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ANALYSIS THE EFFECTIVENESS OF THERMOELECTRIC POWER GENERATION USING WASTE HEAT RECOVERY

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Abstract - Non-renewable energy resources, which account for about 85% of worlds' energy (68% fossil fuels are used for electric power generation), are getting exhausted rapidly. As predicted by the Institute of Sustainable Energy Policies, by the year 2050, only 33% of non-renewable energy resources will be available for electric power generation. Hence, to meet the required demand, the remaining 67% has to be replaced by renewable energy sources. This demand in electric power generation has to be met by a pollution free, low-cost, clean energy resource, which is the need of the hour. The present research targets towards two main applications for generating power using the biomass energy based resources. They are domestic based application – burning biomass wood and utilizing the heat for generating power, industrial based application – combustion of gasified de-oiled Pongamia cake and utilizing the heat energy for generating powerIn order to achieve the proposed target, initially, the theoretical modeling on the performance of (Bi_2Te_3-*PbTe*) hybrid thermoelectric generator (*TEG*) composed of *n-type* Bismuth Telluride - *p-type* Lead Telluride semiconductor materials has been done. The effect of different performance parameters on the maximum conversion and power efficiencies have been theoretically analyzed by varying the hot side temperature.

***Key Words*:** Hybrid Thermoelectric Generator, Electric Power Generation, Graphene Nanoparticles.

1.INTRODUCTION

As the need for pollution free and economical electric power generation increases, researchers have resorted to various green and clean power generation techniques since the mid 1980s. The significant increase in the number of research articles dedicated to this subject thus far shows a noticeable growth along with the importance of thermoelectric technology. The Over the past 17 years, many researchers have worked in the area of thermoelectric generators. The number of publications (with respect to the year of publication) on Bismuth Telluride and Lead Telluride thermoelectric generators. Focusing on the thermoelectric power generation experimentally, several existing published articles which involve the use of recovered waste heat are discussed in the following sections. A survey of literature reveals that some research works have been carried out using thermoelectric generators at national and international levels. However, by and large, it is observed that this is a virgin area to carry out research studies

2. BIOMASS WASTE MANAGEMENT

In recent days, waste management plays an important role in managing waste right from its collection to the final disposal. Biomass waste comprises of municipal solid waste such as door-to-door collection of organic and inorganic waste, agro-based and bagasse based waste such as waste from edible and nonedible energy crops, wood waste such as dry leaves, twigs, saw-dust, wooden pellets, etc. and human and animal manure.

As per Planning Commission, Government of India, 2003, non-edible oil from *Jatropha* (*Jatropha Curcas*) and *Karanja* (*Pongamia Pinnata*) plants are recognized as main resource for biodiesel production in India. About two tons of oil seeds are required to generate one ton of bio-diesel. Radhakrishnan (2003) estimated that 145 kilometric tons of *Pongamia* de-oiled seed cake are generated every year in India. These de-oiled cakes can neither be used as fertilizer for agricultural lands nor as cattle feed owing to its toxicity. Due to the acidic nature of the de-oiled cakes, usage of these cakes as biomass based resources is considered to be the best approach for environmental, energy and economic benefits rather than dumping it as waste in barren land. Chandra et al. (2009) predicted that in near future, production of non-edible *Jatropha* (*Jatropha Curcas*) and *Karanja* (*Pongamia*

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Pinnata) plants and their usage for bio-diesel production is going to increase tremendously. Hence, collection and disposal of the de-oiled cakes will be of huge concern. The only suggested method for disposal of these de-oiled cakes is generation of "syngas" through gasification process. Gasification of de-oiled *Pongamia* cake produces gas products with higher energy content called "syngas". Syngas with various *H2/CO* compositions can be used for many downstream processes such as heat and electricity generation (Balat et al. 2009), synthetic natural gas production (Gassner et al. 2009) and *H2* production (Guoxin et al. 2009). If the syngas is rich in hydrogen content having a very high *H2/CO* molar ratio, it can be used for electric power production using fuel cells. If the ratio of *CO* and *H2* is around 1:2 it can be used as feedstock for Fischer-13 Tropsch Synthesis. If the gas is enriched with *CH4* it can be used as heating fuel.

3. THERMOELECTRIC GENERATORS

Thermoelectric generators (*TEG*) are capable of recovering waste heat energy as effective useful energy and play a major part in reduction of fossil fuel consumption. *TEGs* serve as a potential boon for small scale power production (Ismail et al. 2008). Several researchers have experimentally investigated the conversion of various harvested waste heat energy into useful electrical energy and a survey of their findings is as follows: Liu et al. (2014) carried out experiments on different semiconductor materials and concluded that a *Bi2Te3* semiconductor with less insulator plate thickness was not only economically feasible but also had the highest power cost ratio. A prototype employing thermoelectric modules to generate 500W electrical power at a temperature gradient of 80ºC was proposed. It was found that the overall expenses of a *TEG* system was lower than those of *PV* and wind power systems. Nuwayhid et al. (2005) developed and tested a low cost, high performance thermoelectric module fitted to the upper right hand corner side of a common domestic wooden stove. A maximum of 4.2W was obtained from a single *TEG* module at a temperature difference of 88ºC.

4. HEAT RECOVERY FROM BIOMASS WASTE

Biomass is a fuel that is obtained from organic waste materials such as agricultural crops - left behind organic matter from the edible and non-edible crops, compost and certain types of waste residues such as wood scraps, mill residuals and forest remains, municipal solid waste. Biomass conversion is the process of burning these organic materials and producing a renewable and sustainable energy resource for green energy production such as neutral carbon electricity or other forms of

power. This chapter deals with combustion of biomass wood and combustion and gasification of biomass crop – de-oiled *Pongamia Pinnata* seed cake and utilizing

the obtained waste heat energy for generating electric power using hybrid thermoelectric generators.

5. BIOMASS WOOD

A small set-up is fabricated with bricks to burn the biomass wood waste. In order to avert the heat loss through the walls of the set-up, a thin metal skirting is

placed at the inside surrounding the walls. Four k-type thermocouples were placed on the front, rear, left and right wall of the set-up and named as *T11*, *T33*, *T22* and *T44*.

The photographic view of the real-time temperature measurement is shown in Figure

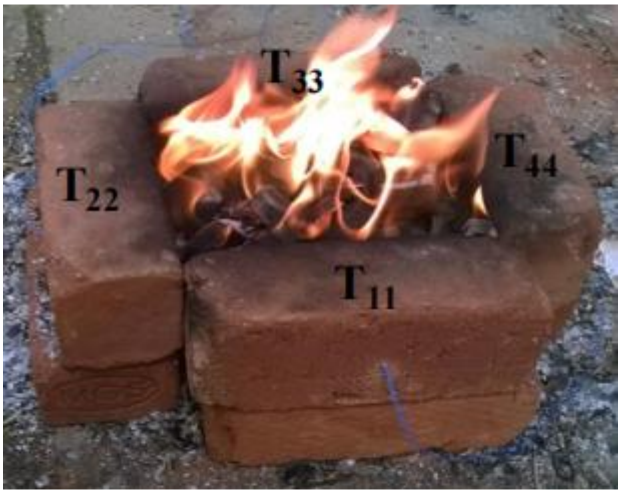

Fig.photographic view of the real-time temperature

6. GAS CHROMATOGRAPHY

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Gas chromatography is usually done to separate and analyze the different compounds that can be vaporized without any decomposition at higher temperatures. When the gas mixture is separated into individual components, it is easy to qualitate and quantitate the amount of the individual samples present in the mixture. Initially, the biomass waste is burnt in a reactor powered by a dimmerstat to analyze the gas samples and perform gas chromatography. On complete combustion, the combusted gases are collected in a bladder through a gas tube. The football bladder is then connected to the gas chromatograph for gas separation and further analysis.

The gas samples were analyzed using *SHIMADZU GC-2014* equipped with *TCD* detector and shin carbon *ST* column (100/120 mesh, 2m and 1mm I.D). Nitrogen is

used as the carrier gas and the flow rate is maintained at 10ml/min. The nitrogen gas is passed through the purifier before entering in *GC* and gas sample (about 0.5ml) is injected into the injection port using a gas sampler. The gas samples are vaporized in the injection port. The vaporized gases (solutes) are transferred to the column using the carrier gas. The column is usually placed in a temperature controlled oven and the oven temperature is kept at 40ºC for 3 minutes and then raised to 250ºC at a rate of 8ºC/min and then the same temperature is maintained for about 10 minutes. Now, the solutes move through the column at different rates. The fastest moving solute leaves the column first pursued by the other solutes in the consequent order. The standard gas with known composition is used for calibration prior to the analysis of gas samples. The eluted solutes enter the heated detector. When a solute hits the detector, a signal is being generated. The size of the generated electronic signal is recorded using a data processor and a graph is plotted against the elapsed time to create a chromatogram.

7. THEORETICAL ANALYSIS OF HYBRID THERMOELECTRIC GENERATORS

A theoretical model is a description of a system using mathematical notions and language. The process of developing a theoretical model is termed as theoretical modeling. In this chapter, theoretical modeling has been done to study the effect of various components of the system and to predict their performance under different environments. Based on the results obtained from the theoretical modeling of the hybrid thermoelectric system, the input parameters at which maximum output is obtained at different load conditions are chosen for carrying out further experimental work.

8. ONE-DIMENSIONAL STEADY STATE ANALYSIS

Thermoelectric generators (*TEGs*) are solid-state semiconductor devices that convert direct heat into electricity as long as the hot side is at a higher temperature than the cold side. The thermoelectric (*TE*) effect includes three individually identified effects: the *Seebeck* effect, *Peltier* effect and *Thomson* effect.

A typical thermoelectric module consists of a large number of *n-type* and *p-type* pellets connected together by a metal plate through soldering. Conversion of temperature difference directly into electricity is termed as *"Seebeck effect*". When current flows through a junction between two conductors, heat is either generated or removed at the junction. This is termed as "*Peltier* effect". The heating or cooling effect of a current carrying conductor with a temperature gradient is described by the "Thomson effect". The *TEG* working principle is based on the *TE* effect and the working of a single *TEG* couple is depicted in Figure 2.

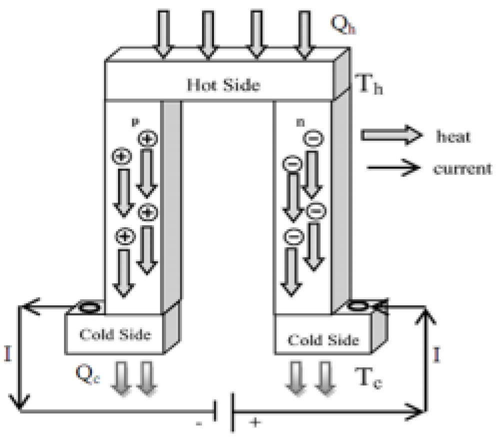

Fig:2 Seebeck Effect

8.1 PERFORMANCE EVALUATION

A hybrid thermoelectric power module (*TEG1-PB-12611-6.0*) composed of *n-type* Bismuth Telluride (*n-Bi2Te3*) and *p-type* Lead Telluride (*p-PbTe*)

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semiconductor material supplied by Thermal Electronics Corporation, Canada is considered for the analysis. The

main parameters considered for analysis include output voltage, output current, output power, maximum power output, open circuit voltage, *Seebeck* co-efficient,

electrical resistance, thermal conductance, figure of merit, efficiency, heat absorbed and heat removed based on maximum conversion and power efficiency. If the

temperature gradient across the thermoelectric module is higher, the electrical output will be higher. The load resistance also plays a major role in influencing the

output of the thermoelectric module.

Table 8.1 *TEG1-PB-12611-6.0* supplier specifications

Parameters Hybrid TEG

Model Number	TEG1-PB-12611-6.0
Composition	Bi2Te3 – PbTe
Dimension	56mm x 56mm
Hot side temperature	350ºC
Cold side temperature	30ºC
Open Circuit Voltage	9.2V
Matched Load Resistance	0.97 Ω
Matched Load output Voltage	4.6V
Matched Load output Current	4.7A
Matched Load output Power	21.7W
Heat flow across the module	≈ 310W
Heat flow density	≈ 9.88W/cm2

AC resistance measured under 27ºC @ 1000 Hz 0.42 ~ 0.52

The *TE* module is analyzed for different cold side temperatures with varying hot side temperatures. The load resistance was increased from a minimum upto 15Ω. Various graphs are drawn between output power, output voltage and output current with respect to load resistance for different values of cold side temperature, *Tc* = 30/50/80/100/150ºC

It was found that the *TE* module worked efficiently when the cold side temperature was maintained at 30ºC with varying hot side temperatures. This is because the output power is directly proportional to square of temperature difference and the load resistance

9. EXPERIMENTAL INVESTIGATION OF HYBRID THERMOELECTRIC GENERATORS

The primary objective of this work is to generate power using biomass waste heat by employing a hybrid thermoelectric system. In order to do this, an experimental test facility is designed and constructed. The experimental test facility consists of a *TEG* test-section with high accuracy measuring device for measuring hot-side temperature, cold-side temperature, water inlet and outlet temperature. A multi-channel data logger is used to record the signals automatically

from these devices. High accuracy voltmeters and ammeters are used for measuring the voltage and current at the input and output side. The post processing of the data is done using *MS EXCEL* for estimation of performance parameters such as temperature gradient across the hot and cold sides, output power, efficiency, figure of merit, electrical resistance and thermal conductance. The test facility is validated using the experimental results with solid copper block over hot side, synthetic oil as heating fluid with nanoparticles suspended in the concentration ratio of 0.01%, 0.03% and 0.05% against the published results. This chapter deals with the working principle of the of the test facility, measurement devices used in the facility, actual experimentation procedure, data reduction and uncertainty analysis of the study.

10. EXPERIMENTAL TEST RIG

To study in detail the performance of the hybrid *TEG* under various operating conditions, an experimental set-up is constructed. The set-up consists of a heater, copper block, hybrid *TEG*, heat sink, electric load and a data acquisition unit. The hybrid *TEG* module is held tightly between the solid copper block embedded with cartridge heaters on the hot side and a heat exchanger unit on the

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cold side of the hybrid *TEG* module by the compression method. The clamping is done using stainless steel screws on either side of the hybrid *TEG*. A pressure load

of 0.176kg/cm2 is applied to hold tightly the hybrid *TEG* module in order to reduce the thermal contact effect. The chilled water unit and the heating (copper) block were placed on either side of the hybrid *TEG* to maintain a temperature difference across the hybrid

TEG. The screws were tightened evenly in small increments. The design, screw

diameter, number of screws and the torque per screw are chosen based on the power module installation notes supplied by Thermal Electronics Corporation, The hot side of the hybrid *TEG* is heated using two cartridge heaters embedded into the copper blocks, controlled by a dimmerstat. The temperature gradient across the hybrid *TEG* is varied by adjusting the power input to the cartridge heaters. Water is used as the coolant/cooling fluid. A chilled water unit with an inlet and outlet port is appended to the cold side of the hybrid *TEG* module

to remove the residual heat energy. The interface between the module, copper block and the chiller unit were covered using thermal grease to diminish the negative effect of the air-gap. The ceramic covers of the *TEG* module are equipped with inbuilt graphite sheets which eliminates the need for thermal interface material. But, a small amount of thermal grease is applied as an interface material to replace the air-gaps, if present. The whole unit is insulated using ceramic wool. A constant

temperature bath is used to maintain the temperature of the cooling water constant at 30ºC. The cooling water gains heat from the hybrid *TEG* and returns to the bath

at a higher temperature. The flow rate of the coolant is controlled using a flow control valve. The flow rates are measured by direct weighing of the fluid and the measuring error of the flow rate is found to be less than 1.5%. A rheostat is connected as an external load to the hybrid *TEG* module to measure the output voltage and current of the module by varying the load resistance, *RL* in the 0 to 2Ω ranges. The temperature sensors are carefully drawn out from the test section and are connected to the data logger (Agilent 34972A). The required data were recorded using a data acquisition unit for further processing.

TEST SECTION

10.1 Copper Block

The test section consists of a hybrid thermoelectric generator of dimensions 56mm x 56mm with the hot side of the *TEG* placed over a solid copper block of dimensions 56mm x 56mm x 14mm. Cartridge heaters are inserted by drilling holes into the solid copper block to provide the input heat energy. The cartridge heaters are controlled using a dimmerstat. The heat sink/chiller unit is a hollow copper block of dimension 56mm x 56mm x 56mm placed over the cold side of the thermoelectric generator. The hybrid *TEG* is clamped tightly using stainless screws between the copper block and the chiller unit by compression method. This is done to reduce the thermal contact effect and also maintain a

temperature gradient across the hybrid *TEG*. The design, screw diameter, number of screws and the torque per screw are chosen based on the power module installation

notes supplied by Thermal Electronics Corporation, Canada. A chilled water unit with an inlet and outlet port as appended to the cold side of the hybrid *TEG* module

in order to remove the residual heat energy.

A temperature gradient is maintained across the hybrid *TEG* by varying the input given to the thermoelectric generator. The hot and cold temperatures were monitored using micro *T*-type thermocouples placed between solid copper blockhybrid *TEG* (hot side) and hybrid *TEG* (cold side)-chiller unit. Thermal grease is

used as the interface material between the hybrid *TEG* module, solid copper block and chiller unit to reduce the negative effect of the air-gap. The entire length of the

test section is wound using high quality glass wool and ceramic wool of thermal conductivity, k = 0.3W/m/K. This ensures that there is no heat interaction with the

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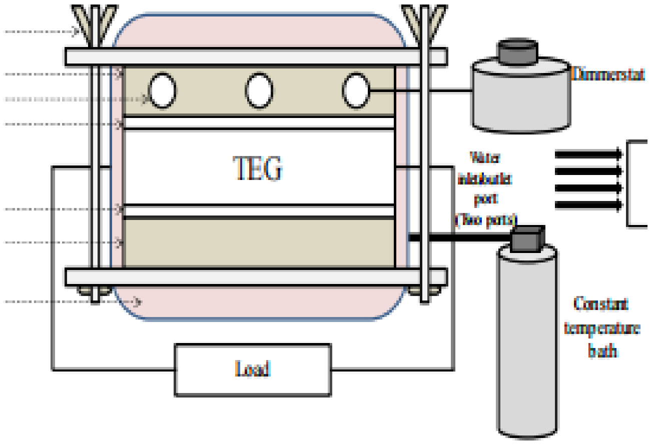

atmosphere. A constant temperature bath is used to maintain the water temperature constant at 30ºC. A rheostat is connected as an external load to the hybrid *TEG* module to measure the output voltage and current of the module by varying the load resistance, *RL* between 0 to 2Ω. The required data were recorded using a data acquisition unit for further processing. The schematic diagram of the test section is given in Figure3.

10.2 Thermocouple positioning

The hot side and cold side temperatures are monitored using five micro *T-type* thermocouples (*T1*, *T2*, *T3*, *T4*, *T5*). The details on how the temperature probes are applied to a water cooled system is given in Figure 5.3. Thermocouple, *T1* is used to measure the heater temperature *(TH)* and is placed inside the copper block

by drilling holes onto it. Thermocouple, *T2* is placed between the copper block and the hot side of the hybrid *TEG* module to measure the hot side temperature *(Th)*.

Thermocouple, *T3* is placed between the cold side of the hybrid *TEG* module and the cold side heat exchanger unit to measure the cold side temperature *(Tc)*. Thermocouples, *T4* and *T5* are used to measure the water inlet *(Tw1)* and outlet temperatures *(Tw2)*.

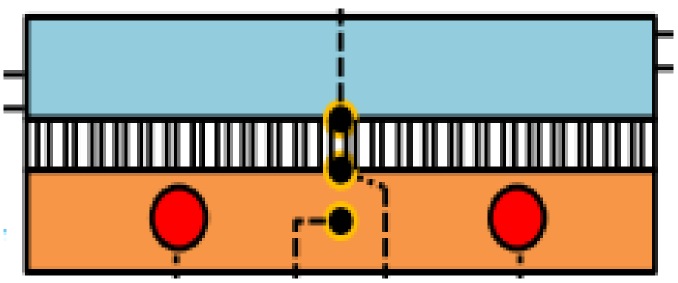

Fig:3 Thermocouple positioning

11. RESULTS AND DISCUSSION

The experiments conducted in the present study are divided into three main parts namely, Experimental study of the performance parameters of the hybrid

thermoelectric generator (*TEG1-PB-12611-6.0*) with (1) copper block , (2) synthetic oil, (3) synthetic oil with nanoparticles suspension. The above results are compiled and discussed in this chapter. In the first part, the effect of flow rate of the coolant, variation in temperature gradient on the performance of three hybrid *TEG*s connected in series under various temperature and loading conditions are presented and discussed. In the second part, Experimental investigation using *Therminol-55* as heat transfer fluid over the hot side of the hybrid *TEG* with water and air cooled techniques employed over the cold side is done and the results are discussed in detail. In the third part, *Therminol-55* with graphene nanoparticles suspended in various concentrations such as 0.01%, 0.03% and 0.05% are used as heat transfer fluid and the enhancement in output power and efficiency due to nanoparticles suspension in synthetic oil is demonstrated and the results presented. Experiments are conducted till 250ºC hot side temperature. But, experiments can be performed

till 350ºC hot side temperature. Hence, using the sample experimental values, the artificial neural networks tool in *MATLAB* is utilized and the performance of the hybrid thermoelectric generator upto a hot side temperature of 250ºC and at ambient cold side a condition (about 30ºC) is analyzed. The simulated *ANN*72 parameters are compared with sample experimental results and based on the closeness between both the methodologies; the performance of the thermoelectric system (upto a maximum temperature gradient of 320ºC) is estimated even without

actually performing the experiments.

12. CONCLUSION AND FUTURE WORK

This dissertation envisages the generation of thermoelectric power from Biomass based wastes using hybrid thermoelectric generators. A survey of published literature has indicated the need for the study of power generation using biomass based waste heat, preferably, a solution to Biomass waste management and small scale electricity production. Hence, the present work targets towards two main applications - Domestic based application by burning biomass wood and utilizing the heat energy for generating power; Industrial based application – combustion of gasified de-oiled *Pongamia* cake and utilizing the heat energy for generating power. Based on the observations from this study, the following conclusions are drawn:

12.1 HEAT RECOVERY FROM BIOMASS WASTE

Now-a-days, waste management plays a major role in managing waste right from the instigation to its final disposal. In order to have effective waste management and proper utilization of the recovered biomass waste heat, the following conclusions are drawn:

- The de-oiled seed cakes of *Pongamia Pinnata* can neither be used as animal feed or fertilizer due to its bitterness, acidic and toxic nature. It is, therefore, recommended to use this de-oiled seed cake for “syngas” generation.Gasification of the de-oiled *Pongamia* seed cake resulted in production of “syngas”. Heat energy produced on combustion of generated “syngas” is used for direct conversion of heat into electricity using a thermoelectric generator.

- The slag left behind gasification process was mixed with cow-dung and used as an organic fertilizer.

- Proximate and Ultimate analysis of *Pongamia* de oiled seed cake showed the presence of high amount of carbon content which on combustion resulted in higher energy content biomass waste heat with a temperature of about 250 - 350ºC.

- Gas chromatography of biomass based wood waste and crop waste was done and chromatogram results showed that the percentage concentration of gas components (mainly *CO* and *CO2*) was found to be present well within the standards

13. SCOPE FOR FUTURE WORK

The performance of hybrid thermoelectric generators with solid copper block and hollow copper block, filled with synthetic oil and synthetic oil-graphene nanofluid under 0.01%, 0.03% and 0.05% concentrations as the heat transfer medium is theoretically and experimentally analyzed. In the previous studies by other researchers, power generation using ordinary *Bi2Te3* modules has received the maximum attention. Till date, no experiments have been carried out using hybrid thermoelectric generators. Moreover, no published literature suggests the use of synthetic oil as heat transfer medium in thermoelectric generators. Also, this research work suggests a solution to disposal of de-oiled *Pongamia* seedcake, thereby playing an important role in Biomass Waste Management. Practically implementing the suggested solutions for effective power generation from Biomass waste using hybrid thermoelectric generators should receive greater attention in the near future.

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