THE UTILIZATION OF WASTE HEAT FROM POLYMERIC ELECTROLYTE MEMBRANE FUEL CELLS (PEMFC) USING THERMOELECTRIC GENERATOR (TEG): A REVIEW

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Abstract – An electrochemical reaction in PEMFC produces waste heat as a side product. Using a thermoelectric generator (TEG) device, it can be converted into electricity as harvesting energy. Many researchers have been investigated and developed models to combine both to result in the optimal system. This study aims to explore the technical utilization of waste heat PEMFC using the TEG device and its challenge. The literature review method is used to obtain each information related to the topic. Integrated TEG to PEMFC capable to manage the waste heat and increase the efficiency of PEMFC. Also, the improvement can be reached by applying the cooling system and the arranging correct composition material of TEG.

Keywords: PEMFC, TEG, harvesting energy, temperature gradient, waste heat.

1. INTRODUCTION

Energy harvesting can be described as a process that produces energy from vibrations [1], temperature gradients [2][3], mechanical load [4], etc. As explained in the law of Conservation of Energy that these energies can change from one form to another. The conversion into electrical energy form is as viewed more utilized and favorable since this energy becomes a primary need of humans in modern life [5].

Regarding the fact, many researchers have been focused on the energy harvesting field and it has become a popular topic in recent years. An energy converter is needed to change energy into another form so that it can be more utilized. One of the devices that can be developed is fuel cells which convert chemical energy into electricity through electrochemical reactions [6]. It offers high electrical productivity of around 50% – 60% [7], even the current research state that the efficiency of fuel cells is up to 85 – 90% [8].

The basic part of fuel cell consists of a cathode, an anode, and an electrolyte. The oxidation reaction occurs on the anode side and produces ions. It moves from the anode side to the cathode side through the electrolyte. Simultaneously, electrons flow from the anode side to the cathode side through an external circuit to produce direct current electricity [9].

Nowadays, a fuel cell has been developed with various types such as Polymeric Electrolyte Membrane Fuel Cells (PEMFC), Solid Oxide Fuel Cell (SOFC), Phosphoric Acid Fuel Cell (PAFC), Direct Methanol Fuel Cells (DMFC), Alkaline Fuel Cells (AFC), and Molten Carbonate Fuel Cell (MCFC). Comparing to the other types, PEMFC is the most popular fuel cell technology which over many application [10] fields such as power generation, transportation, warehouse logistics, etc as shown in Fig. 1.

PEMFC has become a favorite device due to many advantages such as low maintenance, no pollution product, high flexibility, and being portable [11]. Unfortunately, PEMFC has drawbacks such as being expensive, having unknown life cycles, hydrogen as fuel limited, and less efficiency if waste heat high exhausted. The latter drawback is usually produced by the reaction process due to the highly exothermic conditions [12]. In addition, the unutilized waste heat can trigger hydrogen to flam and explode when it is placed in a small fuel tank. Hence, this condition needs a specific treatment to minimize the probability of an accident.

In [13] explained that temperature is the main parameter that determines the efficiency of PEMFC performance. This efficiency is affected by waste heat produced during its operation. Fig. 2 shows the comparison of operating temperature between PEMFC and other types. Previously, the method to remove excess waste heat from the stack of fuel cells has been developed to obtain optimal performance. Adsorbing the maximal portion of the waste heat can increase the performance of the fuel cells. Utilizing a thermoelectric generator (TEG) device is one of the methods to realize it simultaneously as an energy harvesting converter.

TEG is a device that converts a temperature gradient into electricity. TEG has two sides with the applied opposite temperature to obtain gradient temperature between them. The phenomenon causes the electron movement within arrange of the thermocouple to generate electrical energy [14].

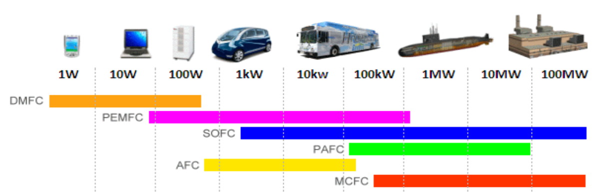

Fig. 1 - Application of fuel cells based on each type

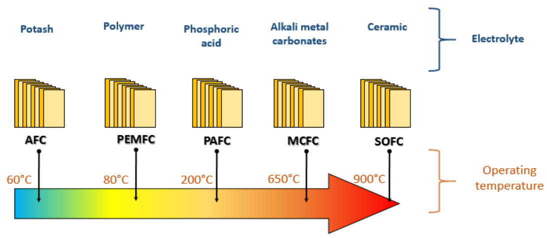

Fig. 2 - The comparison of operating temperature between PEMFC and other types

This manuscript provides a review of energy harvesting from waste heat of PEMFC using a thermoelectric generator (TEG). In section II, the types of fuel cells are discussed. In section III, the principle working of PEMFC systems is explained. Afterward, a thermoelectric generator (TEG) work principle is described in section IV. The technical utilization of waste heat PEMFC and discussion using TEG is explained in section V and VI, respectively.

2. TYPE OF FUEL CELLS

As one of the green energy generators, fuel cells are seen by many researchers as a solution enabling clean efficient production of power. The basic principle of a fuel cell to produce electricity use hydrogen (H_2) or (H_2^-) rich fuels, together with oxygen from air. Nevertheless, it also depends on the type of fuel cell and the fuel used [12].

Based on availability, there are several types of commercialized fuel cells:

a. Alkaline Fuel Cells (AFC)
b. Polymeric Electrolyte Membrane Fuel Cells (PEMFC)
c. Phosphoric Acid Fuel Cell (PAFC)
d. Direct Methanol Fuel Cells (DMFC)
e. Solid Oxide Fuel Cell (SOFC)
f. Molten Carbonate Fuel Cell (MCFC)

AFC was introduced as a fuel cell technology that used catalysts to make a faster reaction by non-precious metals such as lead, nickel, zinc, and copper. This type also uses potassium hydroxide as the main electrolyte. From this configuration, AFC is able to work in operation temperatures between 65°C and 90°C for normal conditions. When AFC works in high concentrate electrolyte and high pressure, it can operate up to 250°C temperature. Besides AFC that operates at low temperatures, PEMFC can be operated below 100°C. This type consists of an acidic polymer membrane as electrolyte and platinum metal as an electrode. As consequence, it can transmit full power very rapidly. PEMFC is very popular to use because it can send usable power in a wider range. Over PEMFC, there is DMFC that operates up to 120 °C. This type using about 3% concentration of methanol solution to bring the reactant into the cell.

The type of fuel cell that can be work at relatively high temperatures is PAFC with 180–210 °C. Phosphoric acid is used for electrolytes while carbon materials are applied for electrodes. PAFC is the most advanced type usually used for commercial purposes even though electricity production is low categorized. On the other hand, this type can operate at a lower amount of hydrogen and oxygen. For more high operation temperate, the MCFC type has been used operating for more than 600°C. This type usually is applied to large stationary systems up to the Megawatts scale. Unfortunately, AFC produces carbon dioxide (CO2) and water during operation because it uses carbon monoxide (CO) injection at the cathode side. The highest operating temperature of the fuel cell type is SOFC that can operate 800–1,000°C. Operating at a high temperature will avoid using a metal catalyst and increase kinetic reactions. This type uses different hydrocarbon fuels to operate without an external reformer. However, it produces carbon dioxide and needs a longer time for starting the reaction process.

3. THE PRINCIPLE WORKING OF PEMFC SYSTEMS

In [15] explained that the most superior of the fuel cell is PEMFC because there are several merits such as very good stability, pollution-free, great durability, and high-power density so that it is noiselessness operation. The working system of PEMFC described in Fig. 3.

The anode side is fulfilled with hydrogen while another side is given oxygen that can be injected from the air through the bipolar plate on both sides. Splitting hydrogen molecules becomes protons and electrons occur at the anode side. The proton is toward the cathode through the electrolyte while the electrons are forced out of the anode side. It repeatedly occurs to produce an electric current. From Fig. 3 it can be seen that when oxygen supply that combines with hydrogen in the cathode side will produce water and waste heat.

The electrochemical reactions at the PEMFC electrodes are as follows:

Anode reaction: $H_2 \rightarrow 2H^+ + 2e^-$

Cathode reaction: $\frac{1}{2}O_2 + 2H^+ + 2e^- \rightarrow H_2O$

Complete reactions: $H_2 + \frac{1}{2}O_2 \rightarrow H_2O + heat$

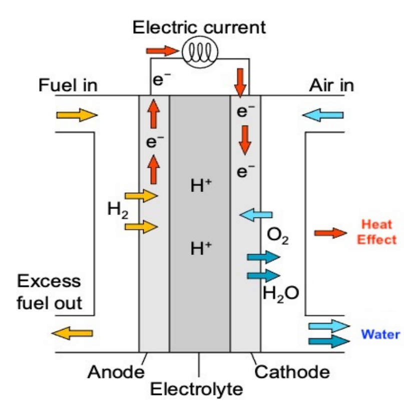

Fig. 3 - The principle working of PEMFC system

PEMFC produces the waste heat generally caused by some factors such as hydrogen-oxygen electrochemical reactions, water vapor condensation process, and membrane resistance [16]. Heat is one of the side products of an electrochemical reaction that occurs in PEMFC beside the water. The heat proportion of the total reaction is about 45-50% of the released energy in PEMFC [6]. This heat can be expressed as heat flux as formulated in Equation 3.

$$V_{tot} = (V_{thm} - V_{PEMFC}) \times I \quad (1)$$

where V_{thm} is the thermal voltage; V_{PEMFC} is the PEMFC operating voltage; and I is the current density. V_{tot} denotes the total possible voltage from PEMFC without heat losses assumption. It is obvious from equation 3 when the current density or the thermal voltage increase, so the heat flux will increase as well.

The waste heat produced by PEMFC can be distributed through two modes i.e., conductive, and convective way. For the former one, it occurs in the device including interconnecting layers, electrodes, electrolytes, porous materials, and solid materials. Meanwhile, the latter process occurs between the PEMFC solid surfaces and the flowing reactant.

4. THERMOELECTRIC GENERATOR (TEG)

There are three operating modes of thermoelectric [14]:

(a) Heating mode
(b) Cooling mode
(c) Power generation mode

To generate electricity, thermoelectric works on the last operating mode and the device is familiar called a thermoelectric generator (TEG). TEG is a solid-state semiconductor device that can be converting a temperature difference from two sides into a power source. TEG builds from the several thermocouples blocks wherein each block is made up of one n-type semiconductor and one p-type semiconductor that is connected by a metal strip in series as shown in Fig. 5.

When one TEG side is hot and the other side is cold, it will produce a temperature difference. The heat that passes through the device is converted to electrical power. If the temperature difference increases, the generating power output also increases. The phenomenon is called the Seebeck effect and it occurs due to the movement of charge carriers within arrange of the thermocouple in TEG. Open circuit voltage (V_{OC}) from the Seebeck effect on TEG is calculated using equation 1.

$$V_{OC} = (\alpha_p - \alpha_n)(T_H - T_C) \quad (2)$$

α_p and α_n define as the Seebeck coefficients of the p-type and n-type semiconductor respectively. T_H is the hot temperature while T_C is the cold temperature of TEG. The difference temperatures from T_H and T_C can be also expressed as ΔT [14]. Subsequently, the electrical current of TEG is obtained as:

$$I_{max} = \frac{V_{OC}}{R + R_L} \quad (3)$$

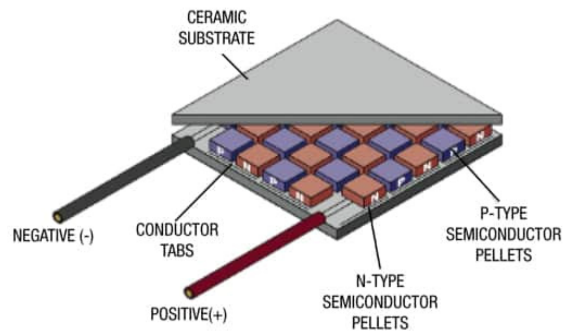

Fig. 4 - Part of thermoelectric generator internal view

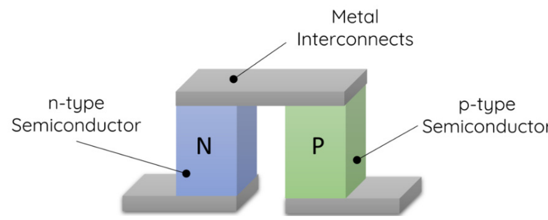

Fig. 5 - Thermocouple block

where the maximum current I_{max} is independent of the number of thermocouple blocks in TEG. Then R_L = 0 because the maximum current inherently occurs.

5. THE TECHNICAL UTILIZATION

As mentioned before that the side product of the overall reaction on PEMFC is water and heat. Removal of waste heat from the stacks becomes the largest issue in PEMFC because of around half of the total output produced. Converting waste heat becomes electricity regarded more useful therefore many researchers perform it. Ref [17] has been experimentally developing a model 5 kW PEMFC with heat recovery using TEG modules and heat sink. Its model also completed by a data logger with temperature sensors, a heat exchanger, and an insulation layer. The complete model is shown in Fig. 6.

The electrical heater part controls water flow into the heat exchanger through the inlet and ensures the same condition in the outlet. Assuming the flow rate and ambient temperature are constant, its research describes open-circuit voltage at TEG as a function of temperature in the outlet side. The implemented external load of around 5.6 Ω < R < 10 Ω can produce maximum power from the waste heat of PEMFC. Meanwhile, the performance of the system shows a constant value of around 0.04% if the temperature starts more than 50°C. The conversion efficiency maximum of TEG reached in its research is 0.35% at 68°C temperature with increments electrical efficiency of approximately around 0.278%. The authors recommend reinvestigating Thermoelectric Hybrid Recovery (THR) array to find the best configuration.

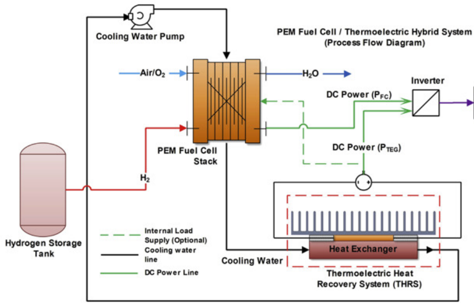

Fig. 6 - The model of PEMFC with Thermoelectric Hybrid Recovery (THR) Systems [17]

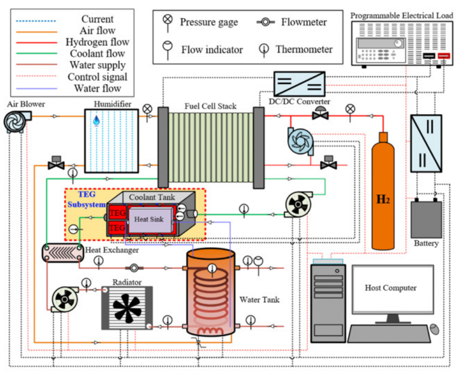

Fig. 7 - The schematic diagram of PEMFC-TEG-CHP [18]

A more complex system has been proposed in [18] that is called a polymer electrolyte membrane fuel cell-thermoelectric generator-based combined heat and power (PEMFC-TEG-CHP) hybrid system. The schematic diagram of its system is shown in Fig. 7.

Rating power PEMFC used in its systems is 5 kW integrated with CHP as subsystems with TEG device. The coolant tank on the systems is placed between PEMFC and TEG subsystems. It is used to transfer the waste heat from PEMFC to the hot side of TEG. It is also attached to the coolant tank metal surface. The Seebeck effect occurs and CHP subsystems produce electricity through the TEG device. Meanwhile, the remaining heat flowed to the heat exchanger. The water tank receives a heat recovery from TEG cold side through it. Hence, the remaining heat can be utilized for daily use.

Its proposed model has been simulated using MATLAB/Simulink and validates via hardware experimental. The dynamic condition has been investigated on its systems to analyze dynamic responses and validate the feasibility for real application. From its research can be obtained that PEMFC-TEG-CHP can increase efficiency up to 85.1% with increments of 0.325% of electrical efficiency. The result of its proposed model shows the performance better than previous research in [17] with the same power rating of PEMFC. In addition, It has the potential also to apply to more general low-temperature heat sources used [18].

A 1 kW PEMFC using open cathode type coupled with a TEG has been proposed in [19]. The proposed model is also completed by the controller, a data logger, hydrogen supply, an insulated flow duct, a heat pipe with a cooling fan, DC power supply, and load. Fig. 8 shows the schematic diagram of its proposed systems. These systems imitate a mini fuel cell applied to the prototype vehicle. The objective of its systems is to analyze the TEG output device utilized waste heat from the fuel cell. The cooling systems on the TEG device consist of 2 methods that are natural convection and forced convection using a variable fan speed. A data logger device is used for collecting results from eight k-type thermocouples. The best result from output TEG is 33.5 mV obtained on 2.30 m/s air velocity with 3.3°C temperature gradient. Meanwhile, the TEG output lowest is 18 mV using natural convention at a 3°C temperature gradient. From its research, it can be obtained validating TEG performance integrated 1 kW PEMFC with 113.96 mW power output. Therefore, TEG is proven to increase the electrical production of PEMFC by converting its waste heat.

As the crucial part to generate electrical power from waste heat PEMFC, the optimum cooling of the TEG cold side is a concern by researchers as well. In [20] has been proposed a model combined PEMFC, TEG device, and a metal hydride (MH) cylinder. MH is used to store a solid form of hydrogen and simultaneously becomes a fuel supply for PEMFC that is helped by a heating system. Fig. 9 shows the schematic diagram of the proposed systems.

Its systems have been tested under three procedures cooling consists of (a) natural cooling (b) a cooling fan and (c) MH cylinder. Each of them applied to the varied heat generation, losses, and temperature operating. The temperature difference on both TEG sides depends on the PEMFC heat waste. The maximum value corresponding to the output power of PEMFC is around 1 kW at 3.2°C different temperatures. From its research, it can be observed that the proposed model is more efficient. MH cylinder makes the system more saving energy because it reduces electricity for supply power of the cooling fan. Subsequently, the different temperatures on the TEG sides can be wider. The waste heat from PEMFC is more useful using the TEG device integrated with the MH cylinder.

The utilization of PEMFC as a green energy device is also applied to trams. In [21] proposed a model of PEMFC trams integrated with TEG device. Its study using two sets of 150 kW PEMFC to supply the tram power with 40-60% electrical efficiency. Its systems produce around 95% of waste heat from the PEMFC stacks. The system configuration is shown in Fig. 10.

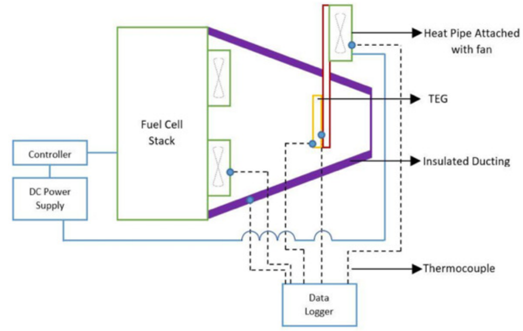

Fig. 8 - The schematic diagram of the proposed systems in Ref [19]

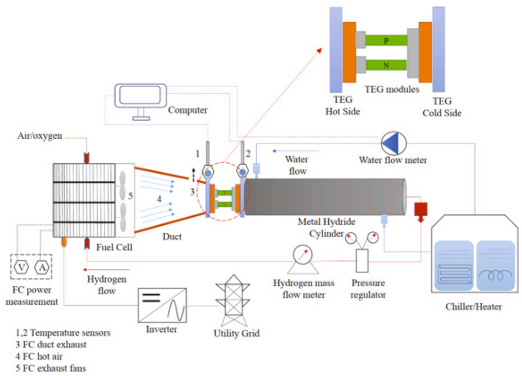

Fig. 9 - The schematic diagram proposed by [20]

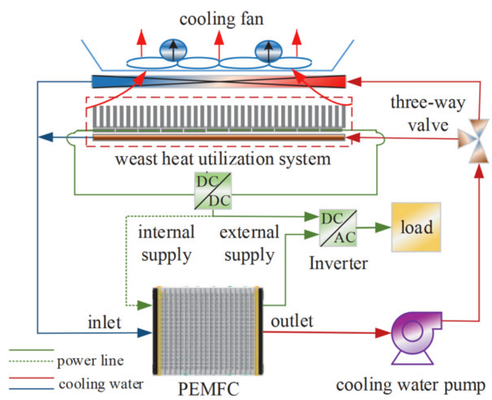

Fig. 10 - The systems topology proposed by [21]

It can be seen that water from the pump flowed through a three-way valve to control the circulating cooling water at the waste heat utilization system (WHUS). The hot side of TEG receives heat waste while the other side is cooled through a heatsink and fan. From this configuration will be produced temperature difference both two sides and generates electrical power.

The proposed systems of its study operate at 36.5°C temperature and gradually increase followed by the output power PEMFC. When the output power generates 117 kW, the temperature reaches 69.4°C and operates in high-speed conditions. It works at 57.1-62.1°C inlet temperature and is capable of stable operation [21].
Based on testing the WHUS using TEG can contribute up to 2.2 kW of excess power that can be utilized for internal or external load supply on trams. In addition, the implementation of WHUS on PEMFC trams leads to less maintenance and management. Hence, its research can be concluded that integrated WHUS at PEMFC for trams application has a great potential for development.

6. DISCUSSION

Increasing the efficiency of the PEMFC systems brings inexpensive maintenance. Therefore, this purpose can be reached by managing the waste heat of PEMFC. waste heat recovery (WHR) utilized TEG device has appeared as an effective way for enhancing efficiency and reducing O&M cost. Integrated TEG device is proven to increase the efficiency of PEMFC systems by converting its waste heat. In addition, the waste heat from PEMFC converts into an electrical energy form so it has been considered to be more utilized. However, there are several challenges faced.

The TEG device is relatively unusable power for a single module. Hence, it should be applied in an array configuration to get feasible power. By this method, it is able to energize the additional components for trams application [21], supply power for standby and driving mode on mini hydrogen vehicles [19], and increase the power level generation on harvester energy devices as the recovery system [18]. On the contrary, using fewer TEG modules leads to adsorb waste heat from PEMFC effectively apart of the lower power production compared to multiple modules [22].

The PEMFC fuel is often associated with the safety of the systems. It is because the primary that is used is hydrogen which incidentally easy to explode. Therefore, [20] proposed systems that used hydrogen solid form saving in the MH cylinder tank. It simultaneously becomes the cooling method for the TEG device to generate temperature gradient. However, it requires thermal coupling as an additional component to connect the MH tank and the PEMFC caused to increase in the complexity and weight of the overall systems.

Despite the TEG device is able to recover waste heat from PEMFC, it is still many drawbacks especially from TEG itself. TEG device is considered an expensive device with low efficiency. The material of TEG is still investigated to find out the optimal composition refers to the previous research in [23][24][25].

7. CONCLUSION

Operating PEMFC as a green energy conversion device produces side products such as water and waste heat. The waste heat is produced from the exothermic reaction process on PEMFC. Many researchers have been investigated the utilization of waste heat PEMFC and it is generally realized by a thermoelectric generator (TEG) device using the Seebeck effect as a heat recovery system.

The waste heat utilization of PEMFC using TEG leads to harvest electrical energy. Hence, it can increase the power levels of PEMFC systems. The integration between PEMFC and TEG has been applied to several benefits such as optimization of power generators, domestic use, and transportation. To generate more optimal electrical energy from both, the cooling system on the TEG device has been improved to obtain a wider temperature gradient. Also, the choice of appropriate material of TEG can increase the waste heat conversion to electrical energy.

ACKNOWLEDGEMENT

The authors would like to thank gratefully for the grants and the research funding from the Indonesia Endowment Fund for Education (LPDP), Ministry of Finance of The Republic of Indonesia for our master study.

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