DEVELOPMENT OF COST EFFECTIVE SOLAR THERMOELECTRIC COGENERATOR WITH EVACUATED TUBE SOLAR COLLECTOR

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ABSTRACT

The evacuated tube solar collectors provide better heat collection efficiency since it reduces conduction and convection heat transfer losses to the environment. A thermoelectric generator is a solid state electric power generation technology, based on the Seebeck effect that converts heat directly into electricity without employing any moving parts. In this work, the concept of thermoelectric generation technology has been utilized for clean electric power generation coupled with the evacuated tube solar collectors. The paper presents development, experimentation and performance of the proposed cogeneration system. It provides electric power and hot water. The experimentation test has shown excellent result. The proposed solar thermoelectric co-generator with evacuated tube solar collectors has the potential to provide electric power for residential and remote area applications, with zero emissions.

***Keywords:* Evacuated Tube, Seebeck Effect, Solar Collectors, Peltier Effect, Thermoelectric Co-Generator**

I INTRODUCTION

Energy is one of the major inputs for the economic development of any country. In case of developing countries, energy sector assumes a critical importance in view of the ever-increasing energy needs requiring huge investments to meet them. The per capita energy consumption is too low for India as compared to developed countries. It is just 4% of USA and 20% of the world average. The per capita consumption is likely to grow in India with growth in economy thus increasing the energy demand [19].

The demographics of India are inclusive of the second most populous country in the world, with over 1.21 billion people (2011 census), more than a sixth of the world's population. India is projected to be the world's most populous country by 2025; its population growth rate is 1.41%. Worldwide scenario on the situation of population growth is nothing but the same. Current projections show a continued increase in population in the near future, with the global population expected to reach between 7.5 and 10.5 billion by 2050 [20]. This analysis of the global population growth and energy consumption is also associated with increasing load on non-renewable energy resources, the conventional fossil fuels such as coal, oil and gas, which are likely to deplete with time and the use of which is also hazardous to environment.

A major portion of the world's electricity production is still fossil-fuel based, but higher fossil-fuel prices together with increasing concerns over energy security and climate change will boost the share of renewable-based electricity in the future years (world energy outlook fact sheet 2009). Heat energy also forms a large fraction of the total energy consumption as the industrial process heat (IPH) as well as for household such as bathing, washing, food processing etc. The processes such as boiling distillation and polymerization that require heat input are common in chemical industries. This heat is often supplied as hot water in the range from 20 to 260 ^{0}C. [21]

1.1 Evacuated-Tube Solar Collector

The evacuated-tube solar collector has become the most popular design for solar water heating in the past decades. Each evacuated tube consists of two glass tubes made from extremely strong borosilicate glass. The outer tube is transparent allowing light rays to pass through with minimal reflection. The inner tube is coated with a special selective, which features excellent solar radiation absorption and minimal reflection properties. The top of the two tubes is fused together and the air contained in the space between the two layers of glass is pumped out, forming a vacuum. A vacuum is an excellent insulator against heat loss, and so evacuated tubes are able to operate very efficiently when there is a big difference between the inside of the tube and the outside ambient air.

The glass evacuated-tube solar collectors have better thermal efficiencies at the higher temperature than the conventional flat-plate solar collectors and they are suitable for applications at the temperature of above 80 ^{0}C. The water temperature is usually required in the range of 35 to 50 ^{0}C for domestic hot water or space heating. Thus, an evacuated tube solar collector may be used at a higher temperature to drive a combined water heating and power generation. One attractive option is to incorporate the evacuated tube solar collectors with thermoelectric modules to produce additional electricity besides its hot water production [8].

1.2 Thermoelectric Power Generator

A thermoelectric device is in essence a simple heat engine which converts heat energy directly into electricity or the reverse. Its operation is based on the three well known interrelated phenomenon of Seebeck, Peltier and Thomson effects.

In its simplest form a thermoelectric generator is formed of p-type and n-type pellets connected electrically in series and thermally in parallel, as shown in figure 1. The hot junction temperature is maintained by a heat flux from a heat source while the cold junction temperature is maintained by a heat sink. The generator operates as an electron-gas Rankine cycle, where the energy level of the electrons is raised at the hot junction and lowered at the cold junction. Due to the temperature difference, charge carriers with energy level clear tile energy level at the hot end will be easily excited to a high energy level and can lower their energies by diffusing to the cold end. Similarly those at the cold end can diffuse toward the hot end at a rate dependent on their energies. Thus, a net current of charge carriers will result. This flow will cause the charge carriers to pile up at one end of the element, usually the cold end, and thereby produces an electromotive force [22].

Compared with solar heat driven mechanical power generation, thermoelectric modules are much more suitable for small-scale applications as they are reliable, light and compact, and have no mechanical moving parts. They are also friendly to the environment as no working fluid is used. [8]

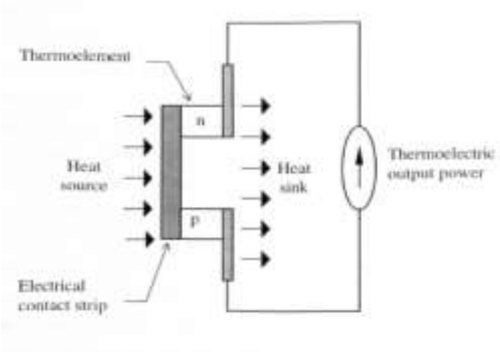


Figure 1: Working of thermoelectric devices

1.3 Selection of Thermoelectric Modules

The TEG modules are selected considering few factors such as dimensions, optimum temperature range, availability of the product etc. The TEG module used in the current work was supplied by Nissan India limited, Banglore. The model no. of the module is TEC1-12708T125. The module material is Bismuth Telluride of dimension 50×50×4.50mm. Each module contains 127 junctions and 254 thermal elements that are formulated for optimum Seebeck effect. The thermal elements in the module are thermally and electrically in series combination for maximum Seebeck coefficient. Perimeter is sealed for moisture protection. TEG module can be operated in the temperature range -60 deg C to +180 deg C.

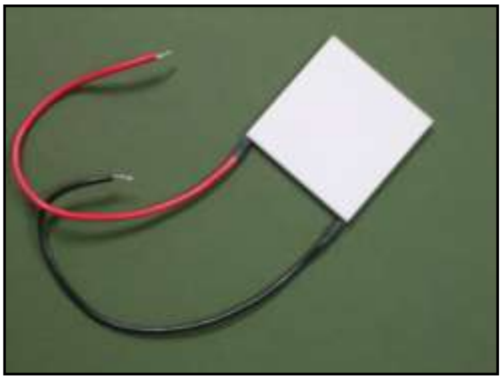


Figure 2: Typical thermoelectric module

II EXPERIMENTAL SET UP

This research work is aimed at capture the solar energy and converts the maximum possible received energy into the electrical energy and thermal energy. The evacuated tube solar collectors in 10 nos. are used to receive the solar radiation. The aluminum rods are inserted into the evacuated tube solar collectors gets heated due to solar energy. These aluminum rods heat the hot plate attached at other end of the rod. This hot plate provides the hot surface to the thermoelectric module. The water is placed into the tank bottom plate serves the purpose of cold side. Thus temperature difference is created across the thermoelectric modules resulting into the electrical output. Ten nos. of thermoelectric modules connected in series are used in this project. The heat from hot plate is passed through the modules to the tank water. The water in the tank keeps modules cool by natural circulation which gets heated over time and can be used as hot water for household or industrial purposes. The electrical power produced can be stored in battery for use at night.

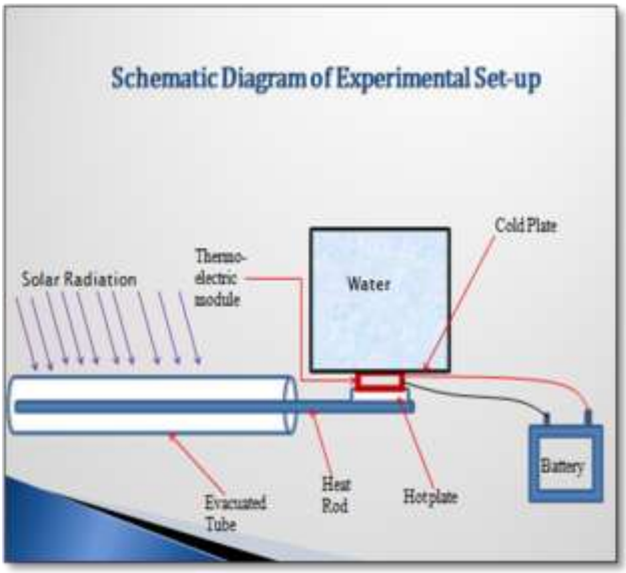


Figure 3: Schematic diagram of the experimental set up

Figure 4: Actual experimental set-up

For experimentation the project setup is placed at prominent place so as to receive direct solar. The modules are connected to the battery and electrical AC power supply extended for temperature measurement and voltmeter and ammeter. The water about fifty liters he filled in the tank. The reading of temperature at hot side, cold side and tank water are noted hourly along with voltage and ampere from 09:00hrs. to 17:00hrs. Following are the readings noted hourly during experimentation.

T_H, T_C : Temperatures at hot and cold ends of TEM respectively

T_W - Temperature of water in storage tank

dT - Temperature difference across the modules

V, I, P-- Voltage, current and power output from TEMs respectively.

The Experimental setup can be divided in different parts as follows,

1) Support structure
2) Heat rods and hot plate
3) Assembly of Thermoelectric Modules
4) Cooling arrangement

The proposed experimental set up work on the principle of, solar energy collection through evacuated tubes, conduction heat transfer in heat rods and natural convection heat transfer in cooling arrangement. The working of the experimental set up can be explained in details as follows,

2.1 The Support Structure

The design of the thermoelectric generator was started with main support structure, which is used to mount thermoelectric modules, the evacuated tube solar collector and the cooling water tank. In the present design support structure body, makes the indirect support hot side of the thermoelectric generator module. The support structure design in the thermoelectric power generator is quite critical because in a very short time the energy (heat) should transfer from source to hot side of the thermoelectric generator module also this design should be such that it should not affect the performance of the cooling arrangement at cold of the thermoelectric generator modules.

Figure 5: Support structure

In the present work the support structure is made out of the mild steel for strength and rigidity and durability of the structure considering the economy of the project work. The support structure is made such as to support the water tank, the evacuated tubes with the heat rods and the thermoelectric modules. As shown in the picture the right rectangular section is for the support of the water tank. The remaining section is occupied by the evacuated tubes with the heat rods and the thermoelectric modules.

The evacuated tubes are supported at two locations, first near open end and second at closed end of the evacuated tubes. For supporting the tube rods, special plates are designed with holes of diameter 64mm at both ends so as to accommodate the tube and the cushion material placed on the tube rods at the point of contact between glass and the metal of the support plate. The insulating material black puff is placed at support plate structure at closed end to protect the tip at the closed end of the evacuated tubes.

Specifications of the support structure:

Material	Mils Steel
Total Length	1800mm
Width	980mm
Height	30mm
Support Length for Tube Rods	1800mm
Closed End Support	50mm
Gap Between Tank and Tubes	50mm
Support Length for Tank	300mm

Table1:-Specifications of the support structure

2.2 Heat Rods and Hot Plate

In this project work the usually used Copper heat pipe is replaced by the aluminum heat rods considering the cost and availability of the copper heat pipes. The readymade straight rods available in market are used to solve the purpose by cutting them in desired length. The aluminum rods used are 12mm diameter and 2000mm in length. One end of the rods are inserted inside the tube, at other end the heat plate is welded. The heat plate is of the size 50*50mm same as the size of thermoelectric modules and thickness of the plate is 3mm. This plate serves the purpose of hot side of the thermoelectric modules.

Figure 6: Heat rods and hot plate

2.3 Assembly of Thermoelectric Modules

The arrangement of thermoelectric generator modules should be such that the thermoelectric generator module should get completely sandwiched between hot side and cold side and that plate should act continuous pressure on the module. In this project the thermoelectric generator modules are sandwiched between the heat plates, welded to the heat rod and the bottom surface of the tank. The studs are fitted in the tank bottom. The holes are drilled through the wooden plate used to fix the modules. The holes drilled in the tank for fitting the studs are properly sealed to avoid water leakage by using rubber and metal washer with the studs. The heat plate surfaces and the tank surfaces which serve as the hot and cold surface for the thermoelectric generator modules is grinded to get the surface finish. For assembly, the thermal grease is applied on the hot and cold surfaces. The thermoelectric generator modules then placed at the bottom of the tank with its cold side facing the surface. Then the heat rods with the heat plates are mounted on the thermoelectric generator modules with its hot side facing the heat plate surface. As all the modules are properly placed, the wooden plate is assembled below the heat plate so as to support the whole assembly with the help of the studs and the nuts. The nuts are then tightened strategically so as to apply even pressure on all the modules. The wooden plate is used for assembly of the modules to avoid any heat loss to from the heat plate and heat rod.

Figure 7(a,b): Assembly of thermoelectric modules

2.4 Cooling Arrangement

The cold side of the module is made with water tank bottom plate. The modules are sandwiched between hot side of the heat plate and cold side of water tank bottom plate. The heat dissipation system is made with water cooling arrangement. The tank with size 975*300*3000mm is designed to cool the modules. The tank is filled with water as the thermoelectric generator modules are attached to the bottom of the tank; they dissipate heat to the tank water through the contact surface and consequently get cooled. The tank is provided with studs to assemble the modules. The fins are provided at inner surface of the tank to facilitate the fast dissipation of heat from the modules.

Figure 8(a, b): Cooling Arrangement

III MEASUREMENTS

For experimentation different instruments were used. The varying elements are temperatures at different points, output voltage and current. The instruments used are listed as follows,

3.1 Thermocouples

For temperature measurement J-type thermocouples were used. The measuring temperature range of this type of thermocouple is in between 0-1200 K. 3 thermocouples are used to measure temperature at hot side temperature (T_h), one at cold side temperature (T_c), and one at tank water temperature (T_w).

3.2 Voltmeter and Ammeter

The output obtained here is Direct current type therefore digital DC Voltmeter and Ammeter is used to measure voltage and current respectively. Multimeter is also used for voltage and current measurements whenever required.

IV RESULT AND DISCUSSION

The experiment of thermoelectric power generator was carried out on the experimental set up discussed in previous section. The size of the TEM is 50 mm*50 mm*4.5 mm and composed by the matrix of 127 thermo elements which had a length of 1.5 mm. Each solar evacuated tube contains one heat rod and one TEM.

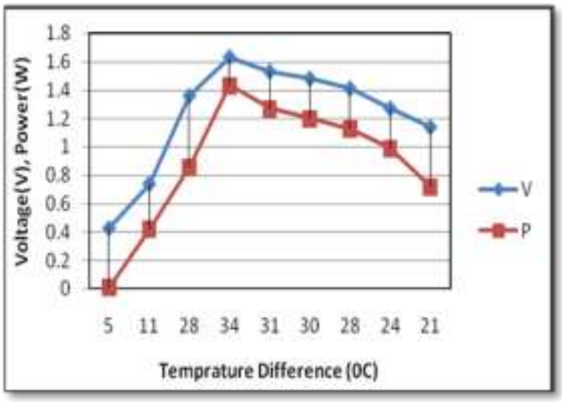
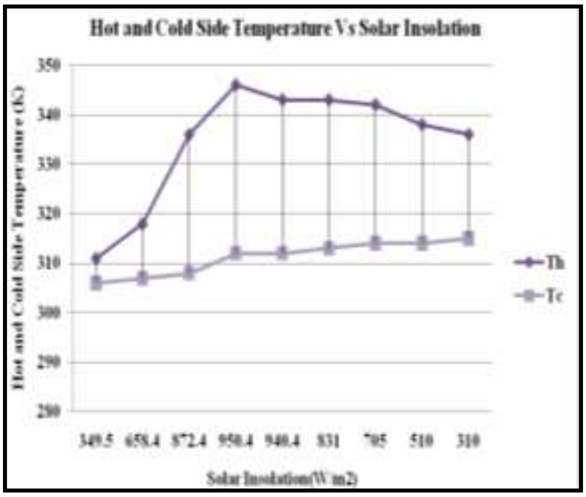


Figure 9: Voltage and electrical power as a function of temperature difference.

As shown in figure 9, voltage varies directly with temperature difference. The rate of voltage rise is high at beginning due to rapid increase in solar insolation and value of Seebeck coefficient [6]. The increase in voltage results in the increase in electrical power output from thermoelectric generator [9]. The output power increases from 0.0086 W at beginning, to the maximum value 1.4344 W at maximum temperature difference of 34 K. The rate of rise is high at beginning due to rapid increase in solar insolation. The drop in power output is gradual with drop in temperature difference.

`The hot side temperature is directly influenced by the solar insolation. From figure 10, it can be seen that both hot side (T_h) and cold side temperature (T_c) increases with increasing solar insolation, but the increase in Th is larger than that of Tc, causing difference between Th and Tc to increase. The maximum temperature difference of is observed at noon. Although the thermal losses to the surrounding atmosphere increases, the rate of increase in electrical power output is larger than the rate of increase in thermal losses. Therefore increased solar insolation promotes greater electrical power output and electrical efficiency [9].



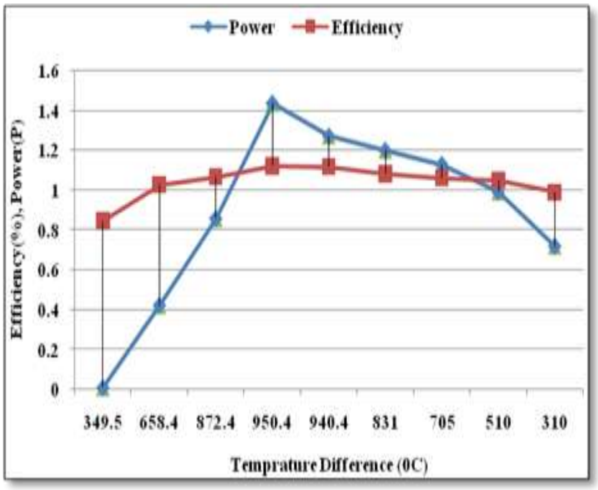


Figure 10 **Figure 11**

Figure 10: Variation of hot and cold side temperature with solar insolation

Figure 11: Efficiency and output electrical power as function of solar insolation.

The conversion efficiency and electrical power generated by the solar thermoelectric generator system as a function of solar insolation shown in figure 11. The temperature difference across the thermoelectric generator modules increases with solar insolation. A larger temperature difference across the thermoelectric generator modules, which is proportional to the heat transfer rate, improves the thermal electromotive force generated by the Seebeck effect and increases the output electrical power [8]. The output electric power of the solar thermoelectric generator system increased sharply with increasing solar insolation reaching a peak around noon [9]. The conversion efficiency increases gradually with solar insolation, up to maximum value of 1.1217 %, and then it decreases. The conversion efficiency is the function of figure of merit, and hot and cold side temperatures. The maximum conversion efficiency is obtained at hot side temperature of 346 K.

V CONCLUSIONS

- In this project work, the fabrication and experimentation is done on low cost solar thermoelectric co-generator (STECG) based on evacuated tubular solar collectors incorporating thermoelectric modules (TEMs), which can supply both electricity and heat simultaneously.
- The STECGs is designed as to be economical and practical, and should be suitable for real-world application. Further breakthroughs research in materials for TEMs will only accelerate this process.
- The maximum value ZTm and conversion efficiency obtained are 0.2898 and 1.1217 % respectively in the temperature range 329 K to 346 K.
- This prototype is having capacity to mount more than 20 thermoelectric generating modules which can increase power, figure of merit of the generator and hence the conversion efficiency for the same generator and corresponding to same temperature difference.
- Power produced by the thermoelectric generator increases with increase in hot side temperature which can be done by increasing number of evacuated tube solar collectors.

- Higher temperature resistance thermoelectric module along with better generator design can improve power output.
- STECGs made from evacuated tubular solar collectors with integrated TEMs are easy to fabricate and only slightly more expensive than solar collectors on their own.
- The STECGs can supply electric energy and hot water simultaneously, will have a wide field of application and require little maintenance, making them ideal for providing power to regions where there is as yet no electricity network.

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