# Thermophotovoltaic Power Generation System using Radiant Heat from Biomass Stove

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***Abstract***

In this research, the potential of electric power generation generated by thermophotovoltaic cells has been studied. A prototype of biomass stove surrounded by thermophotovoltaic cells (TPV cells) as its wall has been designed and constructed. And rice husks were used to be a stove's fuel. At the core of stove, a cylindrical steel emitter was installed for converting the combustion flame to be the radiant heat. The TPV cells which installed around the emitter then convert the radiant heat into electricity. From the experiment, at the rice husk feed rate of 6 kg/h, it was found that the burning rice husks inside a stove could heat the emitter to get highest temperature of about 1173 K (900˚C) which could activate the TPV cells to generate the highest electric power density of 12.5 mW/cm$^2$. By this condition, if install the TPV cells all over the area of the stove's wall, the highest electric power generated by this TPV system will be around 47 W, the highest overall energy conversion efficiency of the system will be equaled to 0.2%. However, the exhausted gas temperature of a stove was still too high; therefore, the waste heat recovery for efficiency improvement should be introduced. In this work, combined system of the Organic Rankine cycle turbine generator with the TPV generator system was numerically investigated. The results were shown that the overall energy conversion efficiency of about 4.44% could be achieved.

***Keywords**:* Thermophotovoltaic cells, Radiant heat, Biomass stove, Energy conversion efficiency.

## 1. Introduction

The easiest way to convert sunlight energy directly into electricity would be the use of solar cells. However, by this way of energy conversion, the availability of the source is still limited. Because the sun can only shines in daytime. Furthermore, during that daytime, the radiant intensity of the sunlight is uncontrollable. Also the expensive batteries will be required for extensive period of electrical energy storage if needed. From these inconvenient usages, the alternative technologies for energy conversion were researched and invented. Thermophotovoltaic (TPV) is one of many energy conversion technologies which works likely that of typical solar cell, but using different photon wavelength range for activating the photovoltaic effect, usually 0.4 – 0.8 μm for typical solar cells, and up to approximately 1.9 μm for TPV cells [1]. Therefore, the TPV cell can converts radiant heat emitted from a high temperature heat source into electricity by means of photovoltaic effect likes as conventional solar cells [2]. The two main differences between TPV systems and solar cells are the thermal radiation source and the temperature of the emitter in the TPV system, typically in the 827-1227 °C range, which is much lower than that of the sun [3]. Some of its advantages are modularity, portability, wide choice of fuels, silent operation, reduced air pollution, rapid startup and high energy density [4]. The main components of the TPV system are the TPV cells, selective emitters, spectral filters, and also the combustors or burners with chambers. In order to develop the system's efficiency, the spectral matching between the emitter and the TPV cell's spectral response is important in the term of radiation transfer efficiency [5]; also all of the system components and the suitable heat source are importance [6].

The concept of this work is that to use the heat from the combustion in a stove by radiate the radiant heat to the thermophotovoiltaic cells that need radiant heat to activate the TPV cells work, and then the TPV cells can generate electrical energy. Therefore, in this work we develop the prototype of a biomass stove that combined with thermophotovoltaic cells to generate the electrical energy. The stove is then designed to be feed by variety of biomass types, and radiate the radiant heat around the stove to the TPV cells. The thermal to electric conversion efficiency and the electric power density generated by the TPV cells are the efficiency indexes [7]. The numerical model of the system's efficiency improvement by combining the Rankine cycle turbine generator with the TPV generator [8-11] is studied; also the simple economics analysis of the TPV system has been analyzed.

## 2. Methods

### 2.1 TPV with Biomass Stove

Thermophotovoltaic system is a two stage energy conversion process where the heat source is used to heat up an emitter; the radiant heat is then radiated to the TPV cells around the emitter to generate the electricity. In this research, to generate the radiant heat for the TPV cells, a rice husk fueled biomass stove has been designed and constructed. The combustion chamber is designed to have a cylindrical shape; the porous steel emitter is also cylindrical shaped and installed around the burning flame inside the combustion chamber. The rice husk feeding rate can be adjustable; also the air flow rate for the combustion is adjustable. At the wall of the combustion chamber, the TPV cells can be installed around to receive the radiated radiant heat from the emitter, and then the TPV cells can generate the electricity, see Fig. 1. In this work, the gallium antimonide (GaSb) TPV cells are used to generate the electricity.

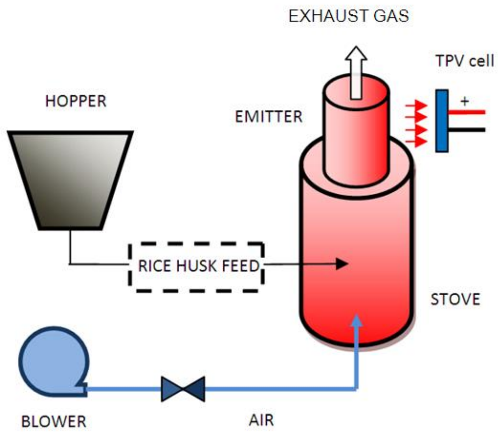


Fig. 1 Biomass stove – thermophotovoltaic generator system

### 2.2 Experimental Process

In the experimental, the electrical generation performance is the main focus on this work. Firstly the electrical power which can generate by TPV cells that installed at the wall of a stove is measured. The effects of emitter temperature and the TPV cell temperature are also investigated. The details of the measurement parameters are shown in Table. 1 as follow

Table. 1 Details of the measurement categories

| Parameter collecting items | | | |
|---|---|---|---|
| fuel feed rate (kg/h) | Excess air for combustion | Exhaust gas temperature | Electric power |
| 2.0 | / | / | / |
| 4.0 | / | / | / |
| 6.0 | / | / | / |

Also the effects of the TPV cell temperature, this done by using water cooling the TPV cells when operating the system.

### 2.3 Combined Organic Rankine Cycle turbine generator with TPV cells system

With the main concept of this work that to use the radiant heat from a biomass stove for generating electricity by TPV cells. However, heat loss with exhaust gas still high and should be recovered back to produce or give any other energy which can improve the system efficiency. Therefore, to improve the system efficiency, in this work we apply the Organic Rankine cycle turbine generator to the system by based on numerical modeling.

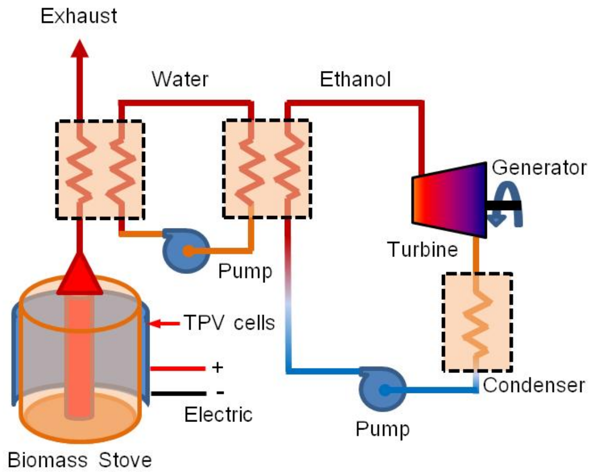


Fig. 2 Combined Organic Rankine Cycle turbine generator with thermophotovoltaic cells system

### 2.2 Efficiency Analysis

By theoretically analysis, when considering the system separately for each part namely thermophotovoltaic and organic rankine cycle turbine generator, the thermophotovoltaic efficiency, $\eta_{TPV}$ is the result of electrical power generated by the TPV cells, $P_{elec,TPV}$ compared to the heat power input from the fuel, $P_{fuel}$, and electric power input for cooling pump, $P_{cooling}$, as

$$\eta_{TPV} = \frac{P_{elec,TPV}}{P_{fuel} + P_{cooling}} \tag{1}$$

when the electrical power generated by the TPV cells can be experimentally examined from the biomass stove thermophotovoltaic system that has been constructed in this work. The heat power from fuel can be calculated from the fuel feed rate, $m_f$, and the low heating value of the fuel, $LHV$, (13,517 kJ/kg for rice husk [12]) as

$$P_{fuel} = m_f \times LHV \tag{2}$$

For the electric power of the cooling pump can be measured from the small electric motor (8 W).

For the Organic Rankine Cycle turbine generator efficiency, $\eta_{ORC}$, it is the result of electrical power generated by Organic Rankine Cycle turbine generator, $P_{elec,ORC}$, compared to the input heat power from the stove's exhaust gas, $Q_{exhaust}$, and the input electric power for water pump and ethanol pump, $P_{pump}$, as

$$\eta_{ORC} = \frac{P_{elec,ORC}}{Q_{exhaust} + P_{pump}} \tag{3}$$

when the electrical power generated by the Rankine cycle turbine generator, $P_{elec,ORC}$, can be estimated and calculated from

$$P_{elec,ORC} = \eta_{gen} \cdot W_{turbine} \tag{4}$$

where $W_{turbine}$ represents the work of turbine generated by Organic Rankine cycle, and $\eta_{gen}$ is the efficiency of generator.

The thermal power introduced to the Rankine cycle can be expressed as the thermal power of the exhaust gas of a stove, $Q_{exhaust}$, which can be calculated from the measured exhaust gas temperature and flow rate as

$$Q_{exhaust} = \dot{m}_e C_e \left(T_{e,in} - T_{e,out}\right) \tag{5}$$

where $\dot{m}_e$ is the exhaust gas mass flow rate, $C_e$ is a specific heat capacity of exhaust gas, $T_{e,in}$ is an inlet exhausted gas temperature, and $T_{e,out}$ is an outlet exhausted gas temperature [13].

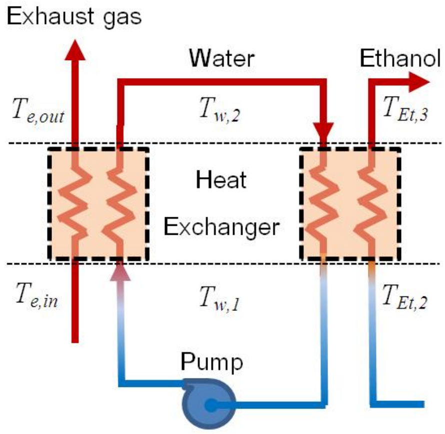


Fig. 3 Heat transfer diagram

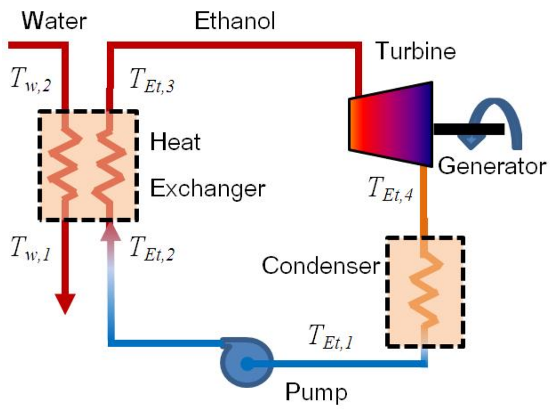


Fig. 4 Organic Rankine Cycle with turbine diagram

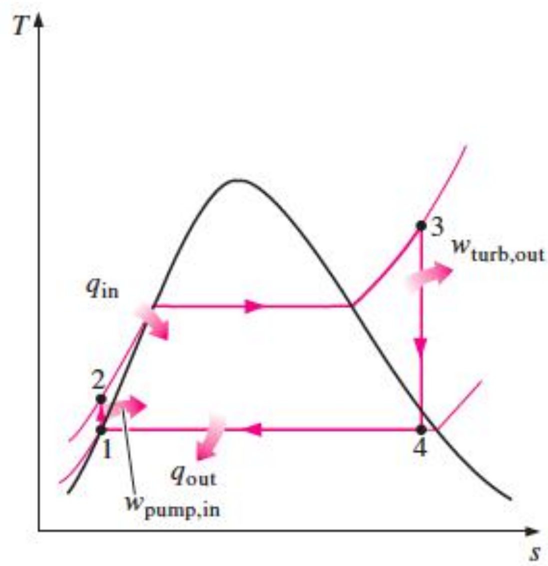


Fig. 5 T-s diagram

From the definition of heat transfer effectiveness, $\varepsilon$ , the actual heat transfer to the water loop, $Q_{water}$ , can be estimated from

$$\varepsilon = \frac{Q_{water}}{Q_{exhaust}} \qquad (6)$$

In this analytical model, the value of heat transfer effectiveness was assumed to be 0.68. In this case, water does not change the phase, therefore, the temperature of the water out from the heat exchanger can be calculated from

$$Q_{water} = \dot{m}_w C_w (T_{w,2} - T_{w,1}) \qquad (7)$$

where $\dot{m}_w$ is the water flow rate, $C_w$ is the specific heat capacity of water, $T_{w,1}$ and $T_{w,2}$ are the temperature of the water at the inlet and at the outlet, respectively.

As the heat from exhaust gas transferred to the water, by this mean of transferring, the heat will be transferred into the ethanol loop through the heat exchanger. Again, the actual heat transfer to the ethanol loop, $Q_{ethanol}$ , can be estimated from the heat transfer effectiveness formula ( $\varepsilon$ = 0.68 same as in Eq. 6) as

$$\varepsilon = \frac{Q_{ethanol}}{Q_{water}} \qquad (8)$$

At this heat transferring process, the phase of ethanol will be changed; the temperature and enthalpy of ethanol out from the heat exchanger can be calculated from

$$Q_{ethanol} = \dot{m}_{ethanol}(h_3 - h_2) \qquad (9)$$

where $\dot{m}_{ethanol}$ is the ethanol mass flow rate, $h_2$ and $h_3$ are the enthalpies of ethanol at the inlet and outlet, respectively. Therefore, the work of turbine, $W_{turbine}$, can be calculated from

$$W_{turbine} = \dot{m}_{ethanol}(h_3 - h_4) \qquad (10)$$

where $h_3$ and $h_4$ are the enthalpies of the ethanol at the inlet and outlet of turbine, respectively.

By performing all the equations above, the overall performance or efficiency of the system can be estimated as the summation of electrical power generated from thermophotovoltaic cells and turbine generator, $P_{elec,out}$ , compared to the heat power of the input fuel, $P_{fuel}$ , and electrical power input, $P_{elec,in}$ , as

$$\eta_{overall} = \frac{P_{elec,out}}{P_{fuel} + P_{elec,in}} \qquad (11)$$

## 3. Results

In the result section, according to the performing processes, therefore this work has separated into three parts of the results as follow.

### 3.1 Performance of Biomass Stove

For the heat source of the power generation system using thermophotovoltaic cells to generate the electrical power, a biomass stove has to be designed and constructed. After the construction is completed, the performance of a stove is then evaluated. The main target of this stove is to heat an emitter to have very high temperature. Anyway, it should be low fuel consumption.

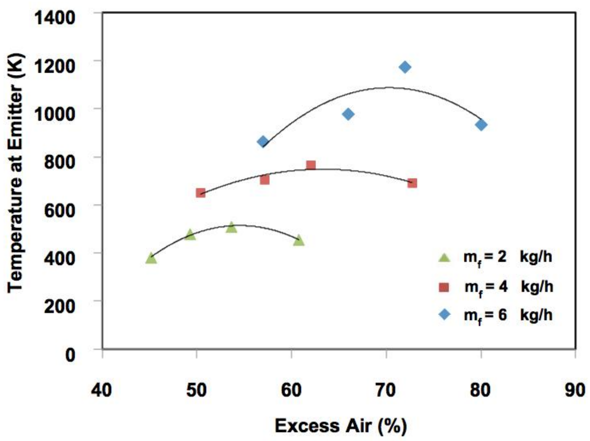


Fig. 6 Relationship between the temperatures of emitter and combustion excess air of a stove

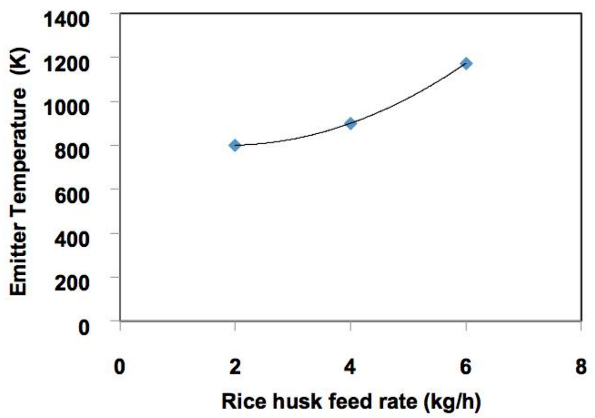


Fig. 7 Temperatures of emitter at various rice husk feed rate.

From Fig. 6, the stove could heat up an emitter to get highest temperature around 1,200 K with the fuel feed rate of 6 kg/h of rice husk. It is also a maximum feed rate for a stove. The result shown that at higher fuel feed rate, a stove needs higher excess air for combustion. In this work also the suitable excess air for rice husk combustion by this stove in various feed rates are preferred. The excess air was measured by flue gas analyzer named CHERRER, Model: VISIT 01 LR. Germany.

As in this Fig. 7, it is shown that the temperature will be increased or decreased upon the rice husk feed rate, the higher feed rate will increase the heat power from the combustion, so the emitter could have higher temperature. However, it is a limitation that the stove could not feed more rice husk feed rate further than 6 kg/h, so the highest emitter temperature in this time is about 1200 K. In general, TPV cell can work well with the range of emission temperature from about 1200 K to 1800 K. Therefore, our emitter temperature is still low and need to be developed to get higher temperature in order to improve the TPV cell efficiency.

### 3.2 Performance of Thermophotovoltaic Generator

In this section, the performance of electrical power generated by TPV cells is presented. The TPV cells were installed at the stove's wall, distance between the surface of an emitter and the TPV cell is equaled to 10 cm. At different temperature of emitter, the performance of the TPV cell will be evaluated by measuring the electrical power generated by the TPV cells. The dependent of emitter temperature with the TPV cell performance are shown in Fig. 8.

At different emitter temperatures, the TPV cell is then worked with different performances. Also at different temperatures of the TPV cell itself, the TPV cell also work with different performances; the results are shown in Fig. 9. Therefore, it is necessarily that the cooling system should be included with the system to cool down the TPV cells to have lowest temperature closed to 25°C (298 K) as other typical PV cells.

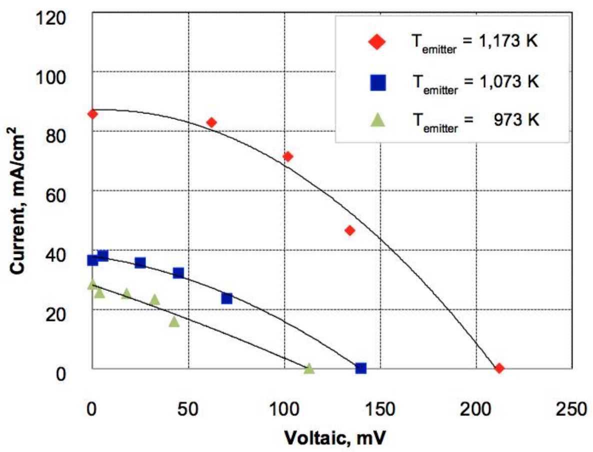


Fig. 8 Electrical performances of the TPV cell at different temperatures of emitter.

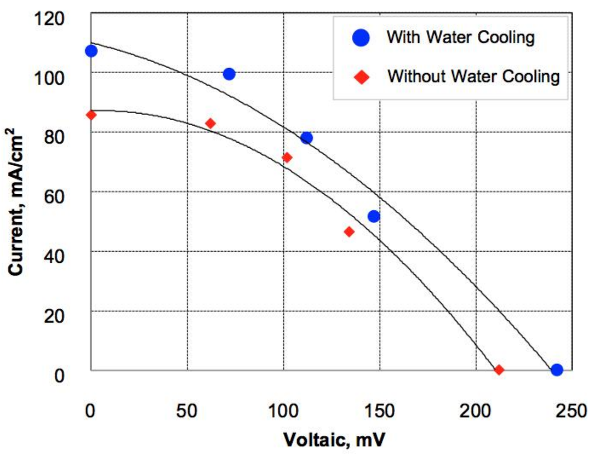


Fig. 9 Electrical performances of the TPV cell at different temperatures of the TPV cell itself.

### 3.3 Performance of a Combined TPV – Organic Rankine Cycle Turbine Generator

In this section, the authors have been investigated, analyzed, and estimated the capacity and performance of the Organic Rankine Cycle turbine generator, and the combined thermophotovoltaic cells generator with the Organic Rankine Cycle turbine generator. The purpose is that to know the feasibility and efficiency of the integrated system between them. The methodology of this study is based on the basic thermodynamics theoretical approach, the time domain does not taking into account in order for this estimation. However, this could be the helpful guidance toward to deal with the integrated thermophotovolatic and Organic Rankine Cycle turbine generator by using heat source from biomass stove or any other heat sources.

The result from the analytical model with partial measured data from the experimental, it was found that with the rice husk feed rate of 6 kg/h, the temperature of the exhaust gas at 450°C, the capacities of turbine and generator output are shown in Fig. 10 as follow

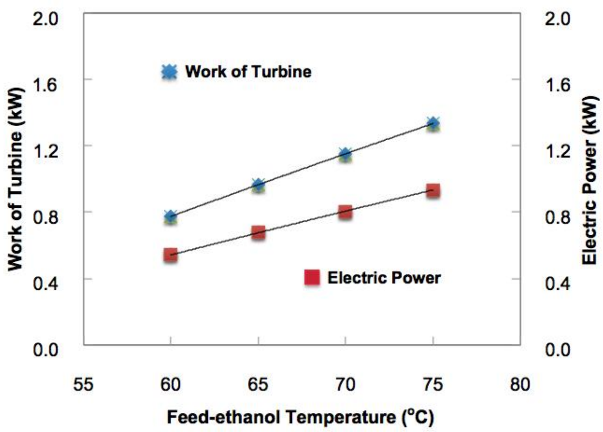


Fig. 10 Estimated turbine and electric power capacities of the Organic Rankine Cycle turbine generator using heat source from biomass stove.

The importance that gives significant to the turbine and electric power of generator is the inlet temperature of ethanol. Because ethanol has boiling point temperature at 77°C, therefore, to keep ethanol to be closed to the boiling temperature is crucial for increasing the system performance.

In summary, in case of only the thermophotovoltaic cells installed around the emitter as a stove's wall, the highest electric power will be around 47 Watts (estimated from the experimental result). The efficiency of thermophotovoltaic power generation calculated based on Eq. 1 will be about 0.2%. It is seemed to be very low efficiency, this because the cells use only the radiant heat from emitter which is not the main output from a stove. So that very large amount of thermal energy has lost as stack loss.

Considering the Organic Rankine Cycle turbine generator, the estimated electric power generated by turbine generator is about 1.0 kW. The system efficiency calculating based on Eq. 3 will be equaled to 4.2% when the pump power, $P_{pump}$, is calculated based on pressure and specific volume of a working fluid required in each loop of the system. When combining the Organic Rankine Cycle turbine generator with thermophotovoltaic cells generator, the overall system efficiency estimated based on Eq. 11 will be around 4.44%.

## 4. Conclusion

In this paper, the performance of power generation system using thermophotovoltaic cell technology together with a biomass stove which is used to generate the radiant heat for the TPV cell requirement has been evaluated through the experimental processes. Also the combination between thermophotovoltaic cells generator and Organic Rankine Cycle turbine generator has been numerically analyzed for estimating the capacity and system performance. It is the feasibility to integrate or combine these two methods of power generation to be a combined power generation system using biomass energy resource. With this concept, the system efficiency will be obviously improved; however, the results shown in this paper are just a part of undergoing research project, the experimental results of the Organic Rankine Cycle turbine generator are important to confirm these estimation results.

## 5. Acknowledgement

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