COMPARATIVE ASSESSMENT OF AIR-COOLED AND WATER-COOLED THERMOELECTRIC POWER SYSTEM “SIMULATION APPROACH”

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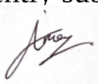
DECLARATION

This work has not previously been accepted in substance for any degree and is not being concurrently submitted in candidature for any degree.



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This thesis is the result of my own investigations, except where otherwise stated.

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LIST OF ABBREVIATIONS

TE	Thermoelectric
LPG	Liquified petroleum gas
CNG	Compressed natural gas
VCO	Vegetable cooking oil
COP	Coefficient of performance
TPV	Thermophotovoltaic
CFD	Computational fluid dynamics
AFR	Air fuel ratio

LIST OF APPENDICES

PENILAIAN PERBANDINGAN ANTARA SISTEM KUASA TERMOELEKTRIK PENYEJUKAN UDARA DAN PENYEJUKAN AIR

ABSTRAK

Populariti dalam sistem penjanaan kuasa berasaskan hidrokarbon telah meningkat secara mendadak dalam beberapa tahun kebelakangan ini merentasi banyak bidang kejuruteraan. Salah satu contoh teknologi yang menawarkan harapan dalam mengurangkan penggunaan berlebihan sumber tenaga konservatif ialah penjana termoelektrik. Walau bagaimanapun, disebabkan cabaran fizikal dalam mengoptimumkan sistem penyejukan, sistem penjana termoelektrik biasanya mengalami tetingkap operasi yang sempit. Kajian ini mensimulasikan sistem kuasa termoelektrik untuk menilai prestasi dan ciri-ciri pembakaran. Sistem penjana termoelektrik telah dibina menggunakan penukar haba yang disejukkan udara dan penyejukan air. Untuk mengoptimumkan sifat terma pembakar dengan lebih baik, percanggahan antara kapasiti haba udara dan air mesti ditangani dengan betul. Kerumitan aliran penukar haba yang disejukkan dengan air boleh menjejaskan kecekapan keseluruhan reka bentuk kerana ia memberikan kecerunan suhu yang lebih besar daripada penukar haba yang disejukkan udara. Dalam kajian ini, kebuk pembakaran, penukar haba sejuk udara dan penukar haba sejuk air telah direka bentuk. Kemudian, simulasi kebuk pembakaran telah disediakan dan dijalankan dengan kadar aliran jisim udara terkawal untuk menyiasat prestasi kebuk pembakaran berdasarkan pembakaran VCO. Keputusan menunjukkan bahawa kebuk pembakaran 1 dengan kadar aliran jisim udara 0.000637kg/s telah dipilih kerana ia mempunyai pelepasan NOx yang lebih rendah dengan 5.44x10-8. Ia juga menghasilkan suhu tinggi di dinding alur keluar dengan suhu 1149.17^{o}C dan mempunyai proses pembakaran yang ideal dengan nisbah kesetaraan 1 yang dianggap sebagai proses pembakaran yang stoikiometrik. Simulasi lain juga disediakan untuk membandingkan prestasi sistem kuasa termoelektrik sejukan udara dan sistem kuasa termoelektrik sejukan air. Keputusan menunjukkan bahawa output kuasa maksimum dijana oleh sistem kuasa TE yang disejukkan air dengan output kuasa 0.628W dengan perbezaan suhu 559.86^{o}C berbanding sistem kuasa TE yang disejukkan udara yang hanya menghasilkan 0.608W pada perbezaan suhu 552.72 ^{o}C. Oleh itu, boleh disimpulkan bahawa sistem kuasa TE yang disejukkan dengan air mempunyai prestasi yang lebih baik berbanding dengan sistem kuasa TE yang disejukkan udara memandangkan sistem kuasa TE yang disejukkan dengan air menggunakan air sebagai penyejuk yang mempunyai kekonduksian terma yang lebih baik yang akan memindahkan dengan cekap haba. Penyelidikan ini akhirnya boleh melihat ke dalam kemungkinan mengoptimumkan kuasa yang dijana.

COMPARATIVE ASSESSMENT OF AIR-COOLED AND WATER-COOLED THERMOELECTRIC POWER SYSTEM

ABSTRACT

The popularity of hydrocarbon-based power generation systems have dramatically increased in the past few years across many engineering fields. One of the examples of the technology that offers hope in reducing the over consumption of conservative energy sources is the thermoelectric generator. However, because of the physical challenge in optimizing the cooling system, the thermoelectric generator systems typically suffer from having a narrow operating window. This study simulated a thermoelectric power system to assess the performance and combustion characteristics. The thermoelectric generator system was constructed using air-cooled and water-cooled heat exchangers. To better optimise the thermal properties of the burner, the discrepancies between the heat capacities of air and water must be properly addressed. The flow complexity of the water-cooled heat exchanger could adversely affect the overall efficiency of the design since it provides a bigger temperature gradient than an air-cooled heat exchanger. In this study, a combustion chamber, an air-cooled heat exchanger, and a water-cooled heat exchanger were designed. Then, the simulation of the combustion chambers was set up and conducted with controlled air mass flow rates to investigate the performance of the combustion chamber based on VCO combustion. The results show that combustion chamber 1 with air mass flow rates of 0.000637kg/s was chosen since it has lower NOx emissions with 5.44x10-8. It also produces a high temperature at the outlet wall with a temperature of 1149.17^{o}C and has an ideal combustion process with an equivalence ratio of 1 that was considered as stoichiometric combustion process. Other simulations were also set up to compare the performance of air-cooled thermoelectric power systems and water-cooled thermoelectric power systems. The results show that the maximum power output was generated by a water-cooled TE power system with 0.628W power output with a temperature difference of 559.86^{o}C compared to an air-cooled TE power system that only generated 0.608W at a temperature difference of 552.72^{o}C. It can thus be concluded that the water-cooled TE power system has a better performance compared to the air-cooled TE power system since the water-cooled TE power system used water as a coolant that has a better

thermal conductivity that will efficiently transfer the heat. This research can eventually look into the possibilities of optimizing the power generated.

CHAPTER 1

INTRODUCTION

1.1 Overview Of Thermoelelectric Power Generation

Thermoelectric (TE) power generation has received a lot of attention as a potential alternative source of energy. Micro combustors, stoves, residential heating systems, and cogeneration have all been widely incorporated as power sources with thermoelectric systems. Salient characteristics of TE devices, such as compactness, noiselessness, robustness, outstanding durability without physical moving parts[1], and low maintenance, have made this power generation device a sought-after system compared with other conventional power generators. By capturing photons of electron mobility in the semiconductor materials of the TE cells, the combustion-driven TE power device converts the temperature difference between a hot and cold junction into electricity. The temperature difference is very important for the TE generator to convert the heat energy into the electrical energy via the Seebeck effect.

One of the most important aspects of the TE generating processes is cooling process at the cold region of the TE device. The cooling method could either be a water-cooled heat exchanger or a air-cooled heat exchanger. The air-cooled and water-cooled heat exchanger absorb the heat dissipated by the TE generator when the TE generates electric power. The difference between the air-cooled and water-cooled heat exchanger is the efficiency to transfer heat from the body to the environment. Therefore, the thermal performance of a heat exchanger must be methodically assessed to fully exploit the potential of a TE generating system. Typically, the hot region is a burner that could be fuelled by gaseous or liquid hydrocarbon fuels. Various commercial gaseous fuels have been studied to evaluate the performance of the TE power generating systems. The majority of research is focused on the use of liquefied petroleum gas (LPG) and compressed natural gas (CNG) in single and dual fuel engines[2]. However, only very few studies have concentrated on the use of bio liquid fuel for the thermoelectric power generation and its development has been generally slow and unexplored. In this research study, the thermoelectric generator will be integrated with waste heat emitted from the porous burner operating on vegetable cooking oil (VCO) as a liquid fuel. VCO is one of the renewable sources of energy. Vegetable oils are easily available and they can be obtained from a wide range of sources. They are non-polluting, locally available, and their molecular structure contains a considerable quantity of oxygen. Then, the combustor and the thermoelectric generators will be incorporated with the air-cooled heat exchanger and water-cooled heat exchanger to determine the performances of both heat exchanger to produces the power output generates from the TE cells.

1.2 Research Background

The lost heat energy or wasted heat from combustion process to the atmosphere can be used to produce electricity with the help of the thermoelectric generators. The thermoelectricity energy sources can reduce production costs but it slowing the technological advancement and conversion efficiency. It might be challenging to locate a reliable supply of heat or power for thermoelectric generators. Alternative energy sources are now being developed by scientists and engineers in an effort to stabilise the global economy and ecology. We can convert the wasted heat energy into electrical energy when we use the thermoelectric energy. The energy generated not only contributes to a greener environment, but has the potential to overtake all other power sources in the world.

The primary driving factor is the temperature difference, which is fundamentally significant in terms of generating electrical power and attaining generate higher efficiency. The heat exchanger is generally incorporated in the system to maintain the required temperature difference. Heat exchanger are used to transfer heat from the TE generator devices to the environment. An air-cooled or water-cooed heat exchanger could be designed and integrated into the thermoelectric system. From the thermal point of view, the efficiency of heat exchangers is extremely vital. Heat exchangers with high efficiencies are great demand these days.

Selecting an appropriate combination of parameter levels for high effectiveness in thermal problems is also a critical challenge. The electric will be generated with the help from the porous combustion chamber that is designed to heat the TE generator. The heterogeneous interaction between two distinct media, usually a solid and a gas, is referred to as porous media combustion, also known as filtration combustion. Filtration combustion is a new type of flame that undergoes exothermic chemical transformations while moving through a porous matrix.

The performance and combustion characteristics of the thermoelectric power system were evaluated at various operating temperatures. This study explored the electrical power output generated by the thermoelectric generator system. The temperature difference will be assessed from the thermoelectric generator system. The emission from the combustion chamber will also be analyzed and the combustion process is based on the vegetable cooking oil (VCO). With a good design of the heat exchanger, this can lead to an efficient thermal output as waste heat can be used to generate an alternative energy in future.

1.3 Problem Statement

TE generator is a solid-state device that directly converts heat flux or temperature difference into the electrical energy via the Seebeck effect. TE system usually suffers from having a limited range in its operating window because of the physical challenge in optimizing the cooling system or maintaining the specific temperature of the system. The system requires relatively constant heat source to generate electrical energy. Since the water-cooled heat exchanger produces greater temperature gradient than does an air-cooled heat exchanger, the flow complexity of the former could significantly and adversely affect the overall efficiency of the design. Substantial differences in the heat capacity of air and water present unique obstacles to better optimize the thermal characteristics of the burner. Therefore, the purpose of this study was to evaluate the performance and combustion characteristics of a thermoelectric power system. A simulation approach will be adopted to analyze the effects of an air-cooled and water-cooled heat exchanger.

1.4 Objectives

The objective of this proposed research work:

1. To design air-cooled and water-cooled heat exchangers for thermoelectric power generation.
2. To evaluate the performance of air-cooled and water-cooled thermoelectric power system.

1.5 Scope Of Research

To achieve the objective of this research, the scope of the work that needs to be done is listed:

1. To design a combustion chamber based on VCO combustion and to design an air-cooled and water-cooled heat exchanger.
2. To simulate the temperature profiles in the combustion chamber and the temperature profile in both an air-cooled and water-cooled heat exchanger.
3. To determine the electrical power output, emission, and the temperature difference of the TE generator.

1.6 Application Of Thermoelectric Generator

Vehicles that use non-renewable energy have become one of the most significant sources of pollution and contributors to energy shortages. Around 30–45% of the fuel energy in such vehicles is released into the atmosphere as heat. The system efficiency of such vehicles would be significantly enhanced if a small part of the massive wasted heat could be recycled and transformed into energy[3]. A TE generator converts temperature difference between semiconductors into electrical power. It is a solid-state heat engine that does not have any moving parts. Compared to a standard heat engine, the TE generator has better reliability, lower maintenance, and longer system lifetime. It also has low noise and negligible environmental impact, as well as the ability to utilize waste heat as an energy source in simple and straight forward methods[4]. As a result, using the TE generator can effectively generate more electrical energy from the waste heat while reducing fossil fuel use.

The researcher used three distinct models based on Effective Medium Theory to analyze the performance of the thermoelectric generator and cooler. These models anticipated the thermal conductivity of the TE generator and calculated the system's thermal efficiency and coefficient of performance (COP)[5]. They discovered that by lowering the thermal conductivity, the thermal efficiency can be boosted by as high as 170%. There was also waste heat recovery research of automobile exhaust applications using TE generator. Other researcher conducted an experiment by installing a heat exchanger after the exhaust pipe of the catalytic converter[6]. The temperature difference of the TE generator was inducted by hot and cold side of the heat exchanger. The design produced 944 W with 1.85% efficiency.

1.7 Water-cooled And Air-cooled Heat Exchanger Application

The previous researcher used a water-cooled heat exchanger design system, with ten TE generator units, two 0.1 mm thick L-shaped copper plates, a butane burner, and two W-shaped cooling blocks[7] (Figure 2.1). Thermal adhesive was used to arrange the TE generator in series and the TE cells were pasted vertically on the surface of the copper plate, as shown in Figure 2.2. Each plate contains five units of the TE generator. The cooling blocks were then mounted to each side of the TE generator. The hot surfaces of the TE generator were attached to the cooper plate, whereas the cold side of the TE generator was coupled to the cooling block. The temperatures on the hot and cold surfaces of the TE generator, the liquid cooling temperatures at both inlets and outlets, the voltage, and the current were all measured. Two thermocouples were used to measure all temperature-related data. At the centre of the five-set TE generator, the hot and cold temperatures were also measured. The temperature at the inlet was also measured inside the water tank, whereas the temperature at the outlet pipe was measured. A multi-meter was used to measure the two electrical output characteristics. All metrics were measured for a total of 220 seconds, mostly up to the point where the heat supply stabilized. From this literature review, it is explained about the experiment setup of the TE generator system for night market explanation. Since temperature is the determining factor for voltage generation, the electrical output characteristics were examined throughout various temperature ranges. At a temperature differential of 35°C, the voltage output stabilises at an average value of 12.7 V. At a temperature differential of 55°C, the current generated takes longer to stabilise and has an average value of 185.8 mA. Since power output is a function of voltage and current and has an average value of 2.4 W, these circumstances have an impact on it. The energy conversion process estimated efficiency ranged from 4.3 percent to 9.2 percent.

Figure 1.1: Aluminium W-shaped water-cooled heat exchanger used in the cooling process by Wahap et al., (2020)

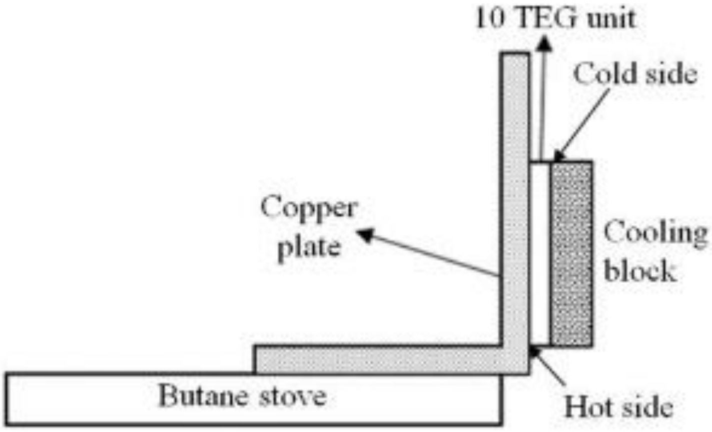

Figure 1.2: Five units of TE generator attached on the copper plate by Wahap et al., (2020)

Another design was presented by other researcher. Figure 2.3 illustrates the two different types of heat exchangers: a tube heat exchanger and a fin heat exchanger [8]. Both types of heat exchanger were attached on the cold side of the TE generator. The fin heat exchanger was smaller than the tube heat exchanger. The flow of water in the heat exchanger was absorbed by the heat generated in the TE generator to produce electricity because of the temperature difference between the hot and cold side of the TE generator. The TE generator was heated by a heater located inside the hot block from the substrate and low temperature was maintained at the TE generator. The temperature difference of the TE generator between the two sides evolved, and electricity was produced. To verify the temperature distributions on the surfaces between the TE generator and both the hot block and heat exchanger, these components were simultaneously assessed in a heat transfer simulation. When the heater is set to

175°C and the cooling water is flowing at a rate of 2.26 L/min, the temperature contours on the cooling water surfaces and the cold side of the TE generator were showed in Figure 2.4. In comparison to the tube exchanger, the fin exchanger is obviously exposed to a lower and more consistent temperature profile.

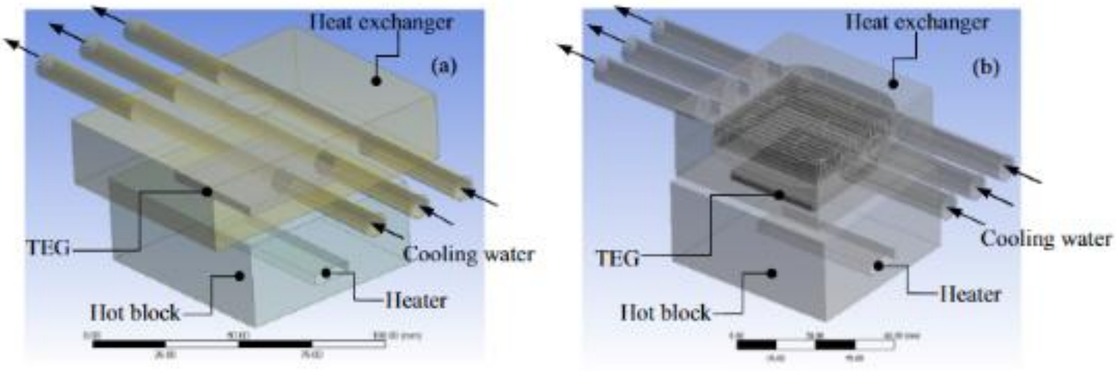

Figure 1.3: (a) Tube exchanger design (b) Finned heat exchanger design.
Li et al., (2016)

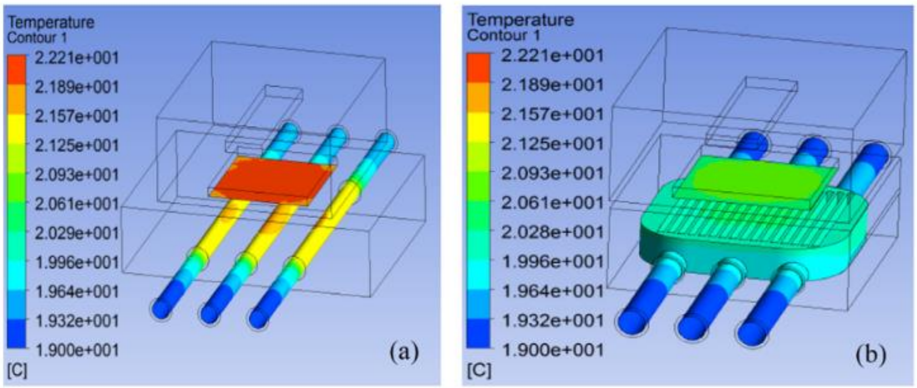

Figure 1.4: Temperature contours on cooling water surfaces and TEG cold side of (a) Tube exchanger design (b) Finned heat exchanger Li et al., (2016)

1.8 Experimental Result Of Thermoelectric Generator System

Cascade thermophotovoltaic (TPV) and TE electric power system experiment were conducted by resercher[9]. This power production system consists of a burner for natural gas, a thermal emitter, an optical filter, TPV cell arrays, a cooling device for the cells, a TE converter, a cooling device for the TE, and an electronic control and data collection unit. High temperature flue gases are produced during the combustion of premixed gas and air in a combustion chamber. The porous SiC emitter is heated to incandescence by the flow of all the flue gases, which emits infrared radiation The chemical energy from fuels is transformed into the radiant energy and sensible heat. The TE converter then transforms the remaining heat into electricity as the combustion products leave the thermal emitter. Based on the experimental results of Qiu & Hayden (2012) the recorded TE converter electric power output against the temperature of the hot side of the inner wall was presented (Figure 2.5). The power output increases exponentially with the hot side temperature or the temperature difference between the cold and hot sides of the TE module. From the results, the electrical power output of the TE generator reached 306.2 W under conditions of a hot side with wall temperature of 496°C and a cold wall temperature of 80°C, with the load voltage and current being 20.5V and 14.9A, respectively.

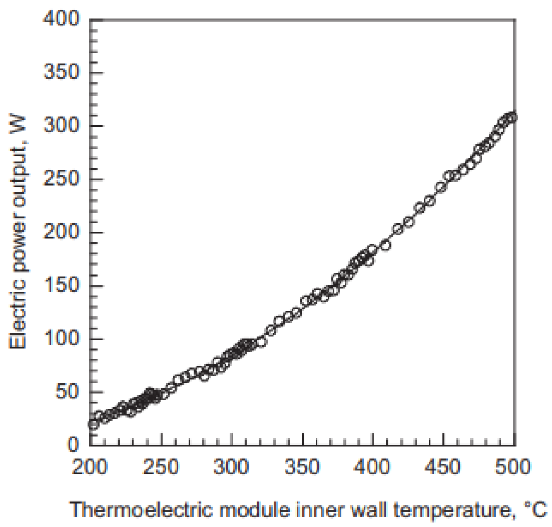

Figure 1.5: Variation of TE power output with converter inner wall temperature by Qiu & Hayden (2012)