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Design of Heat Pipe Assisted Thermoelectric Generator and Experimental Investigaton of the Power Performance

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Murat ÖZSOY[4], Erman ASLAN[5]

Abstract

A thermoelectric generator system has a potential to transform waste heat into electricity. Equate to other technologies of waste heat recover, usage of thermoelectric generators (TEGs) in a waste heat recovery system has many attractive features, for example quite operation, no moving parts, small size and endurance In addition to, thermoelectric generators are environmentally friendly materials that convert thermal energy directly into electricity by Seebeck effect.

In work presented, a heat pipe assisted thermoelectric generator system is designed to generate electricity from the waste heat. Usage of heat pipes can latently decrease the thermal resistance and pressure losses in the system as well as temperature regulation of the TEGs and enhanced design flexibility. The designed system is suitable for the heat recovery from the piped systems such as the exhaust and the cylindrical chimney systems.

The power performance of the designed thermoelectric generator system has been determined both theoretically and experimentally.

Keywords: thermoelectric generator, seebeck effect, heat pipe, experimental methods

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1. INTRODUCTION

Due to the increase in energy consumption, new investments have to be made to produce energy. In order to meet the ascending demand of energy, intensive studies are being made especially in the field of clean energy technologies in order to generate energy by alternative methods because of the harm that fossil fuels give to the environment.

Considering that the most used fossil fuels will be consumed nowadays, renewable energy sources will be preferred more in meeting the increasing energy demand [1-4].

In the past 30 years, there has been growing relevance in applying thermoelectric technology to recovery waste heat [1]. A direct thermal-to-electrical energy transformation of the waste heat can also be realized by using a thermoelectric generator [4]. The thermoelectric generator (TEG) module can also be described as thermal battery. When the gradient of the temperatıre in the TEG module occur, electric power (DC) is directly produced by heat energy as a result of Seebeck effect. Thermoelectric power systems are environmentally friendly power generating and cooling systems [1,5].

Compare to other technologies of waste heat recovery, usage of TEGs in a waste heat recovery system has many attractive features such as silence, small size, scalability and durability. Heat pipes and TEGs could be used in conjunction for use in a waste heat recovery system [6]. There are examples of exhaust heat recovery using both heat pipes and thermolectric generator modules: Orry et al. [7-9] has proposed an exhaust heat recovery system with the potential of decreasing the fuel consumption, emission of CO_2 and running costs of a car. Remeli at al. [4, 10-12] designed and produces a prototype of thermoelectric waste heat recovery system. The system come out of Bismuth Telluride (Bi_2Te_3) based TEG sandwiched between two heat pipes. The first and second pipe were connected to hot and cold side, respectively. A new type of heat pipe assisted thermoelectric generator for automobile exhaust waste heat recovery has been suggested by Cao et al. [13]. In order to verify the optimized configurations of the thermoelectric device, an experimental test set up was built for attaining the best heat pipes insertion depth and the optimum angle between the heat pipe row and the gas flow direction.

Both thermoelectirc generator modules and heat pipes have quite promising property for their usage in exhaust heat recovery system [8,9]. Heat pipes are not active geat transfer devices, in other words, heat pipes are passive heat transfer devices. In passive heat transfer devices like heat pipes, thermal conductivity values are much gerater than copper, it does not need large temperature gradient between eat source and heat sinks for efficient heat transfer [14,15]

It is understood for the literature review that there are many publications for thermoelectric systems both using heat sink and heat pipes. However, the heat sink considered for condenser block is designed as tower type heat sink, which is rarely known in the literature. Therefore, it is expected that the design will provide original conribution when the ease of production and cost are obtained.

In the work presented, heat pipe assists designing of thermoelectric generator system in order to transform waste heat from piping systems such as exhaust and chimney systems. Thanks to the thermoelectric generator module used in the designed system, the thermal energy is directly transformed into electric energy (DC. The designed new system is compact, modular and both easy to manufacture and install.

2. THEORETICAL PRINCIPLES

Thermoelectric devices are able to transform thermal energy from a gradient of a temperature into electrical energy. This phenomon was found out in 1821 and is named as “Seedbeck effecft”. Thermoelectric generators (TEG) are comprise of p and n type semiconductor materials [2,5]. Thermoelectric generator (TEG) modules are formed by series and thermally parallel connection of pairs of leg made of p and n type semiconductor materials [16]. Figure 1. below shows the form of both the thermoelectric generator leg pair (N=1) and the thermoelectric generator module (N>1). As represented in the figures, p and n type semiconductor materials are electrically connected serially to each other with a conductive material. The semiconducting materials are also placed between the insulating plates to provide electrical insulation. The electric current I (A) in the circuit occurs when heat input is provided in Q_H amount from a heat source to a surface of the leg, because of a temperature difference ΔT (K) between two surfaces of thermoelectric legs.

The performance of thermoelectric material, "Figure of Merit", FoM ie Z is calculated by the following formula

$$Z=\frac{S^2\,\sigma}{k} \tag{1}$$

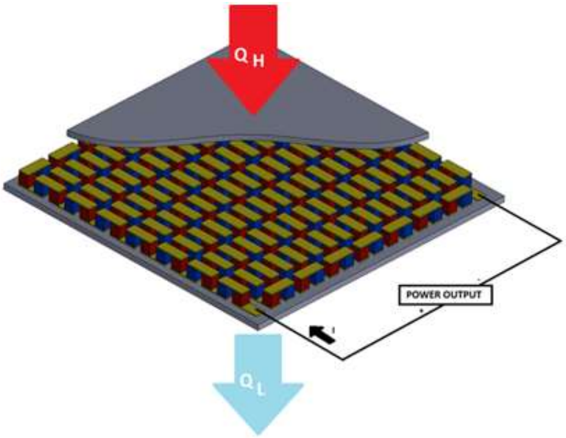
The material performance Z, which is the unit (1 / K), is usually determined by a dimensionless formula multiplied by the average absolute temperature.

$$Z.T=\frac{S^2\,\sigma\,T}{k} \tag{2}$$

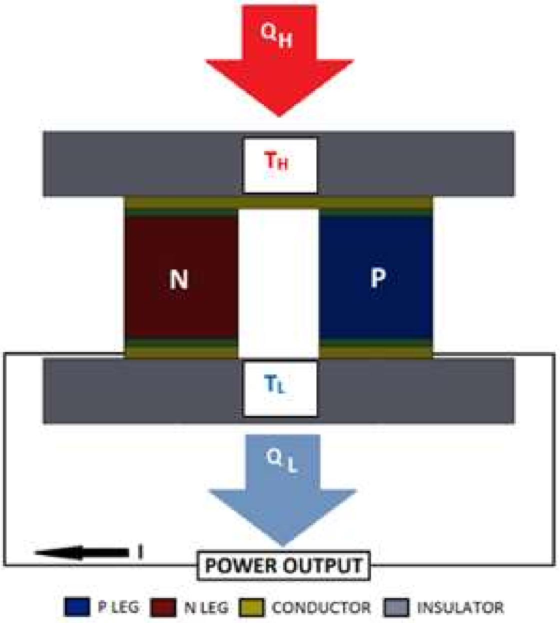
The performance of thermoelectric materials is also expressed as follows.

$$Z=\frac{S^2}{KR} \quad [1/K] \tag{3}$$

Today, the ZT value of thermoelectric materials is even lower than 1. The Z.T value of Bismuth Tellurium (BiTe) thermoelectric material widely used in the industry ranges from 0.5 to 0.8 [16-18].



(a) N>1



(b) N=1

Figure 1 (a) Thermoelectric generator (TEG) module (N> 1) and (b) thermoelectric pair of leg (N = 1)

The ideal thermoelectric equations which are widely used in the analysis of thermoelectric energy systems are given below [19-21]. These equations depend on the Seebeck effect, the heat transmitted and the Joule heat. The following assumptions are made in the derivation of ideal equations:

- Thermal and electrical contact resistances are neglected.
- Thomson heat is neglected because the materials propertie sare assumed not to change with temperature.

- The convection and radiation heat transfer from or to thermoelectric leg are neglected.

The conduction heat transfer:

$$Q=K\Delta T=K(T_H-T_L) \quad [W] \tag{4}$$

Where K is the total heat transfer coefficient of a pair of legs (N = 1), T_H and T_L are the hot and cold surfaces temperatures of the thermoelectric legs consisting of p and n type leg, respectively.

$$K= k_p \frac{A_p}{L_p} + k_n \frac{A_n}{L_n} \quad [W/K] \tag{5}$$

The Joule heat, which flows when the current flows from thermoelectric leg, can be calculated by the following equation, where R [Ω] is the internal resistance of the module.

$$Q_J=I^2R \quad [W] \tag{6}$$

It is assumed that the amount of Joule heat is equal to both surfaces of the thermoelectric leg. In this case, the amount of heat incoming to each surface will be $Q_J/2$.

The internal resistance of the module is calculated as follows.

$$R=\rho_p \frac{L_p}{A_p} + \rho_n \frac{L_n}{A_n} \quad (\Omega) \tag{7}$$

where Ω.m and Ω.m are the electrical resistances of the p and n type legs, respectively.

The heat from the hot surface,

$$Q_H=N[(S_p-S_n).I.T_H+K.(T_H-T_L)-I^2R/2] \quad [W] \tag{8}$$

Heat from cold surface:

$$Q_L=N[(S_p-S_n).I.T_L+K.(T_H-T_L)+I^2R/2] \quad [W] \tag{9}$$

Electrical power generation,

$$P=Q_H-Q_L =N.[S.I.(T_H-T_L)-I^2R]=V.I \quad [W] \tag{10}$$

Efficiency:

$$\eta = \frac{P}{Q_H} = \frac{Q_H-Q_L}{Q_H} = \frac{P}{Q_L+P} \tag{11}$$

Voltage and current are calculated in the following formulas respectively.

$$V=N[S(T_H-T_L)-I.R] \quad [Volt] \tag{12}$$

$$I=\frac{S(T_H-T_L)}{R} \quad (A) \tag{13}$$

3. EXPERIMENTAL STUDY

The shape of the designed and prototype thermoelectric heat recovery system, turning into the energy of waste heat into electricity is shown in Figure 2. All the components except the Peltier module and heat pipe which are used "reversible" in order to produce thermoelectric power in the mentioned system have been manufactured at the CAD / CAM center in the laboratory of Sakarya University Department of Mechanical Engineering.

In our experimental studies, a commercial thermoelectric module (Marlow, SP1848-27154SA) made of Bismuth Telluride (BiTe) semiconducting material and having N = 127 leg pairs of p and n type was used. The module has equal edge lengths of 40 mm and a height of 3.4 mm. The thermophysical properties of thermoelectric materials are given in Table 2.

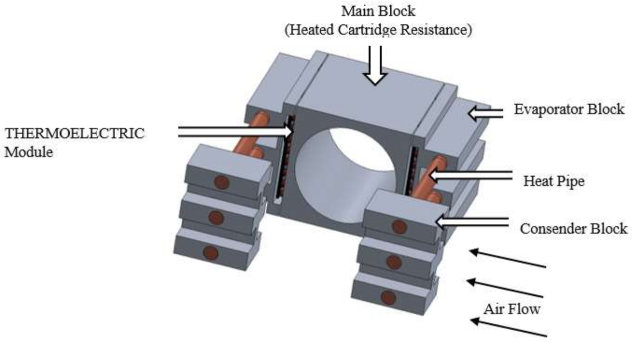
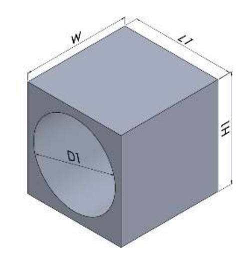
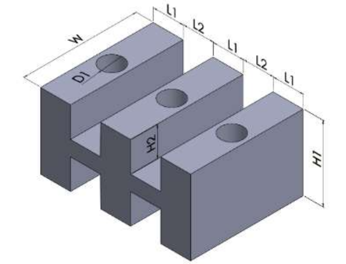


Figure 2 (a) Thermoelectric heat recovery system (a) and developed for experimental operation (b)

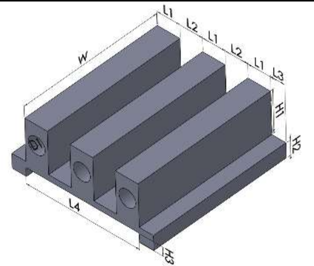
Table 1
Thermophysical properties and geometrical properties of thermoelectric materials [22,23]

		Seebeck coefficient S (μV/K)	Electrical resistivity ρ (μΩ m)	Thermal conductivity k (W/m K)
P	P type leg	210	18	1,32
N	N type leg	-210	12	1,78

The cross-sectional area of thermoelectric feet is $A = 1x1 = 1\ mm^2$ and height $L = 1\ mm$

Main Block	Condenser Block
	

W	L1	H1	D1	W	L1	L2	H1	H2	D1
50	48	50	42	30	8	8	20	8	6

Evaporator Block


W	L1	L2	L3	L4	H1	H2	D1
50	8	8	8	40	14,5	5	6

Figure 3 The shape and dimensions of the heat transfer elements in the thermoelectric heat recovery system

The performance tests of the prototype thermoelectric power generator were carried out in the Heat Transfer Laboratory in Thermoelectric Energy Systems at Sakarya University. The test setup is shown in Fig 4.

The designed generator system is provided with cartridge heaters (Euroheat) which produces 900 W of power at 230 V, which is operated by trasformer (Varatran 36 Y) to supply heat source of Q_H to the newly designed generator for experiment. The size of the cartridge is 130 mm and the diameter is 20 mm. Q_L heat transfer from the system is provided by ambient air. With a valve connected to the duct where the air flow is, the air flow has been changed and it is now possible to work at different air velocities. The speed of the air was measured both by the anemometer connected to the inlet of the test section (Airflow TA2 Anemometer / Thermometer) and by the turbine type flow sensors (Dwyer VT-200 Anemometer) connected to the fan outlet. Air temperature, hot side and cold side temperarure of the thermolectric legs respectively, T_H and T_L measurements were made with digital temperature sensors (Dwyer TC-20 Thermometer).

The DC electrical quantities of the thermoelectric power generator such as current and voltage are measured by a multimeter capable of reading AC / DC (Keithley 197 Autoranging Microvolt DMM). The thermoelectric heat recovery system under test has two thermoelectric modules (n = 2). Table 3 below sets forth the data obtained for one module (n = 1).

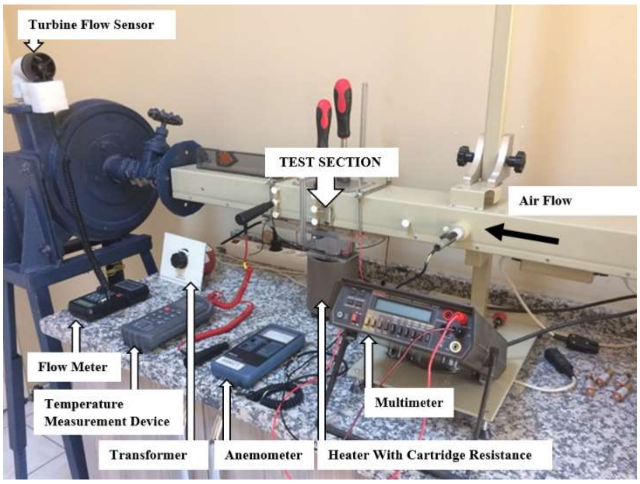


Figure 4 Experimental setup

4. RESULTS

In present study, heat recovery performance of heat pipe assisted thermoelectric generator designed to recover waste heat from piping systems was determined experimentally in Heat

Transfer Laboratory for Thermoelectric Systems at Sakarya University.

The power generation characteristic of the thermoelectric generator was examined by varying the air flow velocity and temperature during the experimental studies. The results are given in Figure 5 and Figure 6.

It is understood from the Figure 5 and 6 that the output powert values increase as both increasing of the hot side legs temperature T_H and cold side air velocity. The cold side legs temperature T_L decreases with increasing air velocity.

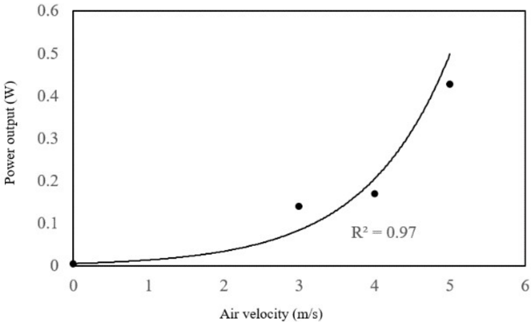


Figure 5 The power output versus air velocity

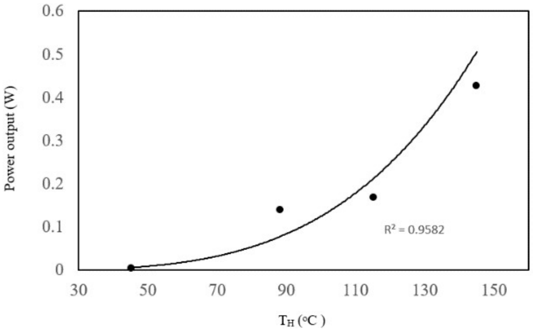


Figure 6 The power output versus the hot side temperature of the legs (air velocity v=4 m/s)

The thermal energy conversion efficiency of the thermoelectric heat recovery system according to the differences of temperature between the hot and cold surfaces of the module is shown in Figure 7 below.

Experimental results are also compared with the theoretical results determined by ideal thermoelectric equations for one generator module (n = 1) in Figure 7. When the figure is examined, it is seen that experimental and theoretical results are not as compatible as expected. Because the equations used in the analysis of thermoelectric energy systems depend on the Seebeck coefficient. Therefore, in determining the thermal-electrical performance of the system, the Seebeck coefficient of the thermoelectric module used in the system must be determined correctly. However, since the Seebeck coefficient of the module is not given by the module manufacturer, the Seebeck coefficient which is widely calculated theoretically is used while the thermoelectric modules and energy systems are designed. Since the theoretical and experimental Seebeck coefficients are incompatible [20], the experimental and theoretical performance data of the system are different as can be seen in the figure.

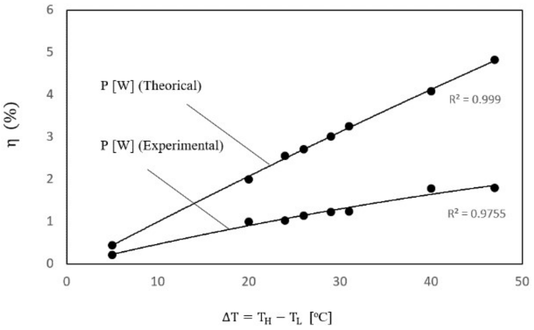


Figure 7 The thermal efficiency (η) of the system according to temperature difference ($\Delta T = T_H - T_L$)

As shown in Figure 7, the thermal efficiency (η) of the thermoelectric heat recovery system is small. For this reason, it is not possible to compete with existing power plants yet. However, since there are no moving parts in the thermoelectric systems, they are preferred for generator and cooler in the military, space and medical industry because of their quiet and vibration-free operation and small size.

The calculated ZT value for thermoelectric module used our experimental studies ($Z = S^2 / KR$ and $T = 300$ K) is 0.588. The Z.T value for commercial Bismuth Tellurium (Bi_2Te_3) material commonly used today is approximately 1. Z value depends upon the Seebeck coefficient, the electrical resistivity and the conductive heat transfer coefficient. For developing the performance of the thermoelectric power system, the Z value of the thermoelectric material must be high. For Z to be high, the Seebeck coefficient should be improved, low resistivity, and low thermoelectric materials with low heat transfer coefficient.

5. CONCLUSION

An thermoelectric generator system has been designed to product electricity using hermoelectric modules and heat pipes. This design is completely solid state and passive. The maximum power generated during testing from one thermoelectric module was about 0,5 W while theorically of 1 W.

In the theoretical calculation of the thermoelectric effects with the ideal equations, electrical and thermal contact resistance, properties of the material depending on the temperature, concective and radiative heat transfer form or to the thermoelectric legs are neglected. In practice or during experimental work, the changing contact resistance between the module and the heat transfer devices, depending on the mounting style of the module and the pressure on it, also changes the effective Seebeck coefficient. Therefore, while thermoelectric power systems are being designed using commercial thermoelectric modules, the use of the "effective" Seebeck coefficient determined by the experimental method will contribute to the correct determination of the thermoelectric performance of the thermoelectric system.

The thermal-electrical performance of thermoelectric power systems depends on both the thermoelectric module and the thermal performance of the heat transfer devices that provide heat transfer from the modulo or to modulo. For the development of thermoelectric power systems with improved performance, thermal resistance must be small or total heat transfer coefficient of devices must be large. Particularly in this context, convective heat transfer improvement studies should be regarded as important. The development of efficient and compact heat transfer devices for thermoelectric power systems will contribute to the design and development of efficient thermoelectric energy systems. These studies will contribute to the much wider use of thermoelectric systems, whose utility is higher environmental friendly clean energy systems. The widespread use of these systems will also contribute to reducing fossil fuel consumption and preventing global warming.

6. NOMENCLATURE

A	Cross-sectional area of a thermoelectric leg [m^2]
H	Height of a thermoelectric leg [m]
I	Electric current [A]
J	Electric current density [A/m^2]
k	Thermal conductivity [W/mK]
N	Number of thermoelectric element or couples
n	Number of thermoelectric module
P	Generated power [W]
Q_H	Heat input [W]
Q_L	Heat rejected [W]
R	Electrical resistance [Ω)
S,	Seebeck coefficient [V/K]
T	Absolute mean temperature ($T = \frac{T_H+T_L}{2}$) [K]
T_H	Hot side temperature [K]
T_L	Cold side temperature [K]
V	Voltage [V]
Z	Figure of merit [1/K]
Z.T	Figure of merit
ρ	Electrical resistivity [Ω.m], [m/S]
σ	Electrical conductivity [1/Ω.m], [S/m]
η	Efficiency

Subscripts

n	n-type
p	p-type

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The Declaration of Conflict of Interest/ Common 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.

Authors' Contribution

Yİ: Conceptualization, methodology, writing, experimental design, experimental studies, investigation, original draft, supervision.
CP: Review, editing, supervision.
İT: Review, editing.
MÖ: Experimental design, investigation.
EA: Review, writing, editing, investigation.

The Declaration of Ethics Committee Approval

The authors declare that this document does not require an ethics committee approval or any special permission.

The Declaration of Research and Publication Ethics

The authors of the paper declare that they comply with the scientific, ethical and quotation rules of SAUJS in all processes of the paper and that they do not make any falsification on the data collected. In addition, they declare that Sakarya University Journal of Science and its editorial board have no responsibility for any ethical violations that may be encountered, and that this study has not been evaluated in any academic publication environment other than Sakarya University Journal of Science.

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