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Energy and Exergy Analysis of Heat Recovery from the Accumulating Tanks of a Central Heating System by Employing a Sample of Thermoelectric Generators

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Abstract

Heat recovery using a series of thermoelectric generator (TEG) samples improved and studied previously is investigated in this paper. For this, such TEGs are connected to the accumulating tanks (ATs) of a geothermal central heating system assisted by natural gas to recover all waste heat from those devices. The study was carried out based on energy and exergy analysis. In the energy analysis part of the study, the proposed energy conversion efficiency of the TEG sample for the temperature difference in an AT-TEG system in this current study, which is 2%, was applied to find power output and energetic efficiency. As a result, total net power production was 9.888 kW, while overall energy efficiency was 7.717%. It can be observed that this amount of net power generation is sufficient to supply 61.262% of the electrical power needed for the circulating pumps in the remaining parts of the central heating system. This research reveals that TEG application in heat recovery is a promising way forward, but there is still a need to enhance the conversion efficiency of such devices.

1. Introduction

The Peltier effect in cooling usage that consumes electricity to be powered and the Seeback impact on a usage that produces electricity due to a temperature difference are the two purposes that define thermoelectric use. In this paper, the former category needs to be studied; only applications producing electricity are addressed.

The applications of a TEG can be categorized into three classes according to the type of heat source: (i) waste source of heat, (ii) natural source of heat, and (iii) radioisotope source of heat.

A substantial amount of low-grade waste heat is discarded into the atmosphere with no attempt to recover it. Thermoelectric (TE) technology may readily be merged with the physical properties of a specified heat recovery (HR) application, such as the pressure, temperature, and heat transfer fluid. A TE's waste heat recovery techniques (WHR) can be divided into two primary groups: WHR from transport systems and WHR from industry and homes.

In Europe, around 20% of the total CO2 emissions are caused by road transportation, of which three-fourths stem from automobiles, and similar percentages are also present in Asia and America. For light commercial vehicles and passenger cars, European policies aim to reach a CO2 emission goal of 95 g/km and 68 g/km by 2021 and 2025, respectively. It is worth considering that 66.66% of the energy produced by combustion in a vehicle is wasted as drain heat, and 40% of this quantity is contained in the hot exhaust gas. Therefore, it will be feasible to decrease fuel consumption by about 10% if around 6% of the waste heat in exhaust gases can be converted into electricity. This is why the central European, Asian, and American automakers are working to improve different types of TEGs to maintain and gain an additional share of the private car market in the future, which is predicted to be more constrained. Furthermore, they collaborate with research universities and institutes to develop vehicle models with better fuel economy [1].

In this regard, Lan et al. [2] designed a dynamic type TEG consisting of commercial thermoelectric modules and counter-flow heat exchangers (HXs) to recuperate refusal

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heat in the exhaust gas of a heavy-duty vehicle. They modeled a TEG mounted on the after-treatment system of the car to estimate the power production and temperatures in the dynamically operated cycle. According to the output data of the simulation, approximately 20% of the power output rise can be realized with an optimal coefficient of heat transfer of the HX on the hot side and the thermal contact conductance. Orr et al. [3] studied two beneficial up-and-coming technologies: TEGs and heat pipes (HPs). They indirectly aimed to enhance a car's efficiency by employing a junk heat retrieving-based system. They concluded that HPs could decrease the thermic resistance between the gases and TEG. Also, HPs can reduce pressure loss in the gas flow thanks to a narrowed fin surface area.

Furthermore, HPs can regulate the temperatures of the TEGs and enable a more flexible design due to the TEG position that is not constrained to the surface of the exhaust pipe. Luo et al. [4] conducted an optimization study based on the structure of a converging TEG to develop the performance of waste heat recovery. Additionally, they assessed the TEG system behavior by proposing a numerical model based on a multiphysics fluid-thermoelectric system. They concluded that the converging TEG produces more electricity, causes a lower pressure loss on the backpressure side, and provides a more uniform temperature gradient than the classic structure. Finally, Ziolkowski et al. [5] applied simulations to a TEG between the cool bypass and hot side stream at the nozzle of an aero turbofan engine. The finite element model (FEM) served as the basis for these simulations. They observed that the output power runs at 1.65 kW per engine when covering the TEG face with the entire nozzle surface.

Moreover, system-level requirements for gravimetric power density greater than 100 W/kg can be met with only a 21% fill factor. F. Kousksou et al. [6] investigated the electric power possible from the conical nozzle of a helicopter with thermoelectric modules (TEMs). The TEM in this system was exposed to hot exhaust gas from the helicopter's turbine and coolant oil. According to the results obtained for different working conditions, the electrical power generation in actual working conditions is notable but insufficient in terms of the weight-to-power ratio. Eddine et al. [7] studied the characterization and optimization of a TEG prototype for a marine engine. The power output of the TEM based on bismuth-teluride was 70% higher than the silicon-germanium TEM, but the first one deteriorated fast at inlet air temperatures higher than 300 °C. Finally, Olaniyi and Prause [8] analyzed investing in building WHR systems in ships' engines using the real-options method and usual budgeting indicators to provide assumed and predicted future alteration in the volatile maritime markets. The capital budget analysis, which provides a more realistic assessment of the project, revealed that investing in the marine WHR system is only profitable under the precise, sketchy circumstances in the study.

According to Dai et al. [9], 33% of the energy produc ed by industry is emitted directly into cooling systems or th e atmosphere as waste heat in the United States. If TEMs w ith ZT values on average varying between 1 and 2 exist, thi s heat could generate between 0.9 TWh and 2.8 TWh of ele ctrical power annually. As a result, technical and economic analyses are required to improve the possibility of widespr ead use of TEGs in the medium and long term. That analys is may make the heat a competitive, clean energy source. O ver the last three decades, a concerted effort has been made to improve the efficacy of TEMs in HR systems [1].

For example, Wang et al. [10] conducted an empirical study to recover waste heat at high temperatures by a heat pipe TEG in industrial applications. They designed and fabricated an experimental rig of HPTEG constituted of skutterudite TEGs and potassium HPs to acquire electric generation and passive thermal management. They realized that the effective thermal conductivity of the HP reaches 35831 W/mK, which is 100 times higher than that of copper at 630 °C. Employing an effective thermal conductivity and seeback coefficient, the simulation deviation of HPTEG system performance has been significantly reduced. Meng et al. [11] analyzed the impacts of some crucial parameters, like cooling water and exhaust gas heat transfer coefficients and the inlet temperature of the exhaust gas, on the ideal length of the TE for industrial gas phase application to recover waste heat. They derived that the temperature of the gas decreased fast due to the less specific heat value of the exhaust gas. Improving gas heat transfer can effectively increase power output but not efficiency. The heat transfer coefficient and inlet temperature of the exhaust gas have a remarkable impact on the ideal length of the thermoelectric elements, which is approximately 2 mm. Araiz et al. [12] suggested applications of TEGs to convert the waste heat of hot gas into beneficial electricity at a stone wool-producing plant. They employed, improved, and validated two models combined to carry out optimization from a double perspective: energy output and economic cost.

According to the simulated findings, the optimal net output power generation was 45838 W with a filling ratio of 0.40 and a fin space of 10 mm. For the filling ratio of 0.24, a minimal installation cost of 10.60 €/W was observed. The levelized cost of electricity for a TEG was computed for the first time in this study, and it was around 15 c€/kWh. Zou et al. [13] conducted an empirical and mathematical modeling study on WHR from wastewater to produce electricity by a Bi2Te3-based TEG system with a low-temperature distribution. They presented data revealing a potential for the direct generation of electricity based on TEG through advanced source recovery from wastewater and motivated the future discovery of this procedure. Ramadan et al. [14] proposed a system based on three components: the condenser exhaust airflow that is emitted by the condenser of a heating, ventilation, and air conditioning (HVAC) system; the exhaust airflow of the HVAC system, which is used as the cool side; and TEG to generate green electricity. According to the findings, with a cooling load of 100 kW for the space, a 40 by 40 cm2 flat plate can produce 90 W of electricity.

All too many home applications emit energy as heat within water or exhaust gases [15]. Therefore, many studies have been conducted to recover this heat from the sources in question. For example, Khaled and Ramadan [16] proposed a system with TEG comprised of a multi-tube tank heat exchanger, utilizing the exhaust gases of a chimney to heat residential water by WHR. They studied the system's thermal behavior to determine the effects of the various heat transfer modes driving the system by presenting a prototype to be applied and tested. According to tests, the temperature of a 95-liter water tank can be raised by 68 °C in one hour. Also, the convection and radiation changes at the tank's bottom surface significantly affect the water's overall heat transfer rate (as high as 70%). Panwar and Kumar [17] developed a family-sized cookstove operated by biomass and equipped with a TEG to generate electricity by using the waste heat released from the outer casing and grill of the cooker. An oblong metal plate with a 0.12×0.08 m2 area was employed to line up five TEG modules. The panel was bonded to the outer casing of the cookstove to derive waste heat lost via conduction. The TEG's produced electricity was utilized to drive a small fan (12 Volt DC, 0.16 A) that provided fuel combustion primary and secondary fans. It was discovered that the generated power was sufficient to run the fan in the mode of forced air supply, while it was insufficient in the natural operating state. Sakdanuphab and Sakulkalavek [18] devised and implemented a waste heat recovery (WHR) system to utilize waste heat from a cooking burner. The thermal energy of the burner was transformed into electrical power by a TEG and used in a hot water boiler. The temperature of the heater was found to be more effective than the volume of water. In addition, the thermal efficiency of a cooking stove outfitted with the WHR system was assessed. Results demonstrated that its thermal efficiency declined by less than 5% when mounting the WHR system. Montecucco et al. [19] presented a TEG application for heat transfer to the water for domestic or heating use while also charging a lead-acid battery for a solid-fuel stove. A general solid-fuel stove indicates the practicability of the suggested combined heat and power (CHP) system. During a 2-hour test, this system generates an average of 27 W (42 W electricity peak) and 600 W of thermal energy, demonstrating the maximum power point tracker (MPPT) efficiency of the power transformers used and the TEG efficiency of about 5%. Jaber et al. [20] studied a hybrid HR system, which produces electrical power by utilizing a TEG and domestic hot water, to evaluate the effect of varying the temperature of exhaust gases on the system's performance. They applied a resistive thermal model to determine the temperature of the exit water and power generation via TEGs. According to the results, when the temperature of the exhaust gas increases, the temperature in the HX without layer discrimination and heat rate rise linearly. Additionally, the power generation of TEGs rises with increasing exhaust gas temperatures.

Producing electrical power from natural heat sources by using TEG can be divided into three groups: (i) sun sources, (ii) human bodies, and (iii) natural gases and biomass.

Applications of solar thermoelectric generators (STEG) are based on recovering heat from solar radiation and transforming it into electrical power using a TEG. Although its conversion efficiency is low, it has been an alternative and is rivaling solar photovoltaic systems [1]. Indra et al. [21] reviewed different combination alternatives of concentrator photovoltaic (CPV)-TEG applications and current developments of various geometries of hybrid CPV-TEG systems containing CPV-TEG with phase-changing material, CPV/thermal-TEG and CPV-TEG with a spectral beam splitter. They dedicated it to the fact that a CPV-TEG solar system has higher thermal and electrical efficiency than a standard PV-TEG system. They also made some suggestions for future improvements to CPV-TEG systems. Faddouli et al. [22] analyzed a novel solar system directly coupled with a TEM regarding energy efficiency to generate electricity and heat simultaneously, use the entire solar spectrum, and enhance the efficiency of conventional solar collectors. They found that the novel hybrid system remarkably enhances the storage process by varying the flow rate depending on the concentration. This flow rate reaches the amount of 1200.453 l/day and provides considerable extra electrical energy around 10.41 W with a 0.92 × 1.9 × 0.05 m3 collector sloping 30° under 20 suns.

Because human body heat is natural and immovable, it may generate energy in specific applications, such as medical ones. The human body generates between 100 and 525 W of heat at rest and during physical exercise. Many investigations have been conducted since 2001 to produce wearable thermoelectric generators (WTEGs) [1]. For instance, Sun et al. [23] made a woven thermoelectric cloth, designing an unostentatious operating TEM without using thermoelectric fibers. Using elasticity welding on interlaced TEMs, tensible 3D TEGs without an underlayer can be produced to achieve sufficient alignment with the heat flux direction. The textile producer demonstrates a maximum power density of 70 mW/m2 and great tensibility with no production deformation at a 44 K temperature difference. Xu et al. [24] proposed a plan of dimensionality morphology to manufacture organic-inorganic TE composites. A maximum normalized power density for a prototype TEM based on suitable flexible composites in the whisker-like semiconductor Ta4SiTe4 with substantial interfacial conformity and chain-shaped polyvinylidene fluoride (PVDF) was stated. It was discovered that a lesser number of n/p pairs are required for a module to satisfy the outset voltage, owing to the composite having a high seeback coefficient.

TEGs, or thermopiles, are currently configured to provide energy for autonomous sensors established in remote locations due to harsh ambient conditions, i.e., inaccessible places with shallow temperatures where traditional alternative energy sources, such as wind and solar energy, are not available regularly. Heat is often delivered via a flameless catalytic burner. TEGs energized by natural gas are fabricated in more than 55 countries. For example, Gentherm produces TEGs whose powers vary between 15 W and 550 W. Those TEGs are generally employed on petrol platforms, at high altitudes, along pipelines, or near gas wells. Farwest Corrosion Control is another case in point, a corporation that produces and installs TEGs to avoid pipe corrosion through cathodic protection and has over 15,000 generators in 51 countries.

Many goods have been designed and marketed for public use. The thermoelectric candle radio (1990) can be cited as an example, which utilizes the heat from candles to energize a radio with iron disulfide (FeSi2) TE. However, these technologies need to be updated due to the appearance of other more advantageous applications. Yet there are even more unique applications like CampStove. In general, this device was projected for camping to generate 5 V and 2 W of 0.4 A power by burning wood and using a TEG to which electrical gadgets can be attached through a USB port [1].

This study examines heat recovery via TEGs from the accumulating tanks (ATs) of a geothermal central heating system (GCHS) assisted by natural gas based on energy and exergy analysis. This application of a TEG falls under the heading of ‘waste heat recovery from industry and homes.' In this field, research has been done on heat recovery from municipal wastewater, hot gases from factories and wood stoves, the heat emitted from air conditioning systems, the heat of boilers for autonomous working, hydronic central heating units on a residential scale to supply electrical power for their equipment, and lastly, work equipment in a natural gas field. However, as seen from the latest explanation, even though there are some applications of heat recovery from industry and homes in the literature, there still needs to be more heat recovery from some devices of a central heating system on an industrial scale. That is the reason that encourages us to carry out the current analysis. In this study, we aim to mount a TEG sample with an 8% conversion efficiency at a 230 °C temperature difference between its hot and cool sides to the ATs of a GCHS and find energetic and exergetic results for the temperature difference and usage proposed in this study. The GCHS was studied by [25], while the TEG was submitted and fabricated by [26].

2. Materials and Methods

2.1. System Description

The GCHS, assisted by liquid natural gas (LNG), is in Oylat Spa Town, Bursa Province, not southwest Turkey. The schematic layout of the GCHS is depicted in Figure 1. The GCHS uses low-enthalpy geothermal water and LNG as energy sources for heat generation to heat the districts' hotel rooms.

The geothermal water (GW) springs from the production well at 40 °C; then, it is conveyed to the geothermal pool (GP). The GW exits the pool at 35 °C since some of its heat is obtained by the heat exchangers (HEs) there. Afterward, the heat derived by the HEs is transferred into the circulating water (CW) between the heat pumps (HPs) and HEs, increasing the temperature of this CW from 20 °C to 30 °C. In the HP-HE cycle, the CW enters the first HP at 30 °C and leaves the second HP at 20 °C. The temperature of the CW decreases by 5 °C in each one of these HPs subsequently. In the AT-HP cycle, the temperature of the CW rises to 60 °C from 50 °C, with a 5 °C increase in each HP. In a word, the heat acquired from the GW is transmitted into the water in the ATs.

Additionally, the heat from firing the natural gas in the condensing combi boilers (CCBs) is transmitted into the ATs through the CCB-AT cycle to supply additional heat for the districts. The CCB group contains 8 CCBs, which raise the water temperature in the CCB-AT cycle from 60 °C to 80 °C.

All heat acquired from the GW and natural gas is first transferred into the water in ATs and then conveyed to the wall heating panels (WHPs). In the case of heating the districts with only the GW, the temperature of water circulated between ATs and WHPs ranges from 53 °C to 60 °C, while it is between 73 °C and 80 °C, providing extra heat by firing natural gas. In this paper, calculations have been performed for the latter case.

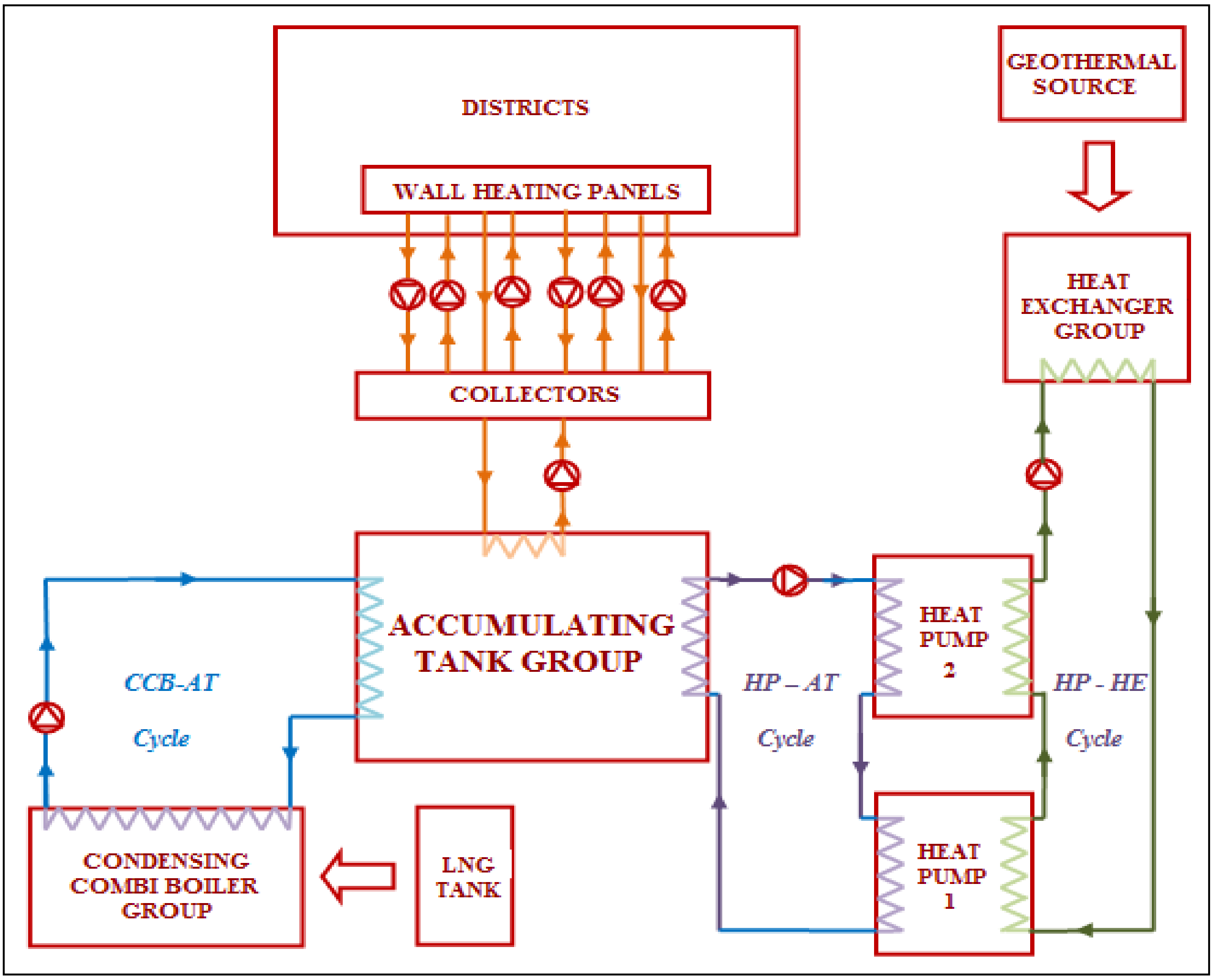

Figure 1. The schematic presentation of the GCHS was studied by [25].

It can be seen that the ATs in the AT group serve as a bridge in the entire system because all heat attracted from the sources is first transferred into the water in this group before it is transported to the WHPs. That is why a significant amount of heat loss occurs in the AT group, and some of it can be recovered by mounting TEGs.

The AT group contains 6 ATs with a total heat loss and storage capacity of 645.960 kW and 30000 lt, respectively. Therefore, the heat loss and storage capacity per AT are 107.660 kW and 5000 lt, respectively. 2 TEGs are connected to an AT, so there are a total of 12 TEGs, and each TEG acquires 53.830 kW of heat energy from an AT. Therefore, the identical AT-TEG systems are working under the same conditions. The calculations have been performed for only one AT-TEG system. The overall energy and exergy results have been determined for all AT-TEG systems by multiplying the values found for one system by 6.

The schematic layout of one AT-TEG system is depicted in Figure 2. In this system, the hot side water leaves the AT at a mass flow rate of 4 kg/s and 80 °C (point 1). Then, it splits in half and enters each of the 2 TEGs at a 2 kg/s flow rate and 80 °C (points 2 and 3). In each TEG, the heat of the hot side water is released into the coolant water. The hot side water then exits each TEG at 2 kg/s and 73.6 °C (points 4 and 5) and returns to the AT at 4 kg/s and 73.6 °C (point 10).

The coolant water is indeed the GW leaving the geothermal pool at 35 °C. We imagine transporting some of this water to the cold sides of the TEGs to be used as coolant water via 12 water lines independent of each other. So, there is one water line for one TEG (6-7 and 8-9). In a water line, the coolant water enters a TEG at 35 °C (points 6 and 8) and exits it at 38.6 °C and 3.5 kg/s mass flow rate (points 7 and 9). The flows of the coolant and hot side water through the TEG are in reverse directions from each other.

A TEG is primarily based on the Seeback effect, invented by Thomas Seeback [27]. As shown in Figure 3, the TEG sample that we use is made up of top and bottom aluminum nitride (AlNi) substrates with low electrical conductivity but high thermal conductivity to effectively transfer heat from the hot side to the TEG, copper (Cu) links that provide a series of electrical connections, joint bars that supply thermal and electrical conduction between

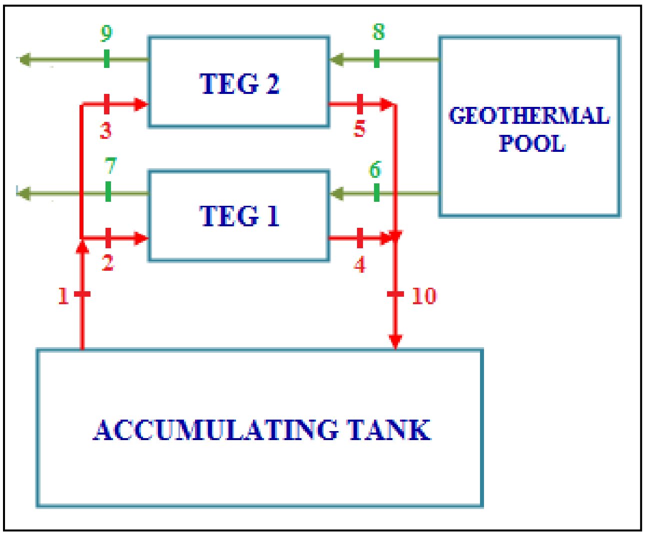

Figure 2. The schematic layout of the AT-TEG system.

Table 1. The inlet and outlet temperatures of the hot side and coolant fluids.

Fluid	Inlet Temperature (°C)	Outlet Temperature (°C)	Mean Temperature (°C)
Hot Water	80	73.5	76.8
Coolant Water	35	38.6	36.8

substrates and legs, and finally p- and n-type TE legs. Bi0.4Sb1.6Te3 and Bi2Te2.7Se0.3S0.01Cu0.01 materials are used for the p-type and n-type legs, respectively [26]. If a temperature difference ΔT occurs between the TEG substrates, the TEG generates electrical voltage [27]. The present TEG sample, developed and fabricated by [26], will be tested for a ΔT value, which is the difference between the mean temperatures of the hot side and coolant water. [26] shows the conversion efficiency for this ΔT value.

2.2. Energy and Exergy Analysis

For energy and exergy analysis of the TEGs, each TEG's energy and exergy balance formulas must be expressed and solved in order. Then, the equations below are applied:

$$\dot{\boldsymbol{Q}}_{C.V} - \dot{\boldsymbol{W}}_{C.V} = \sum \dot{\boldsymbol{m}}_{out}\boldsymbol{h}_{out} - \sum \dot{\boldsymbol{m}}_{in}\boldsymbol{h}_{in} \quad (1)$$

$$\dot{E}_i = \dot{m}_i[(h_i - h_0) - T(s_i - s_0)] \quad (2)$$

Where $\dot{Q}$ indicates the heat rate transferred to the control volume, $\dot{W}$ is the acquired work, h represents the fluid enthalpy, and m˙ denotes the mass flow rate. E˙ and s represent exergy rate and entropy, respectively, and the subscripts in and out mean the inlet and outlet. I substitute the state points.

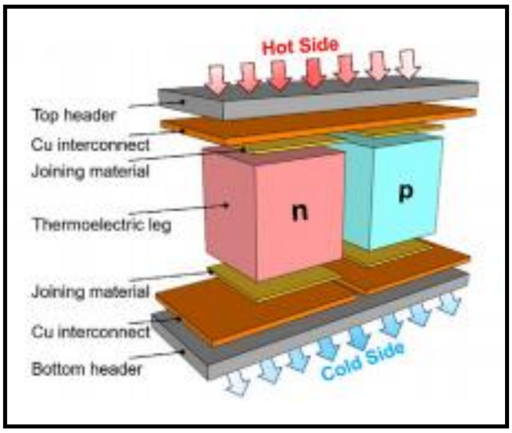

Figure 3. The schematic structure of the TEG used in this study.

The relevant thermoelectric formula is as follows:

$$\eta_{TEG} = \eta_C[(\sqrt{1+ZT_m} - 1)/(\sqrt{1+ZT_m} +)] \quad (3)$$

ZT_m denotes the merit figure, typically between 0.2 and 1.6 up to the construction [28], and is taken as 1 for the temperature difference ΔT in this study.

The Carnot efficiency is denoted as follows:

$$\eta_C = 1 - (T_l/T_h) \quad (4)$$

The following is another functional formula:

$$\eta_{TEG} = 1 - (\dot{W}_{TEG}/\dot{Q}_{ELEGANT}) \quad (5)$$

where $\dot{Q}_{ELEGANT}$ is an effective electricity production apparatus for liquid bases bases and is used for thermos electrics.

$$\dot{Q}_{ELEGANT} = \dot{m}_{cooling}(h_{cold,in} - h_{cold,out}) \quad (6)$$

In other respects, the hot and cold side temperatures can be calculated by an admissible approximation as [28]:

$$T_l = \frac{1}{2}(T_{cold,in} + T_{cold,out}) \quad (7)$$

$$T_h = \frac{1}{2}(T_{hot,in} + T_{hot,out}) \quad (8)$$

where T_h and T_l are the mean temperatures of the fluids on a TEG's hot and cold sides, respectively; their numerical va lues are given in Table 1. The conversion efficiency of the TEG sample can be reviewed for the difference between those temperature values (ΔT) in [26]. As can be calculated from Table 1, the temperature difference ΔT between the hot and cold sides of one TEG is 40 °C. The conversion efficiency η_TEG can be taken as 2% from [26] at this temperature difference, besides Equations 3 and 5.

The main factors for the performance evaluation of the heat recovery system in this work are TEG unit output power, net output work, exergy destruction rate, and second law efficiency.

The total power output of the TEGs can be denoted as follows:

$$\dot{W}_{TEG,tot} = 12\ x\ \dot{W}_{TEG} \quad (9)$$

Besides Equation 5, $\dot{W}_{TEG}$ can be calculated using the conversion efficiency when a TEG's amount of acquired and released energy is known.

The net output power of the whole TEG system is denoted as follows:

$$\dot{W}_{net} = \dot{W}_{TEG,tot} - 6\ x\ \dot{W}_{pump} \quad (10)$$

$\dot{W}_{pump}$ is taken as 0.5 kW to provide power for the water flows on both sides of the TEG.

The overall energy and exergy efficiency of the TEGs can be denoted as follows [28]:

$$\eta_I = \dot{W}_{net}/\dot{Q}_{in} \quad (11)$$

$$\eta_{II} = \dot{W}_{net}/\dot{E}_{in} \quad (12)$$

3. Results and Discussion

The system in this paper is analyzed in two parts: In the first stage, an energy examination was conducted. To that end, the point energy and exergy values were first established. Then, the input and output energy amounts for the TEGs and the AT-TEG system were found for ΔT = 40 °C. As previously noted, the conversion efficiency for this temperature difference is estimated at 2%, according to [26]. The results for that conversion efficiency and point temperature values in the system were determined. The second portion of the study encompasses an exergy analysis. In this respect, the input and output exergy levels for each TEG and the AT-TEG system were calculated. The second law, efficiency, was established. Finally, the total results for all AT-TEG systems were computed. Table 2 displays the point energy and exergy data.

Table 2. Point thermodynamic values of an AT-TEG system in the current study.

Point	ṁ (kg/s)	T (°C)	h (kJ/kg)	s (kJ/kgK)	E (kW)	Ė (kW)
1	4	80	334.910	1.0753	1339.640	136.523
2	2	80	334.910	1.0753	669.820	68.261
3	2	80	334.910	1.0753	669.820	68.261
4	2	73.6	308	0.9982	616	57.584
5	2	73.6	308	0.9982	616	57.584
6	3.507	35	146.680	0.5053	514.406	19.323
7	3.507	38.6	161.720	0.5536	567.152	24.549
8	3.507	35	146.680	0.5053	514.406	19.323
9	3.507	38.6	161.720	0.5536	567.152	24.549
10	4	73.6	308	0.9982	1232	115.168

The energetic values of the TEGs and AT-TEG systems are represented in Table 3. According to this data, the amount of energy acquired by a TEG is 53.820 kW. So, the energy loss per TEG was calculated to be 1.074 kW by using the conversion efficiency of a TEG. Indeed, this energy loss is the amount of electrical power produced by a TEG. Then, the output of the AT-TEG system in terms of electrical power generation was found to be 2.148 kW. The first law efficiency of the AT-TEG system was found to be 1.531%, which is 0.469% lower than a TEG because the circulating pumps in the AT-TEG system consume 0.5 kW of electrical power. The total produced electrical power was 12.888 kW by multiplying the electricity generation of the AT-TEG system by 6. Since the AT-TEG systems are identical, the first law efficiency for all TEG systems was 1.531%, the same value as with only one AT-TEG system.

The results of the TEGs and systems in terms of exergy are presented in Table 4. The data shows that the exergy destruction rate per TEG is 5.451 kW, and for the AT-TEG system, it is 11.402 kW. The total exergy destruction rate is 68.412 kW. The second law efficiency is 10.06% per TEG, which is 8.06% higher than the first law

1 **Table 3.** Energetic results for the components and systems.

Components	E_{input} (kW)	E_{output} (kW)	E_{loss} (kW)	η_I (%)
TEG-1	53.820	52.746	1.074	2
TEG-2	53.820	52.746	1.074	2
Circulating Pump	1340.140	1339.640	0.5	99.5
One AT-TEG system	108.140	105.492	2.648	1.531
All AT-TEG systems	648.840	632.952	15.888	1.531

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efficiency. This is because the input exergy is nearly 80% lower than the exergy input for a TEG. The second-law efficiency of the AT-TEG system is 7.717% and is 2.343% lower than the double-law efficiency of a TEG, which is attributed to the electrical work consumed by the circulating pumps in an AT-TEG system. All AT-TEG systems have the same second-law efficiency because they are identical.

Table 4. Exergetic results for the components and systems.

Components	$\dot{E}_{input}$ (kW)	$\dot{E}_{output}$ (kW)	$\dot{E}_{loss}$ (kW)	η_{II} (%)
TEG-1	10.677	5.226	5.451	10.06
TEG-2	10.677	5.226	5.451	10.06
Circulating Pump	137.023	136.523	0.5	99.635
One AT-TEG system	21.854	10.452	11.402	7.717
All AT-TEG systems	131.124	62.712	68.412	7.717

4. Conclusions

In this paper, a Bi-Te-based TEG, which has a relatively higher conversion efficiency than conventional TEGs, has been employed to recover the waste heat of the ATs of a natural gas-assisted central heating system. There were a total of six AT-TEG systems. In each AT-TG system, there were two TEGs linked to an AT. According to the results, one AT-TEG and the overall design have an energy efficiency of 1.531%. The comprehensive system and one AT-TEG system have an exergetic efficiency of 7.717%. The total system produced a net power output of 9.888 kW. This power can meet 61.262% of the electrical power required for the circulating pumps in the rest of the central heating system.

Declaration of Ethical Standards

The authors of this article declare that the materials and methods used in this study do not require ethical committee permission and/or legal-special permission.

Conflict of 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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