Mathematical Modelling, Simulation and Comparative Study of Seven Gases for a Single Pass, Single Duct PVT System

Bhaskar B. Gardas¹, M.V Tendolkar² & Sunil B. Mahajan³

¹⁶² Dept of Mechanical Engineering, Veermata Jijabai Technological Institute (VJTI), Mumbai University, 400019
¹⁴⁵ Sardar Vallabhbhai Patel Polytechnic, Borivali (W), Mumbai 400103, Maharashtra, India
E-mail : gardas.bhaskar@gmail.com¹, mvtendolkar@vjeti.org.in²

Abstract – Solar cell produces electricity when it receives solar energy. With the increase in module temperature panel electrical efficiency decreases. This undesirable effect can be partially avoided by applying a cooling unit with fluid circulation around the PV module. Such unit is called photovoltaic/thermal collector (PV/T) or hybrid (PV/T). The objective of the present work is to design a heat extracting system for the solar cell in order to increase its power output, electrical efficiency and decrease its specific power output, also to extract the heat energy. A hybrid solar system which generates both electricity and heat energy simultaneously is studied. This hybrid system consists of PV cells attached to an absorber plate with fins attached at the other side of the absorber surface. Simulation model for single pass, single duct solar collector with fins is prepared and performance curves are obtained. Performance with seven different gases analyzed for maximum heat transfer, minimum specific power, minimum mass flow rate & minimum number of fins and maximum electrical efficiency. Hydrogen is found to be the most suitable option with the present. For hydrogen, the system requires a mass flow rate of 0.00275 kg/s, which is the least amongst all, Theoretical number of fins required in this case is found out to be 3.46. Electrical efficiency 32.54 % which is maximum of all other gases, specific power output 3.073x10⁻³ m²/W, which is the least amongst all for n = 4.

Keywords – Flat Plate PV/T Collector, Solar Irradiance, Electrical Efficiency, Electrical Power.

I. INTRODUCTION

Photovoltaic’s (PV) comprises the technology to convert sunlight directly into electricity. The term Photo means light and Voltaic means electricity. A photovoltaic (PV) cell, also known as Solar Cell, is a semiconductor device that generates electricity when light falls on it. When sunlight strikes a PV cell, the photons of the absorbed sunlight dislodge the electrons from the atoms of the cell. The free electrons then move through the cell, creating and filling the holes in the cell. It is this movement of electrons and holes that generates electric current. The Physical process in which a PV cell or Solar cell converts sunlight into electricity is known as the Photovoltaic Effect [1]. A single PV cell will produce between 1 and 1.5 W [2] at a voltage of 0.5 to 0.6 V under standard test conditions, which are 1. An irradiance of 1KW/m², standard reference AM1.5 spectrum. 2. A cell temperature of 25 °C.

A PV cell converts only a small fraction (approximately less than 20 %) of the irradiance into electrical energy [1]. The balance is converted into heating of the cell. As a result, cell can be expected to operate above ambient temperature. If the temperature is increased, there is marked reduction in the cell voltage. Cell voltage decreases by approximately 2.2 mV per 0C rise in operating temperature [1].

In order to increase the electrical efficiency of the PV module, Othman [3] designed a double-pass photovoltaic-thermal solar air heater. In this system the fins are introduced in the second channel flow passage, parallel to the length of the collector, as shown in “Fig. 1”. The fins on the back of the photovoltaic panel increase the heat transfer with the air and enhance the efficiency of the system. The double pass PV/T solar air collector with fins and compound parabolic concentrator (CPC) gives very good electrical and thermal energy output [4]. But, the low thermal conductivity of air results in poor heat transfer between the panel and the flowing air. Hence, the air heater efficiency is low. So, in this study, the comparative study is done to improve the electrical output of the PV system, by passing different gases over a finned, single duct & single pass solar collector, the design of which is simple as compared to double pass system.
II. PROBLEM DEVELOPMENT

Fins are attached to the rear face of the panel as shown in the “Fig. 2”. The rear surface of the panel is a substrate such as aluminum. The fins are modeled as being an extension of this substrate. The substrate material is soldered or attached with adhesive to the rear surface of the cells. In addition, a rectangular duct is attached to the rear surface of the panel, for which the heat transfer parameters are based on the assumption of forced convection.

![Image of the cooling system](image)

Fig. 1: Finned Double-Pass Photovoltaic-Thermal Solar Air Heater [3]

The duct allows the gas to be blown across the rear surface of the panel. Parameters of the system which are required to be fed in the MAT LAB software are solar irradiation, fin thickness, fin height, fin width, flow velocity, and thermal conductivity of the fin material. Outputs of the model are cell temperature, electrical efficiency, electrical power output, number of fins required for cooling, fin efficiency & mass flow rate of the gas used. Constants of the system are emissivities, thermal conductivities, convective thermal resistances, Stefan-Boltzmann constant and the ambient temperature [5].

III. BOUNDARY CONDITIONS

The input to the system is the solar irradiance. The boundary conditions are the heat losses due to the radiation and convection on the front and back ($Q_{rad}, Q_{conv}$) of the panel, as well as the electrical power output. The thermodynamic properties of the panel, thermodynamic properties of the fin, and physical dimensions of the panel layers are held constant [5].

IV. ASSUMPTIONS

To simplify the analysis, the following assumptions are made [5].

1. Steady state of energy transfer is achieved.
2. No heat generation within the fin.
3. Uniform heat transfer coefficient (h) over the entire surface of the fin.
4. Homogeneous and isotropic fin material.
5. Negligible contact thermal resistance.
6. Heat conduction is one dimensional.
7. Capacity effects of the glass cover, solar cells and back plate is neglected.
8. The temperatures of the glass cover, solar cells and plates vary only in the direction of working fluid flow.
9. The side losses from the system are negligible.

![Figure 2. Schematic Representation of the Model](image)

V. CONSTANTS FROM THE LITERATURE

1. $T_a = 25 \degree C = 298 K$.
2. $a = -3.47$ (For open rack) [6]
3. $b = -0.0594$ (For open rack) [6]
4. $I_o = 1000 W/m^2$ [6]
5. $\varepsilon_g = 0.94$ [7]
6. $\varepsilon_b = 0.893$ [7]
7. $\sigma = 5.67 \times 10^{-8} \text{W m}^{-2}\text{K}^{-4}$ [8]
8. $R_{conv} = 0.2 \text{K.m}^2/\text{W}$ [9]
9. $K = 120 \frac{W}{m.K}$ (Al) [9]

VI. EQUATIONS USED

1. $T_b = \left[e^{(a+b) \cdot I_o} \right] + T_a$ [6]
2. $T_C = T_b + \frac{I \cdot \Delta t}{I_o}$ [6]
3. $\Delta t = 3^\circ \text{C}$ [6]
4. $Q_{radf} = \varepsilon_g \cdot \sigma (T_g^4 - T_a^4)$ [10]
5. $Q_{conv f} = \frac{T_b - T_a}{R_{conv}}$ [9]
6. $Q_{conv b} = \frac{T_b - T_a}{R_{conv}}$ [9]
7. $Q_{rad b} = \varepsilon_b \cdot \sigma (T_b^4 - T_a^4)$ [10]
8. \[ \eta_{pv} = \eta_{ref} \left[ 1 - \beta \left( T_e - T_{ref} \right) \right] \] \[ = 0.15 \left[ 1 - 0.0045 \left( T_e - 25 \right) \right] \] [3]

9. \[ P_e = \eta_{pv} \times I \] [9]

10. \[ I = Q_{rad} + Q_{conv} + P_e + Q_{fin} \] [9]

11. \[ A_{CS} = b \times t \]

12. \[ Q_{fin} = n \left[ k \cdot A_{CS} \cdot m \cdot (T_p - T_0) \cdot \tanh(ml) \right] \] [8]

13. Perimeter of the fin (P) = 2(b + t)

14. Reynolds number (Re) = \[ \frac{uL}{v} \] [8]

15. For \( Re = 1.115 \times 10^5 < R_e < 5 \times 10^5 \)

\[ N_{UL} = \frac{hL}{k_f} = 0.664 \times R_e^{1/2} \cdot P_r^{1/3} \] [10]

16. For \( R_e = 5 \times 10^5 < R_e < 10^7 \)

\[ N_{UL} = \frac{hL}{k_f} = P_r^{1/2} \cdot (0.037 \cdot R_e^{0.8} - 850) \] [10]

17. \[ m = \frac{k \cdot P}{\sqrt{K_{AC}}} \] [10]

18. \[ \eta_{fin} = \frac{\tan h \left( ml \right)}{ml} \] [10]

19. \[ T_1 = \left( \frac{T_b + T_0}{2} \right) \]

20. \[ Q = \dot{m} \cdot C_p \cdot \Delta T \]

VII. VALIDATION OF RESULTS

The validation of the present model is carried out with two references. “Fig. 3” shows the relationship between electrical efficiency and cell temperature.

It can be observed from the graph that the increase in temperature of the panel results in decreasing its electrical efficiency. The results from the theoretical model developed are found to be in better agreement with those mentioned in the reference. The discrepancy between the two values is attributed to the unaccounted losses occurring in practice. Also, the relative efficiency and cell efficiency temperature coefficient values (Eq. 8 in Section VI) of both the papers are different. The reference efficiency of 12.7 % and cell efficiency temperature coefficient of 0.0063 is used in the reference [11], whereas in the present work the relative efficiency of 15 % and cell efficiency temperature coefficient 0.0045 are used. The validation of electrical power is shown in “Fig. 4”. It can be observed from the graph that there is much better agreement between the predicted values from the theoretical model developed and those mentioned in the reference. The electrical power output increases with the increase in solar irradiance, being a direct function of solar irradiance.

VIII. RESULTS & DISCUSSIONS

Specific power output is one of the highly important parameters which specifies the minimum space required per unit power generation. Accordingly, it can be treated as one of the criteria for comparison of performance. The variation of specific power output for seven gases is shown in “Fig. 5”.

The graph shows that specific power output is the least when hydrogen is made to flow through the duct.
and is maximum in case of carbon dioxide. This clearly indicates the superiority of hydrogen as a working medium from space considerations also, as the photovoltaic system becomes compact for the same panel area.

“Fig.6” shows the comparison of electrical efficiency for seven gases. Graph shows that the electrical efficiency of the PV module is maximum when hydrogen is made to flow through the duct and is least for water vapor.

![Graph showing electrical efficiency comparison for various gases](image)

**Figure 6. Comparison of Electrical Efficiency for Various Gases.**

[For \( b = 0.6 \text{ m}, l = 0.15 \text{ m}, t = 0.025 \text{ m}, K = 120 \text{ W/m.K}, I = 1000 \text{ W/m}^2 \)]

IX. CONCLUSIONS

Solar cells generate more electricity when receive more solar radiation but the efficiency drops when temperature of solar cells increases. Hybrid photovoltaic and thermal collector is the solution to this problem. Simulation model for single pass, single duct solar collector with fins is developed. The simultaneous use of hybrid PV/T and fins have a potential to significantly increase in power production and reduce the cost of photovoltaic electricity. Seven gases are passed through the duct to identify the gas which would give the maximum heat transfer, maximum electrical efficiency, minimum specific power output. The gas identified is hydrogen. When hydrogen is passed through the duct, the specific power output of the PV module is 3.073 x 10⁻³ m²/W, which is least of all other gases. Electrical efficiency for hydrogen is 32.5 %, which is maximum of all other gases.

X. NOMENCLATURE

- \( T_b \) = Back surface module temperature (°C).
- \( T_a \) = Ambient temperature (°C).
- \( I \) = Solar Irradiance (W/m²).
- \( V \) = Wind speed (m/s).
- \( a \) = empirically determined coefficients establishing the upper limit for the module temperature at low wind speeds and high solar irradiance.
- \( b \) = empirically determined coefficient establishing the rate at which module temperature as Wind speed increases.
- \( T_C \) = Cell temperature of the module (°C).
- \( I_o \) = Reference Solar Irradiance on module.
- \( \Delta t \) = Temperature difference between the cell and the module back surface at an irradiance level of 1000 W/m².
- \( Q_{rady} \) = Radiative heat flux through the front panel.
- \( Q_{convy} \) = Convective heat flux through the front panel (W/m²).
- \( Q_{convy} \) = Convective heat flux through the rear panel (W/m²).
- \( Q_{rady} \) = Convective heat flux through the rear surface of the panel (W/m²).
- \( \epsilon_g \) = Surface emissivity of glass.
- \( \sigma \) = Stefan Boltzmann constant.
- \( t \) = Thickness of the fin (m).
- \( P \) = Perimeter of the fin.
- \( v \) = Kinematic Viscosity (m²/s).
- \( U \) = Velocity of the flowing fluid (m/s)
- \( R_e \) = Reynolds number.
- \( N_{DL} \) = Nusselt Number.
- \( P_r \) = Prandtl Number.
- \( \eta_{fin} \) = Efficiency of the fin.
- \( \Delta T' \) = Difference between mean temperature of the flowing stream and the atmospheric temperature (K).
- \( U \) = velocity of the gas flowing through the duct (m/s).
- \( T_1 \) = Mean temperature of the flowing stream (K).
- \( \eta_{pv} \) = Electrical Efficiency of the PV Panel.
- \( \eta_{ref} \) = Reference efficiency
- \( \beta \) = Cell efficiency temperature coefficient
- \( P_s \) = Electrical Power.
n = No. of Fins.
A_Cs = Cross sectional area of the fin (m^2).
T_g = Glass surface temperature (K).
R_{Conv} = Convective thermal resistance (K . m^2/W).
\epsilon_b = Tedlar Emissivity.
k = Thermal conductivity of fin material (W/m . K).
h = Convective heat transferor coefficient (W/m^2K).
l = length of the fin (m).
b = Width of the fin (m).
C_p = Specific heat of the gas at constant pressure (kJ/kg.K)
k_f = Thermal conductivity of the gas flowing through the back surface of the panel.
L = Length of flow (m)

XI. REFERENCES