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The Experimental Design of Thermoelectric Generator for Industrial Waste Heat Recovery

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Abstract – A new method for the design of Thermo-Electric Generators (TEG) used for recovery of industrial waste heat is discussed in this article. Whilst TEGs now operate autonomously using waste heat and generate power, they can be used to generate hot water, additionally. A hybrid TEG was designed and measurements were made in the laboratory environment. Established with 12 pieces of TEG1-12610-4.3 thermoelectric modules in the design, 26.6 W of power was obtained within a temperature difference of 119.4 °C. The system was provided with the ability to cool itself with the energy it produced without applying any external force. In this case, the water temperature in the reservoir rose from 14 °C to 69 °C whilst 14 W of power was being obtained at the temperature difference of 109 °C. Thus, hybrid-TEGs were noted being the significant alternative for the recovery of waste heat and their necessity were seen in terms of the energy efficiency, as well.

Keywords - *Thermoelectric Generators; Power Generators; Waste Heat Recovery; Renewable Energy.*

1. Introduction

Energy demand, in parallel with the rapid increasing world population and industrialization, cannot be met with limited conventional energy sources that decreasing every day. On the other hand, fossil fuels that meet most of the energy demand are one of the major reasons of environmental pollution today. As a result of industrial activities, 20 billion tons of carbon dioxide, 100 million tons of sulphur components, 2 million tons of lead and other toxic chemical components are released into the atmosphere every year. As

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is known, only one third (1/3) of primary energy resources consumed by people are effectively used, and 2/3 of it are released into atmosphere as waste. Nuclear, thermal, natural gas and steam tribunes and electricity production facilities, industrial production facilities and, all diesel and gasoline-powered vehicles such as automobiles can be given as example. Fuel that cannot be used effectively in the aforementioned facilities released as heat. Often it is released through flue gas. With Waste Heat Recovery (WHR) systems, it is possible to produce electric energy by using hot gases released into the atmosphere. For this reason, waste heat recovery technology is one of the best ways to use fuels more effectively. Thermoelectric (TE) is a technology that can reduce greenhouse gas emissions by generating electricity directly from waste heat sources. Thermoelectric generators (TEGs) can convert heat energy into electrical energy based on the Seebeck effect without using any intermediate elements [1-3].

Thermoelectric Generators (TEG), as an input source, uses waste heat and therefore is environmentally friendly in electricity generation and allows efficient use of energy [4]. Electricity generation from TEGs is based on Seebeck effect. The higher the temperature difference between the TEG surfaces, the more electric energy production increases. Because this temperature difference varies with the source used, they require voltage regulation to obtain a constant voltage [5]. Among the disadvantages of TEGs are; when compared with other renewable energy technologies, the quality factor of the semiconductors used in the TEGs is small and the consequent efficiency of the conversion is less than 10% [6]. Until recent years, while TE applications were limited due to the zT values of the semiconductors used in the production of TEMs being less than 1, reports on the approximation of zTs from 1 to 2 have been published as from the early 1990s. Accordingly, TEM applications have increased rapidly and have been also understood to increase [7]. However, besides this disadvantage, it can be seen that the efficiency of these conversion systems can be overlooked when it is considered that the heat source used in TE power generation systems is renewable, such as waste, geothermal and solar energy heat [8]. Although TEG efficiency is low, the renewability of the energy input source increases the economics of these systems as the applications have shown. In recent years, work on electrical energy production with TEGs has focused on the recovery of waste heat released from industrial plants, geothermal fields, automobile engines, integrated circuits, computers and the human body [9].

Waste heat recovery with the TE method varies depending on the material characteristics and temperature flow. Heating and cooling are required in order to create the temperature difference between the surfaces. In applications where waste heat is used, since the heat source is continuous, heat concentrators are not necessary but heat dissipation in the cold surface gains importance. In the literature, passive-cooling methods such as finned aluminium heat exchangers and active-cooling methods such as fan, refrigerant and heat pipe are used [10-13]. In this study, water-cooling method was used for cold surface heat rejection while using the waste heat. In addition to the production of electric power, a hybrid generator was designed by producing hot water utilizing heat conduction between hot and cold surfaces.

2. Thermoelectric Generators

2.1. Physical Principles

In a circuit formed by connecting the ends of different metals, if one of the interconnection points of the conductors is heated, a heat flow from the heated end to the cold surface occurs. Due to thermo-diffusion, electrons move in conductors. This movement is caused by the potential difference between interconnection points of the conductors and it brings voltage to the measurable value in proportion to the temperature difference. This effect is known as the Seebeck effect. Depending on the temperature the metals shows the vibration effect. For this reason, through vibration, resistance of the metals exposed to heat increases. The Seebeck effect is more effective on semiconductors; because the resistance of the semiconducting materials decreases with temperature and allows more electron movement. Semiconductors with different characteristics of electron movement can be made continuous by electrical series connection.

If a DC current is applied as so a current flows through the conductors, while the heat is absorbed by the joule heat in the conductors at one of the interconnection point, the heat is stored at the other. This heat, which is different from the Joule heat, is called Peltier heat. This effect, known as the Peltier effect, is directly proportional to the magnitude of applied current and varies with the directional change of applied current. Another effect that can be mentioned with the Joule heat is the Thomson effect, albeit very small. Thomson heat is directly proportional to temperature difference and current [14-15].

To obtain efficient power cycling using thermoelectric materials, materials must have very high Seebeck Coefficient (α), high thermal conductivity (λ) and low electrical conductivity(ρ). The open-circuit voltage induced on the TE materials is directly proportional to the temperature difference and the Seebeck coefficient. Seebeck coefficient is the most effective parameter in terms of power cycle efficiency. Low internal resistance of the material reduces the losses and it must have a low coefficient of thermal conductivity to reduce the thermal losses [16].

These three conditions are combined into an equation called figure-of-merit or zT:

$$zT = \frac{\alpha^2}{\lambda.\rho} T \tag{1}$$

Semiconductors are used widely among thermoelectric materials, since they have the best temperature sensitivity. The temperature behaviours of negative (n) and positive (p) type semiconductors are shown in Figure 1. The main difference between n and p type semiconductors is that p type semiconductors have a positive Seebeck coefficient due to the holes while n type semiconductors have negative Seebeck coefficient. Semiconductor materials show different characteristics depending on the temperature and it is very important to choose appropriate materials depending on the usage temperature.

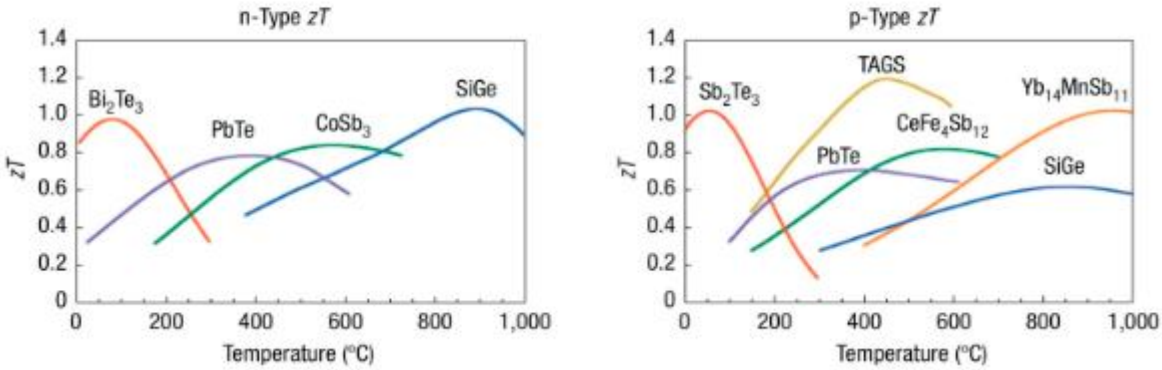

Fig. 1. ZT graphs based on temperature [17].

2.2. Thermoelectric Modules

At the base of the thermoelectric modules (TEM) are the thermo-elements formed by n and p type semiconductors connected in series electrically and in parallel thermally. The thermo-elements are packed in the same way between the two ceramic plates, as in series electrically and in parallel thermally. In Figure 2 the packet, whose basic structure is given, is named TEM. Ceramic plates in the packaging of TEMs; has become the industry standard because it provides the best fit between mechanical stress, electrical resistance and thermal conductivity. The outer surfaces of the ceramic are used as the thermal interface between the external world and TEM.

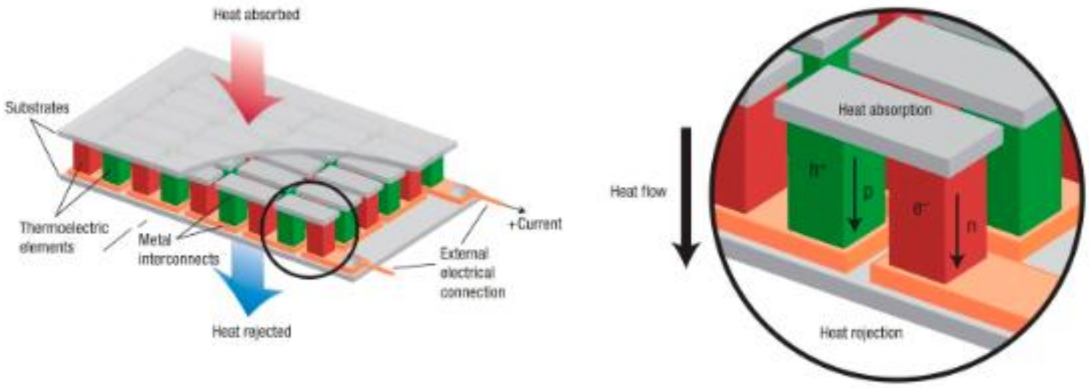

Fig. 2. Thermoelectric module structure [17].

2.3. Use of Thermoelectric Modules as Generator

Figure 3 shows the circuit in which TEM is used in TEG mode. A TEG system basically consists of three parts;

• Heat-absorbed surface

• Heat rejected surface

• TEM

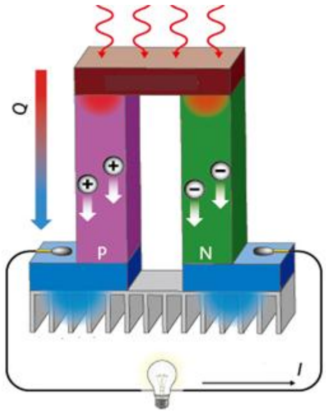

Fig. 3. Use of TEM as generator

When a temperature difference is created between the surfaces of the TEM, the heat will be transferred from the hot surface to the cold surface in accordance with the 2nd law of Thermodynamics, thereby; the electrons will move on the p-type semiconductors in the opposite direction of the holes and reach the n-type semiconductors on the upper conductor. The electrons will continue to move over the n type semiconductors, pass over the load and will complete the circuit. This electron movement will bring a voltage onto the load. The power or I current obtained from TEG depends on the temperature difference ΔT, the characteristics of semiconductor materials (zT) and external load resistance (RL) values. The movement of the electrical load carriers along TE semiconductors produces electric energy, depending on the heat transfer.

In thermoelectric generators, the efficiency (η) is calculated as the ratio of the output power (P), which is obtained electrically, to the thermal input power (Q).

$$\eta = \frac{P}{Q} = \frac{T_H - T_C}{T_H} \cdot \frac{\sqrt{1+zT}-1}{\sqrt{1+zT}+\frac{T_C}{T_H}} \tag{2}$$

Here, TH represents the hot surface temperature, T_C the cold surface temperature and zT the figure-of-merit [18-19].

The highest point of TEG generated tension is when its terminals are open. The open circuit voltage V_{OC} is expressed as follows:

$$V_{OC} = N(\alpha_p - \alpha_n)(T_H - T_C) \tag{3}$$

TEG open-circuit voltage is directly in proportional to the number of thermocouples N, the temperature difference ΔT between the hot-side temperature T_H and the cold-side temperature T_C of the TEG, and the Seebeck constants αp and αn of the used p-type and n-type semiconductor materials, respectively [20].

The power P_L generated on a load R_L connected to a single thermo-element is expressed as follows:

$$P_L = I_L V_L = I_L[\alpha\Delta T - I_L R_{in}] = \alpha^2 \Delta T^2 \frac{R_L}{(R_{in} + R_L)^2} \tag{4}$$

Here; P_L represents the output power of TEG over the load, I_L electric current of that TEG transfers the load over, and V_L the voltage that the TEG generates on the connected load [21]. When the load resistance R_L is equal to internal load resistance R_{in} of the TEG, the maximum power transfer that produced by TEG maximum output power occurs and the maximum power P_{Lmax} value is expressed as follows:

$$P_{Lmax} = \frac{\alpha^2 \Delta T^2}{4R_{in}} \tag{5}$$

When the TEG terminals are open circuit, the maximum voltage V_{OC} is obtained from TEG and the maximum current I_{SC} is obtained when it's short-circuited. The power obtained from the TEG, P_L, varies depending on the value of the connected load [22].

A TEG can be modelled as a V_{OC} voltage source, having a TEG internal resistance R_{in} that can be obtained by dividing the open circuit voltage V_{OC} to the short circuit current I_{SC} (V_{OC} / I_{SC}). Here, the open-circuit voltage V_{OC} is the open circuit voltage proportional to the temperature difference ΔT and the Seebeck constant α. The TEG short circuit current I_{SC} is the current of the TEG with shorted ΔT terminals at a certain temperature difference. The equivalent electrical circuit associated with the use of TEM as TEG is given in Figure 4. The amount of power obtained from TEG varies depending on the R_L value of the load resistance [22].

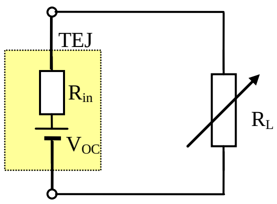

Fig. 4. TEG equivalent electric circuit

3. TEG Design and Experimental Setup

3.1. TEG Design

In TEG design, imported modules with TEG1-12610-4.3 code were used. The modules used can withstand a temperature of 300 °C and have an open circuit voltage of 10.7 V at a temperature difference of 270 °C. 12 modules connected in serial electrically and in parallel thermally. The modules were placed on an aluminium plate that water passing through using thermal paste as shown in Figure 5. The optimal water flow rate of this plate is 1.8 l / min. A black plate with a thermal conductivity of 142 W / m-K was used as the hot surface plate. The black plate and the modules were mounted applying thermal paste between them. At the time of mounting, 0.1 mm thick copper plates were cut and K type thermocouples were connected to their ends and 2 thermocouples were placed as one on the hot surface and one cold surface. The designed TEG is shown in figure 6.

Fig. 5. Mounting the modules on the cooler block

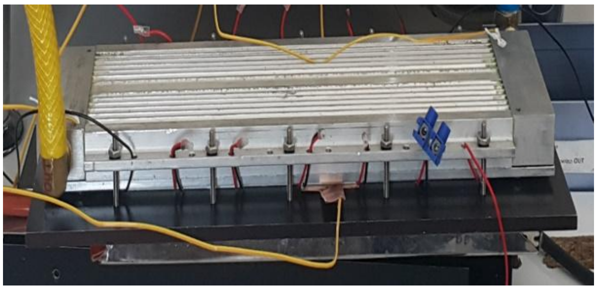

Fig. 6. TEG Structure

3.2. Experimental Setup

In order to carry out the performance tests of the designed TEG, the experimental setup shown in Figure 7 was established in the laboratory environment.

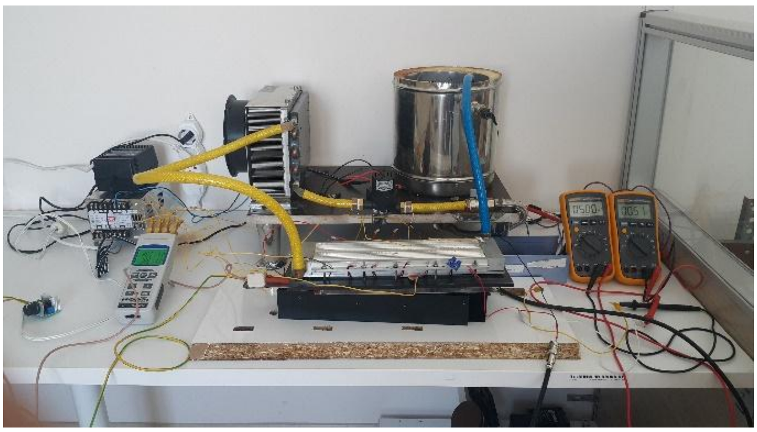

Fig. 7. Experimental setup

The system contains a 5 l water tank. The water tank used for cooling purposes also includes one drain cock connected to the mains water at the same time. The drain cock was used to simulate the use of hot water. Any time through using the drain cock the amount of water is fixed at 5 l by reinforcing it with mains water when heated water is used. The water temperature was measured using a separate thermocouple. The circulating water in the system was circulated using a DC circulation pump, which can operate between 6-24 volts. The output was fixed at 14.2 V by placing a DC-DC converter at the output of TEG. TEG hot surface temperature, cold surface temperature, cooling water temperature, TEG outlet current and voltages were measured and recorded. The TM-946 4-channel digital thermometer was used for the K type thermocouple measurement while FLUKE branded multimeters were used to measure current and the voltage. The DC circulation pump used in the system was connected to an external power supply and an electric heater was used to heat the hot surface.

4. Findings and Discussion

For the experiments in the laboratory environment, the setup in the previous section was carried out using the aforementioned test setup. The performance test was carried out in two stages, loaded and unloaded. In the first stage unloaded test were carried out, and the T_H, T_C temperatures and V_{OC} open circuit voltages of designed TEG were measured and recorded. The ΔT-V_{OC} graph obtained by calculating the ΔT temperature difference as shown in FIG 8. During this test, the water used for cooling was measured as 2.48 litres per minute. Measurements were taken at 23 °C ambient temperature.

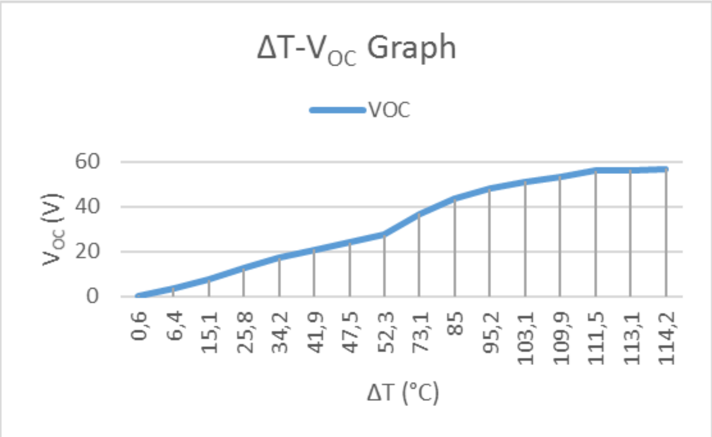

Fig. 8. ΔT-V_{OC} graph

As seen in the graph, the maximum temperature difference in the present system was calculated as 114.2 °C, and the measured voltage V_{OC} at the TEG terminals at this temperature difference is 57 volts. Since 12 modules are connected in series electrically, the voltage per module is calculated as 57/12 = 4.75 volts. As can be seen from Table 4.1, the temperature difference of 114.2 °C was obtained at T_H = 168 °C. In the studies on testing the dynamic operating parameters of the modules, one of the modules has an internal resistance of 4.75 Ω at 168 °C. In this case, a TEG parameter with a total internal resistance of 4.75 * 12 = 57 Ω is obtained. When the system is stable, the potentiometer of

100 Ω is set to 57 Ω and connected to the TEG output. In this case, the current and voltage values were measured as V_L = 35 V and I_L = 0.76 A, assuming maximum power transferred to the load. The power rating was calculated as P = 35 * 0.76 = 26.6 W. The water temperature of the reservoir was measured at 57 °C. In addition to 26.6 W of power generation, hot water was also obtained.

In order to test whether the system is operating autonomously, a DC circulation pump is connected to the converter output and the system was started to heat up. In addition, the voltage at the output of the converter was measured. The converter started to output 14.15 V after 4 minutes of system operation. From this moment the pump operated. When the temperature difference is 13.2 °C, the circulation pump starts working with its own produced energy. The findings are as shown in figure 9. When the temperature difference was obtained as 109 °C, the water temperature of the reservoir was measured as 69 °C. As a dry battery of 12 V was supplied for charging the system, 0,99 A current was measured at a 14.15 V of voltage and 14 W of power was transferred.

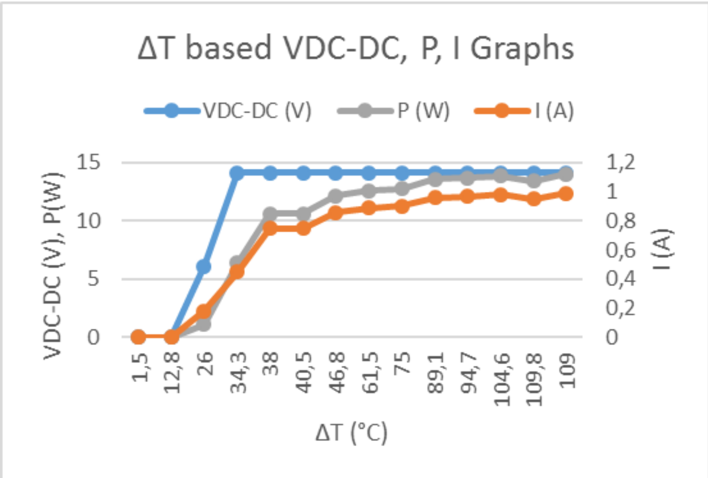

Fig. 9. ΔT based $V_{DC\text{-}DC}$ and I and P graphs

5. Conclusions

The designed TEG system worked autonomously. 14 W power was obtained as the temperature difference reached to 109 °C, and at the same time, the power to run the circulation pump was produced. The system has been seen to be the ideal method for obtaining hot water. 69 °C of water was obtained. Since the T_C temperature automatically dropped as the mains water is added to the system while using the hot water, water started to be reheated while more power is obtained from TEG. It has been shown that it is possible to design a system that can make self-circulation by using waste heat, which can obtain hot water for use at this time and also produce electric energy at the same time. The electrical energy produced was tested using LED luminaires and used for lighting purposes. It is an important technology in terms of energy efficiency.

References

[1] Thermoelectric nanomaterials materials design and applications. Vol. 182.2013: Springer Series in Materials Science.

[2] Hamid Elsheikh M, Shnawah DA, Sabri MFM, Said SM, Haji Hassan M, Ali Bashir MB, Mohamad M. A review on thermoelectric renewable energy: principle parameters that affect their performance. Renew Sustain Energy Rev 2014;30:337–55.

[3] Zheng XF, Liu CX, Yan YY, Wang Q. A review of thermoelectrics research – Recent developments and potentials for sustainable and renewable energy applications. Renew Sustain Energy Rev 2014;32:486–503.

[4] Dai, D., Zhou, Y. ve Liu, J., "Liquid metal based thermoelectric generation system for waste heat recovery", Renewable Energy, 36(12): 3530–3636 (2011).

[5] Nagayoshi, H., Tokimusu, K. ve Kajikawa, T., "Evaluation of multi MPPT thermoelectric generator system", 26th International Conference on Thermoelectrics, Jeju, 318–321 (2007).

[6] Karabetoğlu, S., Şişman, A., Öztürk, Z. F. ve Sahin, T., "Characterization of a thermoelectric generator at low temperatures", Energy Conversion and Management, 62(1): 47–50 (2012).

[7] Zhao, L. D., Zhang, B. P., Li, J. F., Zhou, M., Liu, W. S. ve Liu, J., "Thermoelectric and mechanical properties of nano–SiC–dispersed Bi2Te3 fabricated by mechanical alloying and spark plasma sintering", Journal of Alloys and Compounds, 455(1–2): 259–264 (2008).

[8] Xi, H., Luo, L. ve Fraisse, G., "Development and applications of solar–based thermoelectric technologies", Renewable and Sustainable Energy Reviews, 11(5): 923–936 (2007).

[9] Riffat, S. B. ve Ma, X., "Thermoelectrics: A review of present and potential applications", Applied Thermal Engineering, 23(8): 913–935 (2003).

[10] Date Ashwin, Date Abhijit, Dixon Chris, Singh Randeep, Akbarzadeh Aliakbar.

[11] Theoretical and experimental estimation of limiting input heat flux forthermoelectric power generators with passive cooling. Sol Energy 2015; 111:201–17. ISSN 0038-092X

[12] Djafar Z, Putra N, Koestoer RA. The utilization of heat pipe on cold surface of thermoelectric with low-temperature waste heat. Appl. Mech. Mater. 2013; 302:410–5.

[13] Liu Changwei, Chen Pingyun, Li Kewen. A 500 W low-temperature thermoelectric generator: design and experimental study. Int. J. Hydrogen Energy 2014;39(28):15497–505. ISSN 0360-3199

[14] Remeli Muhammad Fairuz, Tan Lippong, Date Abhijit, Singh Baljit, Akbarzadeh Aliakbar. Simultaneous power generation and heat recovery using a heat pipe assisted thermoelectric generator system. Energy Convers. Manage. 2015; 91:110–9. ISSN 0196-8904

[15] Goldsmid, J. Introduction to Thermoelectricity; Springer: Heidelberg, Germany, 2010.

[16] Rowe, D.M. Handbook of Thermoelectrics; CRC Press: Boca Raton, FL, USA, 1995.

[17] He, W.; Zhang, G.; Zhang, X.; Ji, J.; Li, G.; Zhao, X. Recent development and application of thermoelectric generator and cooler. Appl. Energy 2015, 143, 1–25.

[18] Snyder, G.J.; Toberer, E.S. Comply thermoelectric materials. Nat. Mater. 2008, 7, 105–114.

[19] Ahıska, R., Mamur, H. ve Uliş, M., 2011. Modeling and experimental study of thermoelectric module as generator, Journal of The Faculty of Engineering and Architecture of Gazi University, (26(4): 889–896).

[20] Bierschenk, J., 2008. Optimized thermoelectric for energy harvesting applications, 17th International Symposium on the Applications of Ferroelectrics ISAF 2008, (1–4), Santa Re.
[21] Ferrari, M., Ferrari, V., Guizzetti, M., Marioli, D. ve Taroni, A., 2007. Characterization of thermoelectric modules for powering autonomous sensors, Instrumentation and Measurement Technology Conference, (1–3), Warsaw.
[22] Champier, D., Bedecarrats, J. P., Rivaletto, M. ve Strub, F., “Thermoelectric power generation from biomass cook stoves”, Energy, 35(2): 935–942 (2010).