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Thermoelectric Power Generation from Biomass Cook Stove: A Waste Heat to Energy Conversion

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Abstract-This paper point out the present cooking conditions of rural India and provide a better option for cooking stove for off grid rural areas. The traditional biomass cook stove is associated with number of disadvantages like low efficiency, huge emissions of toxic gases like CO, risks of getting burn. To improve the efficiency of a traditional cook stove it is necessary to provide sufficient air inside the combustion chamber to increase the air-fuel ratio and to achieve complete combustion. For such requirements, mostly improved cook stoves are attached with a small fan. The fan is usually run by electricity or a battery. Most of the rural households do not have access to electricity, so the concept of fan driven improved cook stove fails in those areas. To run a fan off grid, the waste heat from the cook stove is utilized to convert into electricity with the help of a thermoelectric generator. The waste heat of the cook stove is utilized for heating one side of the thermoelectric generator and the other side of thermoelectric generator is cooled by natural or forced convection of air to generate sufficient amount of energy to power a fan for the cook stove. The power generated can also be used for lighting and charging mobile phone.

Keywords-Thermoelectric power generator; Module; TE module; Seebeck cells; Thermoelectricity; Biomass stove; Thermal Energy

I. INTRODUCTION

Biomass is the primary fuel for cooking in rural areas of India. People still rely on natural resources like wood, cow dung, agricultural waste as fuel and built the cook stove with bricks and clay, which gives an investment free cooking. Due to lower efficiency of traditional cook stoves, it results in inefficient use of scarce fuel-wood supplies. Deforestation is increasing in a very alarming rate which is resulting in environmental disturbance. Traditional cook stoves also results in high emissions of air pollutants and the smoke emanating from these cook stoves also causes acute respiratory infection (ARI). In rural household, still people use traditional three stone cook stoves made of brick and clay and biomass/wood as fuel. Most of the houses are without electricity. Only a fraction of the houses in typical "electrified". Few Indian villages have acquired domestic connections for electric lighting; the remaining houses depend on kerosene lamps and candles. In India energy consumption per capita is 631 kWh and the average power per capita (watts per person) is 50.5W which is very low as compared to developed countries. In rural India 400 million (57% of population) is without access to electricity. The cook stove that is presented can provide 5-10W to cover basic needs of the people such as lighting and mobile charging to the low income populations living mostly in rural areas. The TEG modules integrated with cook stove are an essential and interesting option to provide electricity. The aim is to study the feasibility of using TEG in the existing or new cook stove for generation of electricity. The expected power generation from the TEG is 5-10W to run a fan for complete combustion and also for basic needs like lighting, radio and charging cell phones as well as other small electronic devices. Hence, such cook stove can be equipped with a thermoelectric generator either in chimney or in the body of cook stove, which can be fed with hot flue gases from cook stove and ambient and can create the temperature difference.

II. PRINCIPLE

The principle behind TEG is to convert waste heat as heat source into electricity, which is regarded as totally green technology since the input energy is totally free of cost, and the output of the of the TEG module is of high importance due to its power generating feature and making the cook stove economically viable. On the advent of semiconductor material science the thermoelectric generation practical applications got high emphasis of conversion of waste heat into electricity. The features like reliability and ruggedness of semiconductor material that came from solid state function has made this technology more viable and useful.

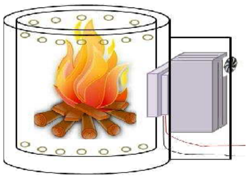

Fig.1. Thermo Electric Generator

In 1821, Thomas J. Seebeck discovered that a potential difference could be produced by a circuit made from two dissimilar wires when one of the junctions was heated. This is called Seebeck effect. The emf is proportional to the temperature difference. The potential difference V = αΔT, where, ΔT = Tc and α is the Seebeck coefficient or thermopower expressed in and the sign of α is positive if emf tends to drive an electric current through wire A from the hot to cold junction. The components of thermoelectric modules comprise of two different semiconductor materials also known as Seebeck cells or thermo elements. The TEG module has many semiconductors thermoelements connected electrically in series to elevate the resulting voltage and due to the temperature difference between the walls of the plate energy is captured from thermally excited electrons. A single thermocouple comprises of two thermoelement, p-type and n-type. The themoelements of the n and p-semiconductors are connected thermally in parallel and electrically in series. After thirteen years of Seebeck effect discovery J .Peltier observed the second thermoelectric effect known as Peltier effect. According to Peltier effect the passage of an electric current through a thermocouple produces a small heating or cooling effect depending on its direction. The interdependency between Seebeck effect and Peltier effect was determined by W .Thomson later known as Thomson effect consists of reversible heating or cooling when there is both a flow of electric current and a temperature gradient.

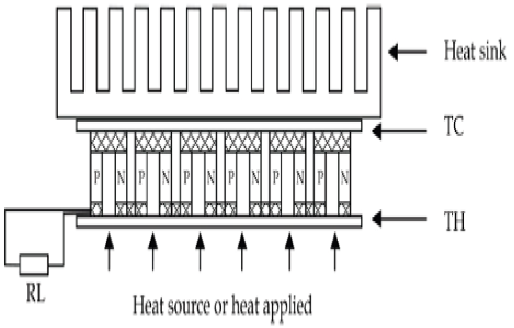

Fig.2. Schematic Diagram of TEG

III. THEORETICAL MODELLING OF TEG

The electrical resistance R and thermal conductance K of a thermocouple of length L and cross-sectional area A_p are defined respectively as

$$R = \frac{2\rho L}{Ap} \quad (1)$$

$$K = \frac{2\lambda Ap}{L} \quad (2)$$

The equations used to model the behavior of TEGs are based on the Seebeck, Fourier and Joule effects. Using the standard model and assuming one dimensional conduction through the module, the rate of heat supply QH and heat removal QC can be estimated at the hot and cold junctions as

$$Q_H = K(\Delta T) + (\alpha_{p,n})IT \quad (3)$$

$$Q_c = K(\Delta T) + (\alpha_{p,n})IT \quad (4)$$

Where $a_{p,n}$ is equal to $(a_p – a_n)$, and I is the current through the thermocouple. The electrical power generated by the TEG is given by the voltage and current across the external load, RL. By applying an energy balance across the module, the electrical power, P_{elec}, is equal to the difference between heat delivered and dissipated, or (QH _ QC).

$$P_{elec} = Q_H = Q_c = \alpha_{pn}\,(I\Delta T) - \quad (5)$$

Dividing across by the current gives the voltage:

$$V = \alpha_{pn}\,\Delta T - IR \qquad (6)$$

This gives voltage as a function of current for a given temperature difference. Using the standard model, the parameter a_{pn} is measured by open-circuiting (I = 0) the TEG, and measuring the applied temperature difference and corresponding voltage. By setting P_{elec} equal to I2RL in Eq. (5), the current can be found from

Figure 3 to be inserted

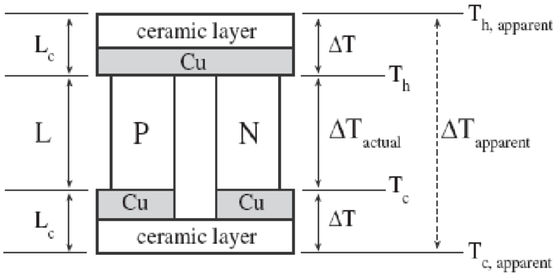

Fig. 3. Diagram of a single thermoelectric thermocouple.

$$\mathrm{I} = \frac{\alpha_{pn}\Delta T}{\mathrm{R_c+R}} \qquad (7)$$

Substituting Eq. (7) into Eq. (5) yields an expression for the electrical power:

$$P_{elec} = (\alpha_{pn}\,\Delta T)^2\,\frac{R_L}{(R_L+R)^2} \qquad (8)$$

A thermoelectric module generates maximum power when the module resistance matches the load resistance, i.e.

when RL = R

It follows that maximum power, P_{max}, is given by

$$P_{max} = \frac{(\alpha_{pn}\,\Delta T)^2}{4R} = \frac{A_p(\alpha_{pn}\,\Delta T)^2}{8\rho L} \qquad (9)$$

From Eqs. (8) and (9), the power produced by each thermocouple is approximately proportional to its cross-sectional area, and inversely proportional to its length. Therefore, power produced by an entire module is dependent on the number of couples N as well as the ratio of the load resistance to that of the TEG itself. Rowe and Min developed a theoretical model which also took into account the thermal and electrical contact resistances across the ceramic and conductive strips, but this model requires detailed knowledge of the contact parameters and the physical properties of the p–n pellets – information that is not always available from the manufacturer or supplier. For this study, an approach used by Hsu et al. is utilized. This method, known as the effective Seebeck coefficient model, calculates the Seebeck coefficient under actual load conditions. This is necessary since the TEG performs differently under open-circuit and load settings. To calculate the effective Seebeck coefficient a fixed temperature difference is applied across the TEG and the load resistance is varied. For the TEG used in this study, Fig. 4 plots the voltage vs. the current for a range of temperature differences. A linear relationship exists between the voltage and current. The 'effective' open-circuit voltage for each DT can be read from Fig. 4 by extrapolating the voltage corresponding to zero current (y-axis intercept). Similar to Eq. (6), the approach of Hsu et al. relates the voltage to the current:

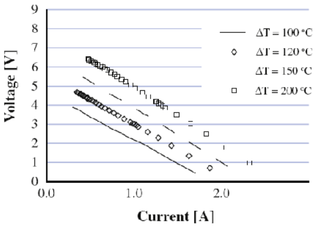

Fig. 4. Voltage vs. current for different DT for TEG

$$V = \alpha_{pn}\,\Delta T - IR = A\Delta T - BI \qquad (10)$$

For the open-circuit voltage (I = 0), ADT has a maximum value in which A can be defined as the effective Seebeck coefficient, a_{eff}.

$$\alpha_{eff} = \frac{V_{oc}}{\Delta T} \qquad (11)$$

The effective Seebeck coefficient specifies the TEG behavior under actual load conditions, indirectly taking into account the contact effects such as interfacial temperature drops which are not measured in this study. This results in a Seebeck coefficient of lesser magnitude than the theoretical value for a given thermocouple. The power may be calculated from the following equation:

$$P_{elec} = (\alpha_{eff}\ \Delta T)^2 \frac{R_L}{(R_L+R)^2} \quad (12)$$

Peltier module was selected to work as generator. The heat input at the hot side is 200˚C and cold side of 30˚C. It was observed that the open circuit voltage at required is 2.5 V but the current output is 220mA. Since the power output of the Peltier module is very low, a TE power generator is considered for the required operation. A 14 W module HZ-14 was taken for testing in an external environment. The external environment was made with a heater of temperature 600˚C which complements the temperature inside the cook stove. The module works on continuous 250˚C on hot side. The hot side temperature may extend upto 360˚C and intermittent 400˚C. The cold side temperature is to be maintained to 50˚C to get maximum power output from the module. The hot side is attached with 7 x 7 x 2 cm3 thick aluminium block.

The cold side is properly insulated with glass wool so that the radiation heat does not affect the temperature on the cold side. The temperatures on the hot side and the cold side were recorded continuously with K-type thermocouples. The aim of the experiment was to check the module performance by providing desired temperature difference. The first experiment was performed in ambient condition. The second experiment was done by forced air cooling using a fan mounted in top of the sink. It is observed that the power output of the HZ-14 module is very high as, but the individual voltage and current output was not sufficient as per our requirement. The voltage output of the HZ-14 is quite low and the current is very high. Hence, the HZ-9, a 9W TEG module was selected for prototype development. This module has a $V_{oc(max)}$ of 6.5V. The module was considered appropriate since it is relatively easier to boost the voltage where we get output voltage soon. The arrangement of TEG for running a fan of 5V is given in fig 5.

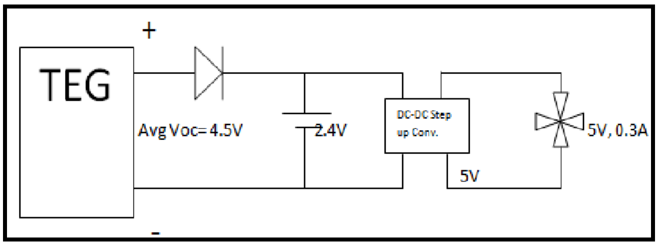

Fig.5. Circuit Diagram TEG arrangement

IV. CONCLUSION

This study describes the design of an energy efficient biomass cook stove for developing countries to accomplish the requirement for both, cook stoves itself and electricity generation. For a simple and low cost application of a rural cook stove, commercially available thermo electric modules are tested and the suitable module is determined for selection. The best power output of the system depends upon the difference in temperatures, through both sides of thermo electric module. A particular attention must be paid to the design of the heat exchangers for heat plate and cold sink. An idea about various parameters associated with the cook stove and TEG module can be viewed with the help of results represented in above graphs. This study shows how that the TE modules can be a used in cook stove in convenient way. In this scenario the best generator module is required but the heat exchanger can be manufactured and assembled in a local workshop. The voltage generated from the modules practically is small due to inability to maintain the temperature difference, hence a dc-dc converter have to be connected to boost output upto the required voltage. The produced electricity will run the fan of the cook stove to increase the combustion efficiency. Thus it will decrease the fuel consumption and the emission level. Extra electricity generated can also be utilized to power up LEDs or charging a mobile phone.

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