Comparative analysis of single and multi-duct air cooling in photovoltaic thermal hybrid system

Rekha L[#1], Vijayalakshmi M M[*2], Natarajan E[#3]

[1] Department of Mechanical Engineering, Government College, Thrissur-680009, India
[2] Department of Civil Engineering, Sathyabama University, Chennai-600119, India
[3]Department of Mechanical Engineering, Anna University, Chennai-600025, India
[1] rekhadinesh05@gmail.com,[2] vijinat@hotmail.com,[3] enat123@gmail.com

***Abstract*—Solar energy is one of the most promising renewable sources of energy for present needs. Solar Photovoltaic Thermal (PV/T) system is a hybrid system to produce both thermal and electrical energy. This paper attempts to investigate the thermal and electrical performance of a solar photovoltaic thermal (PV/T) air collector with single and multi-ducts. The performance of the 50 Wp PV module with and without cooling is analysed. The thermal model is used to estimates the air outlet temperature, cell temperature and back surface temperature. The outcome of the model is verified by the experimental results. The electrical and thermal outputs are suitably combined to get the overall thermal efficiency of a PV/T air collector. The electrical efficiency is found to vary from 10.2 to 11.5%, efficiency being low at high temperature. The air cooling of the module increases the minimum and average efficiency. The maximum and average values of overall thermal efficiency are found to be 49.3% and 43.2% in the single duct case and 39.6% and 36.74% in the multi-duct case, when velocity of air is maintained at 3 m/s. When multi-duct is used, the temperature difference between the cooled and uncooled portion of the module is found to vary from 2o C to 5o C. This temperature difference can be reduced by maintaining the higher flow velocity. The non-uniform temperature profile created by the multi-duct cooling system reduces the module electrical efficiency by 0.4%, compare to single duct cooling. It indicates that the distribution of any coolant at the base for cooling must be distributed as uniformly as possible. Any lack of uniformity in distribution may lead to considerable loss of energy. Thus, proper care must be taken to distribute the coolant by providing proper baffles so as to ensure uniform cooling to obtain best possible performance.**

Keyword-Electrical Efficiency, Multiple Duct, Overall Efficiency, Photovoltaic Thermal PV/T

I. INTRODUCTION

Energy is an essential factor for the human comfort and development. Every energy generation and transmission method affects the environment. About 90% of the world energy supplies are provided by fossil fuels, with the associated emissions causing local, regional, and global environmental problems. Serious environmental concerns like global warming, climate change compel us to think of alternative methods of energy generation and utilization. The major applications of solar energy can be categorized into two groups: solar thermal systems to convert solar energy into thermal energy, and solar photovoltaic (PV) system to convert solar energy into electrical energy.

The efficiency of solar cell is very less (about 15%) and the efficiency of the solar module is still less (about 12%) owing to ohmic loss occurring between the two solar cells connected in series and the low packing factor. To shorten the long payback period of a photovoltaic (PV) module due to its low efficiency, a PV module can also be used for thermal applications such as air/water heating, space heating or solar drying. When solar radiations fall on the solar cells of PV module, a part of its gets converted into electricity and most of it is dissipated as heat, which subsequently heats the solar cells and module. Such heat removal also keeps the temperature of cell and module closer to its design value so that its loss of performance is reduced. It is highly suitable for decentralized power generation and hence the elimination of transmission losses. Although solar photovoltaic system is a viable alternative source of energy, its performance decreases with increase in temperature. Besides, the thermal energy recovered can be used for other useful purposes and hence increasing the overall effectiveness and efficiency of the system. In order to avoid any need for any external energy to circulate the coolant to cool the PV module, the PV/T module can be combined with the solar air/water heater collector as initial preheater. It can considerably reduce the solar heat gain by the buildings when mounted on the building roof. PV/T system is compact due to the use of common frames and brackets as compared to the independent solar PV and solar thermal systems of the same capacity. Although such systems are being analysis for more than three decades, there is a renewed interest in the recent past due to fast depleting fuels, accelerated degradation of the environment, limited space and fast increasing energy demands.

In this paper, the thermal and electrical performance of a solar 50Wp PV/T module with rectangular single and multi-duct air cooling is presented. The temperature profile is also analysed to understand the effect of non-uniform cooling on the thermal, electrical, overall thermal efficiency of the module.

II. EARLIER STUDIES

In the recent times, a considerable attention is focused on the use of air and water cooling to the modules to control its temperature rise [1]-[5]. Bhattarai et al.[1] presented a one-dimensional mathematical model for simulating the transient processes of sheet and tube type photovoltaic/thermal (PV/T) system and conventional type solar collectors. The first order ordinary differential equations were formed and solved in the Matlab computer program using ODE solvers. The results were validated by the performance tests. The thermal efficiency of the PV/T and conventional solar collecting systems were 58.70% and 71.50%, respectively, under steady state conditions. The electrical efficiency of the PV/T system was found to be 13.69%. The daily thermal efficiency of the conventional solar collector was almost 18% higher than that of the PV/T system, but the primary energy saving efficiency of the PV/T system was around 16% higher than that of the conventional solar collecting system. Chow [3] has done a review on PV/T hybrid solar technology especially PV/T hybrid solar technology. His article gives a review of the trend of development of the technology, in particular the advancements in recent years and the future work required. The combined generation of electrical and thermal energy from the PV/T system is an attractive and promising feature as solution for the future energy problems [6]-[7]. The energy and exergy analysis of PV/T systems are widely presented to emphasise the quantity and quality of the energy produced [8]-[9].

Sarhaddi et al. [10] has made an attempt to investigate the thermal and electrical performance of a solar photovoltaic thermal (PV/T) air collector. A detailed thermal and electrical model is developed to calculate the thermal and electrical parameters of a typical PV/T air collector. The thermal and electrical parameters of a PV/T air collector include solar cell temperature, back surface temperature, outlet air temperature, open-circuit voltage, short-circuit current, maximum power point voltage, maximum power point current, etc. It was also found that the thermal efficiency, electrical efficiency and overall energy efficiency of PV/T air collector is about 17.18%, 10.01% and 45%, respectively, for a sample climatic, operating and design parameters.

Tiwari et al. [11] developed an analytical expression for an overall efficiency (electrical and thermal) of a PV/T system by using energy balance equation for each component and evaluated the theoretical and experimental performance for composite climate of India. In addition to 12% electrical efficiency, an additional 18% of thermal efficiency of hybrid PV/T system was reported.

Joshi et al. [12] attempted to evaluate the thermal performance of a hybrid photovoltaic thermal (PV/T) air collector system for two types of photovoltaic (PV) module namely PV module with glass-to-tedlar and glass-to-glass. The hybrid air glass-to-glass PV/T collector was found to be with better performance. The overall equivalent thermal efficiency was found to be in the order of 43.4 – 47.4% for glass-to-glass and 41.6 – 45.4% for glass-to-tedlar case.

Tiwari et al. [13] has presented a comprehensive review of the available literature covering the various types of recent PV modules based on generation of solar cell and their applications in terms of electrical as well thermal outputs. He has presented a detailed modeling procedure. Tian et al. [14] attempted to make a detailed model from cell-to-module-to-array and presented a modified current–voltage relationship for the single-diode model, based on a five-parameter model. The model was found to accurately predict voltage–current (V–I) curves, power–voltage (P–V) curves, maximum power point values, short-circuit current and open-circuit voltage across a range of irradiation levels and cell temperatures.

Siddiqui et al. [15] has developed a novel thermal model to simulate the thermal performance of PV modules with and without cooling. The model was sequentially coupled with a radiation model and an electrical model to calculate the electrical performance of the PV panels. Using the developed model, various studies were performed to evaluate the electrical and thermal performance of the module under different environmental and operating conditions with and without cooling. Within the absorbed radiation range of 200–1000 W/m^2, at an ambient temperature of 25^{o}C, PV panel with cooling showed an improvement in its efficiency from 8.47% to 10.5% with almost linearly increasing electrical power from 17.8 W to 120 W. Whereas, for the same range, efficiency was found to reduce from 7.8% to 7.4% for panel without any cooling.

III. MATHEMATICAL MODEL OF THE HYBRID PV/T AIR COLLECTOR

It is assumed in this study that (i) the system is in quasi-steady state condition, (ii) the transmittivity of EVA is 100%, (iii) The temperature is uniform across the thickness which is very small and (iv) the airflow through duct is uniform. The thermal and electrical output of a PV/T air collector including back surface temperature, and outlet air temperature are analysed. From the energy balance equations of hybrid PV/T system, the air temperature at any distance x in the cooling duct [11] can be written as,

$$T_{air} = \frac{h_{p1} h_{p2} (\alpha\tau)_{eff} G}{U_L} \left(1 - e^{-bxU_L/\dot{m}_{air} c_{air}}\right) + T_a \left(1 - e^{-bxU_L/\dot{m}_{air} c_{air}}\right) + T_{air,in} e^{-bxU_L/\dot{m}_{air} c_{air}} \quad (1)$$

$$U_L = U_{tair} + U_b,\ h_{p1} = U_T/(U_t + U_T),\ h_{p2} = h_T/(U_{tT} + h_T)$$

$$(\alpha\tau)_{eff} = \tau_g \left[\alpha_c \beta_c + \alpha_T (1 - \beta_c) - \eta_e \beta_c\right]$$

Now, the outlet air temperature (Tairout) can be obtained by substituting x =L in Eq. (1)

$$T_{air,out} = \frac{h_{p1} h_{p2} (\alpha\tau)_{eff} G}{U_L} \left(1 - e^{-bLU_L/\dot{m}_{air} c_{air}}\right) + T_a \left(1 - e^{-bLU_L/\dot{m}_{air} c_{air}}\right) + T_{air,in} e^{-bLU_L/\dot{m}_{air} c_{air}} \quad (2)$$

The tedlar base temperature (T_{bs}) and cell temperatures (T_c) are given as,

$$T_{bs} = \frac{h_{p1} (\alpha\tau)_{eff} G + U_{tT} T_a + h_T T_{air}}{U_{tT} + h_T} \quad (3)$$

$$T_c = \frac{\left[\alpha_c \beta_c + \alpha_T (1 - \beta_c)\right] G - \eta_e G \beta_c + U_t T_a + U_T T_{bs}}{U_t + U_T} \quad (4)$$

The rate of useful thermal energy from PV/T collector, expression for thermal efficiency of a system and temperature dependent electrical efficiency of a PV module are given as,

$$\dot{Q}_u = \dot{m}_a c_{air} (T_{air,out} - T_{air,in})$$

$$\dot{Q}_u = \frac{\dot{m}_a c_{air}}{U_L} \left[h_{p1} h_{p2} (\alpha\tau)_{eff} G - U_L (T_{air,in} - T_a)\right] \left(1 - e^{-bLU_L/\dot{m}_{air} c_{air}}\right) \quad (5)$$

$$\eta_{th} = \frac{\dot{Q}_u}{A \cdot G} \quad (6)$$

$$\eta_e = \eta_{e0} [1 - \beta_r (T_c - T_{a0})] \quad (7)$$

Here β_r the efficiency loss coefficient due to temperature and ηe0 is is the reference efficiency of the PV module and T_{a0} is the reference temperature (25^oC) under standard test conditions.

The electrical efficiency is also experimentally measured as,

$$\eta_e = \frac{\text{Electrical energy delivered in a given time}}{\text{Solar energy received during the same time}}$$

In order to calculate overall equivalent thermal efficiency, the electrical efficiency is first converted into equivalent thermal efficiency (known as electrical based thermal efficiency) and then added to thermal efficiency due to air heating. Thus, the overall equivalent thermal efficiency of the system can be written as,

$$\eta_{oth} = \eta_{th} + \frac{\eta_e}{C_f} \quad (8)$$

C_f is the factor for converting electrical efficiency into equivalent thermal efficiency. The value of C_f for a conventional power plant in India varies between 0.20 and 0.40. In this study, C_f is taken as 0.36 [10].

IV. EXPERIMENTAL SET UP

A 50 W_p solar PV module of 650 mm x 600 mm is selected for the study. The specification of the module is shown in Table 1. Design parameters of photovoltaic thermal (PV/T) systems are shown in Table 2.The module is mounted on the structure whose inclination can be adjusted. In the present study, the inclination of module has been fixed at 13^o to the horizontal, that corresponds to the local latitude. The module contained 4 rows of cells each containing nine cells. Three modules are taken for study - one without cooling, another with single duct (SD) covering the complete bottom side of the module. The third module is provided with four cooling ducts (Multi-Duct : MD, made of aluminium, 100 mm width and 20 mm depth), as shown in Fig. 1.

Table 1 Module Specification

Cell Type	Mono – crystalline
Area of Module	0.39 m^2
Packing factor	0.86
Maximum current	2.67 A
Maximum voltage	21 V
Efficiency	12%

The longitudinal axes of the ducts are aligned with the centre lines of the rows of the cell. The width of the channel covers the gap between the two extreme silver electrodes. The outer 2 channels are of 520 mm long and the inner two channels are made 480 mm long due to the presence of the connector box. The air is supplied by the blower through the down header and it passes up through the rectangular aluminium cooling channels to the top header, from where it is released to the atmosphere. The channels are glued to the bottom tedler layer of the PV panel. The temperature of the inlet and outlet air is measured. The temperature of top glass cover and the back surface (tedler) of the PV panel is measured at three levels (bottom, centre and top). Fig. 2 illustrates the various views of the PV panel, showing the cooling channel arrangements. Fig. 3 shows the photographic view of the PV panel.

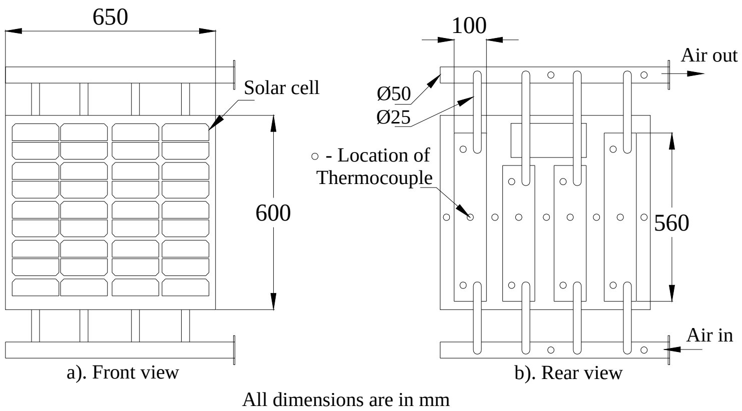

Fig 1. The Front and rear view of the PV panel, showing the cooling channel arrangements.

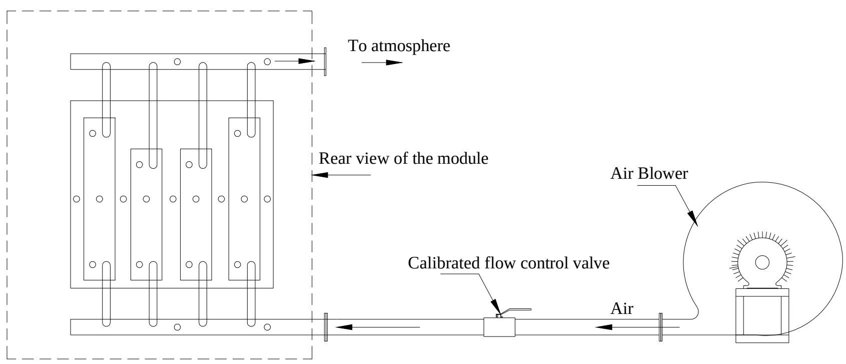

Fig 2. Schematic arrangement of a hybrid PVT system (with rear view of the module).

Fig 3. Photographic view of the PV panel with cooling channels and headers

A blower is used to force the air through the module with sufficient velocity. Two groups of experiments were conducted. In one case, the air speed of 3 m/s is maintained in both the single duct (SD) and multi duct (MD) configuration. It may be noted that in the case of SD configuration, the complete base of the tedlar is cooled by the air flow and in the case of MD configuration, the central portion of the cell alone is cooled as shown in Fig.1b. In another case, air flow rate of 0.5 kg/s that corresponds to 3 m /s velocity in SD configuration is maintained in both the configuration

V. RESULTS AND DISCUSSIONS

The hourly variation of global solar intensity (G), ambient temperature (T_a) and tedlar base temperature for the uncooled (UC), SD and MD configuration on a typical day in the month of May in Chennai are plotted in Fig. 4 for the air flow rate of 3 m/s. In the case of multi-duct, the base temperature refers to the temperature measured within the duct. The temperature difference between the SD and MD configuration increases with the increase in solar intensity and it is about 5^{o}C during noon. The measured values were found to be in closes agreement with the theoretically calculated values based on the equations for the base surface temperature.

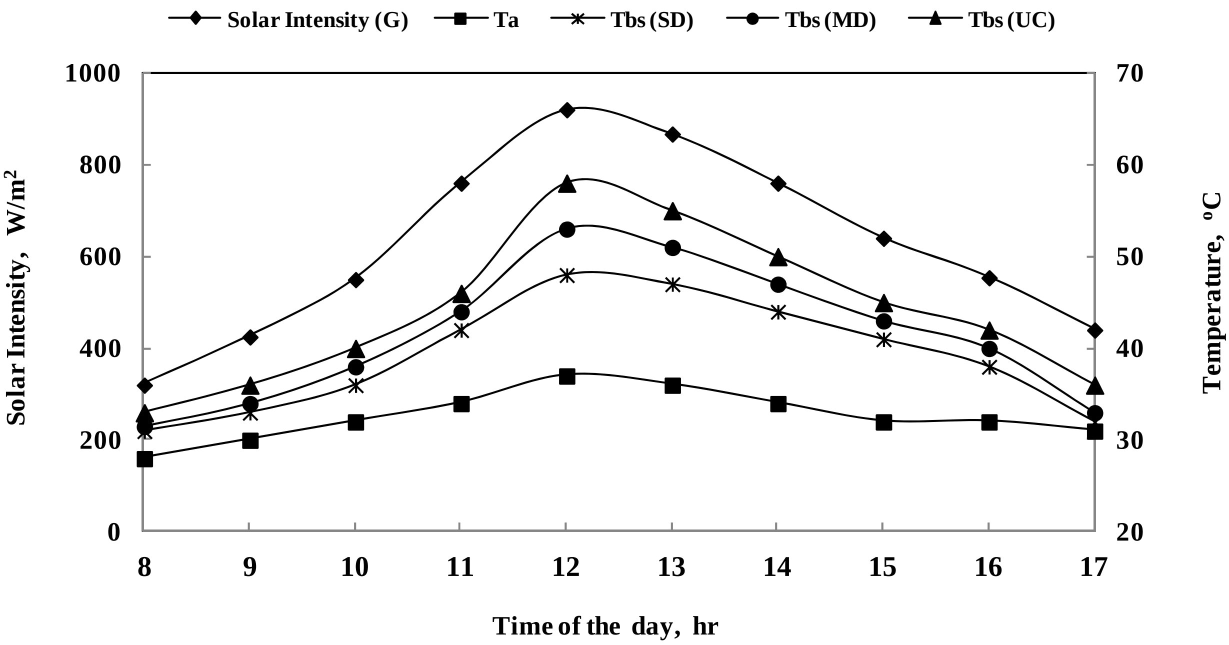

Fig. 4. Hourly variation of solar intensity, ambient and tedlar base temperatures.

The inlet air temperature ($T_{air,in}$) and the outlet air temperature ($T_{air,out}$) for both SD and MD type are shown in Fig. 5. The outlet air temperature for the multiple-duct configuration is high by about 2^{o}C, due to high back surafce temperature and the reduced flow rate of air owing to limited flow area.

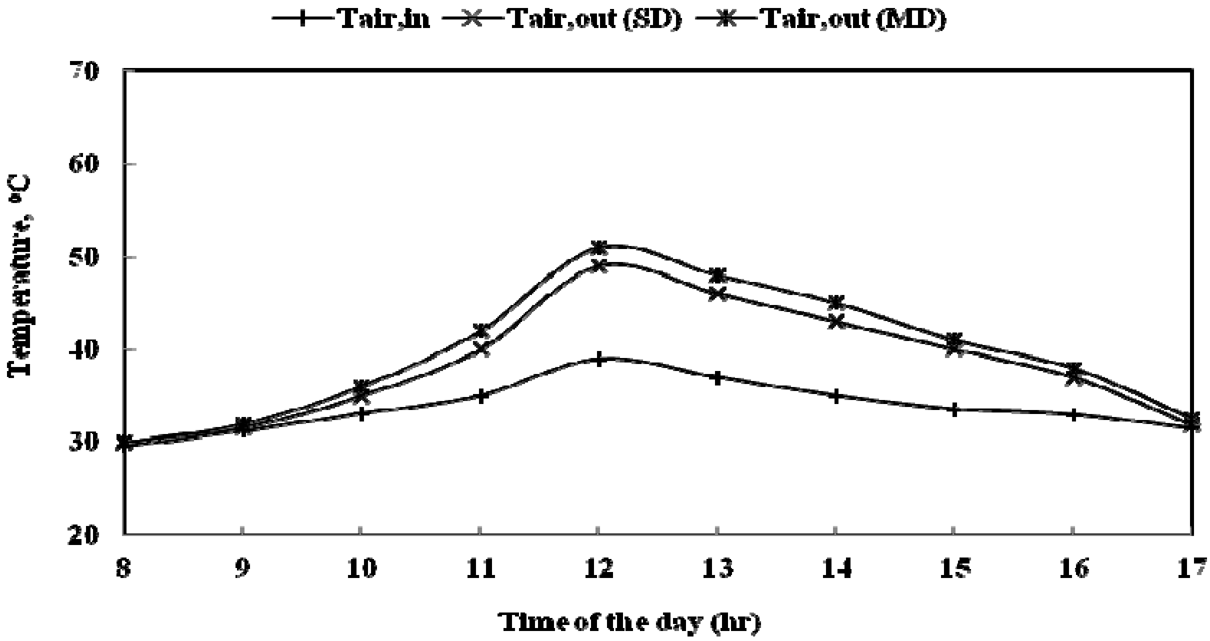

Fig 5 Hourly variation of inlet air temperature and outlet air temperatures of SD and D configuration.

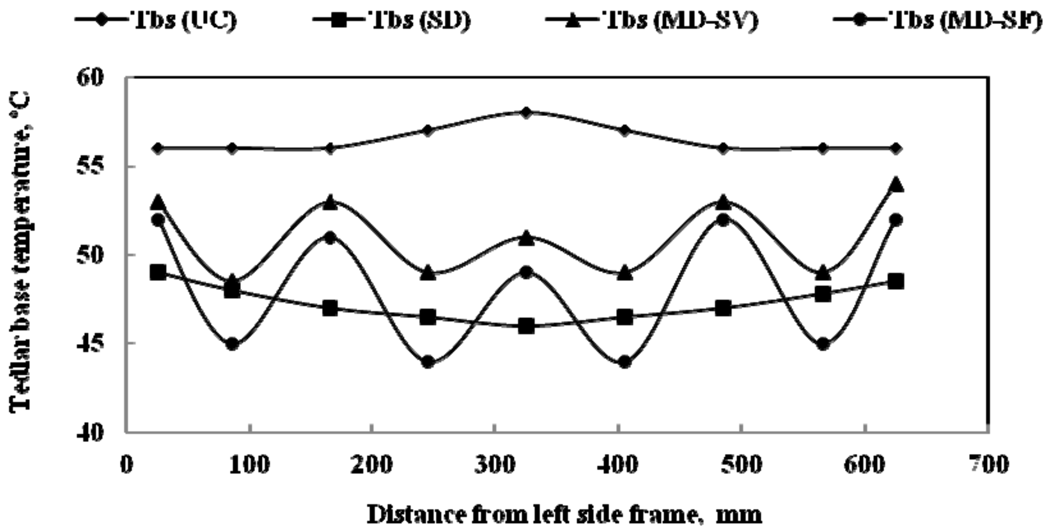

Fig 6. The variation of temperatures along the width of the panel.

The variation of the temperature along the width of the panel is plotted in Fig. 6 during noon – for the case of same velocity (SV) and same flow rate (SF). Velocity of 3m/s and flow rate of 0.5 kg/s are used for this study. It could represent the extreme case of non uniform flow of air in the base. The thermal stress induced is proportional to the maximum temperature differene between the adjacent areas. It is found to be higher near the edges, compared to the middle of the module and less in the case of same flow rate due to higher cooling effect caused by high convective heat transfer. When the same velocity is maintained, the temperature difference between the cooled and uncooled portion of the tedlar in the MD configuration is found to be 2 to 5^{o}C. The average tedlar base temperature in SV case is 3.5^{o}C higher and in SF case 1.5^{o}C higher, compared to SD case. The thermal effciency is computed from the mass flow rate of air and its temperature rise. The electrical efficiency is calculated based on the actual energy delivered and solar energy incident on it. The overall effective thermal efficiency is computed taking electrical conversion efficiency factor as 0.38. The variation of these efficiencies (for the case of air velocity of 3 m/s) with the time of the day is plotted in Fig. 7. Also during the local time of 10.00 hr -15.00 hr the variation of electrical efficiency is significant because of the cell temperature variation. The average solar cell temperature is 47^{o}C, while its maximum temperature is about 58^{o}C. The electrical efficiency of the uncooled module is found to vary from 10.2 to 11.5%, efficiency being low at high temperature, as shown in Fig. 7. The temperature difference between the back surface and the front glass cover vary from 2 to 5^{o}C.

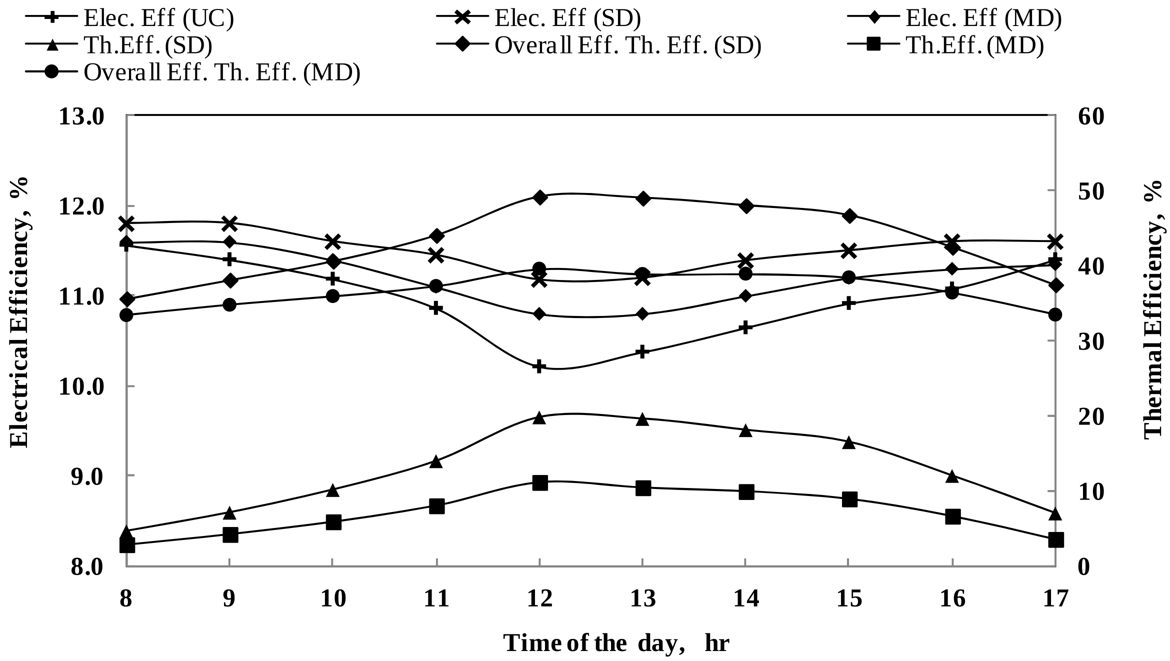

Fig.7. Hourly variation of various efficiencies with diffrent cooling temprature strategy.

The maximum and average thermal efficiency are found to be 19.8% and 12.9% for SD case and 11.2% and 7.2% for MD case. The lower values in MD case is due to the limited area of contact of the air. If the same air flow rate is maintained, the maximum and average thermal efficiency are found to improve to 12.6% and 8.2% for MD case.

The electrical efficiency of the uncooled(UC) module drops to 10.2% at 12 noon, while it is 10.8% for MD case and 11.2% for SD case. It indicates the maximum loss of electrical efficiency is about 0.4%. If air velocity is increased in the MD case to maintain the same air flow rate, the electrical efficiency improves to 11% in MD case, reducing the loss of efficiency, due to reduced average tedlar base temperature. The maximum and average values of overall thermal efficiency are found to be 49.3% and 43.2% in the SD case and 39.6% and 36.74% in the MD case, when same velocity of air is maintained at 3 m/s. If the same air flow rate is maintained, the maximum and average thermal efficiency are increased to 42.6% and 38.3% for MD case. The effect of cooling seems to considerably increase the performance due to high solar irradiance and ambient temperature.

VI. Conclusion

The performance of the 50 W_p PV module with and without cooling is analysed. The performance of the module with single duct for cooling complete base area suffers low loss of performance. Another module with multi-duct to cool only the centre portions of the cell is used to understand the effect of temperature non-uniformity and the performance loss. When multi-duct is used, the temperature difference between the cooled and uncooled portion of the module is found to vary from 2^oC to 5^oC. This temperature difference can be reduced by maintaining the higher flow velocity. The electrical efficiency is found to vary from 10.2% to 11.5%, efficiency being low at high temperature. The air cooling of the module increases the minimum and average efficiency. The maximum and average values of overall thermal efficiency are found to be 49.3% and 43.2% in the single duct case and 39.6% and 36.74% in the multi-duct case, when velocity of air is maintained at 3 m/s.

The non-uniform temperature profile created by the multi-duct cooling system reduces the module electrical efficiency by 0.4%. It indicates that the distribution of any coolant at the base for cooling must be distributed as uniformly as possible. Any lack of uniformity in distribution may lead to considerable loss of energy. Thus, proper care must be taken to distribute the coolant by providing proper baffles so as to ensure uniform cooling to obtain best possible performance. Extracting thermal energy from the PV module not only improves its electrical performance but also increases its overall efficiency and thereby improves its efficacy. This type of system can be installed at remote areas for generating electrical energy, with hot air that can be used for closed door air drying purposes. Moreover it works noiselessly, with no toxic residues or unwanted pollutants or radioactive materials. It has high reliability with expected life span of 20 and 30 years and very low maintenance cost. It can be easily integrated with the buildings to make it self-sustainable and such system can be a preferable option for achieving goals of green buildings.

Nomenclature

A	area (m^2)
b	breadth (m)
c	specific heat of air (J/kg K)
G	solar insolation (W/m^2)
h_T	heat transfer coefficient from back surface to air through tedlar (W/m2 K)
h_{p_1}	penalty factor penalty factor due to the presence of solar cell material, glass and EVA/ from PVT
h_{p_2}	penalty factor due to the presence of interface between tedlar and working fluid through the duct
k	thermal conductivity (W/m K)
$\dot{m}$	mass flow rate of air (kg/s)
MD	multi duct
$\dot{Q}_u$	rate of useful energy transfer (W)
SD	single duct
SF	same flow
SV	same Velocity
T	temperature (K)
U_b	an overall heat transfer coefficient from water to ambient (W/m^2 K)
U_{tf}	an overall heat transfer coefficient from glass to fluid through solar cell and the tedlar (W/m^2 K)
U_L	collector overall loss coefficient (W/m^2 K)
U_T	conductive heat transfer coefficient from solar cell to air through tedlar (W/m^2 K)
U_t	an overall heat transfer coefficient from solar cell to ambient through the glass cover
U_{tT}	an overall heat transfer coefficient from glass to tedlar through solar cell

Subscripts

0	reference
a	ambient
b	from water to ambient
bs	tedlar base
c	solar cell
e	electrical
th	thermal
oth	overall equivalent thermal

Greek symbols

τ	transmittivity
α	absorptivity
ε	emissivity
$(\alpha\tau)$	effective absorptivity and transmittivity
β	packing factor/collector tilt
η	efficiency

Table 2 .Typical values of the system used for the analysis.

c	1005 J/kg K	
η_{e0}	12%	
h_i	5.8	W/m^2K

h_o	9.5	W/m^2K
h_f	10	W/m^2K
k	385	W/m K
k_c	0.039	W/m K
k_g	1.00	W/m K
k_T	0.033	W/m K
L_c	0.0003	m
L_g	0.003	m
L_{ins}	0.05	m
U_L	66	W/m^2 K
U_b	0.62	W/m^2 K
U_T	66.00	W/m^2 K
U_t	9.24	W/m^2 K
U_{tT}	8.10	W/m^2 K
U_{tf}	7.97	W/m^2 K
α_c	0.85	
α_T	0.5	
β_c	0.86	
η_e	0.12	
τ_g	0.95	

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