

Renewable Energy from Biomass Cookstoves for Off Grid Rural Areas

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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 cookstove 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 cookstove 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 cookstoves 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 cookstove fails in those areas. To run a fan off grid, the waste heat from the cookstove is utilized to convert into electricity with the help of a thermoelectric generator. The waste heat of the cookstove 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 cookstove. The power generated can also be used for lighting and charging mobile phone.

Keywords: thermoelectric generator (TEG), cookstove, thermocouple, waste heat.

1. Introduction

Around 2.5 billion people are still widely dependent on traditional cookstoves [1]. Due to lower efficiency of traditional cookstoves, 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 cookstoves also results in high emissions of air pollutants and the smoke emanating from these cookstoves also causes acute respiratory infection (ARI) [2]. In rural household, still people use traditional three stone cookstoves 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 cookstove 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 cookstoves are an essential and interesting option to provide electricity.

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 cookstove 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.

The advantages of TEG integrated with cookstove are stated as below:

- The flame heat from the cookstove serves as input to the TEG and no extra energy is required.

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- The TEG module is incorporated in the wall of the cookstove, unlike solar panel it do not require external electric link. The module is used to charge battery and run equipments.
- The TEG have no moving parts hence the operation is silent.
- TEG is very rugged and almost maintenance free; whole module is placed indoor and no moving parts only battery needs replacement when exhausted or can be recharged with module power continuously.
- TEG starts working as the cookstove is set on fire irrespective of day and night, windy or rainy weather unlike solar panels. Rechargeable batteries serve the purpose and need not be oversized batteries as used in solar panels to store energy.

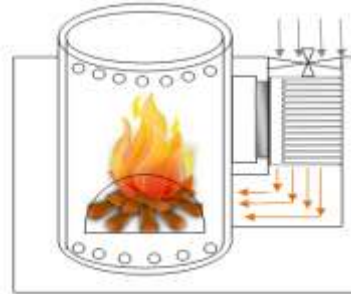


Fig. 1: Thermoelectric generator cookstove layout

The aim is to study the feasibility of using TEG in the existing or new cookstove 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 cookstoves can be equipped with a thermoelectric generator either in chimney or in the body of cookstove, which can be fed with hot flue gases from cookstove and ambient and can create the temperature difference.

2. Thermoelectric generation

2.1. TEG Fundamentals

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 $V = \alpha \Delta T$, where, $\Delta T = T_h - T_c$ and α is the Seebeck coefficient or thermopower expressed in $\mu\text{V}/\text{K}$ 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. TEG exhibits Seebeck effect for conversion of heat energy into electricity as shown in fig. 2. The TEG module has many semiconductors 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.

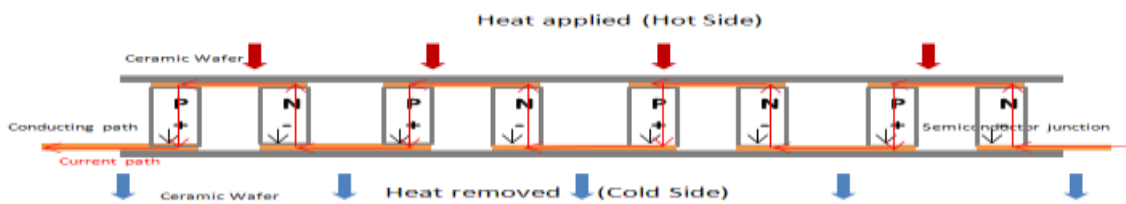


Fig. 2: Seebeck cells arrangement in a module.

The components of thermoelectric modules comprise of two different semiconductor materials also known as Seebeck cells. The legs of the n and p-semiconductors are connected thermally in parallel and electrically in series. As shown in above fig 2. Two ceramic wafers are placed in both faces of the TEG to provide insulation. Thermal grease (heat conductive paste) is applied to attach the wafers. Thermal Grease has higher thermal conductivity and is considered to be of a higher quality and include high performance levels during long periods of time, the ability to withstand higher temperatures and lower vaporization potential. The function of the semiconductor device is that when heat flows through the module, the N-type

material have highly negative charges i.e. excess of electrons and the P-type material has more positively charged ions i.e. excess of holes which results in electric flow of current. Most of them are alloys based on bismuth integrated with materials like tellurium, antimony and selenium which are generally operated in low temperatures to around 450K to 1300 K. The commercially available TEG for ambient air application and with reasonable price, is Bismuth Telluride Bi_2Te_3 . The efficiency of TEG is the function of temperature; it is called ‘goodness factor’ or ‘figure-of-merit’ of the thermocouple material $Z = \frac{\alpha^2 \sigma}{k}$, where Z is the electrical power factor, α , the Seebeck coefficient, σ the electrical conductivity and k is the total thermal conductivity. The FOM is considered as a dimensionless form, ZT where T is absolute temperature. The highest FOM for bismuth tellurium fabricated from p- and n- thermocouple is recorded around $2.0 \times 10^{-3} \text{K}^{-1}$

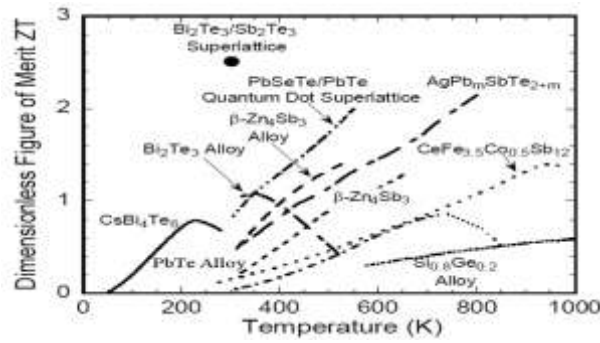


Fig. 3: Figure-of-Merit of a selection of materials [10]

2.2 Modeling of TEG performance (Theoretical)

A simple electrical circuit for a thermoelectric generator is shown in Figure 4. The thermoelectric couple is composed of two elements: a p-type and an n-type semiconductor. The heat flow at the hot junction involves three terms: the heat associated with the Seebeck effect: the half of joule heating, and the thermal conduction.

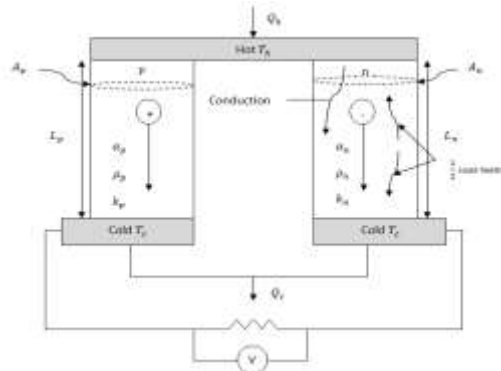


Fig. 4: Single thermocouple [10]

The similar materials here are interpreted as having the same base materials and the same geometry for thermoelectric elements. In this case, the analysis becomes simpler as $L_p = L_n = L$ and $A_p = A_n = A$, where L is the length of the thermoelement and A is the cross-sectional area of the thermoelement. Dissimilar materials are interpreted as both dissimilar materials and dissimilar geometry for the thermoelectric elements. Thermoelectric materials in commercial products are mostly dissimilar. Hence, the analysis for the dissimilar materials is considered. The electric circuit for which the Seebeck coefficient for a single thermocouple is defined as $\alpha = \alpha_p - \alpha_n$. The electrical resistance R and thermal conductance K of a thermocouple of a single thermocouple are defined respectively as $R = \frac{\rho_p L_p}{A_p} + \frac{\rho_n L_n}{A_n}$ and $K = \frac{k_p A_p}{L_p} + \frac{k_n A_n}{L_n}$.

The equations used to model the behavior of TEGs are based on the Seebeck, Fourier and Joule effects. The rate of heat supply Q_H and heat removal Q_C can be estimated at the hot and cold junctions as:

$$Q_H = K(\Delta T) + (\alpha_p - \alpha_n) I T_h - \frac{I^2 R}{2} \quad \text{and} \quad Q_C = K(\Delta T) + (\alpha_p - \alpha_n) I T_c - \frac{I^2 R}{2}$$

$\Delta T = T_h - T_c$ and I is the current through the thermocouple. The power generated by the TEG is given by the voltage and current across the external load, R_L . The power generated, $P = (Q_H - Q_C)$. This gives

voltage as a function of current for a given temperature difference. Using the standard model, the parameter $(\alpha_p - \alpha_n)$ is measured by open-circuiting ($I = 0$) the TEG, and measuring the applied temperature difference and corresponding voltage. Since, P equal to $I R$, the voltage, current and power is given as $V = (\alpha_p - \alpha_n)(\Delta T)$; $I = \frac{(\alpha_p - \alpha_n)(\Delta T)}{R_L + R}$ and $P = \left(\frac{(\alpha_p - \alpha_n)(\Delta T)}{R_L + R}\right)^2 R_L$. A thermoelectric module generates maximum power when the module resistance matches the load resistance, i.e. when $R_L = R$. It follows that maximum power, $P_{\max} = \frac{(\alpha_p - \alpha_n)(\Delta T)^2}{4R} = \frac{(\alpha_p - \alpha_n)(\Delta T)^2 A}{8\rho L}$.

The power produced by each thermocouple is approximately proportional to its cross-sectional area, and inversely proportional to its length. Hence, the power produced by the TEG is entirely dependent on the number of couples N and the ratio of the TEG itself. The method utilized is known as Seebeck co-efficient model, which calculates the Seebeck co-efficient under actual load conditions. This is considered since TEG operates differently in open circuit and on load conditions. The conversion efficiency is of a TEG is defined as the ratio of power generated by the load is to rate of heat supply $\eta_t = \frac{I^2 R_L}{K(\Delta T) + (\alpha_p - \alpha_n) I T_h - \frac{I^2 R}{2}}$. ie useful power reaches its maximum value when load resistance is equal to the generator resistance. However, even if there were no loss of heat through thermal conduction, the efficiency could then never exceed 50%. An increase in the load resistance reduces the power output but increases the efficiency [10].

3. Results

All the parameters of a TEG depend on temperature difference. The peltier coolers can also work as power generators (proposed by D.M Rowe and Min) [14]. The heat from the cookstove (approx. 600°C) is high enough to attenuate the materials and the conductive path between the junctions of the semiconductors. The TEG made of PbTe and SiGe is more reliable for high heat application. Another option is to use so-called type-II bismuth telluride based modules specifically designed to withstand operation up to about 230°C . Hi-Z/USA (e.g HZ-14/HZ-9) [15]. These modules are larger in size and have no insulating layers at the hot and cold ends but have insulation between the p and n junctions. The power produced per module higher mostly due to the large cross section area ($5.81\text{cm} \times 5.81\text{cm} \times 0.46\text{cm}$) with 98 thermoelements. For better insulation ceramic wafers are attached to the TEG with the help of heat conductive grease. The heat is collected in an aluminium plate of 1 cm thick placed on the outer chamber of the cookstove where the average temperature is 250°C . The results of a HZ-14 module are presented in the following graphs presenting different parameter variation with temperature.

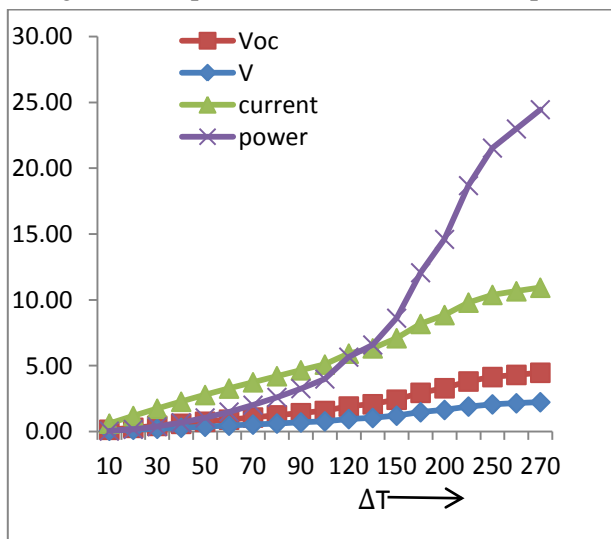


Fig. 5: Variation of open circuit voltage, load voltage, current, and power with differential temperature

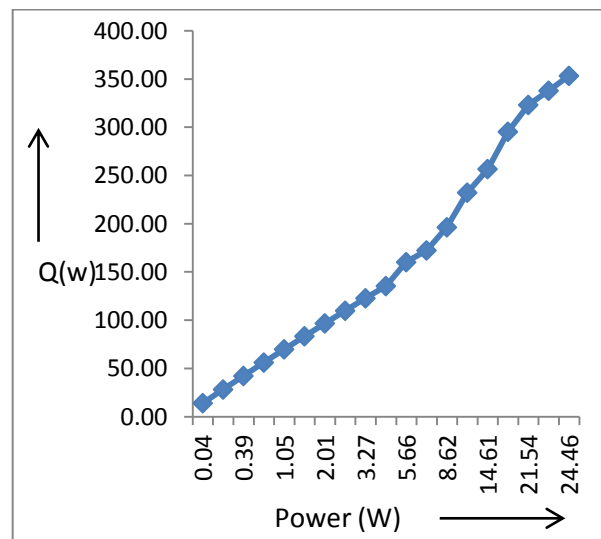


Fig. 6: Power generated with rise in heat flux.

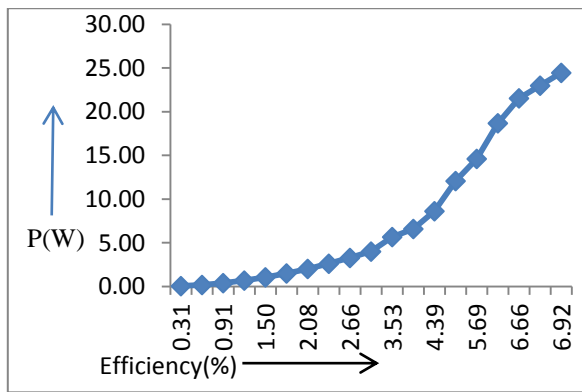


Fig.7: Rise in power increases efficiency

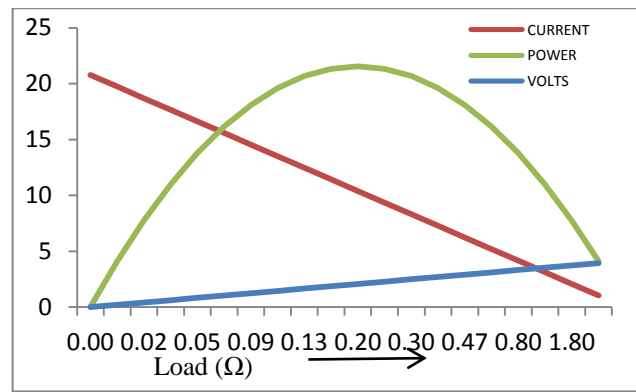


Fig. 8: comparison of I (amps), P(W) and V(volts) with different loads

4. Conclusion

This study describes the design of an energy efficient biomass cookstove for developing countries to accomplish the requirement for both, cookstoves itself and electricity generation. For a simple and low cost application of a rural cookstove, 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 cookstove 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 cookstoves 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 cookstove 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.

5. References

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