



2013 International Conference on Alternative Energy in Developing Countries and Emerging Economies

Study of Combined Rice Husk Gasifier Thermoelectric Generator

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Abstract

The use of a rice husk gasifier as a cook stove is limited to the domestic sector of developing countries primarily because it needs electrical energy to drive a blower for the gasification process. To solve this problem, we investigated the feasibility of attaching commercial thermoelectric (TE) modules made of bismuth–telluride materials to the gasifier's side wall, thereby creating a TE generator system that utilizes a proportion of the gasifier's waste heat. A rice husk gasifier TE generator (TE-RSG) having an internal diameter of 16 cm was fabricated and tested. The TE generator system consisted of two commercial TE modules, a metal sheet wall which acted as one side of the gasifier's structure and served as the hot side of the TE modules and a rectangular fin heat sink at the cold side of the TE modules. A blower was used to suck the ambient air to cool the heat sink and blow the air from the heat sink to the reactor of the gasifier. Gasification was conducted in a temperature range of 500–700°C and gasification agent, air feeding rate of 18.6 m³/h. The results revealed that the electrical power output and the conversion efficiency depend on the temperature difference between the cold and hot sides of the TE modules. At the temperature difference of approximately 60°C, the unit achieved a power output of 3.9 W and a conversion efficiency of 2.01%. Through a comparison of results between the theoretic model and the experimental system, the reasonability of this system model has been verified.

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Selection and peer-review under responsibility of the Organizing Committee of 2013 AEDCEE

Keywords: Conversion efficiency; Thermal efficiency Reactor

1. Introduction

The demand for renewable sources of energy is increasing due to an elevated concern about global warming, climate change and the decline of fossil fuel reserves. Compared with other renewable energy resources, biomass is huge. Its annual production rate is high and it is geographically widespread throughout the world. In general, paddy, or rice, is one of the earths' most prolific crops. Rice husk is a residue from rice farming and is considered an agricultural waste. In Thailand, where the average gross rice production is approximately 32.09 Mtons/yr., 6 Mtons of rice husk is produced and around 600 thousand tons of ash is generated by burning the rice husk [1]. Currently, rice husk is widely used in stall mats, compost and fillers. However, due to increasing demands for utilization of waste-to-energy, many researches are actively involved in researching ways to use rice husk as a fuel. Approximately 2.4 billion people depend on wood, dung, charcoal and other biomass fuels for cooking. Most of these people cook on open fires that burn poorly leading to low thermal efficiency and high pollution emissions. The current patterns of use cause significant negative impact of several types, including human morbidity and mortality, outdoor air pollution, climate change and deforestation. One interesting alternative to these inefficient cooking methods is a rice husk gasifier; it is more efficient than biomass cook stoves [2]. However, electrical power is needed to drive a blower that is part of the rice husk gasifier system. Individual thermoelectric (TE) power generators coupled with rice husk gasifier offer an interesting option to provide electricity. In past years, TE generators have been coupled with biomass stoves. As the examples, Nuwayhid et al. [3] considered the prospect of applying TE modules located on a wood stove-top to produce power. That system is well known and could be useful in regions with unreliable electricity supply. The stove-top TE system produces a maximum power output of 2.7 W per module. A heat sink composed of a thermosyphonic heat pipe has been adapted to further improve the power output of a TE module [4]. These developments revealed that a commercially available TE module could provide over 3 W of power with a temperature difference between the hot and cold side of the TE module of 70-80°C. Experiments have also been conducted on the side-walls of cook stove. Stove wall temperatures are likely to be in the range of 150-300°C. Lertsatitthanakorn [5] investigated a combined biomass cook stove thermoelectric (BITE) generator. The results of that investigation showed that the BITE produces a maximum power output of 2.4 W at a temperature difference of 150°C. The conversion efficiency of 3.2% was enough to drive a low power incandescent light bulb or a small portable radio. Meanwhile, the payback period of the BITE is 0.74 years if compared with batteries supplying power to a 1.8 W load with an annual operating time of 365 hours. Champier et al. [6] studied a TE generator incorporated in a multifunction wood stove to produce electrical power from the exhaust gas of the wood stove. One-dimensional heat flow was used to predict the system's performance. The TE module produced maximum power output of 9.5 W. An economic analysis showed that the price of TE modules varied with order volume. By comparison between the cost per watt of the PV panels and the TE generator, it was found that the cost per watt of the TE module is very competitive with PV panels. The objective of this work was to study the feasibility of using TE modules coupled with a rice husk gas gasifier in order to generate electricity. A more reasonable model of a TE generator has been adopted for system analysis. Testing results showed promise of using a TE generator for waste heat recovery in a gasifier stove.

Nomenclature

α	Seebeck coefficient
A	area of thermoelement

C_{pw}	specific heat of water
H_f	calorific value of rice husk (higher heating value)
I	input electric current
K	thermal conductivity of the TE module
l	length (height) of thermoelement
L	latent heat of vaporization
l_c	length (thickness) of solder/contact in module
m_w	mass of water initially in the pot
$m_{w, \text{evap}}$	mass of water evaporated
m_f	mass of rice husk
n	contact parameter
N	number of thermoelements per module
r	contact parameter
R	electric resistance of the TE module
T_i	initial temperature of water in the pot
T_e	temperature of boiling water
T_h	hot side temperatures of the TE module
T_c	cold side temperatures of the TE module
T_m	average temperature
V	voltage of the TE modules
Z	figure of merit of the TE material ($Z=1.6 \times 10^{-3} \text{ 1/K}$)

2. Methods

2.1. Calculating Methods

The equations used to model the behavior of the TE power generator are based on the Seebeck, Fourier and Joule effects. Using the standard model [7] and assuming one dimensional conduction through the module, the rate of heat supply (Q_h) and heat removal (Q_c) can be estimated at the hot and cold junctions as

$$Q_h = \alpha IT_h - 0.5I^2R + K(T_h - T_c) \quad (1)$$

$$Q_c = \alpha IT_c + 0.5I^2R + K(T_h - T_c) \quad (2)$$

Theoretically, the maximum power output (P) of a realistic TE modules takes into account the contact resistance as given by [8]

$$P = \frac{\alpha^2}{2R} \frac{NA(T_h - T_c)^2}{(L + n) \left(1 + \frac{2rl_c}{L}\right)^2} \quad (3)$$

Typically, $n = 0.1$ mm, $r = 0.2$, $l = 1.2$ mm, $l_c = 0.8$ mm, $\alpha = 3.92 \times 10^{-4}$ V/K, $N = 127$ couples, $R = 1.48 \times 10^{-5}$ Ω m, $K = 1.63$ W/mK and $A = 1.96$ mm².

The electrical output of the TE modules (P) is also calculated from the measured data as follows:

$$P = I \cdot V \quad (4)$$

Miller et al. [9] suggested that the conversion efficiency is as follows

$$\eta_e = \eta_c \frac{M - 1}{M + \frac{T_c}{T_h}} \quad (5)$$

where $M = \sqrt{1 + ZT_m}$ which $T_m = 0.5(T_h + T_c)$

Note that ZT_m is a characteristic parameter of the thermoelectric element and essentially governs its internal conversion efficiency. It is well known that the value of Z can have strong variations in temperature. In this study, in order to gain insight into the optimal collector operating temperatures, the value of Z is assumed to be constant. Although this may be an over simplification of the actual situation, it provides tractable solutions for the solar collector temperature and operating efficiency of the thermoelectric element.

$$\eta_c \text{ is the Carnot efficiency; } \eta_c = \frac{T_h - T_c}{T_h} \quad (6)$$

The thermal efficiency of the gasifier is defined as the ratio of the energy entering the pot to the energy content of the fuel consumed. The standard water boiling test (WBT) [10] is used for testing the efficiency of the gasifier. The thermal efficiency (η_{th}) can be calculated using the formula:

$$\eta_{th} = \frac{m_w C_{pw} (T_e - T_i) + m_{w, \text{evap}} L}{m_f H_f} \quad (7)$$

It is a given that electrical energy is higher in grade than thermal energy. Therefore, Ji et al. [11] used the overall efficiency η_o for a TE-RSG as.

$$\eta_o = \eta_{th} + \frac{\eta_e}{\eta_{\text{power}}} \quad (8)$$

where η_{power} , often assigned a value of 38%, is the electrical-power generation efficiency of a conventional thermal power plant.

2.2. Experimental Apparatus

The TE-RSG was a batch fed up-draft gasifier. It consists of two main parts: a thermal part (gasifier) and an electrical part (TE). The gasifier basically consists of a reactor, a burner and a blower. The reactor

is a concentric cylinder in tube having an inside tube diameter of 17 cm and a height of 70 cm. The reactor is made of 2 mm thick galvanized iron sheet. The outer cylinder has a diameter of 21 cm. An annular space between the inside and outside cylinder holds a ceramic fiber insulator to prevent heat loss from the reactor. The inner cylinder is fixed to the top flange. The flange, together with the inner cylinder, can be made removable from the outer cylinder for easy cleaning and replacement when worn out. At the lower end of the reactor inner cylinder is a fuel grate made of mild steel used to hold the rice husk during gasification. A blower is used to supply the air needed for gasification of rice husks and to release heat from the cold side of the TE modules. The inlet of the blower is connected with an air duct to suck the ambient air through a rectangular fin heat sink, while the outlet of the blower is connected to the lower end of the reactor outer cylinder. The schematic view of the TE-RSG is shown in Fig. 1. Metal steel was installed at the upper of the side of the reactor outer cylinder. The hot side of two TE modules was fixed on the metal sheet. Meanwhile, the cold side was fixed on the rectangular fin heat sink. The air-cool fin heat sink was made of aluminum with 21 rectangular fins. The fins were 1 mm thick, 85 mm long and had a height of 35 mm from the base of the heat sink. The space between the TE modules, hot plate and heat sink was insulated using a locally made ceramic fiber.

The gasifier was instrumented with K-type (accuracy $\pm 0.5^{\circ}\text{C}$) thermocouples that measured the temperature of the hot side and the cold side of the TE modules and the gas. The thermocouple that measured the ambient temperature was kept in a shelter to protect it from direct sunlight. The current and voltage were measured with a multi-meter (Fluke model 189, accuracy VDC $\pm 0.025\%$, A $\pm 0.5\%$). Air velocity was measured by a hot bulb velocity probe (accuracy ± 0.03 m/s) at the inlet of the air duct. A DC power supply was used to drive the blower. The blower was supplied 18.6 m³/h of the air. A data acquisition system was used to collect the data at regular intervals every 1 minute.

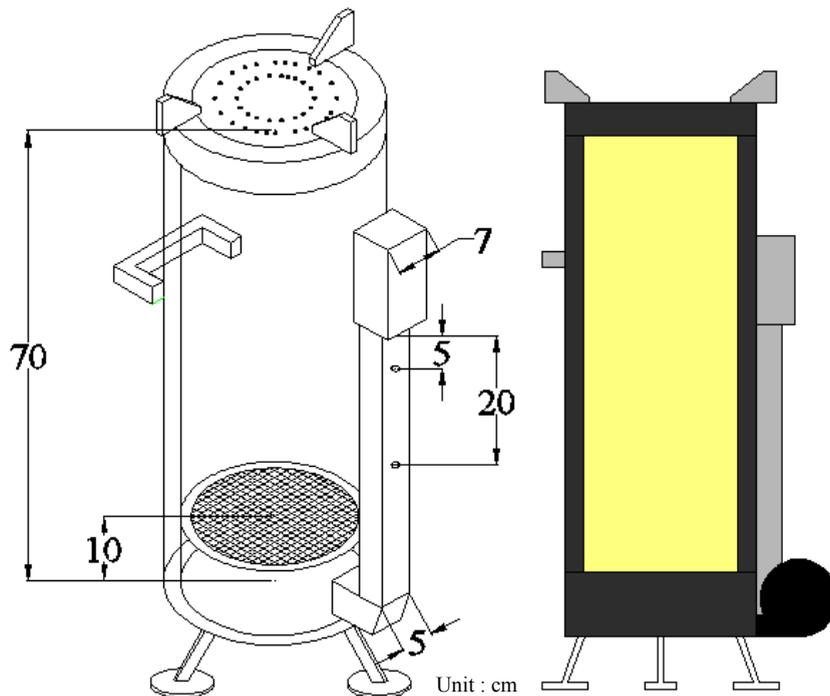


Fig. 1. Schematic diagram of the TE-RSG

3. Results and Discussion

Fig. 2 presents the flaming temperature profile from the initiation until steady state gasification conditions were established. The rice husk was ignited at the top of the reduction zone. After about 13 min, heat propagated upwards and the flaming pyrolysis zone was formed. Indeed, the temperature at the heart of the fire reaches almost 700°C.

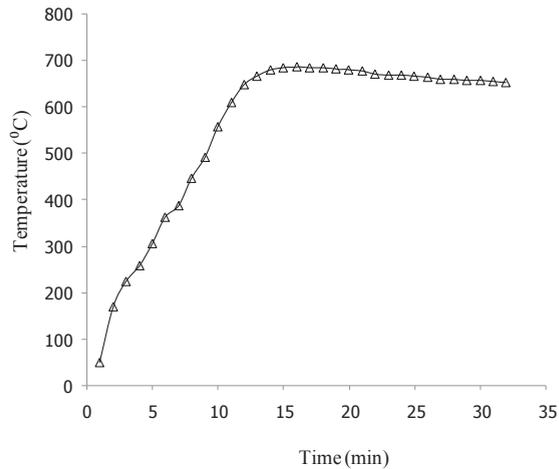


Fig. 2. Rice husk gasification temperature profile

Fig. 3 shows the hot and cold side temperatures and the corresponding electrical power for a half hour experiment. The TE modules produced a maximum electrical power of 3.9 W at a temperature difference of 60°C.

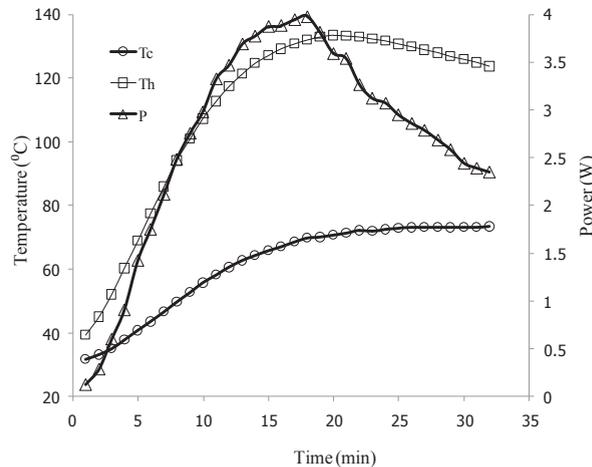


Fig. 3. The hot and cold side temperatures and power output of TE generator versus time

In order to verify the validity of the theoretical power model given by Eq. (3) of this paper, the calculation and the experimental result are compared, as shown in Fig. 4, with abscissa for temperature difference and ordinate as output electrical power. As can be seen in the temperature range shown in the figure, good agreement exists with those obtained in this paper, so the model calculation results are reliable. Through the adoption of blower can greatly promote system performance, the blower itself is driven by a power supply. In this case, a blower need a 4.5 W power to drive, that is to say, this experimental setup is a system unable to run by itself. Fortunately, there are still some methods, such as increasing TE modules in series, expanding heat sink surface, which could make the system work so effectively that it would self-power or even generate additional power.

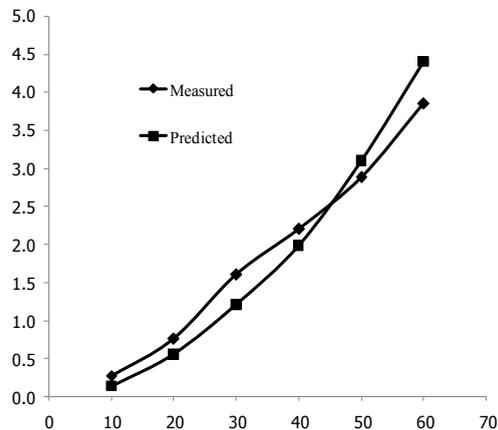


Fig. 4. Comparison between measurement and theoretical power model of TE generator

By using Eqs. (5), (7) and (8), the conversion, thermal and overall efficiencies were 2.01%, 20.5% and 25.79%, respectively. The conversion efficiency of this TE generator is only a few percent (2%). However, the conversion efficiency is not a prime consideration, when the waste heat utilized here is assumed to be no-cost.

4. Conclusion

An experimental TE generator suitable for electricity production in a rice husk gasifier stove has been presented. The comparison between a theoretic model and an experiment system proved the reasonability of this model. The results showed that the TE modules produced up to 3.9 W. The thermal and overall efficiencies of the TE-RSG were 20.5% and 25.79% respectively. Further work is planned to conduct a system level optimization study. Areas of concern will be energy efficiency and system power capacity. Cooling technologies such as liquid cooling and heat pipes operating in a more effective manner will also be examined for their potential for TE generator waste heat power recovery.

Acknowledgements

The help provided by Mr. ParinyaNuwaboot and Miss BuangurnSnepim for setting up the experiment is deeply acknowledged.

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