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An Integrated SiGe Based Thermoelectric Generator with Parabolic Trough Collector Using Nano HTF for Effective Harvesting of Solar Radiant Energy

PON VENGATESH RAMAMURTHI[1]
and EDWARD RAJAN SAMUEL NADAR[1,2]

1.—Department of Electrical and Electronics Engineering, Mepco Schlenk Engineering College (Autonomous), Sivakasi, Tamil Nadu, India. 2.—e-mail: sedward@mepcoeng.ac.in

An integrated thermoelectric generator (TEG) with the parabolic trough collector (PTC) for renewable power generation system has been investigated under different solar irradiations, heat transfer fluids (HTF) and TEG materials. In this research work, the idea of using a TEG for effective heat recovery from a solar collector is implemented in an innovative approach. The heat absorbed from PTC is supplied with the hot junction of the TEG and the cold junction being maintained less than surrounding temperature with cold water using an earthen pot surrounded by a thermocole. The temperature gradient between the hot and cold junction of TEG establishes the amount of power extraction. The high temperature absorption is enhanced by the use of synthetic HTF and nanofluids with nano particles (Alumina, Silica, TiO_2 and CuO), which increases the effective harvesting of solar radiant energy. Moreover, the research work focuses to find the most efficient material for the hot and cold part of TEG. Silicon Germanium (SiGe) material for fabrication of TEG is suggested which has good ZT (figure of merit) values and electrical profile as compared to conventional Bismuth Telluride (Bi_2Te_3) under different solar irradiation conditions has been evaluated. The mathematical modelling of this proposed integrated energy harvesting system has been developed. The modelling and array configuration of TEG has been analysed with conventional Bi_2Te_3 and proposed SiGe materials. The performance of TEG with a PTC integrated system has been experimentally tested and the obtained results illustrate the better effective harvesting of solar energy for electrical power generation.

Key words: Bi_2Te_3, SiGe, solar energy, parabolic trough collector, thermoelectric generator, heat transfer, fluids

INTRODUCTION

Energy has been universally recognized as one of the most important inputs for economic growth and human development. The world consumption of all energy resources is forecasted to increase at a terrifying pace and resulting in a prediction of over 260 quadrillion watts in 2030. Now a day, a green and clean renewable energy sources are providing power generation with technological advancement which focuses on the world problems of green house gas emissions and energy storage. One among them is solar energy, which is attractive to substitute for the conventional fuels due to its abundant availability and safe source of energy in its conversion processes.

An integrated PTC with TEG has been investigated effectively under different solar irradiations,

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HTF and TEG materials. The mathematical modelling of PTC has been developed and the effects of heat absorption are studied with different HTF including an innovative nanofluid. The heat transfer enhancement is achieved with nano particles like alumina, silica, TiO_2 and CuO. The comparison of heat loss between different HTFs is also studied. The research work has the following sections: literature survey, mathematical modelling of PTC, heat transfer fluid and its heat enhancement using nanofluids, mathematical modelling of TEG with hot and cold junction materials, analysis of an integrated PTC & TEG system, an experimental analysis of the proposed system and concluded with the finding of the work.

An integrated proposed system (Fig. 1) for generating electrical power by the TEG is proportional to the temperature gradient, where the heat absorbed from the solar collector is used as a heat source of the hot junction of the TEG and the cold junction is maintained by ice cubes or cryogenic fluids with special and safety arrangements. Higher the temperature gradient between hot and cold junctions produces high electrical output from TEG. Moreover, the heat absorption from the solar collect has been effectively improved by the selection of synthetic HTF and nanofluids.

A solar driven thermoelectric[1] power generator is a solid state direct energy conversion device, consists of a thermoelectric generator and a thermal collector. The concentrated solar heat is absorbed by the thermal collector and then conducted over the thermoelectric generator by a HTF pipe. The thermal resistance of the thermoelectric generator causes a temperature difference that is proportional to the heat flux from the absorber of the thermal collector to the fluid. The major challenges faced during this proposed study are, the selection of absorber material and HTF, since the absorption of heat in the absorber tube depends on the type of HTF and varies with respect to several parameters such as thermal conductivity, density, specific heat at constant pressure, and kinematic viscosity,[2] and the selection of novel hot and cold junction materials apart from the conventional Bi_2Te_3 and PbTe TEG and maintaining the cold junction temperature of TEG at the lowest temperature close to 0°C for making greater temperature gradient.

LITERATURE SURVEY

The performance of a solar collector by using a physical model and the suggested values of diameters and other input parameters for the simulation have been studied.[3] The numerical modelling of parabolic trough collectors [4] is developed with the output heat gain in terms of (°C) temperature. A detailed survey of various types of solar thermal collectors like flat plate, compound parabolic, evacuated tube, parabolic trough, Fresnel lens, parabolic dish and heliostat field collectors were explained with their applications.[5] Different types of parabolic trough collectors and about their coatings and absorber materials used in each collector have been investigated.[6–8] The potential of nanofluid based collectors to harness solar radiant energy more efficiently as compared to a conventional parabolic trough [9,10] is described and furthermore it briefs the nano particle shape, size, and material that need to be optimized in order to get the desired output in terms of thermal efficiency and maximum outlet fluid temperatures. The main idea of dispersing

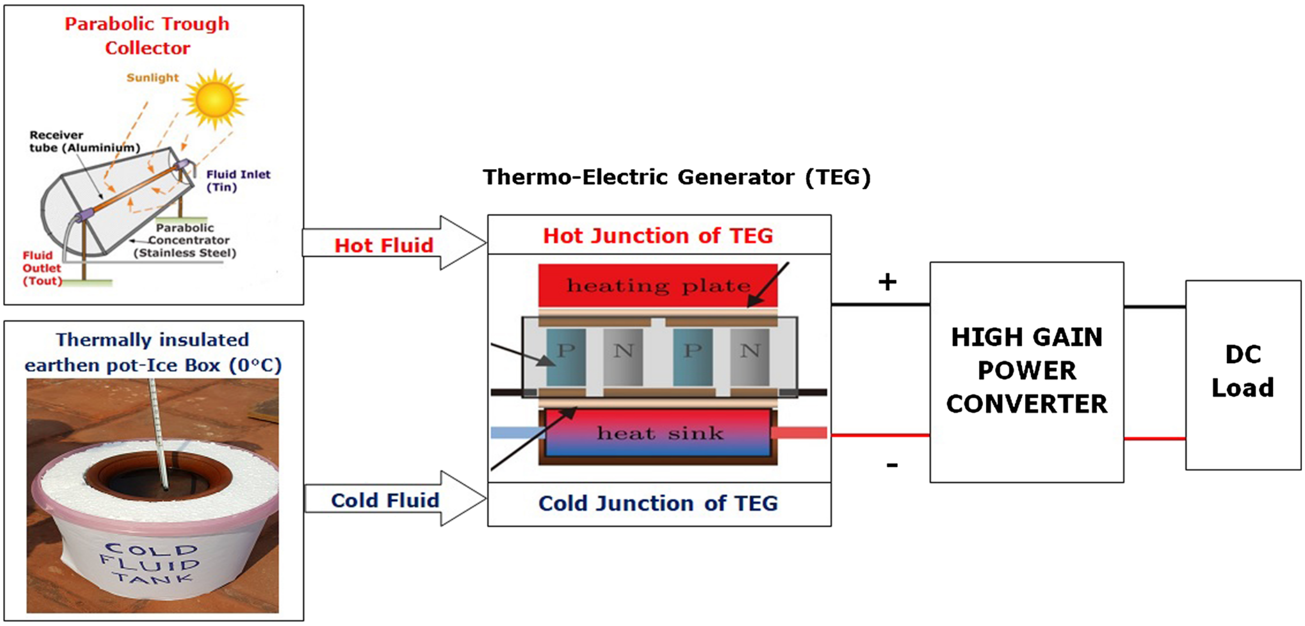

Fig. 1. An integrated parabolic trough solar collector with TEG for renewable power generation system.

trace amounts of nano particles into common base fluids has a significant impact on the optical as well as thermo physical properties of the base fluid are well discussed. The specific heat, conductivity is an important parameter required in the design of PTC [11,12] that is studied. The thermal conductivity of various nanofluids as the miniaturization of mechanical and electrical components creates a need for heat transfer fluids with improved thermal characteristics over those of conventional fluids.[13]

In the eighteenth century, an idea of a thermoelectric was discovered, such that between two dissimilar materials a small voltage has been generated, and it was used as the thermocouples. A development has been experienced in the invention of semiconductors in this thermoelectric technology for energy generation (Seebeck effect) and cooling (Peltier effect) purposed over the last 60 years. Although finding a new material with low thermal conductivity, high electrical conductivity is still under the development stage. Many literature studies have been carried out for the development of TEG with materials and their applications,[14,15] working of a miniature thermoelectric device at low temperatures, analysis of power density [16] with the ceramic material, cooling power [17] as a thermoelectric cooling device and generalized optimization of a thermoelectric model.[18,19] Several models [20–22] have studied the basics of TEG, fabrication, the cost analysis and implementations on measuring the thermoelectric behavior using Matlab Simulink to estimate the thermal conductivity of thermoelectric material and the conventional method of using TEG for the process of waste heat recovery. Also this provides values for resistivity and conductivity with specific Seebeck coefficients that are available. The effects of temperature mismatch on different configured thermoelectric generators [23,24] is mentioned.

MATHEMATICAL MODELLING OF PTC

The solar collectors serve as the main part of this proposed work which produces the required hot junction temperature for the TEG. Among various types of solar collectors, the selection of suitable type of solar collector for the specific application is very important. Here, the concentrated type PTC is found to be suitable for TEG application with being simple in construction and with ease of heat transfer.

The solar sun light hitting the solar collector surface is absorbed by the glass enveloped with absorber coating. The absorbed solar energy is effectively transmitted to the heat transfer fluids by convection and few of them have been lost in heat collector element (HCE) support bracket by conduction mode. In the absence of glass envelope, more amount of heat is lost to the atmosphere directly. The temperatures, heat fluxes, and thermodynamic properties of the model used are assumed uniformly around the HCE.[25]

The performance model of HCE uses an energy balance between the HTF and the atmosphere, and includes all equations and correlations necessary to predict the terms in the energy balance, which depend on the collector type, HCE condition, optical properties, and ambient conditions. The following assumptions were taken during this analysis: solar irradiation is uniform both around and along the length of the receiver, the flow rate of HTF and temperature profile is considered as uniform, solar radiation loss is relatively small compared to convection loss, and; hence, radiation between the heat collector element to the ground and the surrounding atmosphere is neglected.

The solar absorption in the glass envelope is a heat generation phenomenon. An optical efficiency is estimated to calculate the solar absorption. The Eq. 1 represents the solar absorption in the glass envelope as becoming:

$$H_{(\mathrm{glass})} = q_i\, \eta_{\mathrm{env}}\, \alpha_{\mathrm{env}}, \tag{1}$$

where, q_i—solar irradiation per receiver length (W/m), η_{env}—effective optical efficiency at the glass envelope & α_{env}—absorptance of the glass envelope (Pyrexglass).

The solar energy absorption in the absorber occurs very close to the surface; therefore, it is treated as a heat flux, and it is represented in Eq. 2 as below:

$$H_{(\mathrm{abs})} = q_i\, \eta_{\mathrm{abs}}\, \alpha_{\mathrm{abs}}, \tag{2}$$

$$\eta_{\mathrm{abs}} = \eta_{\mathrm{env}}\, \tau_{\mathrm{env}}, \tag{3}$$

where, η_{abs}—effective optical efficiency at absorber, α_{abs}—absorptance of absorber & τ_{env}—transmittance of the glass envelope (0.86).

The convection heat transfer mechanism between the absorber and glass envelope (Eqs. 4 and 5) occurs by natural convection. Raithby and Holland's correlation[26] for natural convection in an annular space between horizontal cylinders is used here.

$$H_{34\mathrm{conv}} = \frac{2.425\, k_{34}(T_3 - T_4)(\mathrm{Pr}\, Ra/0.861 + \mathrm{Pr})^{1/4}}{(1 + (D3/D4)^{3/5})^{5/4}}, \tag{4}$$

$$Ra = \frac{g\beta(T_3 - T_4)D_3^3}{\alpha v}, \tag{5}$$

where k_{34}—thermal conductance of annulus gas at T_{34} (W/m–K), T_3—outer absorber surface temperature (°C), T_4—inner glass envelope surface temperature (°C), D_3—outer absorber diameter (m), D_4—inner glass envelope diameter (m), Pr—Prandtl number, Ra = Rayleigh number evaluated at D_3, β—volumetric thermal expansion coefficient (1/K) & T_{avg}—average temperature, $(T_3 + T_4)/2$ (°C) for an ideal gas, $\beta = 1/T_{\mathrm{avg}}$.

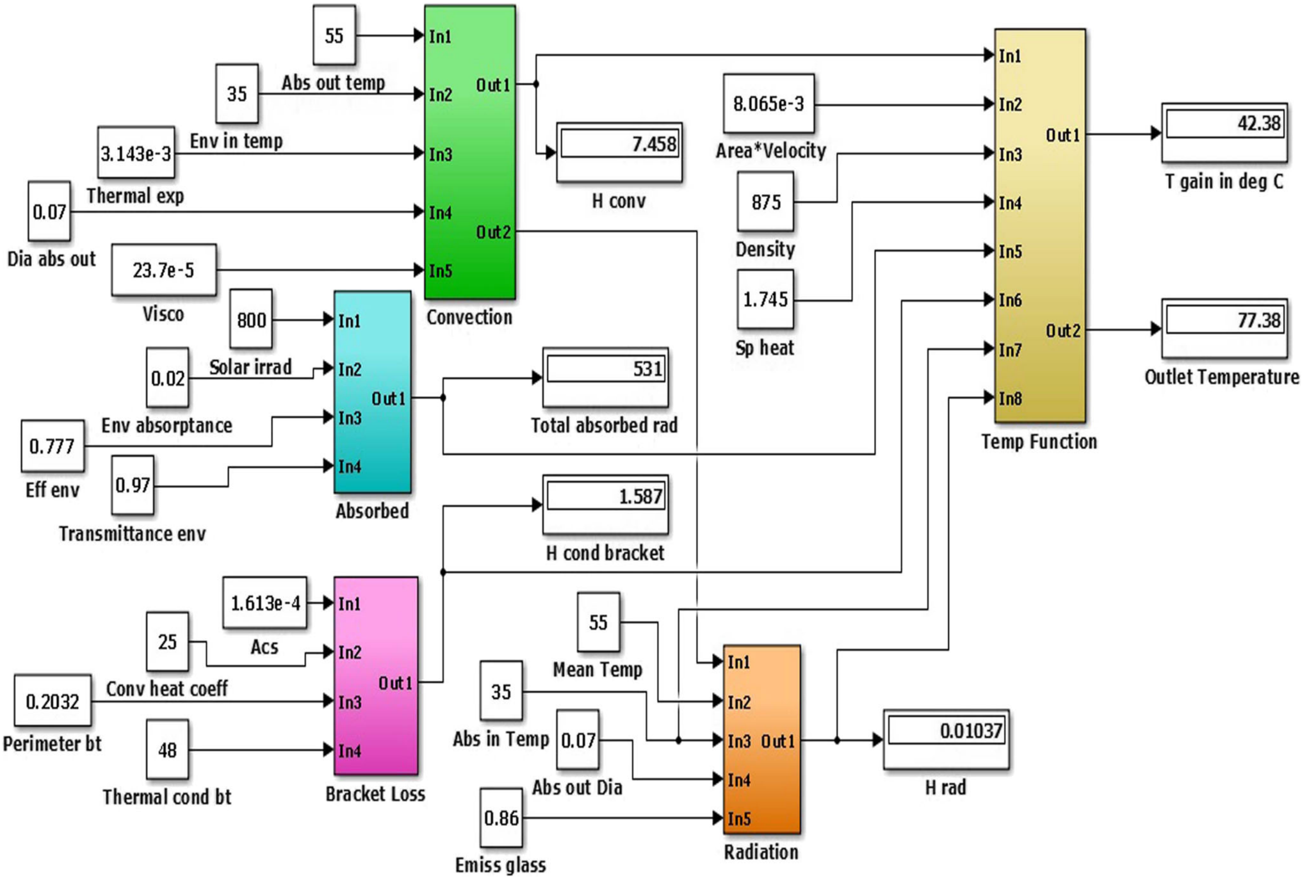

Fig. 2. Simulink model of a PTC.

The radiation heat transfer between the absorber and glass envelope is estimated using Eq. 6 as below:

$$H_{34\mathrm{rad}} = \frac{\sigma \Pi D_3 (T_3^4 - T_4^4)}{1/\varepsilon_3 + (1-\varepsilon_4)(D_3/\varepsilon_4 D_4)}, \qquad (6)$$

where σ—Stefan Boltzmann constant (W/m^2-K^4), D_3—outer absorber diameter (m), D_4—inner glass envelope diameter (m), T_3—outer absorber surface temperature (K), T_4—inner glass envelope surface temperature (K), ε_3—absorber selective coating emissivity & ε_4—glass envelope emissivity.

The heat Loss through HCE support bracket [27,28] is also accounted for effective calculation of extracted outlet temperature (T_{out} in °C) and its support bracket has been fixed approximately for every 4 m length of the total receiver path. The bracket heat loss is estimated with the following Eq. 7.

$$H_{\mathrm{cond-bracket}} = \sqrt{hP_b k A_{cs}} \, \frac{(T_{\mathrm{base}} - T_6)}{L_{\mathrm{HCE}}}, \qquad (7)$$

where h—average convection coefficient of bracket (W/m^2-K), P_b—perimeter of bracket (m), k—conduction coefficient (W/m–K), Acs—area of cross-section of bracket (m^2), T_{base}—temperature at base of bracket (°C), T_6—ambient temperature (°C) & L_{HCE}—length (m) of HCE.

The extracted outlet temperature (°C) of the PTC is estimated using Eq. 8 as below:

$$T_{\mathrm{out}} = \frac{H_{\mathrm{totalabs}} - H_{34\mathrm{rad}} - H_{34\mathrm{conv}} - H_{\mathrm{cond}}}{mC_p}. \qquad (8)$$

The Simulink modelling of PTC has been developed by using Eqs. 1 to 8 under Matlab Simulink environment is illustrated in Fig. 2.

HEAT TRANSFER FLUID AND ITS HEAT ENHANCEMENT USING NANOFLUIDS

A heat transfer fluid is a liquid or a gas that transfers heat from PTC to a hot junction of TEG for electric power generation. The following criteria that have to be considered for selecting a HTF are, coefficient of expansion (the fractional change in length, volume of a material for a unit change in temperature), viscosity(resistance of a liquid to sheer forces/flow, thermal capacity (the ability of matter to store heat), freezing point, boiling point and the flash point. The most commonly used HTF are air, water, hydrocarbon oils. In this research work, Hitec XL, Caloria, Solar salt, Dowtherm Q, Dowtherm RP, Therminol VP1, Therminol XP are

Table I. Performance of HTF under different solar irradiation

	Outlet temperature of HTF (°C)			
Solar irradiation (W/m^2)	VP1	RP	XL 600	XP
400	52.43	53.13	55.17	55.82
500	57.27	58.01	60.54	61.21
600	62.1	62.84	65.91	66.6
700	66.94	67.68	71.28	71.99
800	71.78	72.52	76.66	77.38

different HTF considered and their physical properties (density, viscocity, specific heat and temperature gain) are accounted for. Among them, Therminol XP has been identified at the best suitable HTF for concentrated PTC and it is commercially available with cheap cost. The other two of HTFs, Hitec XL and Caloriaare are not commercially available and under research. The relationship between the density of the fluid and the temperature gain has been investigated where, it is observed that as density increases, temperature gain decreases and the optimum temperature gain is obtained, when the density of fluid lies between 800 kg/m^3 and 1000 kg/m^3.

Performance of HTF Under Different Solar Irradiation

The performance of HTF has been studied under different solar irradiation conditions. As the solar irradiation is changed, the amount of heat flux exposed to the fluid keeps on changing which in turn affects the temperature absorption of the fluid. On clear & sunny days without partial shadings, the outlet temperature is producing more electrical power output from TEG. Moreover it is observed that the outlet temperature of each HTF increases proportionally with respect to the solar irradiation. Table I illustrates the comparative analysis of performance of HTFs under different solar irradiation and results found that, Therminol XP as heat transfer fluid is better as compared to the others.

Heat Transfer Enhancement Using Nanofluids

Heat transfer enhancement is aimed to collect maximum outlet temperature at the collector surface towards the hot junction of TEG which is one of the most important criteria for a TEG. The power produced is directly proportional to the temperature difference between the hot and cold junction. This is achieved with the usage of nanofluids as HTF in PTC. The performance of nanofluid based direct solar absorption PTC has been investigated in this research work and suggests the idea of using nanofluids in the place of HTF in solar collectors for heat transfer enhancement. The potential of a nanofluid is to harness solar radiant energy absorption and it is more efficient as compared to PTC with regular HTFs. Nanofluids are particle suspensions of metals, metal oxides, carbides, nitrides, carbon nanotubes, etc., dispersed in a continuous medium such as water, ethylene glycol, refrigerants, and engine oil of size less than 100 nm. The unique features of using nanofluids as HTF are: abnormal enhancement of thermal conductivity, stability, concentration and Newtonian behaviour and particles size dependence. The thermal conductivity of nanofluids increases with decreasing particle size.

The thermo physical properties of nanofluids [29,30] (viscosity, thermal conductivity, specific heat & density) are important for applications involving convective heat transfer and four mechanisms [31] (collision between the base fluid molecules, thermal diffusion of nano particles, collision of nano particles with each other due to Brownian motion, collision between the base fluid molecules and nano particles due to thermally induced fluctuation) contributing to the energy transfer enhancement of thermal conductivity of nanofluids have been are analysed in this research work.

The Matlab Simulink model of PTC is simulated with CuO nanofluid as HTF is illustrated in Fig. 3. The performance of nanofluids (Alumina, Silica, TiO$_2$ and CuO) under different irradiation (Table II) conditions was studied and a graph was plotted (Fig. 4) between the outlet temperature & solar irradiation and it is observed that the CuO nanofluid has a higher outlet temperature value. The gain in outlet temperature of PTC is double the times of the conventional HTFs used under the same solar irradiations. Moreover the heat transfer enhancement depends on the nano particle concentration in the base fluid.

MATHEMATICAL MODELLING OF TEG WITH HOT & COLD JUNCTION MATERIALS

The temperature gradient of hot and cold junction (diverse materials) of TEG is directly converted into an electric voltage which is higher for good electrical and low thermal conductivity materials. A temperature gradient of the material makes the electron flow and its magnitude is referred to as the Seebeck coefficient (S).[32] Another factor to be considered is referred as ZT and the conventional TEG of Bi$_2$Te$_3$ and PbTe having the value near to ‘1’.

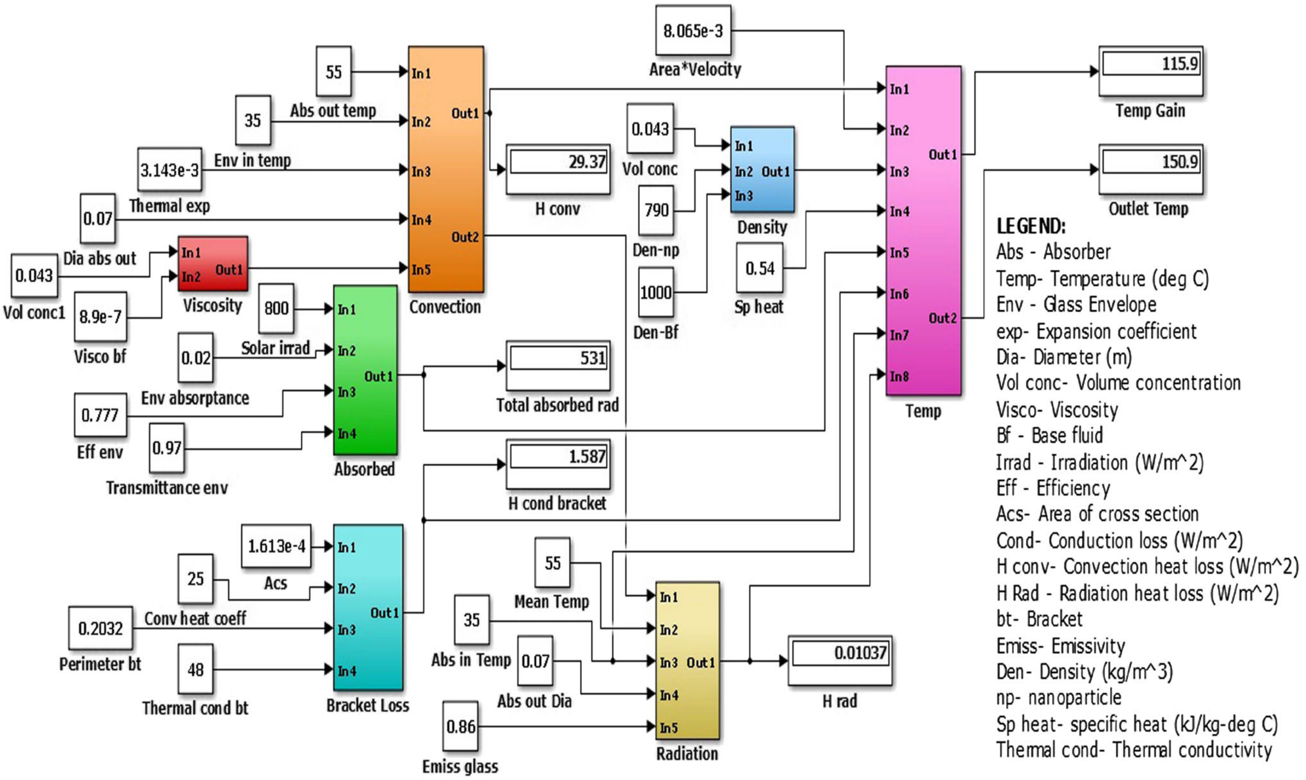

Fig. 3. Modelling of PTC with nanofluid as HTF.

Table II. Comparative analysis of nanofluids as HTF under different solar irradiations

	Input parameters		Output temperature (°C) at different solar irradiation (W/m²)				
HTF Nanofluids	Density (kg/m³)	SHC (kJ/kg °C)	400 (W/m²)	500 (W/m²)	600 (W/m²)	700 (W/m²)	800 (W/m²)
Al_2O_3	1124	0.81	66.93	75.97	85.01	94.04	103.1
SiO_2	1060	0.75	71.57	81.92	92.27	102.6	113
TiO_2	958.7	0.69	78.96	91.4	103.8	116.3	128.7
CuO	991	0.536	89.34	104.7	120.1	135.5	150.9

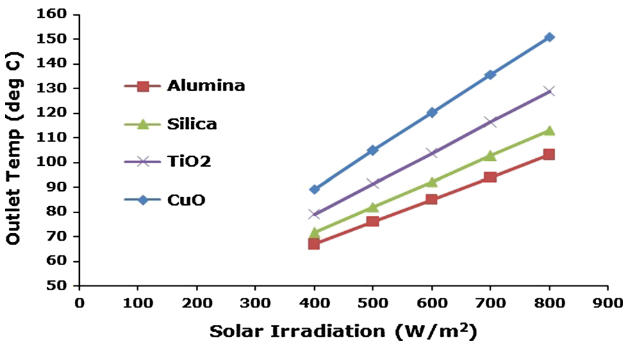

Fig. 4. Outlet temperature of PTC with nanofluids as HTF under different solar irradiations.

However, the maximum electrical output is achieved from TEG with higher value of ZT and lower value of thermal conductivity. The Simulink model of TEG has been described by the Eqs. 9, 10 and 11 as below:

$$V = V_{\max} - S\left(\left(T_H - \Delta T\right)^2 - 2\,\Delta T/2\right)^{0.5}, \quad (9)$$

$$V_{\max} = S\,T_H, \quad (10)$$

$$R = \frac{\rho_p \ell_p}{A_p} + \frac{\rho_n \ell_n}{A_n}. \quad (11)$$

Where S—seebeck co-efficient (V/°C), R—resistance (Ω), ρ—resistivity (Ω-m), l-length of leg (m), ΔT—temperature gradient and A—area (m^2).

Conventional materials that were used include alloys based on bismuth in combination with antimony or tellurium or alloys of lead. Though they remain as one of the key materials for the

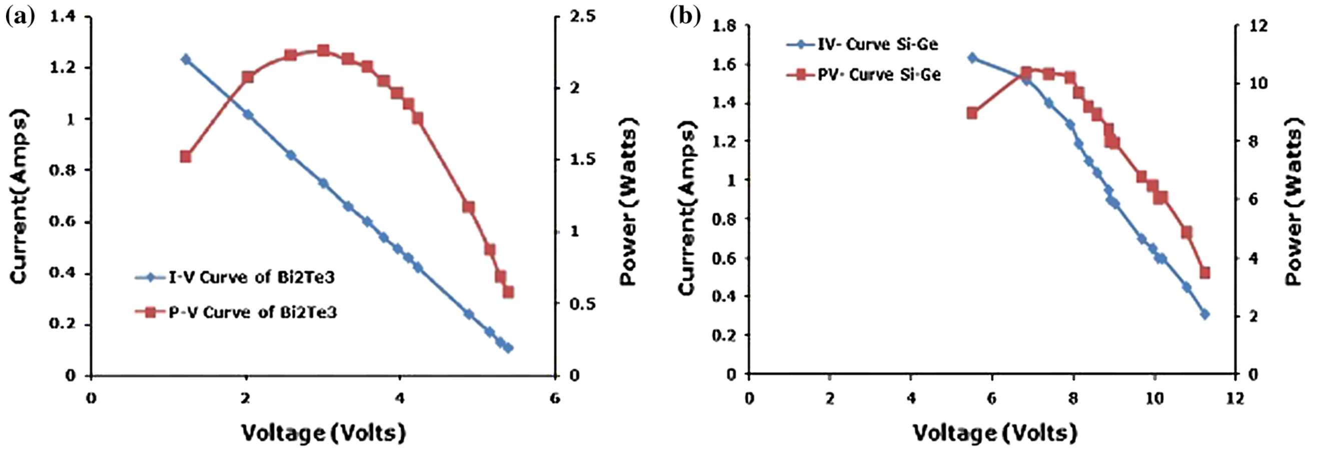

Fig. 5. I–V and P–V characteristics curve for (a) Bi_2Te_3 and (b) SiGe.

Table III. Comparison of TEG material efficiency under different cold side temperature and hot side temperature as 600°K

	Efficiency of TEG under different T_c and T_h at 600°K			
TEG material	T_c = 310°K	T_c = 300°K	T_c = 273°K	T_c = 253°K
Bi_2Te_3	10.36	10.81	12	13.01
SiGe	15.73	16.39	18.24	19.6

construction of TEG, significant advances have been made in synthesizing new materials to improve the material's ZT and hence the conversion efficiency. The Simulink model of Bi_2Te_3 module has been simulated with the temperature of 150°C and the cold temperature is assumed to be 0°C under different load resistances and it is inferred that for varying resistance, the maximum power point is reached at a resistance of 3.7 Ω which is the source internal resistance of TEG.

The selection of suitable material for TEG with lower lattice thermal conductivity is analysed with fewer materials of alloy,[33] crystal [34] and nanocomposites.[35] The various materials that can be used for the fabrication of TEG were analysed which includes, bismuth chalcogenides and their nanostructures, lead telluride, inorganic clathrates, silicides, platinum, constantan and SiGe. One parameter for consideration is the Seebeck coefficient which is referred as the voltage generated/°C. Moreover, the Seebeck coefficient of platinum is zero and its voltage equation becomes negated and hence not suitable for the fabrication of TEG. The performance characteristics curve (Current–Voltage (I–V) & Power–Voltage (P–V)) for Bi_2Te_3 and SiGe have been plotted in Fig. 5.

The power/unit area of Bi_2Te_3 is 0.282 W/cm^2 with maximum power of 2.539 watts and for SiGe, it is accounted for as 1.134 W/cm^2 with maximum power of 10.21 watts. (Area = 3 cm × 3 cm). The efficiency of TEG has been modelled and calculated under different cold side temperatures by keeping constant hot side temperature of 600°K using the Eqs. 12, 13, 14, 15 and 16 as below and the obtained results have been tabulated in Table III.

$$\eta_{\max} = \frac{\Delta T(m-1)}{\left[T_h\left(m+\frac{T_c}{T_h}\right)\right]} \tag{12}$$

$$m = \sqrt{1+ZT}, \tag{13}$$

where ZT—figure of merit, T_c, T_h cold and hot side temperature of TEG

$$\eta_{\max} = \frac{\Delta T(\sqrt{1+ZT}-1)}{\left[T_h\left(\sqrt{1+ZT}+\frac{T_c}{T_h}\right)\right]} \tag{14}$$

$$\eta_{\max} = \frac{(T_h-T_c)}{T_h}\frac{(\sqrt{1+ZT}-1)}{\left(\sqrt{1+ZT}+\frac{T_c}{T_h}\right)} \tag{15}$$

$$\eta_{\max} = \left(1-\frac{T_c}{T_h}\right)\frac{(\sqrt{1+ZT}-1)}{\left(\sqrt{1+ZT}+\frac{T_c}{T_h}\right)} \tag{16}$$

As a result, the proposed research work recommends, SiGe were found to be most efficient as TEG, which enhances the electrical power generation

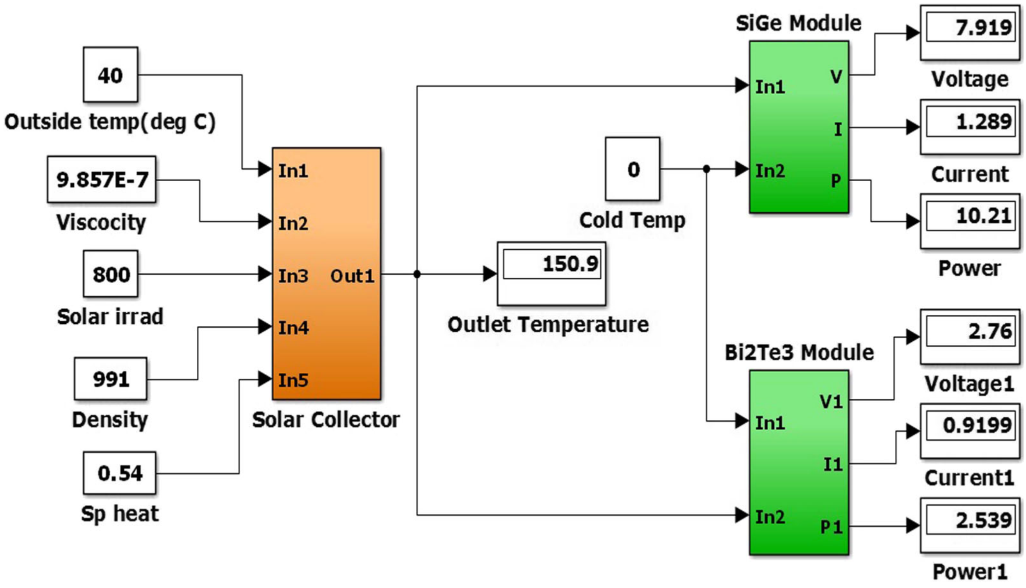

Fig. 6. An integrated Simulink model of TEG with CuO as HTF.

Table IV. Performance of TEG array configuration using Bi_2Te_3 and SiGe materials

Number of TEGs	TEG configuration	Voltage (V) Bi_2Te_3	Voltage (V) SiGe	Current (A) Bi_2Te_3	Current (A) SiGe	Power (W) Bi_2Te_3	Power (W) SiGe
16	Series	170.4	338	1.7	3.38	290.3	1146
	Series and Parallel (4 × 4)	79.56	127.5	0.79	1.27	63.29	162.7
64	Series	274	651	2.74	6.51	751.1	4249
	Series and Parallel (8 × 8)	159.1	255.1	1.59	2.55	253.2	650.6
256	Series	323.2	848.2	3.23	8.48	1045	7194
	Series and Parallel (16 × 16)	166.3	510.1	1.66	5.1	276.6	2602.5

when a high temperature gradient is maintained at its hot and cold junctions. Moreover, the main advantages of using this combination is that, both Si and Ge can either be used as a p-type or n-type material. The mathematical Simulink of an integrated SiGe based TEG model is illustrated in Fig. 6. The electrical output characteristics of Bi_2Te_3 and SiGe under different configuration (series and series & parallel) have been investigated with 2^n, where n-represents the $(n \times n)$ combination of TEG array system and obtained results are tabulated in Table IV stated that, the SiGe based TEG gives maximum of power extraction than the Bi_2Te_3 for the same configurations and same operating conditions.

ANALYSIS OF AN INTEGRATED PTC AND TEG SYSTEM

The purpose of this proposed research work is to extract maximum electrical power from TEG with a solar collector as the hot junction where the heat collected from them is made to pass on the hot junction of TEG with the help of the pipe and tank arrangements with taking care of cold junction temperature close to zero degree temperature. In real time the cold junction temperature is maintained closer to zero degree temperature with the help of a heat sink that is dipped inside an earthen pot filled with cold fluid.

The arrangement of an earthen pot and thermocol is used to maintain constant cold junction temperature without much affect from atmosphere temperature for effective extraction power from TEG. An integrated Simulink model of TEG (Bi_2Te_3 and SiGe) with solar collector and CuO as HTF for effective heat absorption followed by electrical power generation is illustrated in Fig. 6.

The comparative analyses of an integrated system under different solar irradiations and various HTFs have been investigated and the obtained results are tabulated in Table V. The SiGe based TEG has good electrical profile under different solar irradiation conditions than conventional Bi_2Te_3. The number of TEGs requirement also reduces with SiGe for the

Table V. Comparative analysis of integrated systems under different solar irradiations

Solar irradiation (W/m^2)	HTF	Outlet Temp (°C)	TEG Voltage (Volts)		TEG Current (Amps)		TEG Power (Watts)	
			Bi_2Te_3	SiGe	Bi_2Te_3	SiGe	Bi_2Te_3	SiGe
800	Therminol XP	77.38	1.788	5.83	0.596	0.95	1.07	5.53
	Therminol VP1	71.78	1.71	5.63	0.57	0.92	0.97	5.16
	Alumina (Nano)	103.1	2.15	6.65	0.72	1.08	1.54	7.19
	CuO (Nano)	150.9	2.76	7.92	0.92	1.29	2.54	10.21
700	Therminol XP	71.99	1.708	5.64	0.57	0.92	0.97	5.18
	Therminol VP1	66.94	1.63	5.46	0.54	0.89	0.89	4.85
	Alumina (Nano)	94.06	2.03	6.37	0.68	1.04	1.37	6.61
	CuO (Nano)	135.5	2.57	7.54	0.86	1.23	2.2	9.244
600	Therminol XP	66.6	1.63	5.44	0.54	0.89	0.88	4.82
	Therminol VP1	62.1	1.56	5.27	0.52	0.86	0.81	4.52
	Alumina (Nano)	85.02	1.9	6.09	0.63	0.99	1.2	6.03
	CuO (Nano)	120	2.37	7.13	0.79	1.16	1.88	8.28
500	Therminol XP	61.21	1.54	5.24	0.51	0.85	0.79	4.47
	Therminol VP1	57.27	1.48	5.08	0.49	0.83	0.73	4.2
	Alumina (Nano)	75.98	1.77	5.78	0.59	0.94	1.04	5.44
	CuO (Nano)	104.7	2.17	6.7	0.72	1.09	1.57	7.3
400	Therminol XP	55.82	1.46	5.02	0.49	0.82	0.71	4.11
	Therminol VP1	52.43	1.4	4.88	0.47	0.79	0.66	3.88
	Alumina (Nano)	66.94	1.63	5.46	0.544	0.89	0.89	4.85
	CuO (Nano)	89.34	1.96	6.23	0.65	1.01	1.28	6.31

same power production when compared with Bi_2Te_3. The enhancement of heat transfer is achieved by CuO as HTF in a solar collector pipe as compared with other HTFs.

EXPERIMENTAL ANALYSIS OF AN INTEGRATED PTC &TEG SYSTEM

The experimental analysis has three major parts for effective implementation of this research work.

- To design and develop a PTC model
- To develop a hardware set up of TEG with separation of hot and cold junction heat transfer
- To develop a novel arrangement of an earthen pot and thermocol at cold junction

The PTC has been constructed with stainless steel having higher degree of reflectivity as a reflector portion and the aluminium (Al) metal has a higher degree of absorptivity which is used as the receiver tube. The HTF is flowing through it which absorbs the heat. The lesser the diameter of the tube the higher the heat gain. Moreover the aluminium metal is cost efficient also as compared to a copper tube. The aluminium tube is placed at the focal point of the parabolic reflector in order to concentrate more solar radiation and transfer maximum heat to the fluid. The trough arrangement is also provided with manually tilt adjustment of the trough according to the angle of solar radiation received. Further, reflectivity of sun light over the receiver tube can be improved by a set of mirrors placed on the reflective surface of the PTC. The performance of developed prototype has been experimentally conducted with water inlet and the temperature gained is accounted as 60°C with the outside temperature of 38°C.

Hot Side Arrangement

The absorbed heat from the PTC is provided with hot junction region of TEG. The commercially available Bi_2Te_3 TEG module (GM 200-127-10-15) is used in this study. The cold and hot junction of TEG fixed in a cardboard is shown in Fig. 7. The cardboard sheet helps to isolate the heat transfer between hot and cold junctions. The aluminium plate which absorbs temperature was used initially as shown in Fig. 8a. This arrangement is not helping much and the heat absorbed was not fully transferred to the TEG hot side. So an aluminium foil (Fig. 8b) was used to cover the cardboard so that the thickness is much reduced compared to the aluminium plate, at the same time enhancing the temperature on the hot side of the TEG. The higher temperature difference has thereby higher voltage developed.

Cold Side Arrangement

The proper functioning of a TEG depends on the temperature difference maintained at the junctions of the TEG. In order to assure maximum temperature difference the cold side has to be maintained nearly at 0°C. To maintain the cold junction temperature an earthen pot arrangement and a heat

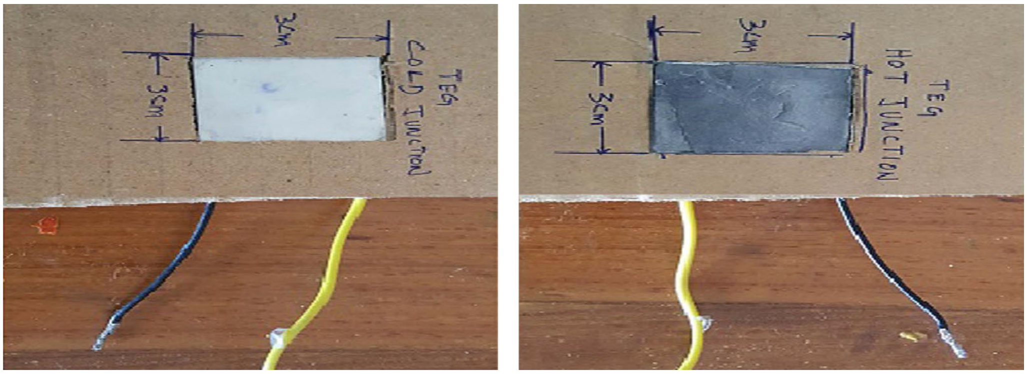

Fig. 7. Cold and hot junction of TEG fixed in a cardboard.

(a) (b)

Fig. 8. (a) Aluminium plate covering the TEG (b) cardboard sheet wrapped with Al foil.

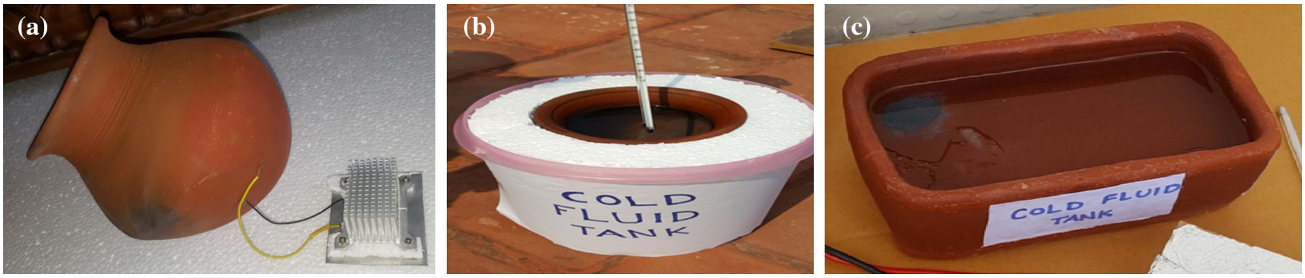

Fig. 9. (a) An earthen pot arrangement and a heat sink (b) earthen pot was placed inside a plastic container filled with thermocol alongside the wall (c) flat base rectangular shaped earthen pot.

sink was included in contact with the TEG cold side as shown in Fig. 9a and the earthen pot was placed inside a plastic container filled with thermocol alongside the wall (Fig. 9b). Then the depth of the earthen pot used was very high hence the temperature maintained was nearly 10°C. As the preferred temperature could not be maintained with the early arrangement, and a new arrangement was sought out by using a flat base rectangular shaped earthen pot as shown in (Fig. 9c), this arrangement was efficient and the cold side temperature was maintained below 5°C.

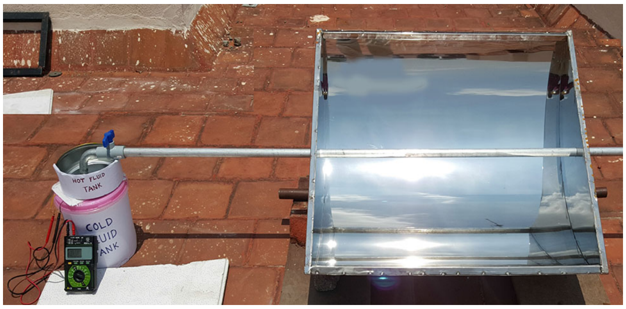

Fig. 10. Integrated experimental setup for the energy harvesting system.

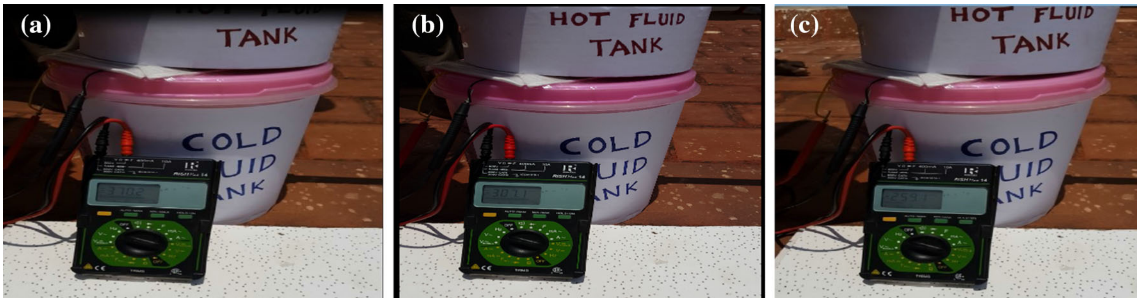

Fig. 11. Experimental results at (a) 12 noon (b) 1 p.m (c) 2 p.m.

Fig. 12. Modified cold junction arrangement of TEG.

Integrated Hardware Setup

An integrated hardware setup is as shown in Fig. 10. The HTF was passed through the inlet and the outlet was collected in the hot fluid tank which is placed in contact with the TEG hot side surface. The highest temperature absorbed by the water with the surrounding temperature of 38°C is 60°C and with the temperature at the cold side was nearly 8°C. The voltage produced by the TEG is measured using the multimeter as shown Fig. 11a–c at different intervals of time.

Modified Cold Side Arrangement

The maximum voltage produced with the early arrangement was achieved with only 0.37 V at 12 noon under direct solar irradiation. With the modified cold side arrangement (Fig. 12), the maximum voltage obtained is measured as 0.732 V. Moreover, in the earthen pot arrangement with ice cubes that are filled to maintain a temperature of nearly 0°C.

CONCLUSION

The proposed research work describes the design and development of an integrated PTC with TEG model with an investigation of effectiveness of different HTF and TEG materials under different solar irradiation conditions for effective renewable electric power generation. An attractive solar driven thermoelectric technology that not only can serve the needs for power generation, but also meets demand for energy conservation and environment protection. The mathematical modelling of PTC has been developed and the effects of heat absorption are studied with different HTF. The heat transfer enhancement is also achieved with proposed nanofluid and their nano particles are Alumina, Silica, TiO_2 and CuO. The comparison of heat loss between different HTFs is also studied. The temperature gain is increased more than 50% when the nanofluids are used as HTF. The absorbed heat energy is utilised for providing hot junction of the TEG. The modelling and array configuration of TEG has been analysed with conventional Bi_2Te_3 and proposed SiGe materials. The major challenge in improving the performance of a TEG is the temperature grading. A larger temperature grading is achieved by maintaining of cold junction temperature as closer to 0°C with an efficient arrangement of earthen pot and an ice box with proper insulations for providing a lower cold junction temperature. For higher temperature difference, the voltage and power developed across SiGe based TEG is higher and the number of TEGs requirement also reduces for the same electrical power generation when compared with Bi_2Te_3. The performance of TEG with the PTC integrated system has been experimentally tested and the obtained results illustrate the better effective harvesting of solar energy for electrical power generation.

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