Enhanced energy harvesting and analysis of a High Concentration Photovoltaic / Thermal System with support of Cooling fluid and Increased Mass Flow Rates

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***Abstract*— In this paper a high concentration photovoltaic (HCPV) system is considered. A parabolic dish collector focuses the incident energy on to a triple junction solar system. High concentration ratios ranging from 10 x to 1000x increases the cell temperature, resulting in a decrease in electrical efficiency. Thermal analysis of a water based cooling system is modeled to enhance the electrical efficiency and also to study the thermal efficiency of such HCPV system. It is to be noted that with an increase in mass flow rate of water, the electrical efficiency increases and the thermal efficiency decreases. Finally, a comparison of efficiencies with and without cooling are presented.**

Keyword- Thermal analysis, Concentration photovoltaics, Cooling, Energy enhancement

I. INTRODUCTION

Solar energy is harvested in two modes a) Photovoltaic (PV) and b) Solar Thermal. Both these modes were exploited to harvest the solar energy available in several methods. First, the photovoltaic device is made by Fritts in 1883 by melting Se [1]. Bell labs discovered p-n junction diodes with 6 % efficiency [2]. Thereafter, many methods for enhancing PV output are considered such as using a) Multi-Junction solar cells, b) Concentrated Photovoltaics (CPV), c) Photon Enhanced Thermionic Emission (PETE) [3] etc. CPV seemed to be a promising alternative for improving the efficiencies of the PV devices. CPV systems use optical systems to focus sunlight onto a small solar cell [4]. CPV technologies were extensively studied at National Sandia Laboratories [5] and efficient Si concentrator cells are developed [6]. Entch [7] used Fresnel lens for concentration. Multijunction solar cells were developed which provided high efficiencies up to 40% [8]. Other than Multijunction solar cells, new conceptual cells called third generation or new generation solar cells are developed [9, 10]. Operation at higher concentrations above 1000 was ventured [11]. Due to such high concentrations, the cell temperature optimization has become a major problem as the efficiency of the cell depends on it. This temperature dependence made researchers choose alternate methodologies for cooling the PV cell. The efficiency of the module also depends on the environmental factors like temperature. [12, 13]. Teo et al. [14] conducted experiments by cooling solar cell with a fan. Tonui et al. [15] considered air cooling of PV cell to enhance the efficiency. Leonardo Micheli et al. studied passive cooling of PV's using micro fins [16]. Haifei Chen et al. [17] considered the thermal analysis of HCPV system. Hiren D, Ravel et al. performed analysis on improving total energy by surface water cooling [18]. There are four major cooling techniques based on air, water, refrigerant and heat pipe respectively [19]. This paper presents the study of a high concentration photovoltaic (HCPV) system. A numerical simulation and thermal analysis is conducted to investigate the water-based cooling system on thermal and electrical efficiencies for such HCPV system.

II. PHYSICAL DESCRIPTION OF THE PV/T MODEL

A concentrated photovoltaic system (CPV) is represented in Fig. 1. The radiation from the sun is concentrated on the multijunction solar cells. The concentration ratios can vary from 10x to 1000x. A tracking device lets the concentrator track the sun using a photosensitive control device. Under such high concentrations, the temperature of the cell increases rapidly. A cooling device is hence essential to maintain the cell temperature at an optimal level. The fluid under consideration is water. Water is allowed to flow through the inlet channel and the heat from the cell is carried by water through outlet thereby, cooling the solar cell.

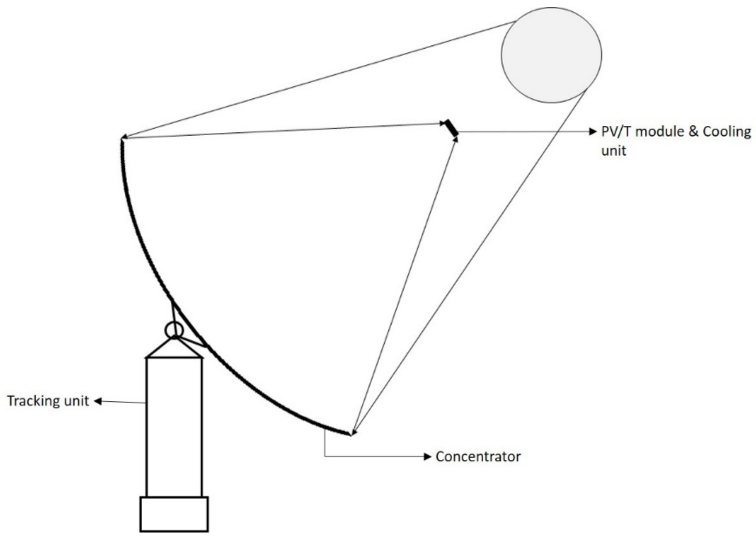

Fig. 1. Physical model of PV/T system

A triple junction solar cell is considered for the following study. It consists of three layers with GaInP2/GaAs/Ge cells placed on the top, middle and bottom layers of the cell respectively [20]. These layers are connected in series.

III. THERMAL ANALYSIS

The heat flow and fluid flow schematics with electric analog are shown in Fig. 2. The following assumptions were made during the analysis: (i) steady state operation; (ii) solar module is in thermal equilibrium with the environment; (iii) uniform radiation onto the PV module.

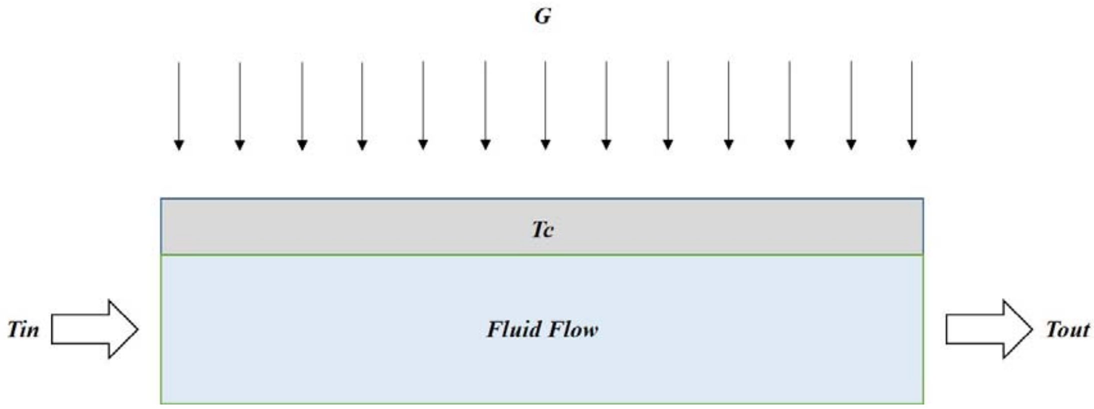

Fig. 2. Simplified model of the cooling channel

The solar radiation G that is being focused on to the solar panel is

$$G = \rho CIA \tag{1}$$

Where ρ is the reflectivity, C is the concentration ratio, I is the direct irradiance and A is the area of the CPV module.

The solar cell converts a part of the solar energy into electrical energy. The electrical output of triple junction solar cell depends upon the cell efficiency and the radiation flux as

$$E = r_p G \eta_r [1 - \beta_r (T_c - T_r)] \tag{2}$$

Where r_p is the packing factor of solar cells i.e. the area of the module with cells to the empty area, η_r is the reference temperature of the triple junction solar cell for a reference temperature T_r and β_r is a constant temperature coefficient [21] and T_c is the temperature of the solar panel.

Fig. 3 shows the schematic diagram of a simplified thermal model where T_c is the uniform temperature of the triple junction solar cell. The module receives energy from the concentrator of which a portion is lost from top and bottom surfaces in the form of convection and radiation losses. T_{in} is the water inlet temperature and T_{out} is water outlet temperature. A thermal resistance model is presented in Fig. 3. T_o is the ambient temperature, R_{rl} is the thermal resistance due to radiation losses, R_{nc} is the resistance due to natural convective losses caused by local wind gusts, R_{conv} is the resistance due to convective heat transfer of water.

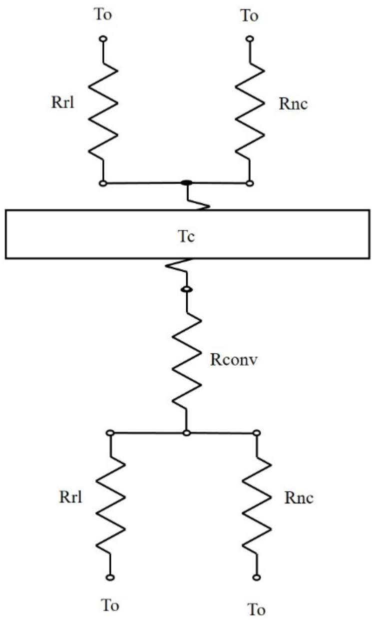

Fig. 3. Thermal resistance model of the system

The energy from the solar radiation is transferred to the cooling water; losses in the form natural convection Q_{nc} and in the form of radiation from cell Q_{rl} from top and bottom surfaces. The losses from sides can be neglected. The energy balance equations are as follows

$$\alpha G - E - Q_{nc} - Q_{rl} = Q_{conv} \tag{3}$$

where α is the absorptance of triple-junction solar cells.

The radiative losses can be estimated as follows

$$Q_{rl} = \varepsilon\sigma A(T_c^4 - T_0^4) \tag{4}$$

where T_c is the surface temperature, T_o is the ambient temperature, ε is the surface emissivity and σ is the Stephan–Boltzmann constant.

By determining a thermal resistance R_{nc} for convective heat transfer from a surface, depending on surface and ambient parameters, the heat flux through convection from the surface is simply given by

$$Q_{nc} = T_c - T_0 / R_{nc} \tag{5}$$

Where $R_{nc} = 1/h_{nc} A$ (6)

The convective heat transfer coefficient at the outer surface of solar cells is given by [22]

$$h_{nc} = 3.8u_a + 5.7 \tag{7}$$

where u_a is the wind velocity.

The forced convective heat is given by Q_{conv} is given by

$$Q_{conv} = T_c - T_0 / R_{conv} \tag{8}$$

Where $R_{conv} = 1/h_{conv} A$ (9)

$$h_{conv} = Nu_D \frac{k_w}{D_h} \tag{10}$$

where k_w and D_h re the thermal conductivity of water and hydraulic diameter respectively. The Nusselt number that is applicable to a large range of Reynolds number, including the transition region [23] is given by

$$Nu_D = \frac{\left(\frac{f}{8}\right)(\mathrm{Re}_D - 1000)P_r}{1 + 12.7\left(\frac{f}{8}\right)^{\frac{1}{2}}(\mathrm{Pr}^{\frac{2}{3}} - 1)} \tag{11}$$

where P_r is the Prandtl number, f is Moody (or Darcy) friction factor, and R_e is Reynolds number.

The pumping power P_{pump} in the channel can be calculated from [23]

$$P_{pump} = \Delta p \cdot A_{in} \cdot u_m \tag{12}$$

$$\Delta p = f\frac{L}{D}\rho\frac{u_m^2}{2} \tag{13}$$

Δp is the pressure drop across the channel, L and D are the length and width of the channel respectively and u_m is the mean water velocity.

The thermal output is

$$\dot{Q}_w = \dot{m}_w C_w (T_{out} - T_{in}) \tag{14}$$

where T_{in} and T_{out} are the inlet and outlet temperatures of water, respectively.

The thermal efficiency of the system is given by

$$\eta_t = \frac{\dot{Q}_w}{G} \tag{15}$$

The electrical efficiency is

$$\eta_e = \frac{E}{G} \tag{16}$$

And the overall efficiency is

$$\eta_o = \eta_t + \eta_e \tag{17}$$

TABLE 1. Concentrator Parameters

To	**ε**	**σ**	**ρ**	**α**	**η_r**	**β_r**	**r_p**	**Tr**
298	0.85	5.67E-08	0.92	0.95	0.366	0.002	0.83	298

TABLE 2. Cooling Channel parameters

Length of Box L, (mm)	**Width of box (mm)**	**Area (m2)**	**Height of box D, (mm)**	**Ain (m2)**
75	45	0.0034	15	0.001125

TABLE 3. Cooling Channel parameters

ρ(water) kg/m^3	**μ(water) kg/m/s**	**k(water) W/mk**	**k (cell)**	**Cp (water) J/(kg K)**
1000	0.00089	0.63	46	4182

IV. RESULTS AND DISCUSSIONS

The resulting transcendental equations from (3) are solved numerically and following results are reported. The concentration ratio and direct irradiance are chosen 500 and 550 W/m2 respectively, and the inlet temperature as 25 ^{0}C.

Fig. 4 shows the influence of thermal and electrical efficiencies on mass flow rate. As the mass flow rate decreases from 0.1 kg/s to 0.06 kg/s, the electrical efficiency of triple-junction solar cells will drop rapidly. The maximum electrical efficiency of 26.8 % is obtained at a mass flow rate of 0.1 Kg/s.

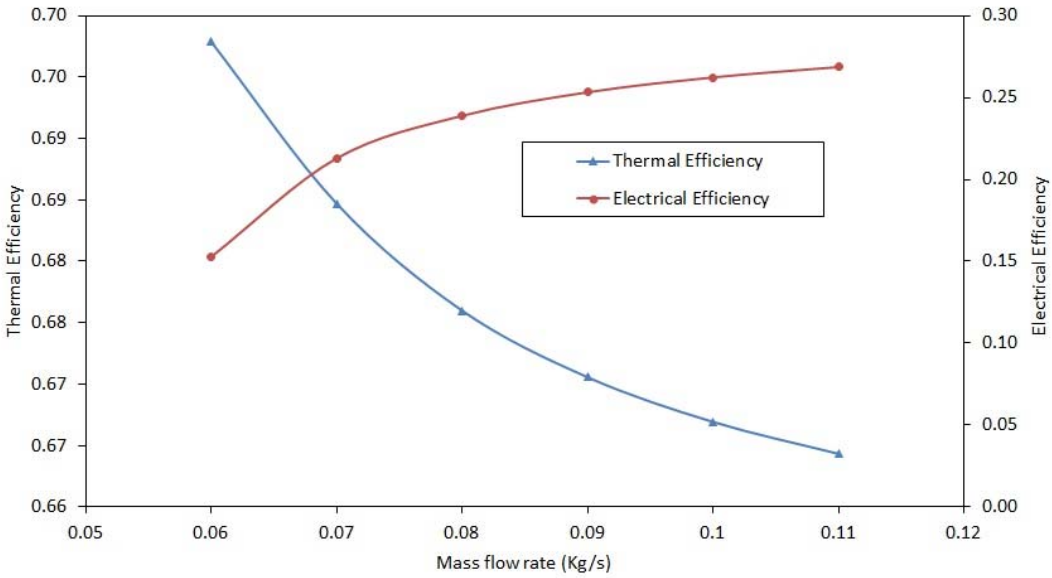

Fig. 4. Influence of mass flow rate on efficiencies

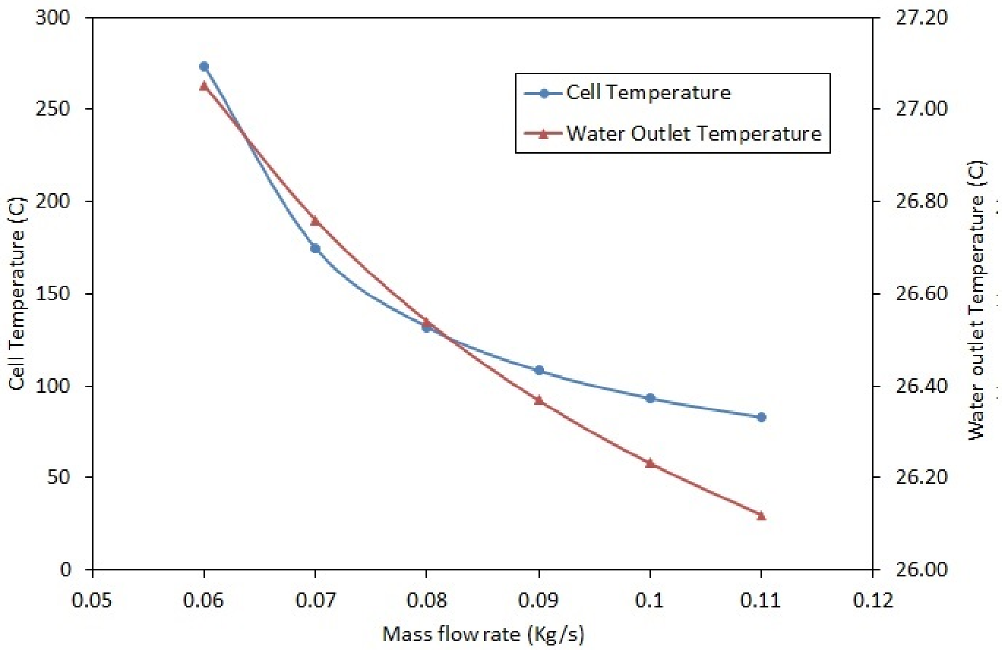

Fig. 1. Influence of mass flow rate on Cell and water outlet temperatures

The temperature of triple-junction solar cells will increase fast as shown in Fig.5. With lower mass flow rates the solar cell gets damaged due to the increase in cell temperature. This is due to the fact that the forced convective heat transfer coefficient is dependent on the mass flow rate. As the mass flow rate decreases the heat transfer coefficient also decreases. This reduction in mass flow rate below 0.06 Kg/s, in present case, decreases the heat transfer capability from the cell resulting in an obvious decrease in the electrical efficiency. On increasing mass flow rate from 0.06 kg/s to 0.1 kg/s, solar cell performance can be improved by providing necessary cooling.

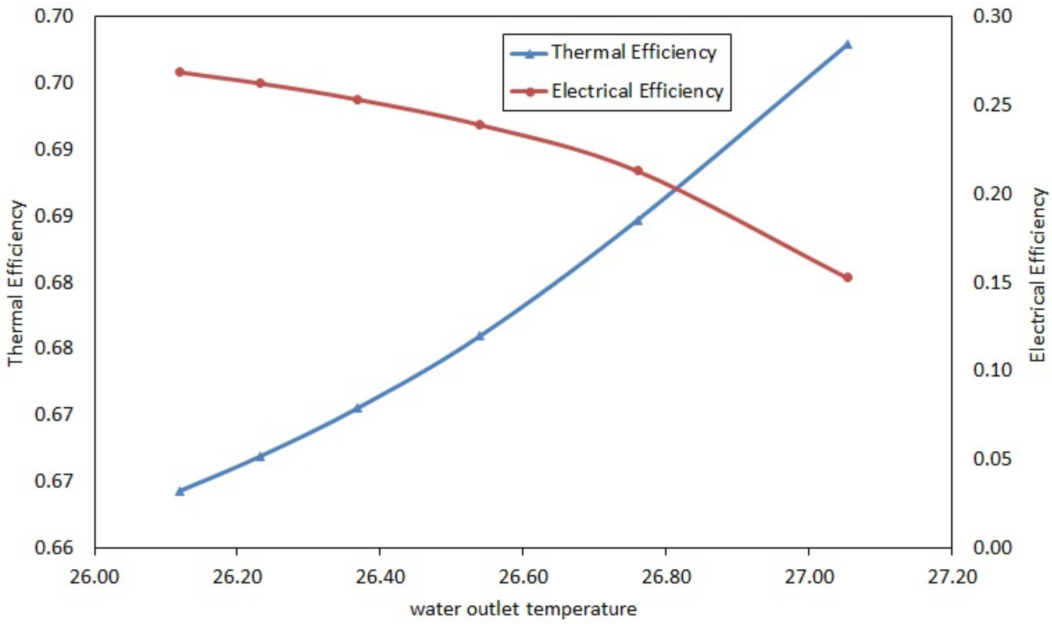

Fig. 2. Influence of Water outlet temperature on efficiencies

Fig. 6 shows the influence of efficiency with the water outlet temperature. The electrical efficiency is reduced as the outlet temperature of the water is increased. But, the thermal efficiency increased as the outlet temperature is increased as it is directly proportional to the temperature difference. Electrical efficiency decreased as the temperature of the cell is increased. Thus, convective cooling is essential to maintain proper electrical output.

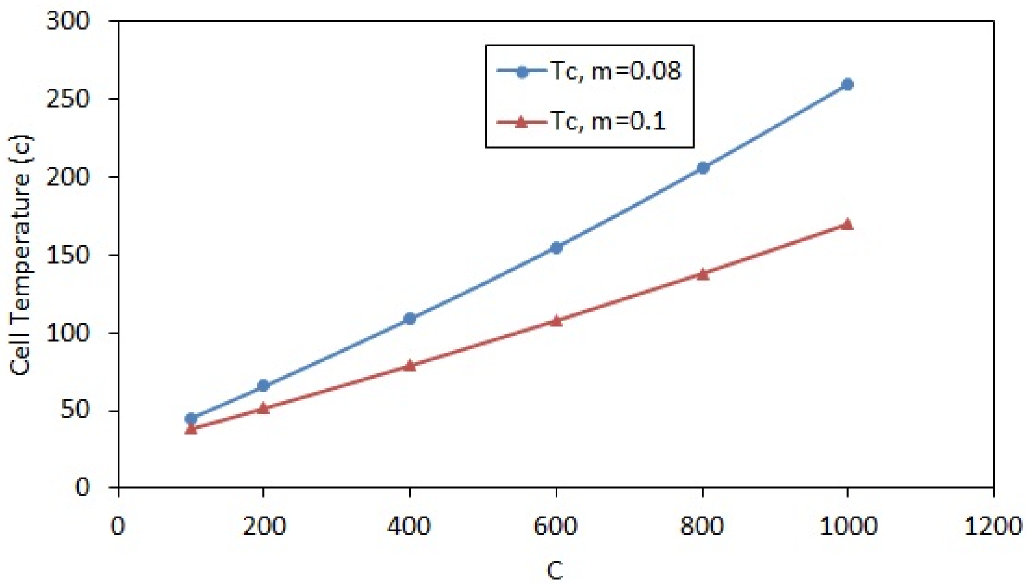

Fig. 3. Influence of concentration ratio on cell temperature

Fig. 7 shows the influence of cell temperature on concentration ratio. As the concentration ratio increases the temperature of cell increases. Thus, the need for cooling is very much evident as concentration ratio increases.

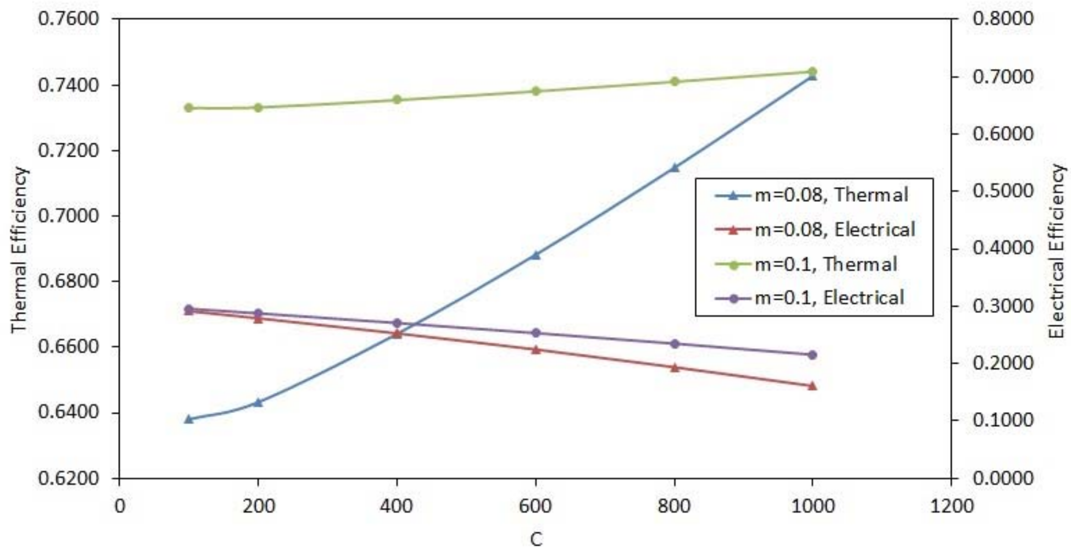

Fig. 4. Influence of Efficiency on Concentration ratio

The influence of thermal and electrical efficiencies on concentration ratios are shown in Fig.8 for two different mass flow rates. As the concentration ratios are increasing the thermal efficiencies are increasing while the electrical efficiency is reducing. But as the mass flow rates vary from 0.8 Kg/s to 0.1 Kg/s the electrical efficiencies tend to improve.

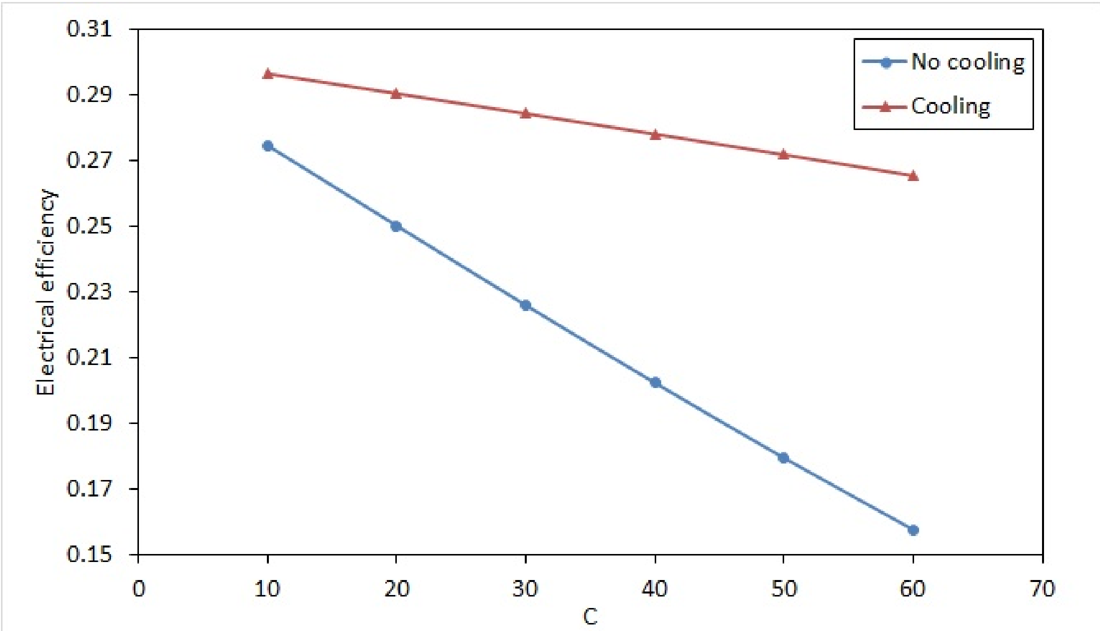

Fig. 5. Influence of Concentration ratio for cooling and no cooling cases

Fig. 9 shows a study on the variation electrical efficiency for cooling and no cooling cases. The electrical efficiency is higher as expected for the cooling case. There is a maximum improvement of 10.7 % increase in the electrical efficiency at a concentration ratio of 60 and a minimal improvement of 2.18% at a concentration ratio of 10 for cooling and no cooling cases respectively.

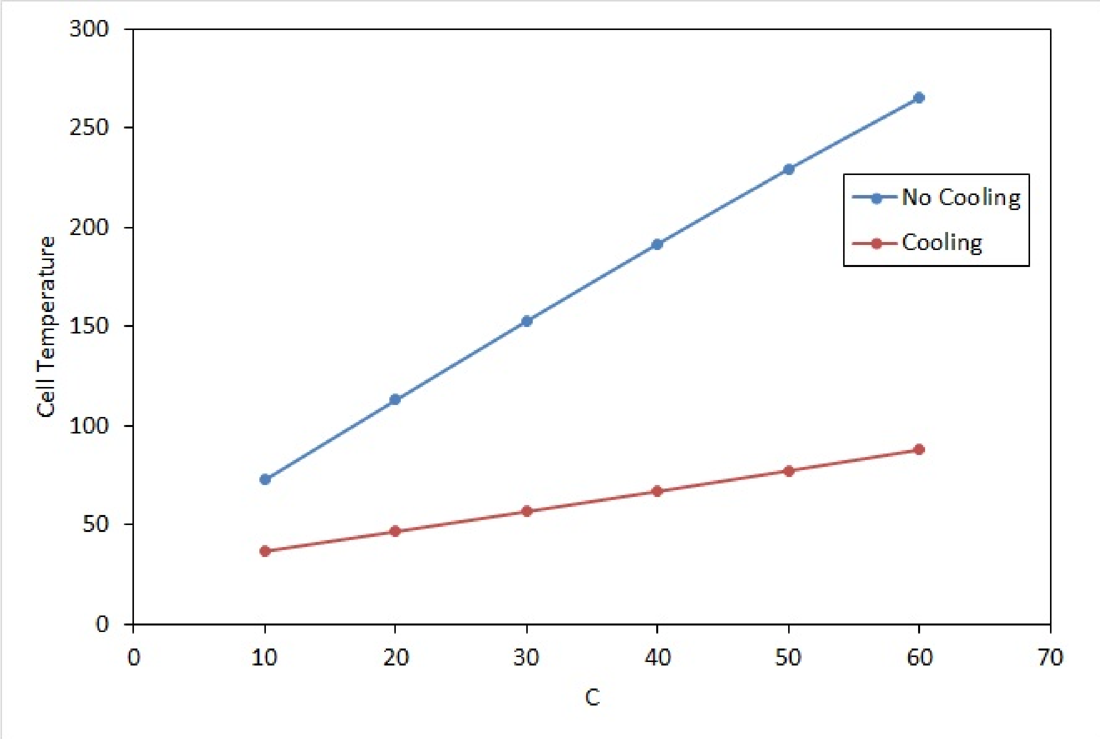

Fig. 6. Influence of concentration ratio on Cell Temperature for cooling and no cooling cases

The above trend is continued even for the cell temperatures and can be seen in Fig. 10. The cell temperatures during no cooling cases are very high. At a concentration ration of 60, the cell temperature reaches 538.45 K. such elevated temperatures certainly damages the cell and hence cooling is an important technique for enhancing energy output for concentrated photovoltaics.

V. CONCLUSION

In this paper, a mathematical model is developed for studying the thermal and electrical performance of triple junction solar cell PV/T system. Water is used to cool the solar cell by forced convection. The simulation results predict that the electrical efficiency achieved by the cell is about 29.15 % and the thermal efficiencies are as high as 70 %. There is an increase in efficiency of 10 % through cooling of the triple junction solar cell. Thus, the simulation results promise that the hybrid operation of a triple junction solar cell for both electrical as well as thermal aspects is possible with optimum mass flow rates. It is concluded that it is an attractive proposition to resort to P.V cell electrical energy as well as the solar thermal energy simultaneously that is a dual or combined mode harvest while seeking optimal points for peak harvests.

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