The hybrid Photovoltaic-Thermal double-pass solar system for drying applications

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Abstract. In this paper, is devoted to evaluating the performance of the double-pass hybrid Photovoltaic-Thermal (PVT) solar system proposed for drying purposes theoretically and experimentally as well as the system is designed, fabricate and modeled in order to simulate the productivity of this system. The hot air extracted from the PVT collector can be used as a heat source for the drying application. The critical parameter such as temperature distribution, useful heat gain, electrical power, and thermal efficiency are computed using MATLAB 2015b program built for this purpose. Results show that the higher output fluid temperature was 63°C at a lesser mass flow rate which 0.017 kg/s and the maximum efficiencies of electrical, thermal and overall at a higher mass flow rate which reached 12.65%, 56.73%, and 85% respectively at mass flow rate 0.031 kg/s. In addition, the optimum electrical power and thermal energy reached 50.57 W and 389.37 W at 0.031 kg/s.

Key Words; photovoltaic cell, thermal collector, performance, dryer, heat gain

Nomenclature

| Symbol | Description                     | Unit |
|--------|---------------------------------|------|
| Am     | PV module area                  | m²   |
| Ap     | absorber plate area             | m²   |
| Af     | fin area                        | m²   |
| Ab     | backplate area                  | m²   |
| Agd    | area of dryer glasses           | m²   |
| Ac     | cross-section of channel        | m²   |
| a      | ideality factor of diode        |      |
| cpa    | specific heat of the air        | kJ/kg.k |
| F, F.  | fill factor                     |      |
| Gt     | total solar radiation           | W/m² |
| Gtr    | total solar radiation at STC    | W/m² |
| hr     | radiative heat coefficient      | W/m².k |
| hc     | convective heat coefficient     | W/m².k |
| hw     | convective heat by wind         | W/m².k |
| Hf     | high of fin                     | m    |
| kg     | glass thermal conductivity      | W/m.k |
1. Introduction

The modern (PVT) solar system technologies are a special design of solar collectors that consists of a flat plate thermal collector with a PV collector which attached to the top of the thermal collector. The PVT solar system is used for generating electrical and thermal energy at the same time. The useful heat output from this system can be used for drying applications as dryer and also cause an improvement in electrical efficiency by cooling the back PV cells by blowing air to extract heat from back PV cells with thermal collector and produce high air temperature output applied dryer chamber. The PVT solar dryer system is one of the clean and renewable technologies because of self-generated electricity without using traditional sources; hence, the dependence upon fossil fuel and global warming problems are reduced [1]. A lot of previous works of scholars have studied theoretically and experimentally of hybrid PVT solar system technologies for drying applications.

Yuting et al. reviewed various types of PVT systems, using different kinds of working fluids. They also presented the utilization and improvement of the PV/T systems in a different application [2]. Ahmed et al. developed and predicted an indirect type of solar dryer that operates at both forced and natural convection modes in the different weather conditions [3]. Sumit et al. designed and fabricated a hybrid PVT air collector connected with a dryer and analyzed a thermal model of this system. The performance of the dryer chamber under forced convection mode was better for crops than natural convection mode [4]. Abhay et al. developed an indirect solar dryer system for drying crops. It was found the indirect dryer is more efficient than an open sun dryer [5]. Essalhi et al. developed an
indirect solar dryer system for drying pear. The results showed the higher output temperature reached 57°C when solar radiation 900 W/m² and the thermal efficiency of the drying room was 11.11% [6]. Neha et al. developed a thermal model for the proposed translucent photovoltaic thermal with a thermoelectric cooler collector. It was found that a lesser mass flow rate causes higher in temperature of outlet air [7]. Ehsan et al. analyzed experimentally a solar dryer with the storage of thermal energy and the hot output air is supplied the dryer chamber with 50°C [8]. G.N.Satyender and Prashant compared between the airflow patterns, single and double pass airflow and found that the double-pass is more efficient than a single pass because more heat extraction can be obtained from a double pass of counterflow [9]. Jin-Hee et al. designed a hybrid PVT air-based solar system and analyzed the electrical and thermal performance with experimental results. The output warm air from the PVT collector could be used as a heat supply in the buildings [10]. Ahmad et al. developed thermal modeling of dual-pass solar collector in two cases, fins and without fins. Results showed that in the case of fins, the solar system is more cost-effective compared to the solar system without fins [11].

In this work, we will focus on design, fabrication, and simulation of the hybrid PVT solar system for drying purposes. The PVT system is locally unused for drying; therefore, the whole PVT solar system proposed in this work is designed and utilized for drying applications. Besides, analysing the performance of hybrid PVT with the solar dryer has been made to check out from the match between the theoretical and experimental results. In addition, adding fins and double pass technologies are utilized to improve thermal performance. The general schematic shape of the system in this study is shown in figure (1).

2- Methodology
The hybrid PVT system with the solar dryer was modeled. The electrical characteristics of the PV module depend on a single diode have been carried out by using the MATLAB SIMULINK 2015b and the electrical model has presented to calculate the electrical power, electrical efficiency and fill factor. In addition, the energy balance equations were applied to the different sections of the PVT system components with solar dryer room to evaluate the temperature of PV cell, absorber plate, backplate, output fluid, and dryer chamber respectively and estimate the useful heat gain, thermal efficiency, and overall efficiency.

2.1 Theoretical Work

2.1.1 Electrical Model
The electrical model of the PV module can be accomplished by analyzing the equations built on the single diode equivalent circuits of the PV module which presented in [12]. At a constant cell temperature (25°C) and incident radiation (1000 W/m²), the mathematical expressions of the PV module are expressed as:

\[ I = I_{pv} - I_D \]  

(1)

Whereas:
- \( I \): load current.
- \( I_{pv} \): light current.
- \( I_D \): saturation current.

The load current in Eq. (1). can be described as:

\[ I = \frac{G_t}{G_{sc,r}} (I_{sc,r} + \alpha_I (T_C - T_{C,r})) - I_{sh} \left( \frac{T_c}{T_{c,r}} \right)^3 e^{\left[ \frac{q E_g}{\pi R_s} \left( \frac{1}{T_{c,r}} - \frac{1}{T_C} \right) \right]} \left[ e^{\left( \frac{v + IR_s}{q} \right)} - 1 \right] \]  

(2)

Where:
- shunt current \( I_{sh} \):
- \( R_s \): series resistance.
- \( R_{sh} \): shunt resistance.
- \( E_g \): bandgap energy.
q: electron charge.

k: Boltzmann’s constant.

α_c: current temperature coefficient.

I_{mp}: current at the maximum power point.

V_{mp}: voltage at the maximum power point.

The electrical efficiency and fill factor can be calculated from Eq. (3, 4) [12].

\[ \eta_E = \frac{p_E}{G_i A_m} = \frac{I V}{G_i A_m} \quad (3) \]

\[ F, F_i = \frac{I_{mp} V_{mp}}{I_{sc} V_{oc}} \quad (4) \]

2.1.2 Thermal Model

The energy balance equation of thermal modelling of each PVT part component was carried out for assuming the quasi-steady-state condition has considered, the airflow through the duct is uniform, the electrical losses of PV cells and heat losses from edges of the system are negligible, and the heat transfer coefficients by convection mode from absorber and back plates to fluid are equal. All heat transfer coefficients by convection and radiation distributions, top losses, and bottom losses in the hybrid PVT system and in the dryer chamber are illustrated in figure (2) and (3). Energy balance equations for each part of the PVT system in watts unit are obvious in the block diagram which illustrated in figure (4). The energy equation of the PVT system with the dryer room states the input and output energies and taking into consideration the heat losses from the PVT and dryer system. The energy balance equations in each part of the hybrid PVT and dryer chamber are expressed below:

1. Energy Balance of Solar cells of PV module:

According to Eq. (5), the input energy is represented by the amount of solar radiation that is absorbed by the solar cells on the left side. On the right side, the output energies from PV cell comprises the heat transfer by radiation between solar cell and thermal collector, the heat transfer by convection between the solar cell and airflow, and the electrical productivity. The heat losses include the losses by radiation between the solar cell and ambient air, the top losses by convection between the top cell surface and ambient air.

\[ G_t \alpha_c \tau_g = h_{r,c-p}(T_c - T_p) + U_{t,c-a}(T_c - T_a) + h_{r,c-sky}(T_c - T_{sky}) + h_{c,c-f1}(T_c - T_{f1}) + h_{r,c-a}(T_c - T_a) + G_t \beta_c \tau_g \eta_e \quad (5) \]

From Eq. (5), the cell temperature expression can be written as:

\[ T_c = G_t \tau_g(\alpha_c - \eta_e \beta_c) + \left( \frac{1}{h_w} + \frac{1}{h_{r,c-sky}} + \frac{1}{h_{c,c-f1} + h_{r,c-p} T_p + 0.5 h_{c,c-f1} (T_{f1} + T_{f2})} \right)^{-1} h_{r,c-p} + h_{c,c-f1} + h_{r,c-sky} \quad (6) \]

The mathematical expressions of heat transfer coefficients such as \( h_w, h_{c,c-f1}, h_{r,c-sky}, h_{r,p-b} \) and, \( h_{r,c-p} \) are illustrated in [13].

2. Energy Balance of Fluid Flow in The Upper Pass:

The left side in Eq. (7) shows the output energy or heat gain from the PVT system as hot air in the upper channel. The input energies in the right side contain the heat transfer between the back surface of solar cell to airflow and heat transfer between solar collector and airflow.
\[ m_a c_{pa} (T_{f2} - T_{f1}) = h_{c,p-f1} (T_p - T_{f1}) A_{pf} + h_{c,cc-f1} (T_c - T_{f1}) A_m \] (7)

From Eq. (7), the airflow temperature in the upper channel can be expressed as Eq. (8).

\[ T_{f2} = \frac{(m_a c_{pa} - 0.5 A_{pf} h_{c,p-f1} - 0.5 A_m h_{c,cc-f1}) T_o + A_m h_{c,cc-f1} T_c + A_{pf} h_{c,p-f1} T_p}{(m_a c_{pa} + 0.5 A_{pf} h_{c,p-f1} + 0.5 A_m h_{c,cc-f1})} \] (8)

Whereas:

\[ T_{f1} = \frac{T_{f1} + T_{f2}}{2} \] (9)

3. Energy Balance of Absorber Plate:

The left side in Eq. (10) shows the input energies to solar collector and the output energies in the right side are contains the convective heat transfer between the absorber plate and airflow in upper and lower channel, the convective heat transfer between the backplate and airflow in lower channel, and heat transfer by radiation between absorber plate and backplate.

\[ G_t (1 - \beta_c) \alpha_p T_0^2 A_p + h_{r,c-p} (T_c - T_p) A_p = h_{c,p-f1} (T_p - T_{f1}) A_{pf} + h_{c,p-f2} (T_p - T_{f2}) A_{pf} + h_{r,p-b} (T_p - T_b) A_b \] (10)

From Eq. (10), the plate temperature can be expressed as:

\[ T_p = \frac{(G_t (1 - \beta_c) \alpha_p T_0^2 A_p + h_{r,c-p} T_c + h_{r,p-b} T_b) A_p + 0.5 A_{pf} (h_{c,p-f1} (T_{f1} + T_{f2}) + h_{c,p-f2} (T_{f2} + T_{f3}))}{A_p (h_{r,p-b} + h_{r,c-p}) + 0.5 A_{pf} (h_{c,p-f1} + h_{c,p-f2})} \] (11)

Where:

\[ A_{pf} = A_p + A_f \] (12)

4. Energy Balance of Fluid Flow in the Lower Pass:

The left side in Eq. (13) shows the output energy or heat gain from the PVT system as hot air in the lower channel. The input energies on the right side contain the heat transfer by convection between the solar collector to airflow and heat transfer between backplate and airflow.

\[ m_a c_{pa} (T_{f2} - T_{f3}) = h_{c,p-f2} (T_p - T_{f2}) A_{pf} + h_{c,b-f2} (T_b - T_{f2}) A_b \] (13)

\[ T_{f3} = \frac{(m_a c_{pa} - 0.5 A_{pf} h_{c,p-f2} - 0.5 A_b h_{c,b-f2}) T_{f2} + A_{pf} h_{c,p-f2} T_p + A_b h_{c,b-f2} T_b}{(m_a c_{pa} + 0.5 A_{pf} h_{c,p-f2} + 0.5 A_b h_{c,b-f2})} \] (14)

Whereas:

\[ T_{f1} = \frac{T_{f1} + T_{f2}}{2} \] (15)

5. Energy Balance of Back Plate:

Heat transfer by radiation represents the input energy on the left side from collector to backplate. The back losses and output energy are illustrated in right side.

\[ h_{r,p-b} (T_p - T_b) = U_b (T_b - T_o) + h_{c,f2-b} (T_b - T_{f2}) \] (16)

By arranging the equation Eq. (16), the backplate temperature can be expressed as:
\[ T_b = \frac{h_{r-p-b} T_p A_p + (\frac{1}{\eta_w} + \frac{1}{\eta_b})^{-1} A_b T_a + 0.5 h_{c-b-f} A_b (T_{f2} + T_{f3})}{(\frac{1}{\eta_w} + \frac{1}{\eta_b})^{-1} A_b + h_{r-p-b} A_p + h_{c-b-f} A_b} \]  \hspace{1cm} (17)

6. Energy Balance of Dryer Chamber:

The output useful heat gain from the PVT system considers the input energy to solar dryer on the left side. Besides, from Eq. (18), the solar radiation that passes from the glass walls of solar dryer from all directions. The output energies contain the top and back losses from glass covers and back dryer respectively.

\[ \dot{m}_a c_{pa}(T_{f3} - T_d) + \tau_g (G_E A_E + G_w A_w + G_N A_N + G_T A_T) = (U_d A_g (T_d - T_a) + U_{bd} A_b (T_d - T_a)) \]  \hspace{1cm} (18)

From Eq. (18), the dryer temperature can be written as:

\[ T_d = \frac{\dot{m}_a c_{pa} T_{f3} + (G_E + G_w + G_N + G_T) \tau_g (G_E A_E + G_w A_w + G_N A_N + G_T A_T) + (\frac{1}{\eta_w} + \frac{1}{\eta_{gd}})^{-1} A_g (\tau_g A_g + (\frac{1}{\eta_w} + \frac{1}{\eta_{gd}})^{-1} A_g) + (\frac{1}{\eta_w} + \frac{1}{\eta_{bd}})^{-1} A_{bd}}{\dot{m}_a c_{pa} + (\frac{1}{\eta_w} + \frac{1}{\eta_{gd}})^{-1} A_g + (\frac{1}{\eta_w} + \frac{1}{\eta_{bd}})^{-1} A_{bd}} \]  \hspace{1cm} (19)

Where \((G_E, G_w, G_N, G_T)\) are represented the value of solar radiation from east, west, north, and top of the dryer room which measured experimentally by the solar power meter. The air has thermo physical properties such as density, viscosity, specific heat capacity, Prandtl number, and thermal conductivity, also, the heat transfer coefficients by forced mode. These properties are significant parameters to solve the thermal model of the PVT system and solar dryer. All expressions of these properties are illustrated in [14]. The rate of useful heat gain that carried away from the PVT system by fluid in watt unit and the thermal and overall efficiencies are described as [15]:

\[ Q_u = \dot{m}_a c_{pa} (T_{f0} - T_{fi}) \]  \hspace{1cm} (20)

\[ \eta_{th} = \frac{Q_u}{\dot{m}_a c_{pa} (T_{f0} - T_{fi})} \]  \hspace{1cm} (21)

\[ \eta_{overall} = \eta_{th} + \frac{\eta_e}{0.36} = \frac{1}{\dot{m}_a c_{pa} (T_{f0} - T_{fi})} + \frac{I V}{0.36} \]  \hspace{1cm} (22)

2.1.3 Computer Model

The design parameters of the electrical model such as voltage, current, and power were solved by using the MATLAB program in an iteration manner and displayed the behavior of the PV module. The flowing chart of the PVT system program is shown in figure (5). The heat transfer coefficients by convection and radiation were calculated theoretically by MATLAB, and these coefficients need initial trails of temperatures and electrical efficiency, moreover, the properties of air are evaluated. By solving the energy balance equations, the temperature distributions have been solved by built program numerically. The MATLAB program needs input parameters to generate, which contain the value of mass flow rate of air, the design dimensions of the hybrid PV/T system with dryer room, and condition weather parameters such as solar radiation, ambient temperature, and wind speed. Finally, it has been conducted the temperatures of the PVT system, electrical efficiency, heat gain, thermal efficiency, and overall efficiency.

2.2 Experimental Work
The system consists of 32 solar cells of a monocrystalline silicon that connects in series as the PV module and surrounds double glass covers from the top and below of PV cells as shown in figure (6) and the dimensions of each glass cover such as length, width, and thickness are 120 cm, 56 cm, and 1.75 cm respectively. The electrical characteristics such as voltage, current, and power of PV module are demonstrated in Table (1). The components of the proposed PVT solar system with the dryer chamber are illustrated in the figure (7). The solar collector locates directly under the PV module with dimensions (110 cm*54 cm*0.1 cm) and the backplate is in parallel with the thermal collector with dimensions (120 cm*54 cm*0.1 cm). The backside of the PVT system is covered by insulating layer to prevent heat leakage and decrease back losses. The thermal solar collector is made from pure aluminum metal and contains 20 fins in the upper and lower surface. The rectangular fin type is utilized in this study with dimensions (100 cm*3 cm*0.1 cm) in order to increase the surface area and heat transfer coefficient by convection between the airflow and solar collector. The double pass counterflow technique is utilized to extract more heat from the system. A DC fan used for blowing air into the PVT system, the fan is generated by the PV module and the table (3) shows the power consumption by DC fan which depends on the amount of airflow rate. The solar dryer system is connected to the PVT system by a duct that carries the hot air output from the hybrid PVT system to the dryer chamber. The solar dryer volume in this work is (52cm*42cm*60cm) that consists of a wooden frame, glass covers, and, chimney for exhausting air. The PVT solar system faces south and tilted at 33° to collect more radiation intensity. The experimental work starts with measure the solar radiation, ambient air, and wind velocity by utilizing solar power meter, temperature sensor, and speed meter. Further, the DC fan is operated by the PV module and set the speed of fan at a convenient mass of airflow by using voltage regulator to control in fan speed. Further, the thermal and electrical behavior of PVT system with dryer solar system is measured by utilizing the measurement devices which are illustrated in figure (8). Repeat the measuring process each hour and record the output readings.

3. Results and Discussion
The experimental results were taken on, 19th of June in 2019 for Baghdad, Iraq. The statistical analysis for quantifying the degree of identity between the theoretical and the experimental results of hybrid PVT solar system have been depended to evaluate the root mean square of percentage deviation (e) and linear coefficient of correlation (r) with based on the equations of approach study which presented by [15], and these values in this work are illustrated in Table 2. Figure (9) illustrates the effect of solar intensity on the open-circuit voltage and short circuit current and can be noticed that the current has more sensitive at changing solar radiation than voltage. For this reason, the electrical power dropped because of reduction current. Figure (10) shows the effect of solar cell temperature on the open-circuit voltage and electrical power and can be found that voltage affected by changing the cell temperatures. Hence, electrical power decreased when the voltage decreased. Figure (11) shows the effect of solar radiation on the open-circuit voltage and electrical power and can be found that electrical power affected by changing solar radiation. Hence, electrical power decreased when solar radiation increased. Figure (12) clarifies the hourly variations of solar intensity with time in the summer day. Figure (13) shows the hourly change of inlet temperature which measured experimentally with time in the summer day. Figures (14, 15, 16, 17, and, 18) demonstrate the comparisons between the theoretical and the experimental results of useful heat gain and temperatures of PV cell, absorber plate, backplate, and output fluid at the same input fluid temperature. Figure (17) shows that the output fluid temperature when the mass flow rate increased because the fluid at high velocity cannot extract further heat from PV cell and absorber plates and maximum temperature is obtained at 0.017 kg/s and 1100 W/m², and it was 63°C when the input fluid temperature was 44°C. It is obvious from figure (18) that the useful heat gain is directly proportional to the mass flow rate according to Eq. (21), the maximum value of useful heat gain reached 389.375 W at 0.031 kg/s when the solar radiation 1100 W/m². The root mean square of percentage deviations (e) and linear coefficients of correlation (r) to approve the agreement between these results are obvious in Table 2. Figure (19) represents the variation of electrical power (Pₑ) in each hour of the day at different solar
radiation and mass flow rate. It is evident that electrical power is increased by increasing the solar intensity because more electrons are emitted from solar cells and generate more current. Further, the change of mass flow rate effects on the electrical power which increases when the mass flow rate increases due to the cell temperature decreased and that cause increasing voltage and electrical power, and the maximum power is found at $1100 \text{ W/m}^2$ and $0.031 \text{ kg/s}$. Figure (20) states the change of electrical efficiency ($\eta$) with time. The electrical efficiency mainly depends on solar radiation and cell temperature, therefore, the increase of mass flow causes raise in electrical efficiency by extracted heat from PV cell and reduction cell temperature. The electrical efficiency is decreased in spite of the electrical power is increased due to the electrical efficiency depends significantly on cell temperature that causes drop in efficiency but the electrical power continues in increasing when solar radiation increases. The maximum electrical efficiency is 12.6% at 750 W/m² and 0.031 kg/s at 10:00 p.m. Figure (21) demonstrates the hourly change of thermal efficiency and indicates that the maximum thermal efficiency is 56.73% when solar radiation 1050 W/m² at 0.031 kg/s. Figure (22) displays the hourly change of overall efficiency and found that the maximum overall efficiency is about 85% when solar radiation 750 W/m² at 0.031 kg/s because of the electrical efficiency at 750 W/m² is high.

4. Conclusion
A mathematical model of the electrical and thermal performance was presented in this study; also, the predicting of results were simulated by utilizing MATLAB program. The comparison between the theoretical and experimental results has been proven. The double pass technology and adding fins were applied in the PVT system for two reasons, firstly, to raise the heat extraction from the absorber plate and secondly, to increase the surface area to transfer further heat from plate to fluid. The maximum temperature difference between input and output airflow was 19°C at a low mass flow rate 0.017 kg/s which considers acceptable temperature to supply the solar dryer. In addition, the results indicated that the maximum electrical and thermal efficiencies of the PVT system were 12.65% and about 56.73%, respectively, at a higher mass flow rate about 0.031 kg/s.

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Table 1. Specifications of designed PVT solar system.

| Parameter   | Value   | Parameter   | Value   |
|-------------|---------|-------------|---------|
| $V_{oc}$    | 21.55 V | $R_C$       | 0.74    |
| $I_{sc}$    | 5.33 A  | $R_g$       | 0.95    |
| $A_m$       | 0.66 m² | $α_c$       | 0.88    |
| $P_{mp}$    | 84.3 W  | $τ_g$       | 0.0035 m|
| $V_{mp}$    | 16.99 V | $α_p$       | 0.8     |
| $I_{mp}$    | 4.962 A | $k_p$       | 200 W/m.k |
| F. F.       | 0.734   | $k_g$       | 0.8 W/m.k |
| No. of cells| 32      | $τ_f$       | 0.0009 m |
| $L_p$       | 1.1 m   | $τ_p$       | 0.001 m |
| $L_b$       | 1.2 m   | $τ_b$       | 0.001 m |
| $L_f$       | 1 m     | $τ_f$       | 0.0009 m |
| $H_f$       | 0.03 m  | $ε_g$       | 0.9     |
| $W_p$       | 0.54 m  | $ε_p$       | 0.9     |
| $W_b$       | 0.54 m  | No. of fins | 20      |

Table 2. Produced power by DC fan.

| Mass Flow of Air (kg/s) | Consumed Power (W) |
|------------------------|--------------------|
| 0.017                  | 6.78 W             |
| 0.023                  | 6.5 W              |
| 0.032                  | 7.5 W              |

Table 2. Values of (e%) and (r) at a different mass flow rate.

| m=0.017kg/s | $T_C$ | $T_p$ | $T_b$ | $T_{fo}$ | $Q_u$ |
|-------------|-------|-------|-------|----------|------|
| e %         | 2.3   | 3.2   | 2.8   | 1.7      | 8.3  |
| r           | 0.992 | 0.988 | 0.987 | 0.995    | 0.996|
At $m=0.023\text{kg/s}$

|   | $e\%$ | 1.9 | 2.3 | 2.7 | 2.19 | 10.7 |
|---|---|---|---|---|---|---|
| $r$ | 0.995 | 0.983 | 0.995 | 0.993 | 0.996 |

At $m=0.031\text{kg/s}$

|   | $e\%$ | 2.3 | 2.6 | 3.02 | 1.7 | 10.4 |
|---|---|---|---|---|---|---|
| $r$ | 0.978 | 0.989 | 0.992 | 0.995 | 0.997 |

Figure 1. Schematic diagram of the PVT solar system with dryer.
Figure 2. Convection and radiation heat transfer coefficients distribution in the PVT system.

Figure 3. Convection and radiation heat transfer coefficients distribution in the solar dryer.

Figure 4. The block diagram of energy balance equations.

Figure 5. Flow chart of the PVT system.
Figure 6. The double glass PV module component.

(a) Figure 7. The hybrid PVT solar system with dryer.

(b) Figure 8. Measurements devices.
Figure 9. Effect of solar radiation on voltage and current.

Figure 10. Effect of cell temperature on voltage and power.

Figure 11. Effect of solar radiation on voltage and power.

Figure 12. Hourly variations of solar intensity.

Figure 13. Hourly variations of inlet temperature.
Figure 14. Experimented and predicted cell temperature at several mass flow rates.

Figure 15. Experimented and predicted absorber plate temperature at several mass flow rates.

Figure 16. Experimented and predicted backplate temperature at several mass flow rates.

Figure 17. Experiment and predicted output fluid temperature at several mass flow rates.

Figure 18. Experimented and predicted useful heat at several mass flow rates.
Figure 19. Variation of electrical power with time at a different mass flow rate.

Figure 20. Variation of electrical efficiency with time at a different mass flow rate.

Figure 21. Effect of increasing mass flow rate on thermal efficiency.

Figure 22. Variation of overall efficiency with time.