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Design and Implementation of a Thermoelectric Power Generation Panel Utilizing Waste Heat Based on Solar Energy

Mohammed A. Qasim*‡, Vladimir I. Velkin**, Seepana Praveenkumar***, Du Yang****, Ahmed H. Mola*****, Sergey E. Shcheklein******

* Nuclear Power Plants and Renewable Energy Sources Department, Ural Federal University Named after the First President of Russia Boris Yeltsin, 19 Mira Street, Yekaterinburg 620002, Russia, and,
Department of Projects and Engineering Services, Ministry of Health, Bab Al Mu'adham, Baghdad 10047, Iraq

** Nuclear Power Plants and Renewable Energy Sources Department, Ural Federal University Named after the First President of Russia Boris Yeltsin, 19 Mira Street, Yekaterinburg 620002, Russia

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**** Nuclear Power Plants and Renewable Energy Sources Department, Ural Federal University Named after the First President of Russia Boris Yeltsin, 19 Mira Street, Yekaterinburg 620002, Russia

***** Nuclear Power Plants and Renewable Energy Sources Department, Ural Federal University Named after the First President of Russia Boris Yeltsin, 19 Mira Street, Yekaterinburg 620002, Russia, and,
University of Technology, Mechanical Engineering Department, Al Sina'a Street, Baghdad 10066, Iraq

****** Nuclear Power Plants and Renewable Energy Sources Department, Ural Federal University Named after the First President of Russia Boris Yeltsin, 19 Mira Street, Yekaterinburg 620002, Russia

(mohammed.a.k.qasim@gmail.com (M.A.Q.), v.i.velkin@urfu.ru (V.I.V.), seepanapraveenkumar5@gmail.com (S.P.), erica002@163.com (D.Y.), ahmed.h.mola@uotechnology.edu.iq (A.H.M.), s.e.shcheklein@urfu.ru (S.E.S.))

‡ Corresponding Author; Mohammed A. Qasim, Nuclear Power Plants and Renewable Energy Sources Department, Ural Federal University Named after the First President of Russia Boris Yeltin, 19 Mira Street, Yekaterinburg 620002, Russia, and, Department of Projects and Engineering Services, Ministry of Health, Bab Al Mu'adham, Baghdad 10047, Iraq, Tel: +7(999)-570-34-47, mkasim@urfu.ru, or, mohammed.a.k.qasim@gmail.com

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Abstract- Thermoelectric power generation (TEG) can be considered a free energy conversion system, especially if it converts waste heat into electricity. The proposed system is based on a high temperature side that is heated by waste heat from a solar water heater. In this work, a TEG panel is designed and fabricated from 20 TEGs, where 10 are connected in series, forming two sets that are then connected in parallel. The panel's cold side is cooled using water passed through an aluminium block heat exchanger. The design is implemented and its operation is investigated experimentally. The average power output from this TEG panel is 3.55 *W*, which is equivalent to an average generated energy of 85.2 *Wh* for one day. This power can be increased with a greater temperature difference between its upper and lower sides. Also, the design employs active heating and cooling methods to attain a uniform temperature distribution on both sides of the panel. This new design had an average Carnot efficiency of 11.04% with a maximum value of 12.44%.

Keywords- Cold, Heat, Pipeline Radiation, Seebeck, Solar, Thermoelectric generator.

1. Introduction

At present, mankind is facing challenging issues, such as growing power costs, global warming and environmental pollution. To mitigate these problems, scientists are studying power generator enhancements dedicated to harvesting energy [1-2]. Various forms of renewable energy, including solar, wind, geothermal, and hydro power have undergone extensive development in the last few decades. Accordingly, thermoelectric generators (TEGs) are being extensively studied. TEGs convert heat into electricity directly *via* the Seebeck effect, a phenomenon that is exhibited by thermoelectric materials [3-4]. They are reliable, flexible and robust since they require no working fluids and have no moving parts [5]. There are many studies concerning use of the thermoelectric effect for heat energy conversion into electricity. This is because the number of thermoelectric applications is potentially limitless [6-7]. Researchers have employed TEG modules in various designs of thermoelectric generators.

D.N. Kossyvakis *et al*. [8] did a performance evaluation of a tandem PV–TEG hybrid connection. In their design, a TEG is mounted directly below a solar panel. The analysis specified that the use of shorter TEGs enhances output power levels, especially if the actual operating conditions are taken into consideration. Furthermore, improved power output is obtained by employing polycrystalline cells. P. Bargiel *et al.* [9] designed and optimized a TEG heated by combustion of natural gas. Their goal was to develop a reliable and independent power source in the range of 50–100 *W*. This design could be employed in remote areas isolated from the electric grid. The device consists of a combustion heater, channels for the flow of air and exhaust gases, and TEG modules that generate electric current. Y. Kim *et al.* [10] proposed direct contact of TEG modules with the exhaust of a diesel engine, thereby generating electricity. The other side of the TEG module is directly cooled with a water–ethylene glycol mixture. In their design, the maximum power output is 43 *W* with a conversion efficiency of 2.0%. These results were with the engine operating at its fastest rotational speed and maximal engine load. E. Yin *et al.* [11] proposed a hybrid system for concentration spectrum splitting using PV-TEGs. They tried to optimize solar energy distribution using this system. An optimal cut-off wavelength and maximal efficiency are obtained by comparing the performance of this system with various cut-off wavelengths. J. Wang *et al*. [12] did an experimental investigation of thermostatically heated TEGs to provide a constant temperature. The cold side of the TEGs is cooled using water. They found that the Peltier yields a lower experimental power output than the theoretical limit. Thus, this change causes the maximum power point to diverge from the point where the load resistance matches the internal resistance. H. Ishaq *et al.* [13] validated and analyzed a novel TEG integration in a biomass gasifier. In their design, the major integrated subsystems are a cryogenic air separation unit, gasification, heat recovery and hot water production. The system is simulated using Aspen plus and the Engineering Equation Solver (EES) is used to model TEGs. Waste heat from TEGs is utilized in a Rankine cycle to provide power. The energy generated by the TEGs is utilized in a proton exchange membrane electrolyzer for H_2 production. F. Susanto *et al*. [14] interconnected series and parallel TEG modules that generate electricity from the heat of a rocket stove. The temperature of the water in the chamber may reach 90 ^{0}C. Power is electrically generated through TEG interconnections. A test is done by loading a 1kΩ-10kΩ resistor.

In the current research, a newly designed TEG system is developed and experimentally implemented with the goal of converting waste heat from hot water pipelines into electricity. The influence of various factors on the system's performance is evaluated with the goal of increasing its overall output capacity to a level that can power LED lights. A TEG panel design employs 20 TEG modules where two sets of 10 are connected in series. Then, the resulting two sets are connected in parallel. The source of heat is waste heat from to pipes of a residential solar water heater. The other side is cooled using tap water flowing through a water-cooled block system, which is an active cooling method. This paper is organized as follows: An introduction is presented, followed by materials and methodology. Finally, the results and discussion are given and conclusions presented.

2. Materials and Methodology

2.1. Materials

A thermoelectric generator is a direct mode of energy conversion. TEGs have no moving parts or intermediate modes in their operation. They transform thermal or heat energy into electricity [15]. TEGs have two surfaces, a hot and a cold side. The Seebeck effect [16] occurs in a thermoelectric material when a temperature difference is established between these two surfaces. This results in an energy flow from a lower to higher level and a voltage difference. The voltage difference is proportional to the temperature differential between the hot and cold sides of a TEG. The resulting current density can be expressed as

$$J = \sigma\left(-\Delta V + E_{emf}\right) \qquad (1)$$

where E is the electric field, σ is the electrical conductivity, and ΔV is a voltage difference.

The Peltier effect [17-18] describes heat dissipation or absorption processes at the junction of p- and n-type materials. If the Peltier model absorbs heat, electrical power is generated. When the Peltier model dissipates heat, electrical power is consumed.

TEGs are made of components with p-type junctions having high concentrations of positive charge, while n-type junctions have high concentrations of negative charge. A p-type material is doped with a large number of positive charges or holes, resulting in a positive Seebeck coefficient [19]. An n-type material is doped with a high concentration of negative charges or electrons, resulting in a negative Seebeck coefficient. A schematic of a TEG module is depicted in Fig. 1. The rate of absorbed heat Q_h and dissipated heat Q_c at the hot and cold junctions of a TEG module can be determined by [20]

$$Q_h = (K_p + k_n)(T_h - T_c) + (\alpha_p - \alpha_n)IT_h - \frac{I^2R}{2} \quad (2)$$

$$Q_c = (K_p + k_n)(T_h - T_c) + (\alpha_p - \alpha_n)IT_c + \frac{I^2R}{2} \quad (3)$$

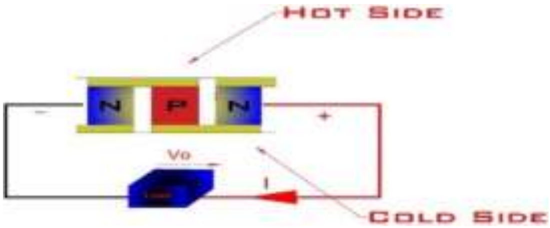


Fig. 1. Schematic diagram illustrating a TEG module.

k_p and k_n are the thermal conductivities of the p-type and n-type TEG legs, respectively. T_h and T_c are the hot and cold junction temperatures, while $\alpha_p$and $\alpha_n$are the Seebeck coefficients of the p-type and n-type TE legs, respectively.

By employing power balance equations, the electrical power of a TEG is just the voltage throughout the external load and the current in the circuit, as shown in Fig. 1. It is possible to obtain output power as

$$W = Q_h - Q_c = V.I \quad (4)$$

Equations (2)-(4) can be rearranged and simplified to obtain

$$V = (\alpha_p - \alpha_n)(T_h - T_c) - IR \quad (5)$$

Then, simplifying Equation (5) and assuming that $\alpha = (\alpha_p - \alpha_n)$ and $\Delta T = (T_h - T_c)$ yields

$$V = \alpha \, x \, \Delta T - IR \quad (6)$$

Equation (6) shows the output voltage when an electric current flows. When the current flow is zero, the open circuit voltage will be produced, which can be calculated as [21]

$$Voc = \alpha \, x \, \Delta T \quad (7)$$

$$\Delta T = T_h - T_c \quad (8)$$

where α represents the Seebeck coefficient, and Voc refers to a TEG module's open circuit voltage. An increased voltage can be achieved using multiple TEG modules connected in series or parallel [22].

The TEG modules used in this research are made from bismuth telluride. The specifications of a single TEG module of this type are given in Table 1 [15][23][24].

Table 1. Specifications of the TEG modules used in the current study

Specifications	Value
Material	Ceramic/Bismuth Telluride
Model number	SP1848-27145
Maximum Temperature (^{0}C)	150 °C
Open-circuit voltage (v)	4.8V
Color	White
Wire length (mm)	350
Length (mm)	40
Width (mm)	40
Height (mm)	4
Weight (gm)	30

Series and parallel connections of TEGs are used to fabricate a TEG panel. The aim of this research is to convert waste heat from hot water pipelines that are fed from solar water heaters into electricity, as depicted in Fig. 2. The TEG panel will convert the ΔT on both sides of it into an electric voltage that can charge a battery. The DC voltage of the battery can be converted into AC through an inverter to supply loads such as LED lights. During the night, the TEG can supply electric current since the hot water is fed in pipelines using an electric heater. Certainly, this will reduce electricity bills of homes.

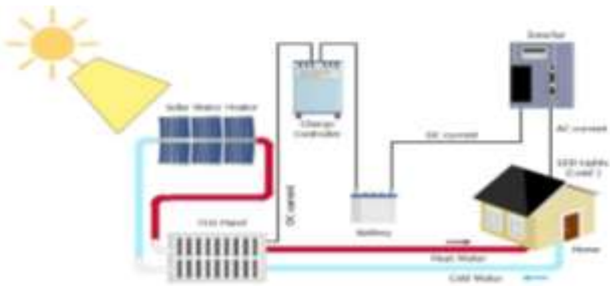
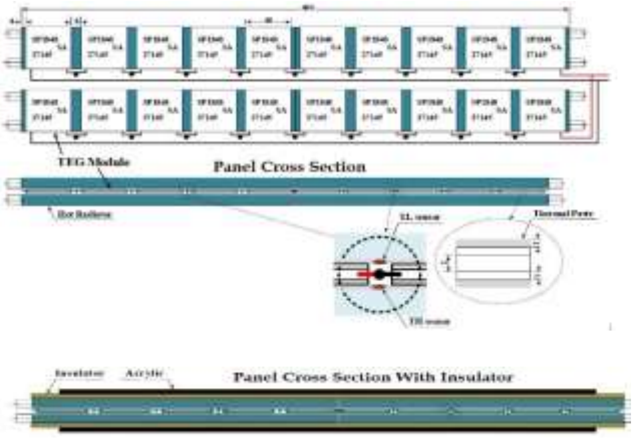


Figure 2. Role of TEG panel with solar water heater as renewable energy system.

2.2. Proposed 2 x 10 TEG panel

The series connections of 10 TEG modules are connected in parallel to form two lines of TEG modules, as shown in Fig. 3.

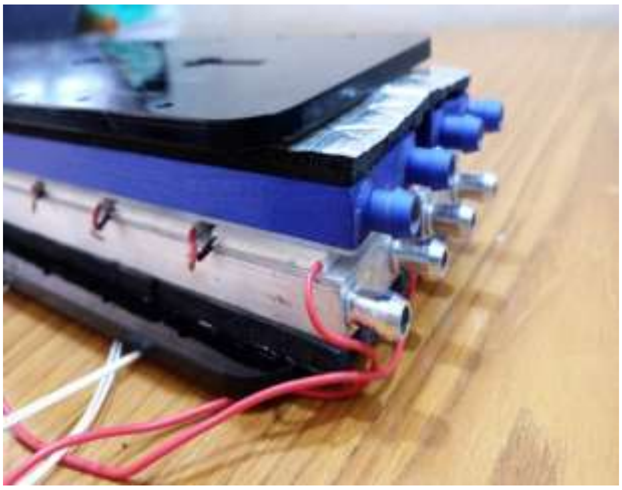


(a)

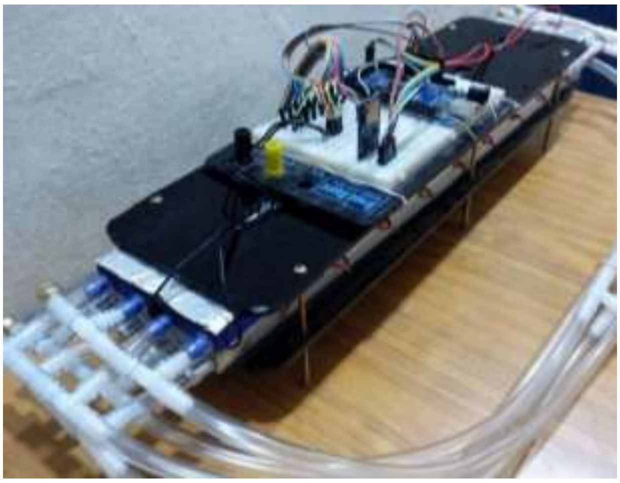
(b)

Figure 3. (a) Schematic diagram of a 2 x 10 TEG panel and (b) TEG module connections of the panel used in the current study.

The source of heat is hot water supplied from a solar water heater. The active cooling effect is from tap water. Both hot and cold water are passed through pipes connected at the appropriate sides of the TEG panel. Thermal paste is used to allow for a uniform temperature distribution at each side of the TEG panel. Additionally, thermal insulators are used at both sides of the TEG panel to mitigate heat losses from the system. Acrylic glass covers both sides of the TEG panel, as shown in Fig. 4. A ClYXGS aluminium water-cooling block is used on the other side of the TEG. The size this heat exchanger is (40 x 160 x 10) mm^3 and it is constructed from an aluminium alloy [25]. Water enters each heat exchanger in parallel flow to ensure good low temperature distribution on the cool side of the TEG panel.



(a)



(b)

Figure 4. Implementation of the designed TEG panel experimentally, (a) side view showing the various layers of the panel, (b) connection with an Arduino Mega microcontroller and measuring devices.

On each side of the panel, multiple temperature sensors are used to measure the temperature at various points. These readings are fed to an Arduino Mega microcontroller as shown in Fig. 5. The role of the Arduino Mega board is to record temperature readings and save them to a text file. So, it serves as a data logger.

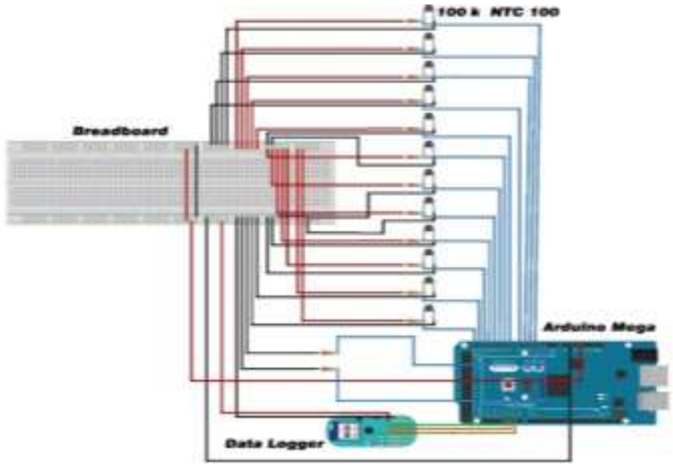


Figure 5. Temperature data logging *via* an Arduino Mega microcontroller.

2.3. Efficiency of the TEG System

The highest possible efficiency of any energy conversion is the Carnot efficiency. The Seebeck effect uses a temperature differential to generate electricity in a thermoelectric device built from the junction of two materials. Temperature differentials can be converted to other kinds of energy by several technologies [26-27]. Thermoelectric and pyroelectric systems, for example, convert temperature differentials to electricity, whereas Stirling engines and steam turbines transform them to mechanical work. Any device that transforms a temperature differential into another source of energy has its Carnot efficiency as a fundamental limit. The Carnot efficiency can be calculated using Equation (9) below [28-30]. T_h and T_c, respectively, represent the hot and cold temperatures that comprise a temperature differential,

$$\eta_c = \frac{T_h - T_c}{T_h} \qquad (9)$$

3. Results and Discussion

3.1. Effect of Active Cooling and Heating Methods on the Temperature Difference of a 2 x 10 TEG Panel

Cooling and heating of the appropriate sides of a thermoelectric material leads to increased efficiency. These methods are either active or passive cooling methods [31]. Passive cooling appears to be the better option at first glance because it requires no electrical inputs. However, the yield of a thermoelectric material is sensitive to the magnitude of the temperature differential across it. Here, passive cooling has a comparatively large thermal resistance that detrimentally impacts the power yield.

The temperature differential can be considerably increased using an active approach. However, a pressure differential must be established for active cooling and in most situations, this requires electrical power, which might negatively impact the net electrical output power. On further consideration, the net output power can be increased because, in many circumstances, the temperature differential has a bigger positive impact on the net output power than the active cooling's negative effect.

The proposed TEG panel is tested experimentally. The experimental work was started at 12:00 PM and lasted for two hours. The hot (T_h) and cold side temperatures (T_c) are depicted in Fig. 6. In this figure, it can be seen that at the beginning of the experimental work, (T_c) is low. Then, it increased since (T_h) affects (T_c) over time until a stable or equilibrium condition is reached. This effect decreases the ΔT between the hot and cold sides of the 2 x 10 *TEG* panel. The TEG panel recorded a low temperature of 67.3 °C and a high temperature of 67.59 °C on the hot side. Nevertheless, its average temperature was 67.44 °C. The cold side saw a low temperature of 25.2 °Cand a maximum temperature of 33.12 °C, with an average temperature of 29.86 °C. Thermocouples of the microcontroller recorded an average temperature difference of 37.58 °C on the surface of the panel. The highest and lowest temperature differences were 42.38 °C and 34.19 °C, respectively, over the same time period. These results were obtained using thermocouples that were in direct contact with panel surfaces, providing more precise results.

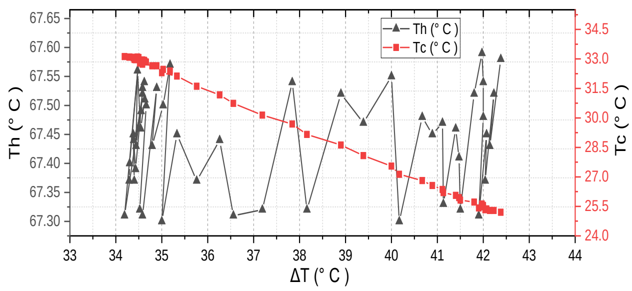


Figure 6. ΔT, T_h and T_c of a 2 x 10 *TEG* panel

3.2. Performance in Terms of Electricity for the 2 x 10 TEG panel

With a ΔT across the TEG module, an output voltage at the TEG terminals is generated, as shown in Fig. 7. In this figure, it can be seen that the output voltage is proportional to ΔT. At the beginning of the experimental work, the open circuit voltage (Voc) is 15.05 V and then its value settled to 12.7 V.

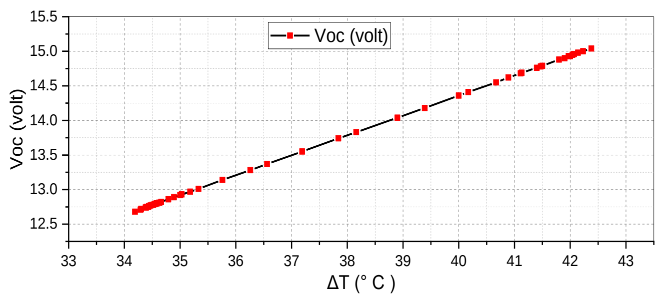


Figure 7. Open circuit voltage of the proposed 2 x 10 *TEG* panel.

If a 5 Ω resistance is connected at the TEG panel terminals, current will flow. Figure 8 represents the output power versus ΔT. Since the initial generated voltage is higher than the steady state condition, the output power behaves the same since it is proportional to the squared value of the voltage. The minimum and maximum power values are 3.04 W and 4.28 W, respectively, with an average of 3.55 W. However, it is notable that good output power is obtained due to the use of active cooling and heating systems compared to less efficient (passive) TEG systems [31]. The output voltage and power of the panel can be increased if the ΔT is made greater or by increasing the number of TEG modules.

3.3. Carnot Efficiency of the Proposed System

The Carnot efficiency (η_c) of a TEG depends on the temperatures of the hot and cold sides of the module. The TEG showed Carnot efficiencies at various ΔT values determined using Equation (9) and the results are presented in Fig. 9. The calculated average efficiency of the module is 11.04%. Its maximum and minimum efficiencies are 12.44% and 10.43%, respectively, which are acceptable in small systems such as this.

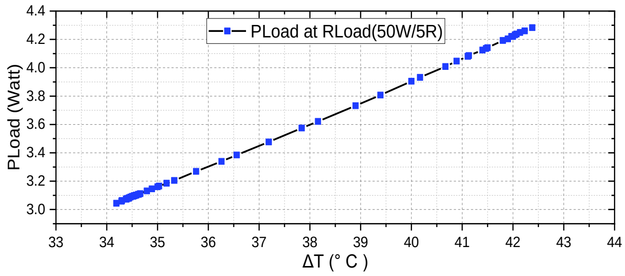


Figure 8. Load power of the proposed 2 x 10 *TEG* panel versus ΔT.

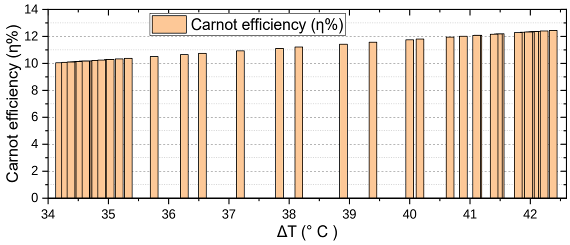


Figure 9. Carnot efficiency of a 2 x 10 *TEG* panel.

3.4. System Implementation Cost Estimation and Economic Analysis

Economic analysis and cost assessment for system installation are two important considerations of the project [32]. This section estimates the cost of a 2 x 10 TEG panel from its key components, as shown in Table (2).

Table 2. Component costs of the TEG panel

Component	Cost US $
TEG module	1.60
Water cooling block (Heat exchanger)	1.10
Flexible plastic water pipes	3.00

A thermoelectric system was improved using water cooling block heat exchangers, which are less expensive, more efficient, and less energy intensive [33]. Other consideration for the system's economic analysis have been presented [33-35]. In reality, the heat exchanger accounts for the majority of the cost of a thermoelectric generator system, which can range from $1/(W/K) to $10/(W/K) and higher. The heat exchanger costs are measured in dollars per the ratio of Watts and degrees of absolute temperature $/(W/K). At maximum power, the lowest thermoelectric cost is determined, but not at the highest power density, largest thermoelectric module, or system efficiency. The cost of a water-cooled block exchanger, according to literature [32], is nearly $13.81/(W/K), which is reasonable when compared to other heat exchangers.

4. Conclusions and Future Work

From this research, it can be concluded that the designed TEG panel generates acceptable power and voltage levels. Also, the temperature distribution is uniform due to utilization of an active cooling method. This increases the efficiency for converting thermal energy into electricity. Furthermore, the cost of such system implementation is low and effective in generating good power levels from waste heat of pipes flowing hot water for domestic use. Thus, this approach can be recommended to use waste heat from hot water pipes to generate inexpensive electricity both day and night. To generate more power, one can either use a larger number of TEG modules, increase ΔT, or both. This system presents a novel technique for generating small-scale off-grid electricity in developing countries.

In the future, the ten check (TC) algorithm presented in [36] can be used to do a comparative examination of diverse electrical loads. This algorithm's effectiveness can be considered under unsteady operating conditions. Furthermore, when this panel is connected to other renewable energy resources such as PV panels, the ten check algorithm TCA in terms of MPPT speed and efficiency and another technologies shown in [37-40] can be used to improve the performance of TEG panels.

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