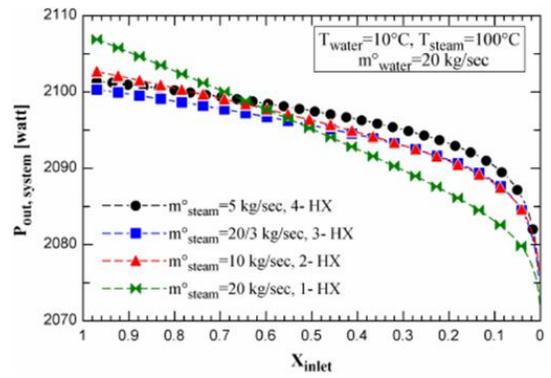

Fig. 6.   b. Effect of distribute steam mass flow rate on system output power
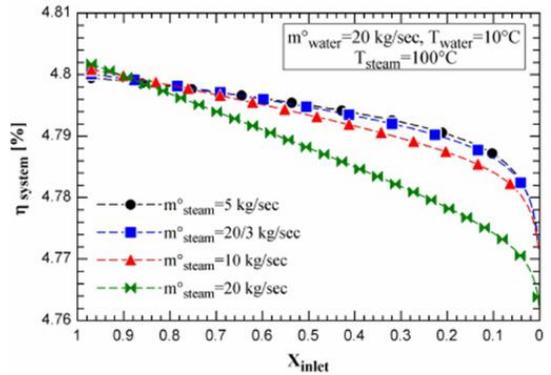

Fig. 6.   c. Effect of change steam mass flow rate on system efficiency

B. Effect of Changing Cooling Fluid Inlet Temperature on TEG Performance

The inlet temperature of the cooling fluid plays a crucial role in shaping the performance of a thermoelectric generator (TEG) system. This study delves into the influence of variations in the cooling fluid temperature on both the power output and efficiency of the system. Specifically, the investigation considers a range of cooling fluid inlet temperatures, spanning from 7.5°C to 15°C, while maintaining a constant mass flow rate of 20 kg/sec for both water and steam across a single heat exchanger. Through this analysis, we aim to uncover the intricate interplay between temperature differentials and power generation efficiency in TEG systems.

As depicted in Fig. 7. a, the impact of inlet water temperature on power generation per module becomes apparent. At an inlet water temperature of 7.5°C, the first TEG module generates 1.77413 watts, with the last one generating 1.74553 watts after 1221 TEGs. This consistent power generation suggests a potential stabilizing effect. Conversely, as the water temperature increases, the power output per TEG module decreases. For example, at 12.5°C, TEG modules generate 1.588613 watts initially, reducing to 1.561895 watts after 1289 TEGs. This decline necessitates the use of additional TEG modules to extract energy from saturated steam, primarily due to the reduced temperature differential between the hot and cold sides, as depicted in equations (1) and (2).

Subsequently, Fig.7. b illustrates the variation in total power generation across different cases. At an inlet water temperature of 7.5°C, the system yields 2153.465 watts of total power using 1221 TEGs, whereas, at 12.5°C, it generates 2034.982 watts using 1289 TEGs. Notably, total power generation is higher at lower inlet water temperatures, indicating a direct correlation between cooling fluid temperature and power output. This correlation can be attributed to the Seebeck coefficient, a pivotal factor influencing power generation, which depends on the temperature difference between the two sides of the TEG. By lowering the cooling fluid temperature, a larger temperature differential is maintained, facilitating greater power extraction from the hot source while ensuring system stability.

Finally, as highlighted in Fig. 7. c, the system's efficiency diminishes with increasing inlet cooling fluid temperature, as per Equation 14. This decline stems from the reduced amount of power extracted from each system, despite employing a greater number of TEGs. For instance, at a water temperature of 7.5°C, the system achieves an efficiency of 4.922%, generating 2153.465 watts using 1221 TEGs. In contrast, with a water temperature of 15°C, the system yields 1975.724 watts using 1326 TEGs, resulting in an efficiency of 4.515%. This discrepancy underscores the adverse impact of rising water temperature on the TEG system's efficiency.
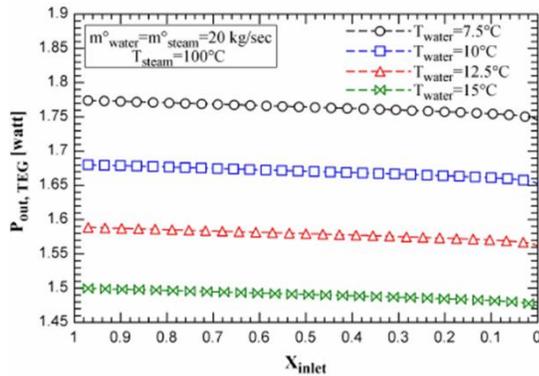

Fig. 7. a. Effect of change the inlet water temperature on TEG output power
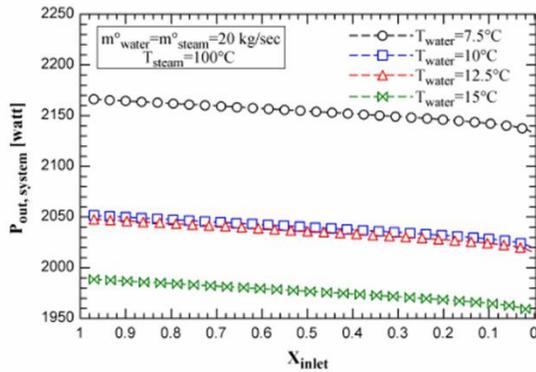

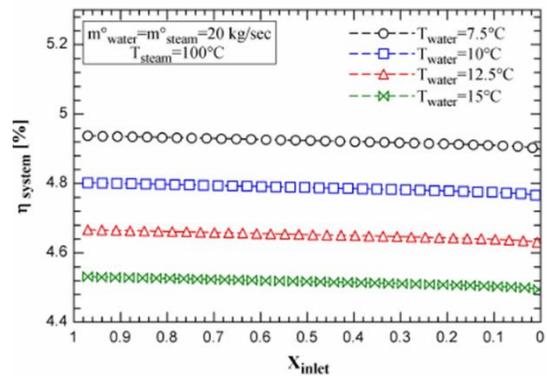Fig. 7. b. Effect of change the inlet water temperature on system output power

Fig. 7. c. Effect of change in inlet water temperature on system efficiency

Conclusions

A significant amount of water vapor exists in the exhaust-saturated steam from steam turbines. As this vapor condenses, it releases substantial latent heat until it transforms into saturated liquid. Drawing inspiration from this phenomenon, the paper examined the performance of a waste heat recovery system. The primary conclusions are outlined below:. The main conclusions are as follows:

Distributing the steam mass flow rate across four heat exchangers increases the power generation performance due to higher heat transfer between hot and cold fluids in each heat exchanger. This suggests that optimizing the number of heat exchangers can significantly enhance system efficiency and power output.

The water inlet temperature plays a critical role in increasing the amount of power generation. While the power generation is not directly affected by changes in water temperature, the system efficiency is notably impacted. Lower water temperatures result in increased power generation and overall system efficiency, highlighting the importance of controlling cooling fluid temperatures for optimal system performance.

In conclusion, optimizing the distribution of steam mass flow rate and controlling water inlet temperatures are key factors for improving the performance of waste heat recovery systems. By carefully considering these variables, significant enhancements in power generation and overall system efficiency can be achieved, contributing to more sustainable energy practices and resource utilization.

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Author's Background Information

Note: *Please fill in every author's background information. It will help us understand the paper better and will not be published.

*Title could be Prof., Assoc. Prof., Assist. Prof., Dr., Senior Lecturer, etc.

Author's name:	Position:	Research areas:	Personal Website:
Mohamed Asharf Mohamed Mahmoud	**Ph.d candidate**	**Heat transfer, waste heat recovery**	https://scholar.google.com/citations?hl=en&user=81cwk8kAAAAJ
Sameh nada	**Professor**	**Energy systems, Renewable energy, Heat transfer, Air conditioning**	https://scholar.google.com.eg/citations?user=SmeJwUAAAAAJ&hl=en
Hidetoshi Sekiguchi[b]	**Professor**		https://orcid.org/0000-0002-6721-3153
Hamdy Hassan Abo ali	**Professor**	**Energy systems, Renewable energy, Hydrogen production, Energy storage/management, PV Cooling**	https://scholar.google.com/citations?user=K6tQRdwAAAAJ&hl=en