Devise of Thermoelectric Generator Incorporated of a Heat Exchanger for Power Generation and Heat Recovery

Kanokorn Chooplod and Paisan Kittisupakorn
Intelligence Control Automation of Process System (iCAPS) Research Unit
Department of Chemical Engineering
Faculty of Engineering, Chulalongkorn University, 254 Phayathai Road, Bangkok, 10330 Thailand
Email: Kanokorn.C@student.chula.ac.th, Paisan.K@chula.ac.th

***Abstract*—Thermoelectric generators are considered as direct energy conversions between thermal and electrical energy. There are many applications in thermoelectric generators for energy harvesting and heat dissipation. Bismuth Telluride (Bi_2Te_3) is chosen as thermoelectric material because it is conveniently used in low quality waste heat. This paper aims to devise and set up a high efficiency heat exchanger for gas to gas application which mimics general waste heat with an additional function of partially converting thermal energy into electrical energy. This heat exchanger has a potential to reduce heat loss in the form of flue gas typically released to the environment. Some of the thermal energy that transfers through this unit is directly converted into electrical energy by using integrated thermoelectric generators (TEGs). An equipment in the form of countercurrent heat exchanger equipped with integrated TEGs is installed and tested. The results show temperature dependent thermoelectric properties from an open circuit experiment. They show power output in several cases of TEG connection patterns from a closed circuit experiment. The best power output of this system is 1,752 mW. The most thermoelectric efficiency is 0.16%. The best value of the maximum thermoelectric efficiency is 0.65%. The maximum heat recovery of the system is 23.35%.**

***Index Terms*—heat exchanger, power generation, devise of experiment testbed, heat recovery**

I. Introduction

One of the fundamental problems of electricity generation is a method to convert thermal energy into mechanical energy and then into electrical energy which hinders the overall efficiency of converting thermal energy into electrical energy [1]. If thermal energy can be converted directly into electrical energy, an energy loss in the form of friction will be eliminated. Hence, several projects have emerged to explore this concept. The development of an equipment in this paper is also based on the similar concept by focusing on the thermal design with integrated thermoelectric generators (TEGs).

TEG is a clean solid-state device made from electronic materials such as conductors and semiconductors. TEG structure contains pairs of electronic materials with different work functions connected electrically in series and thermally in parallel. Thermoelectric phenomena occur in solid phase. It is the combination of three theories which are Seebeck, Peltier, and Thomson effects [3]. When there is a temperature difference at two tips of the materials, heat will flow from a hot side to a cold side. As a result, kinetic energy of electric carriers will enhance. Electric carriers such as electrons and holes will move from the hot side to accumulate at the cold side according to potential law. Voltage, current and electric field will be generated from electric carrier movements respectively. Stimulated electrons will move in gradient resulting in the power output [4].

Common thermoelectric materials are alloys of chalcogenides. Chalcogen materials or IUPAC group 16 anion are sulfides, selenides, tellurides, and polonides. These materials are either based on bismuth telluride (Bi_2Te_3) or lead telluride (PbTe). Bi_2Te_3 can be alloyed with Bi_2Se_3 and with Sb_2Te_3 to form n-type $Bi_2Te_{3-x}Se_x$ and p-type $Bi_xSb_{2-x}Te_3$ respectively. Bi_2Te_3 and its alloys, extrinsic semiconductor, are widely used as materials for thermoelectric refrigeration. They are suitable for moderate heat source and accepted by most power generation projects even though mechanical properties are weak during thermal exploitation from varied temperature gradients. Low efficiency at high temperature of Bi_2Te_3 is caused by the chemical decomposition due to the vaporization of tellurium [3,4].

A plate-fin heat exchanger is normally used in many industries due to its high efficiency and compact structures. There are numerous studies about gas-gas application in order to investigate the heat transfer effect [5].

The paper is organized as follows. Next section presents the devise of experiment testbed, followed by analysis in Section 3. Section 4 presents the results and discussion. Summary of the main outputs is given in Section 5.

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II. Devise of Experiment Testbed

A. Equipment

Thermoelectric modules model SP1848-27145 were chosen for this research. The thermoelectric material was Bismuth Telluride (Bi_2Te_3). This category of thermoelectric module has been commercially used as a standard thermoelectric generator due to many reasons such as high Seebeck coefficients and normal operational ranges of temperature. The thermoelectric modules model SP1848-27145 had 128 couples of TEG cells. There were 256 cells in 1 module. Dimensions of 1 cell were 1mm in width, 1mm in length, and 1 mm in height. Electrode dimensions were 1 mm in width and 3.5 mm in length. The heat transfer area of one module was 1,600 mm^2. The thickness of the module was 3.5 mm. Ten pieces of thermoelectric modules were assembled in this system. Computer heat sinks, model LD963 XigmatekPraeton, were selected as additional heat transfer area. Each sink consisted of 1,350 cm^2 of aluminum fin surface area and 3 legs of 6-mm diameter copper pipes. Twenty pieces of computer heat sinks were assembled in this system. Ten pieces of computer heat sinks were installed in a hot stream pipe and ten pieces of computer heat sinks were installed in a cold stream pipe. Thermal grease, model Alseye S420, was opted to attach thermoelectric modules with some parts of heat exchanger. The thermal conductivity of the thermal grease was higher than 1.63 W/mK. An electric blower conveying constant air velocity of 10 m/s was chosen to create the circulation of working fluid in the system. An electric heater generated thermal energy to the working fluid.

B. Measurement and Instrumentations

Thermocouples type K were used to measure cold and hot stream temperatures at 20 positions which were 10 positions of cold stream and 10 positions of hot stream in order to get temperature difference of each thermoelectric module. One unit of RKC temperature monitor and control were applied with the thermocouple in order to control electric heater. A temperature display with datalogger model Khoat paperless recorder was adopted with thermocouples so as to collect temperature data. A multimeter with datalogger model Fluke289 was applied to measure and collect electrical data. A digital anemometer model smart sensor AS816 was chosen to measure air velocity.

C. Assembly

A heat exchanger was made of stainless steel 304. It consisted of 2 parallel rectangular pipes located in the bottom and top positions which were cold and hot stream pipes, respectively. The thermoelectric modules were installed in between these pipes by the thermal grease. The computer heat sinks were installed inside each rectangular pipe at the position of located thermoelectric modules in order to enhance heat exchanger area. The cylindrical shape of stainless steel 304 was placed at one end of the two pipes. The electric heater was installed inside this part as the heat source of the system. The blower was installed at the entrance of the bottom rectangular pipe to create cold stream working fluid to the system.

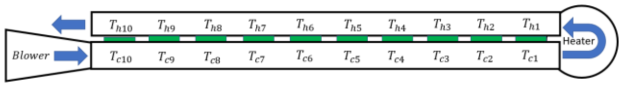

Figure 1. Schematic representation of heat exchanger device

Figure 2. Fabricated heat exchanger device

Figure 3. Cross sectional representation of heat exchanger device

III. Analysis

A. Thermoelectric Analysis

The Seebeck effect (S) is the phenomenon of power generation from thermal energy. If a temperature gradient exists across the thermoelectric junctions, a voltage occurs in the circuit [2,4].

Dimensionless figure-of-merit (ZT) is one of the main features of thermoelectric materials. It expresses the relationship among electrical conductivity (σ), Seebeck coefficient (S), thermal conductivity (κ), and absolute temperature (T) [2,4].

Thermoelectric efficiency (η_{TEG}) shows how much thermal energy can be converted to electricity. The maximum efficiency of thermoelectric module ($\eta_{TEG.max}$) consists of Carnot efficiency and dimensionless figure of merit [2,4].

$$S=\frac{\Delta V}{T_h-T_c} \quad (1)$$

$$ZT=\frac{\sigma S^2 T}{\kappa} \quad (2)$$

$$\eta_{TEG}=\frac{P}{Q} \quad (3)$$

$$\eta_{TEG,max}=\frac{T_h-T_c}{T_h}\cdot\frac{\sqrt{1+ZT_m}-1}{\sqrt{1+ZT_m}+\frac{T_c}{T_h}} \quad (4)$$

where Th is hot temperature, Tc is cold temperature, Tm is mean temperature, V is electric voltage, P is electric power, Q is total quantity of heat.

B. System Analysis

The heat exchanger was designed as a counter-current flow in order to enhance the log mean temperature difference. The efficiency of this system can be calculated as Eq 5-8 [6].

$$\eta_{hx}=\frac{\dot{m}C_p(T_{co}-T_{ci})}{\dot{m}C_p(T_{hi}-T_{ho})}\times 100 \quad (5)$$

$$\eta_{elec}=\frac{IV}{\dot{m}C_p(T_{hi}-T_{ho})}\times 100 \quad (6)$$

$$\eta_{sys}=\frac{\dot{m}C_p(T_{co}-T_{ci})+IV}{\dot{m}C_p(T_{hi}-T_{ho})}\times 100 \quad (7)$$

$$\eta_{sys}=\eta_{hx}+\eta_{elec} \quad (8)$$

where $\dot{m}$ is mass flow rate, C_p is specific heat capacity, T_{ci} is temperature of cold stream inlet, T_{co} is temperature of cold stream outlet, T_{hi} is temperature of hot stream inlet, T_{ho} is temperature of hot stream outlet, I is electric current, V is electric voltage, η_{hx} is heat exchanger efficiency, η_{elec} is exact electrical efficiency, η_{sys} is system efficiency.

IV. Results and Discussion

A. Open Circuit Condition

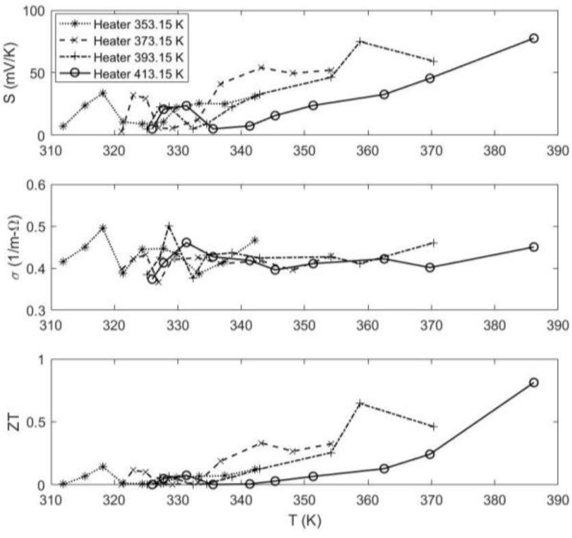

Figure 4. Temperature dependent variables of Bi2Te3 material

Open circuit results show temperature dependent thermoelectric properties for various heater temperatures. All the properties are retrieved from an experiment except for thermal conductivity. The thermal conductivity of Bi_2Te_3 is considered as 1.2 W/mK due to the range of operating temperature [2].

Seebeck coefficient is positive due to the p-type material. For these reasons, holes play an important role in electrical transport. The highest value of Seebeck coefficient is 77.56 mV/K at 386.15 K.

The electrical conductivity of Bi_2Te_3 tends to enhance when the temperature increases. The results state that Bi_2Te_3 has general semiconductor behavior. In semiconductor, the mobility of electrons and holes is affected by lattice scattering and impurity scattering. At high temperature carriers move faster, which decreases impurity scattering.

The dimensionless figure-of-merit (ZT) expresses the suitable range of operational temperature. The best value of ZT is 0.81 at 386.15 K.

B. Closed Circuit Condition

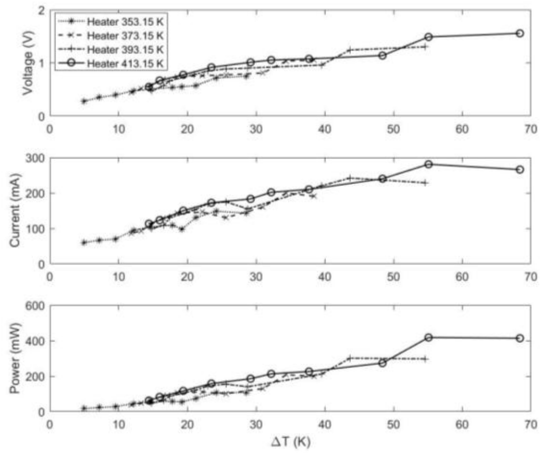

Figure 5. Electrical output from individual TEG

Electrical output is studied as a closed circuit condition by using 1Ω of an external resistor. Closed circuit results show the greater temperature difference becomes, the higher power output achieves. Electrons get excited because they receive enough thermal energy to jump from the valance band to the conduction band.

The maximum electrical output of individual TEG generates from 413.15 K of heater temperature at 68.4 K of the temperature difference. The highest voltage, current, and power are 1.56 VDC, 265.79 mADC, 413.54 mW, respectively.

The minimum electrical output of individual TEG generates from 353.15 K of heater temperature at 5 K of the temperature difference. The lowest voltage, current, and power are 0.28 VDC, 60.15 mADC, and 16.99 mW, respectively.

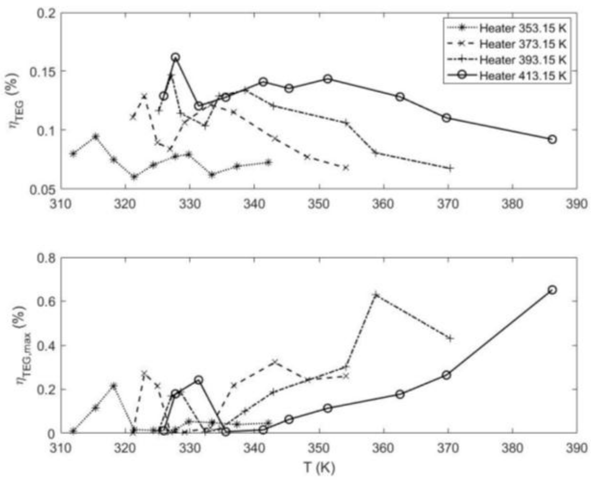

Figure 6. Thermoelectric efficiency of independent TEG

According to fluid characteristics, the Reynold's number of air flow over smooth flat plate is 18,324 which states that the air moves in laminar pattern. Therefore, the sheer static fluid is attached to stainless steel surface while the rest of the fluid is flowing in the parabolic pattern. The overall heat transfer coefficient determined by using the summation of thermal resistance is approximately 11.42 W/m^{2}K. The heat transfer area per one TEG unit is 0.43 m^2. The net quantity of heat can be calculated by using these parameters.

Thermoelectric efficiency expresses that there is the highest conversion from the net quantity of heat to electric power by using 413.15 K of heater temperature. The best thermoelectric efficiency is 0.16% at 327.75 K.

The maximum thermoelectric efficiency is a function of ZT and Carnot efficiency. Its best value is 0.65% at 386.15 K of temperature difference.

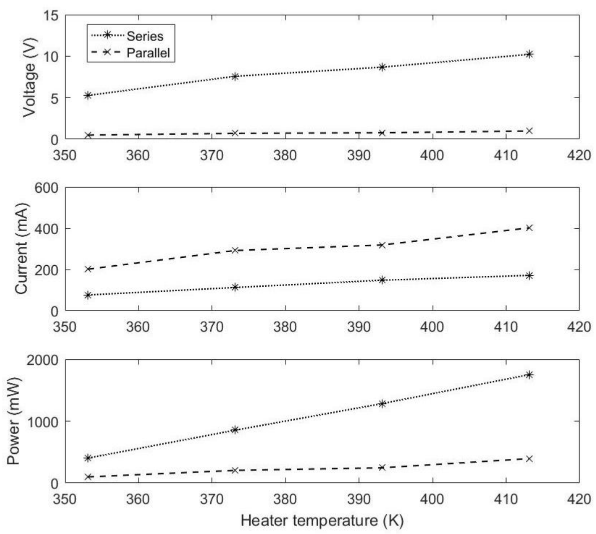

Figure 7. Electrical output from connected TEGs

From connected TEGs experiment, the series connection provides more power output than the parallel one because electric voltage influences power rather than current.

In case of series connection, voltage, current, and power are 10.22 VDC, 171.46 mADC, and 1,752 mW respectively at 413.15 K of heater temperature.

In case of parallel connection, voltage, current, and power are 0.98 VDC, 401.90 mADC, and 394 mW respectively at 413.15 K of heater temperature.

C. Heat Recovery Condition

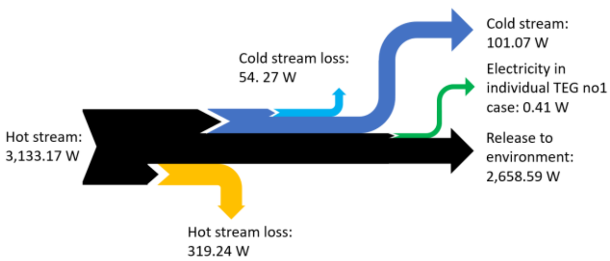

Figure 8. Sankey diagram of individual TEG no1 case

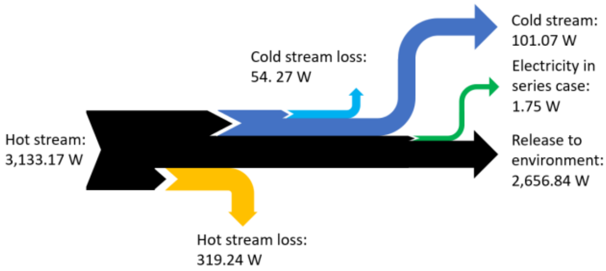

Figure 9. Sankey diagram of series case

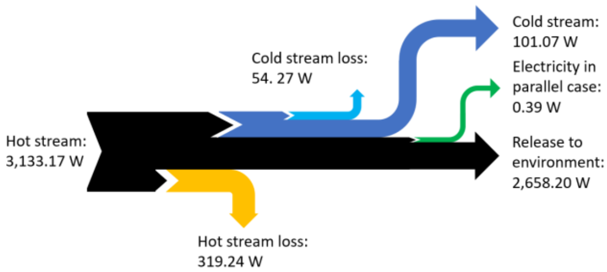

Figure 10. Sankey diagram of parallel case

Sankey diagrams explain how much energy from the hot stream allocates to various parts. Fig. 8-10 are Sankey diagrams at 413.15 K of heater temperature because it is the best condition to generate the most power output in each case. Thermal energy from hot stream (3,133.17 W) loses to environment through exposed surface of stainless steel (319.24 W). The remaining energy from hot stream transfer to cold stream (101.07 W). Thermal energy from cold stream loses to environment through exposed surface of stainless steel (54.27 W). Curtain amount of thermal energy is converted to electrical energy. Waste heat from this system is ventilated along the air to environment.

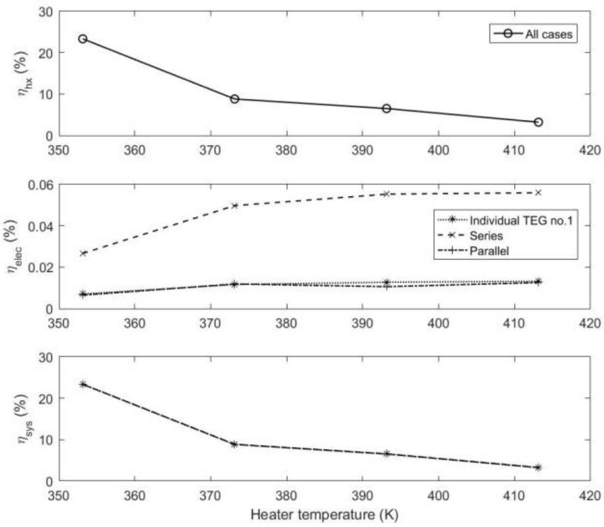

Figure 11. System efficiency

The maximum heat exchanger efficiency is 23.33% at 353.15 K of heater temperature for all cases and the maximum exact electrical efficiency is 0.056% at 413.15 K of heater temperature for the series case. Heat recovery of this device can be considered from the system efficiency. The maximum system efficiency is 23.35%, which occurs in series case at 353.15 K of heater temperature.

V. Summary

Thermoelectric generators with Bi_2Te_3 material are installed in the heat exchanger device in order to enhance the performance of the system. Thermoelectric properties of Bi_2Te_3 such as Seebeck coefficient, electrical conductivity, and dimensionless figure-of-merit can be retrieved from an open circuit experiment. TEGs generated power outputs from temperature gradients along the distance. Power outputs are measured as a closed circuit. In case of individual TEG, the TEGs nearby heat source generate more power output than the ones that installed in a distant area due to temperature difference. In case of connected TEG, the series connection generated more power output than parallel connection. The thermoelectric efficiency and the maximum thermoelectric efficiency are conducted. Heat recovery of the device can be figured out from Sankey diagrams and the system efficiency.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

KC and PK designed the device and experiment; KC carried out experimental study, collected experimental data, performed the analysis, and wrote the paper; PK conceived of the study, supervised analysis, checked the data and corrected the paper; All authors had approved the final version.

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Kanokorn Chooplod has B.Eng. with First Class Honors from Food Engineering, King Mongkut's Institute of Technology Ladkrabang, Bangkok, Thailand in 2011.

During undergraduate period, she went on international internship program at Chemical Engineering, Tokai University, Japan in 2010. After graduation, she worked at Kasetphand Industry, Samutprakarn, Thailand as a Sales Engineer. Next, she worked at C.P. Intertrade, Bangkok, Thailand as a Mechanical Engineer. Her current position is a Master student, Chemical Engineering, Chulalongkorn university.

Paisan Kittisupakorn has B.Eng. from Chemical Engineering, Chulalongkorn University, Bangkok, Thailand in 1990, M. Eng., Chemical Engineering, Imperial College, London, UK in 1992, and Ph.D., Chemical Engineering, Imperial College, London, UK in 1995. His current position is Professor, Department of Chemical Engineering, Chulalongkorn University. His research interests are neural network based modeling and control for a batch heating/cooling evaporative crystallization process, improvement of palladium ions recovery via hollow fiber supported liquid membrane with model predictive control, and 3D computational fluid dynamics study of a drying process in a can making industry.

Prof. Kittisupakorn has several professional activities such as a project leader of clean technology for food packaging in 2013, clean technology for fruit and vegetable can packaging in 2013, and clean technology communication for minor industries-rubber industry in 2012. His awards and honors are best student paper award of the 2015 IAENG international conference on control and automation, IAENG international association of engineers, the international multi-conference of engineers and computer scientists, 2015, honorable mention for award contest of the 5th science and technology initiative and sustainability, 2012, and 100 innovation ambassador, design and improvement of software and mechatronics, national innovation agency, Thailand, 2009.