Optimization of Design Parameters of Glazed Hybrid Photovoltaic Thermal Module using Genetic Algorithm

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***Abstract*— The aim of this paper is to maximize the overall exergy efficiency of single channel photovoltaic thermal module. The solar panel (PV module) generally gives electrical efficiency in the range of 7% to 12%, the rest energy being dissipated in the form of heat losses. To recover thermal energy from the module photovoltaic thermal system has been simulated. The analysis in this work investigates the influence of seven important parameters on the efficiency of PVT solar system which inter alia includes length and depth of the channel, depth of insulation, velocity of fluid in the channel, depth of the tedlar and glass, and temperature of the fluid at the inlet on the basis of which optimization of the exergy efficiency of the module is done. Attempt is made to develop mathematical model and optimize parameters of glazed hybrid single channel photovoltaic thermal (PVT) module. The relevant mathematical equations for the glazed hybrid single channel photovoltaic thermal module are derived and genetic algorithm (GA) used to optimize overall exergy efficiency of the module. Only the parameters that could physically be varied are included in this optimization analysis while naturally occurring parameters like ambient temperature and solar intensity which vary naturally are excluded from design parameters in the algorithm. During second stage following first optimization only one parameter is varied at a time in the course of analysis while others are kept constant at the previously obtained optimal value.**

Keywords- Genetic Algorithm; PVT module; Single objective optimization

I. INTRODUCTION

Quite a number of theoretical and experimental researches on hybrid photovoltaic thermal system have appeared in the literature. The PVT systems were initially developed to utilize both thermal and electric energies from the sun. Zondag et al [2] developed a model of hybrid PVT air collector and performed experimental studies on the systems of varying sizes. Tiwari et al [3] validated the theoretical and experimental results for PV module integrated with air duct for composite climate of India and concluded that the overall thermal efficiency of PVT system is significantly increased (18%) due to utilization of thermal energy from PV module. Tiwari and Sodha [4] experimentally validated theoretical model of different configurations of hybrid PVT air collector with the help of parametric study. Dubey and Tiwari [5] made detailed analysis of thermal energy, exergy and electrical energy yield by varying the number of collectors and considering four weather conditions. Agrawal and Tiwari [6-8] evaluated theoretically the performance of a modified micro-channel solar cell thermal tile followed by its experimental validation and later replicated the same work on glazed hybrid micro channel solar cell thermal tile concluding that the glazed hybrid MCPVT module gives higher electrical efficiency in comparison with SCPVT module by 26.7% and obtained 20.28% overall exergy efficiency. The concept of series and parallel connections of micro-channel solar cell thermal tiles was also presented by them in these studies. Rajoria et al [9] validated theoretical model relating to thermal energy and exergy analysis of hybrid photovoltaic thermal array and gave four array configuration concluding that case III is better than other cases. Agrawal et al [10] have reported indoor experimental analysis of glazed hybrid photovoltaic thermal tiles air collector connected in series and concluded that connecting a number of glazed PVT tiles in series shall be more beneficial from overall energy and overall exergy point of view. Bonanno et al.[11] proposed a novel neural network based technique for the modeling of electrical output characteristics of a solar cell using a radial basis function neural network (RBFNN). Vats and Tiwari [12] derived the analytical expression for room air temperature of building integrated semitransparent photovoltaic thermal (BISPVT) and building integrated opaque photovoltaic thermal (BIOPVT) systems each integrated to the roof of a room with and without air duct. The comparative study revealed that increase of air mass flow rate (0.85–10 kg/s) through duct increases the room air temperature from 9.4 to 15.2^{0}C for SPVT roof for the given climatic and design parameters. Agarwal and Tiwari [13] performed overall energy, exergy and carbon credit analysis on different types of hybrid PVT air collectors concluding that overall annual thermal energy, exergy gain and exergy efficiency given by the unglazed hybrid PVT tile air collector improved over the conventional PVT air collector by 32%, 55.9% and 53% respectively. This research also showed that the cost of the carbon emission reduction of unglazed and glazed hybrid PVT tiles air collector is 62.3% and 27.% more than the conventional hybrid PVT air collector. Kulaksiz [14] did ANFIS-based estimation of PV module equivalent parameters and concluded that the developed model can be used to implement the MPPT controller as software embedded in a cost effective microcontroller which needs low processing power. Venkateswarlu and Raju [15] have done modeling and parameter extraction of PV modules using Genetic Algorithms and differential evaluation.

II. SYSTEM DESCRIPTION

In this work, the proposed PVT module is analyzed with a channel between tedlar and Insulation. The glass formation is considered above the solar cell. The schematic view of the proposed PVT module is shown in fig. 1which is usually called the single channel photovoltaic thermal tile (SCPVTC). In order to realize maximum overall thermal efficiency different parameters of the SCPVT module are optimized using Genetic Algorithm. When solar radiation is incident on the SCPVT module, the solar energy is converted into electrical and thermal energies. Out of these electrical energy is stored in a battery. Due to thermal energy the SCPVT cell gets heated giving reduced electrical efficiency because the module is constructed using semiconductor material.

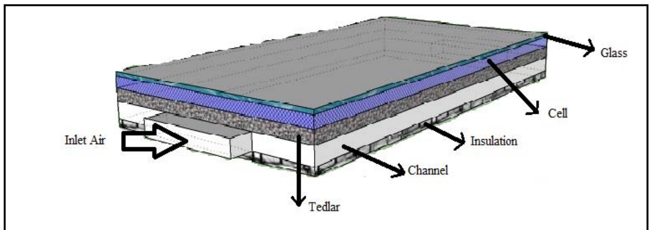

Figure 1. Proposed single channel photovoltaic thermal cell (SCPVT)

So, for optimizing electrical efficiency of the SCPVT module heat removal is essential. In order to convert this heat into useful thermal energy the SCPVT model is proposed in which the channel is formed below the tedlar and air flow occurs in the form of a flowing fluid through a DC fan. In SCPVT module solar radiation is absorbed by solar cell which conducts into to the base of the tedlar causing thermally heated air flowing into the channel below the tedlar as shown in figure 1.

III. THERMAL MODELING

In order to analyze energy balance of SCPVT module, the following assumptions are made:

1. there is no temperature gradient along the thickness of solar cell.
2. Heat capacity of solar cell is negligible
3. Specific heat of air remains constant in the course of observations.
4. The system is in the quasi-steady state.
5. Packing factor is unity.

The SCPVT cell is shown in figure 1. The small area of SCPVT cell is the bdx. The energy balance equation of glazed hybrid SCPVTC by Agrwal and Tiwari [7] is, by using symbols, and nomenclature of Table 1 given as follows:

TABLE I. NOMENCLATURE

Nomenclature of used parameters			
Symbol	***Name***	***Symbol***	***Name***
A_{SC}	Area of solar cell, m^2	b	Width of the channel, m
D	Depth of the channel, m	C_{air}	Specific heat of air, J/KgK
Dx	Small length, m	dt	Small time, s
H	Heat transfer coefficients, W/m^2K	h_{TA}	Heat transfer coefficient from back of tedlar to ambient, W/m^2K
In	Incident solar Intensity, W/m^2	h_{GA}	Heat transfer coefficient from top glass cover to ambient, W/m^2K
K_T	Thermal conductivity, W/mK	h_{TF}	Heat transfer coefficient from back of tedlar to flowing fluid, W/m^2K
L	Length of the channel, m	h_{IA}	Heat transfer coefficient from back of insulation to ambient, W/m^2K
m_F	Mass flow rate of fluid, kg/s	N_C	Number of channel in SCPVT module
Q_U	Useful heat, W	U	Overall heat transfer coefficient, W/m^2K
T_A	Ambient Temperature, K	U_{SCAG}	Overall heat transfer coefficient from cell to ambient through glass, W/m^2K
T_{Avg}	Average Temperature, K	U_{SCFT}	Overall heat transfer coefficient from cell to fluid through tedlar, W/m^2K
V_F	Velocity of fluid in channel, m/s	U_{FA}	Overall back loss heat transfer coefficient from fluid to ambient, W/m^2K
β_0	Temperature coefficient of efficiency, 1/K	η_{TC}	Efficiency at standard test condition when In =1000w/m^2 and T_A=25^{0}C
V_{air}	Velocity of air, m/s	$\eta_{C,power}$	Power conversion factor
A_m	Area of module, m^2	n_R	Number of rows in PVT module
Α	Absorptivity	β	Packing factor
η	Efficiency	ρ	Density, Kg/m^3
T_{FI}	Temperature of fluid at inlet, K	T_{FO}	Temperature of fluid at outlet, K

$$\begin{bmatrix}\text{Rate of solar}\\ \text{energy available}\\ \text{on glazed solar cell}\end{bmatrix} = \begin{bmatrix}\text{Rate of heat loss}\\ \text{from top surface of solar}\\ \text{cell to ambient through glass cover}\end{bmatrix} + \begin{bmatrix}\text{Rate of heat transfer}\\ \text{from solar cell to}\\ \text{flowing fluid i.e. air through tedlar}\end{bmatrix} + \begin{bmatrix}\text{Rate of electrical}\\ \text{energy produced}\end{bmatrix} ------(1)$$

$$\left[\alpha_c \tau_g In^* bdx\right] = \left[\left[U_{SCAG}(T_{SC}-T_A)bdx\right]\right] + \left[\left[U_{SCFT}(T_{SC}-T_F)bdx\right]\right] + \left[\tau_g \eta_{TC} In^* bdx\right] ----(2)$$

After solving equation 1, we get

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$$T_{SC} = \frac{\alpha_{eff} In + U_{SCAG} T_A + U_{SCFT} T_F}{U_{SCAG} + U_{SCFT}} -----(3)$$

where $\alpha_{eff} = \tau_g (\alpha_{SC} - \eta_{TC})$

Energy balance for air flowing in the channel of Single channel PVT for elemental area bdx is given by –

$$\begin{bmatrix}\text{Rate of heat transfer} \\ \text{from solar cell to} \\ \text{flowing fluid (air) through tedlar}\end{bmatrix} = \begin{bmatrix}\text{The rate of heat gain by} \\ \text{flowing fluid i.e. air in channel}\end{bmatrix} + \begin{bmatrix}\text{Rate of heat transfer} \\ \text{from flowing fluid} \\ \text{to ambient}\end{bmatrix} —(4)$$

$$U_{SCFT}(T_{SC} - T_F) bdx = m_F C_{air} \frac{dT_F}{dx} dx + U_{FA}(T_F - T_A) bdx ----(5)$$

where $m_F = \rho L d V_F$

The thermal gain is given by Agrwal and Tiwari [7] as follows:

$$\eta_{th} = \frac{m_F C_{air}}{U_L N A_{SC}}\left[1 - \exp\left(\frac{-NbU_L L}{m_F C_{air}}\right)\right]\left[h_p \alpha_{eff} - U_L \frac{(T_{FI} - T_A)}{In}\right] -----(6)$$

The rate of useful thermal energy obtained for n_R row of SCPVT module

$$Q_{U,N} = n_R m_F C_{air}\left[\frac{h_p \alpha_{eff}}{U_L} In + T_A - T_{FI}\right] * \left[1 - \exp\left(\frac{-N_C b U_L L}{m_F C_{air}}\right)\right] ---(7)$$

A. *Instantaneous Electrical Efficiency*

An expression for electrical efficiency of hybrid SCPVT which is temperature dependent is given by Agrwal and Tiwari [7] as follows:

$$\eta = \eta_{TC}\left[1 - \beta_0\left\{\frac{\alpha_{eff} In}{U_{SCAG} + U_{SCFT}} - (T_{FO} - T_A) + \frac{U_{SCFT} h_p \alpha_{eff} In}{U_L (U_{SCAG} + U_{SCFT})}\left\{1 - \frac{\exp\left(\frac{-NbU_L L}{m_F C_{air}}\right)}{\left(\frac{NbU_L L}{m_F C_{air}}\right)}\right\} + \frac{U_{SCFT}}{U_{SCAG} + U_{SCFT}}\left\{\frac{1 - \exp\left(\frac{-NbU_L L}{m_F C_{air}}\right)}{\left(\frac{NbU_L L}{m_F C_{air}}\right)}\right\}(T_A - T_{FI})\right\}\right] -----(8)$$

B. *Energy Analysis*

The energy analysis is based on the first law of thermodynamics, where the total thermal gain can be represented as follows :

$$\Sigma Q_{UT} = \Sigma Q_{U,Th} + \frac{\Sigma Q_{U,EL}}{\eta_{C,power}} --------(9)$$

where

$$\Sigma Q_{U,Th} = \frac{Q_{U,N}}{1000} ---------(10)$$

Here $\eta_{C,power}$ is the electric power generation efficiency conversion factor of the conventional power plant for India which is within the range of 0.20-0.40, given by Huang et al [1] and is based on the quality of coal. It is usually assumed as 0.38 .

C. *Exergy Analysis*

The general exergy balance by Agarwal & Tiwari [7] for a Single channel PVT module is expressed as:

$$\Sigma Ex_{OUT} = \Sigma Ex_{Th} + \Sigma Ex_{EL} ------(11)$$

$$where\ \Sigma Ex_{Th} = Q_{U,N}\left[1 - \frac{T_A + 273}{T_{FO} + 273}\right]\ and\ \Sigma Ex_{EL} = \left[\frac{\eta A_m In}{1000}\right]$$

The expression for input exergy is given by Petela [2003] as:

$$\Sigma Ex_{IN} = A_{SC} N_C * In\left[1 - \left(\frac{4}{3}\right)\left(\frac{T_A}{T_{Sun}}\right) + \left(\frac{1}{3}\right)\left(\frac{T_A}{T_{Sun}}\right)^4\right] ------(12)$$

The exergy efficiency of SCPVT module is given by Hepbasli [2008] as follows:

$$\eta_{Ex} = \left(\frac{Ex_{OUT}}{Ex_{IN}}\right) * 100 -----(13)$$

Design parameters of single channel PVT module [that are constant] are given here below in Table II

TABLE II. DESIGN PARAMETERS

S.No.	Parameters And Their Value		
	Parameters	***Value***	***Unit***
1.	τ_g	0.95	
2.	η_{TC}	0.15	
3.	α_C	0.9	
4.	β_0	0.0045	
5.	C_{air}	1012	J/KgK
6.	T_{FO}	25	^0C
7.	V_{air}	1.5	m/s
8.	K_g	1.1	W/mK
9.	K_T	0.033	W/m^2K
10.	K_{in}	0.089	W/m^2K
11.	h_{GA}	$5.7+3.8*V_{air}$	W/m^2K
12.	h_{TF}	4.3	W/m^2K
13.	ρ	1.29	kg/m^3
14.	N, n_R	4, 9	
15.	$\eta_{C,Power}$	0.38	
16.	h_{IA}	$2.8 + 3*V_F$	

IV. INTRODUCTION TO GENETIC ALGORITHM

Genetic Algorithms (GAs) are adaptive heuristic search algorithms based on the evolutionary ideas of natural selection and genetics. As such, these represent an intelligent exploitation of a random search used to solve optimization problems. Although randomized, GAs are by no means random, instead these exploit historical information to direct the search into the region of best performance within the search space. The basic techniques of the GAs are designed to simulate processes in natural systems necessary for evolution;

especially those following the principles first laid down by Charles Darwin of "survival of the fittest” since in nature, competition among individuals for scanty resources, results in the fittest individuals dominating over the weaker ones.

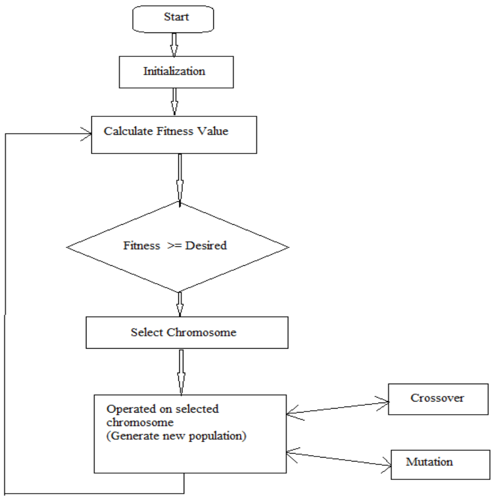

Figure 2. Genetic Algorithm flow chart

GAs are based on an analogy with the genetic structure and behavior of chromosomes within a population of individuals using the following foundations:

- Individuals in a population compete to gain resources and mates.
- The individuals most successful in each 'competition' shall produce more offsprings than those individuals performing poorly.
- Genes from `good' individuals propagate throughout the population so that two good parents shall generally produce offsprings that are better than either parent.

Thus each successive generation will become more suited to their environment. Genetic Algorithm Flow chart has been shown in Figure 2.

V. RESULTS AND DISCUSSION

In this paper, seven parameters, namely, the length (L) and depth of the channel (d), insulation thickness (L_{in}), velocity of fluid (V_F) in the channel, thickness of the tedlar (L_t) and of top glass cover (L_g), and temperature of the fluid at the inlet (T_{FL}) are varied to optimize overall efficiency of the SCPVT module. A genetic algorithm is applied in the present problem to determine optimized values of each of these parameter to realize maximum overall exergy efficiency. The stepwise procedure adopted to achieve this is as follows:

- Identify control parameters influencing overall exergy efficiency of the proposed SCPVT module.
- Define upper and lower bound of each parameter value feasible for designing the SCPVTC module.
- Decide the objective function (also known as fitness function).
- Develop the program MATLAB program for optimizing each parameter as based on the flow chart shown in figure 2.

A. Analysis on single data

Overall exergy efficiency of glazed PVT module has been optimized and the results obtained. The analysis has been done at 11:00AM at a single intensity and at ambient

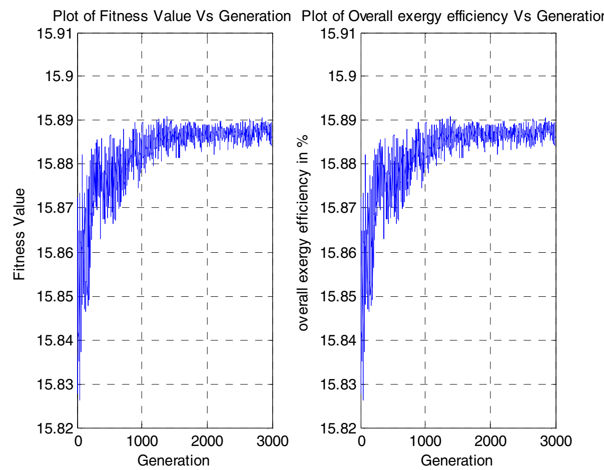

Figure 3. (a) Plot of fitness value Vs Generation (b) Plot of overall exergy efficiency Vs Generation

temperature. Following results have been obtained:

Input Data:

Intensity of Solar Light (In) - 680.73 KWH at 11:00AM
Ambient Temperature (T_A) - 6.6^{0}C at 11:00AM

Output Data:

The maximum overall exergy efficiency of the single channel PVT module is 15.89% which was obtained using the optimize parameter as given below in Table III. The convergence curve obtained is as shown in figure 3(b). The value of exergy efficiency has been optimized by genetic algorithm within 1500 generations.

TABLE III. OPTIMIZE PARAMETERS

S. No	Optimize Parameters			
	Name of Parameter	***Symbol***	***Optimize value***	***Unit***
1.	Depth of the channel	d	0.00075	m
2.	Length of the channel	L	0.0181	m
3.	Depth of insulation	L_{in}	0.1194	m
4.	Velocity of fluid in the channel	V_F	0.6554	m/s
5.	Depth of the tedlar	L_t	0.0001	m
6.	Depth of top glass cover	L_g	0.00021	m
7.	Temperature of fluid at inlet	T_{FI}	14.91	^{0}C

Optimum value of overall exergy efficiency = 15.89 %
Worst value of overall exergy efficiency = 15.82 %
Average value of overall exergy efficiency = 15.88 %

B. Analysis on varying parameter

The analysis has been done by varying one parameter at a time keeping all other parameters fixed at its optimum value as shown in Table II

Observations relating to overall exergy efficiency in figure 4 shows that when depth of the channel is varied with other parameters are fixed at optimized value, the overall exergy efficiency of module is maximum at d = 0.00075m.

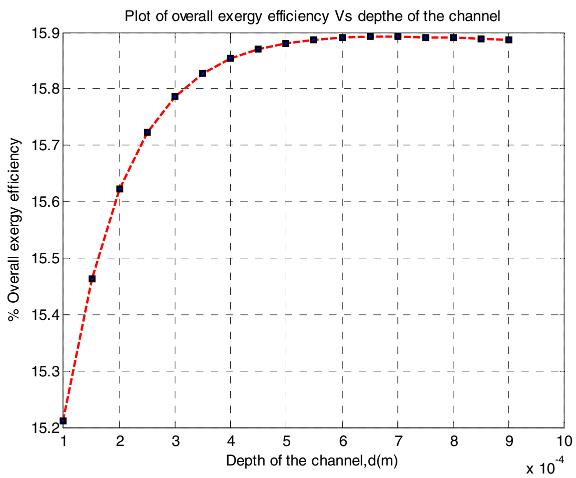

Figure 4. Plot of overall exergy efficiency Vs Depth of the channel

Observations relating to overall exergy efficiency in figure 5 shows that when length of the channel is varied with other parameters are fixed at optimized value, the overall maximum exergy efficiency of the module is obtained at L = 0.0181m.

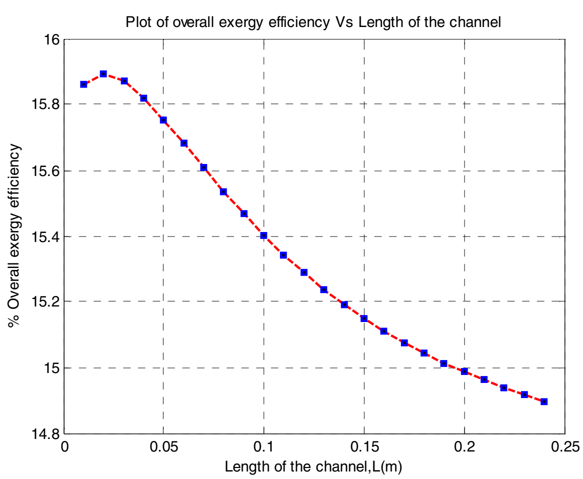

Figure 5: Plot of overall exergy efficiency Vs Length of the channel

Observations relating to fig 6 in which the depth the depth of insulation is varied to optimize overall exergy efficiency of the module keeping other parameters fixed, the overall exergy efficiency of the module is maximum at L_{in} = 0.1194m

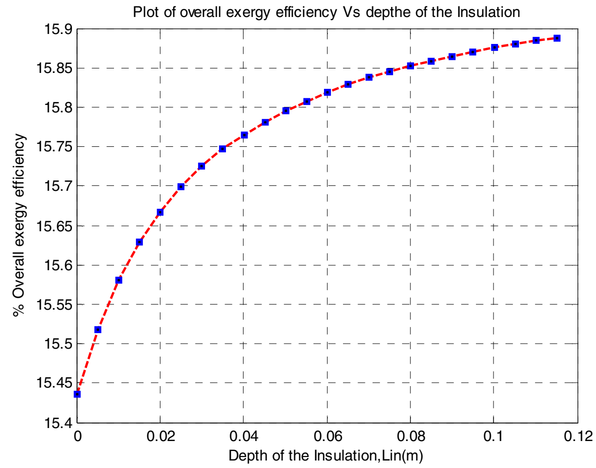

Figure 6: Plot of overall exergy efficiency Vs. Depth of the Insulation

From figure 7, it is seen that when velocity of flowing fluid is varied keeping all other parameters fixed at optimized value. the overall exergy efficiency of the module is maximum at V_F = 0.6554m/s.

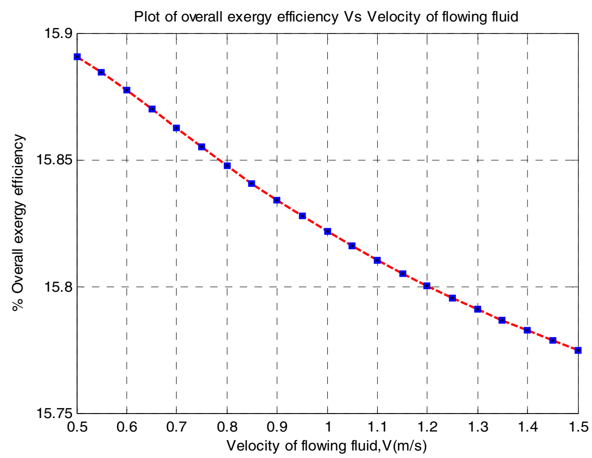

Figure 7: Plot of overall exergy efficiency Vs Velocity of flowing fluid

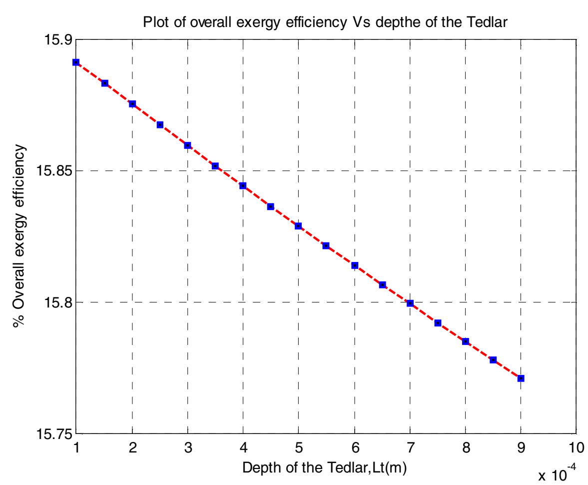

Figure 8: Plot of overall exergy efficiency Vs Depth of the tedlar

In figure 8, it is seen that when depth of the tedlar is varied keeping other parameters fixed at optimized value, the overall exergy efficiency of the module is at maximum for L_t = 0.0001m..

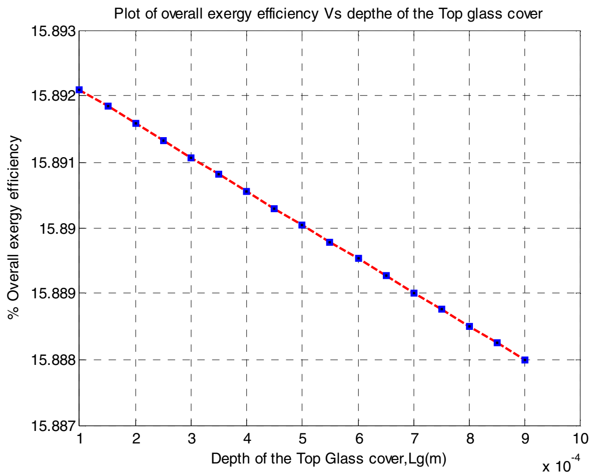

Figure 9: Plot of overall exergy efficiency Vs Depth of the top glass cover

Figure 9 shows that when depth of the top glass cover is varied with other parameters fixed at optimized value of exergy efficiency, the overall exergy efficiency of the module is maximum for L_g = 0.0001m

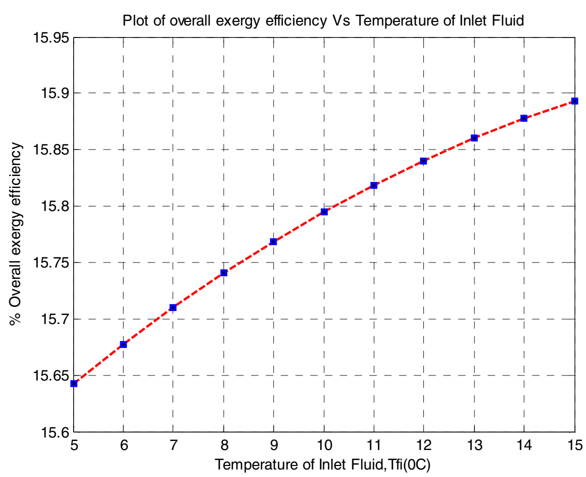

Figure 10: Plot of overall exergy efficiency Vs Temperature of inlet fluid

From figure 10, it is observed that when temperature of the inlet fluid is varied keeping all other parameters fixed at optimized value of exergy efficiency, the overall exergy efficiency of the module is maximum at $T_{FI} = 14.91^0$C.

VI. CONCLUSIONS

- The observation from figure 3 to 10 above lead to the coclusion that the overall exergy efficiency of the single channel PVT module is 15.8910% bringing an improvement of approximately 11.27% over the model suggested by Agrwal and Tiwari [7].
- Reoptimization of all the seven parameters given in Table III leads to the maximum overall exergy efficiency of SCPVT module .

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