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Solar hybrid PV/T panels for drying

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Abstract
This paper addresses a solar dryer based on hybrid solar panels (PV/T) and waste heat recovery. The PV/T dynamic model is firstly presented. Further, air recirculation in the PV/T solar dryer is discussed and linked to the mass flow rate and to the outlet air temperature. Simulation results are given to illustrate the proposed developments and to show the usefulness of PV/Ts and of air recirculation.

Keywords: *solar drying; hybrid solar panels; PV/T; simulation; energy efficiency.*

1. Introduction

Drying is a fundamental process in many industrial applications using more or less advanced technologies. The drying process is very critical and must ensure that the dried material satisfies recommended specifications. Therefore, a lot of research has been done and is always ongoing to:

- Define the features and characteristics of good dried material, not only in terms of moisture content but also in terms of composition, mechanical and biological properties…
- Recommend a drying scenario in terms of drying temperature, residence time as well as other physical variables.
- Design a drying process.
- Consider different energy sources specially to incorporate renewable ones.
- Minimize energy consumption.
- Control the dehydration process…

Drying is very popular in developing countries for the preservation of agricultural products and food by simply using solar dryers that have a lot of various typologies widely discussed in the literature. Dried products are a very good source of nutrients but the dehydration process may alter the quality of the products. This can be limited by having proper pre-treatment of the materials and also by

Controlling the drying process is very important in order to guarantee the quality of dried products in terms of color, visual aspects, flavor, retention of nutrients, contaminants content…

Paper [1] gave a comprehensive review and classification of existing solar-energy drying. In [2], one can find a review of simulation tools for solar dryers. In [3], continuous and intermittent ventilation has been compared as control strategies to improve the efficiency of a solar dryer. [4] designed a solar-powered automatic drier combining solar energy and an electric heater. They proposed a PI controller as well as an intelligent control algorithm to maintain the temperature in the heating chambers at the desired temperature.

This paper deals with a solar dryer using hybrid solar panels called PV/T that simultaneously deliver electric power as well as heat. In general, most of the absorbed solar radiation by a PV module is converted into heat, which increases the cell temperature and decreases its PV efficiency. In fact, every rise of $1^{o}C$ in the cell temperature, drops PV efficiency approximately 0.5%. To overcome this problem, the PV collector is combined with a thermal module which captures the lost heat and simultaneously acts as a cooler for the solar cells. This is achieved by using a flow of a suitable fluid (air or water) which circulates under the PV cells and captures the heat and hence decreasing their temperature. In this way, PV/T panels improves PV efficiency while producing a useful thermal output which can be used for suitable applications such as drying.

The design and material of the PV/T hybrid system play a vital role in achieving high energy conversion efficiency. These Hybrid PV/Ts have an efficiency of more than 50%, between 15 to 20% of electrical and the rest is thermal. In the past few decades, various models with improved performance and efficiency have been presented with a large number of theoretical and experimental results.

The reference [4] gives the state-of-the-art on developments, theory, and applications hybrid of PV/Ts. [5] covers basic and advanced types of collectors, absorbers, working fluids, thermodynamic approaches, optimization of design parameters and mass flow rates, performance enhancement, and assessment. [6] considered a solar dryer composed of a solar air heater, a PV panel of 35 Wp, and a drying chamber with an interesting economic analysis. Even if they refer to their system as a PV/T solar dryer, this is not the case in the present work where PV/T refers to the simultaneous production of heat and electricity by the same hybrid panel. [7] discussed remedy to the intermittence of solar energy for Solar drying by integrating heat storage, auxiliary energy source, feedback control, larger surface collector, and hybrid systems. They studied four solar-assisted drying systems for crop drying using different collector types: (i) V-groove solar collector with cabinet dryer, (ii) double-pass solar collector with porous media in the lower channel and a flatbed drying chamber, (iii) Solar dehumidification system, and (iv) Photovoltaic-thermal solar drying system. [8] analyzed the techno-economic performance of PV/T Dryer with load condition. An expression for an outlet air temperature of PV/T air collector as well as an analytical expression for crop temperatures have been derived in terms of design and climatic parameters of New Delhi and experimentally validated.

In this paper, the use of PV/Ts for drying is analyzed and their performance evaluated from the technical point of view. To this end, we first present the PV/T dynamic model in section 2. In section 3, the overall PV/T solar drying system is represented as a block diagram. The recirculation of the outlet hot air is also considered to increase the solar dryer efficiency by heat recovery. Simulation results are given in section 4 to illustrate the usefulness of this recycling. Conclusion and perspectives are given to close the paper.

2. The PV/T Modelling

Let us consider a solar hybrid PV/T with five layers: a protective transparent glass cover, a mono-crystalline PV cell layer, a protective tedlar layer below the cells, an air duct through which air flows and an insulator to minimize heat losses as illustrated in Figure 1:

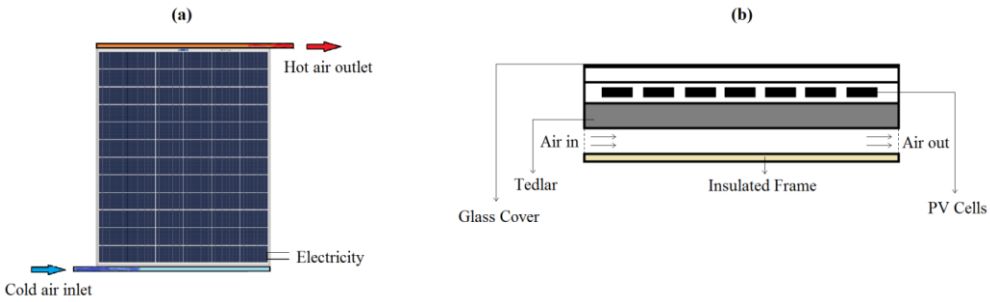

Fig 1: Thermal Model with Air

Fig. 1(a) shows that cold air is supplied to the one side of PV/T panel and heat (warm air) is gained along with the electrical gain on the other end side of the panel.

Energy conservation principle is used for the various layers constituting the hybrid collector to obtain the equations as shown in Fig. 1(b). The stored energy or generated in each of the layer is the sum of received energies and lost energies by the layers. In writing the model equations, few assumptions are made: pressure losses, dust and edge losses are neglected. Various heat transfer coefficients are used in the model equations. These heat transfer coefficients are determined using standard relations. By considering radiative, convective

and conductive thermal exchanges between the layers, each of the layers can be described in the following five thermal equations;

$$M_g C_g \frac{dT_g}{dt} = A_m[\alpha_g I_{sun} - h_{r,gs}(T_g - T_s) - h_{v,ga}(T_g - T_a) - h_{c,gc}(T_g - T_c)] \quad (1)$$

where $A_m\alpha_g I_{sun}$ is the energy emitted by the sun on the top glass cover of the collector and $A_m\tau_g\alpha_c\beta I_{sun}$ absorbed by the PV cell layer.

$$M_c C_c \frac{dT_c}{dt} = A_m[\tau_g\alpha_c\beta I_{sun} + h_{c,gc}(T_g - T_c) - h_{c,ct}(T_c - T_t) - E_p \quad (2)$$

$$M_t C_t \frac{dT_t}{dt} = A_m[\tau\alpha_t(1-\beta)I_{sun} + h_{c,ct}(T_c - T_t) + h_{v,ft}\psi(T_f - T_t) - h_{r,ti}\psi(T_t - T_i)] \quad (3)$$

$$M_i C_i \frac{dT_i}{dt} = A_c[h_{r,ti}(T_t - T_i) + h_{v,fi}(T_f - T_i) - h_{v,a}(T_i - T_a)] \quad (4)$$

Finally, for the air inside the collector, the useful energy gain is the sum of convection heat flow between (tedlar-fluid) and (fluid-insulator) where h_v is the heat transfer coefficient for the fluid. The equation for air as a working fluid is expressed as

$$\dot{m}_f C_f(T_{fo} - T_{fi}) = A_c[h_{v,ft}(T_t - T_f) + h_{v,fi}(T_i - T_f)] \quad (5)$$

where T_f is the mean temperature and can be found as;

$$T_f = \frac{T_{fo} + T_{fi}}{2}$$

Where ([9]):

$$T_s = 0.0552T_a^{1.5}.$$

The radiative heat transfer coefficient between glass cover and sky ($h_{r,gs}$), the convective heat transfer coefficient ($h_{v,ga}$) for wind (V_w), the conductive heat transfer coefficient (h_c) between two parallel layers (*a*-*b*) and the most important heat transfer process for this investigation (h_v) are expressed as

$$h_{r,gs} = \sigma\varepsilon_g \frac{(T_g{}^2 - T_s{}^2)(T_c{}^2 + T_s{}^2)}{(T_g - T_a)}; \qquad h_{v,ga} = 5.7 + 3.8V_w; \qquad h_{c,ab} = \frac{1}{\left(\frac{l_a}{\lambda_a} + \frac{l_b}{\lambda_b}\right)};$$

$$h_{v,ft} = h_{v,fi} = N_u \frac{\lambda_f}{D_H} = h_v;\ h_{r,ti} = \sigma\left[\frac{(T_i + T_t)(T_i{}^2 + T_t{}^2)}{\frac{1}{\varepsilon_i} + \frac{1}{\varepsilon_t} - 1}\right]$$

whereas Nusselt number (N_u), Reynold number (R_e) and Prandtl number (P_r) are given as;

$$N_u = 0.023R_e{}^{0.8}P_r{}^{0.4}, \qquad R_e = \frac{\rho_f V_f D_H}{\mu_f}, \qquad P_r = \frac{\mu_f}{\lambda_f}C_f$$

The electric power (E_p) produced by the panel can be written as;

$$E_p = I_{sun}A_{mod}\eta_c = I_{sun}A_{mod}\eta_{ref}[1 - \beta_p(T_c - T_{c,ref})] \quad (6)$$

The above equation (5) using the mean air temperature can be written as;

$$T_{fo} = \frac{h_v A_c(T_t + T_i) - h_v A_c T_{fi} + \dot{m}_f C_f T_{fi}}{\dot{m}_f C_f + h_v A_c} \quad (7)$$

The thermal efficiency and the electric efficiency of the PV/T are calculated using

$$\eta_{th} = \frac{\dot{m}_f C_f(T_{fo} - T_{fi})}{A_m I_{sun}}, \qquad \eta_E = \frac{E_p}{A_m I_{sun}}. \quad (8)$$

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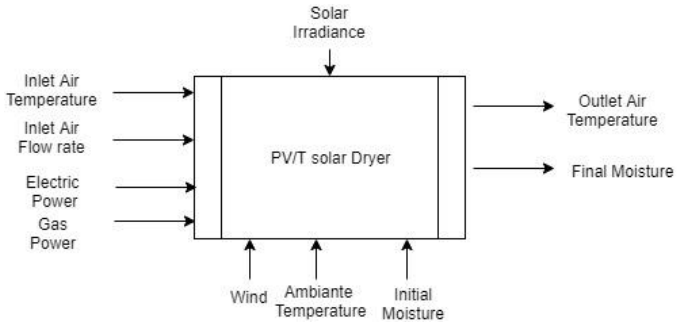

Fig. 2: Bloc-diagram of the solar dryer

3. The proposed scheme for the PV/T solar dryer

The main factors influencing drying are:

- Drying temperature: high value may damage the product to dry and the germination capacity while low temperature may extend drying time and microbial contamination. Examples of recommended drying temperature with the initial and permissible moisture content as well as the recommended temperature for different products are ([10]): Grapes: 80%-20%-70°C, Chilly: 80%-5%- 65°C, Fish: 75%-15%-50°C. Moisture and drying temperature are the main output variables that have to be controlled to their desired values during a specified time span.
- Mass flow rate: it is the main control action that must be designed to ensure the temperature requirement in the drying chamber. The influence of this variable is not very well documented in the literature on solar drying.
- Solar radiation: It is obviously very important for a solar dryer but it can't be controlled as one generally benefit from all what is available.
- Energy sources such as electric and thermal that constitute control actions to be used in order to compensate the solar intermittence.
- Other: relative humidity and temperature of the inlet air, initial moisture of the product to be dried, wind speed … These are variables that can induce significant perturbations for the drying process.

To summarize, the bloc-diagram in Fig. 2 highlights the main control actions (air flow rate, air inlet temperature), relevant outputs (temperature, humidity) as well as other uncontrollable inputs and perturbations (radiation, ambient temperature and product moisture, wind…). Energy is mainly solar but other sources may be added to overcome the solar intermittence (gas, electric, geothermal…).

The waste heat at the outlet air can also be recovered and used to improve the system efficiency. The electricity produced by the PV/T can be stored in batteries and used when needed through a heating resistance (see Fig. 3). Similarly, heat storage can also be included to increase the drying duration and then the efficiency of the device.
Given a reference temperature T_{fo}^{ref} for drying to be maintained during a given time period, then the air flow rate $\dot{m}_f$ has to be set to the following value:

$$\dot{m}_f = \frac{h_v A_c\left(T_t + T_i - \left(T_{fo}^{ref} + T_{fi}\right)\right)}{C_f\left(T_{fo}^{ref} - T_{fi}\right)} \tag{9}$$

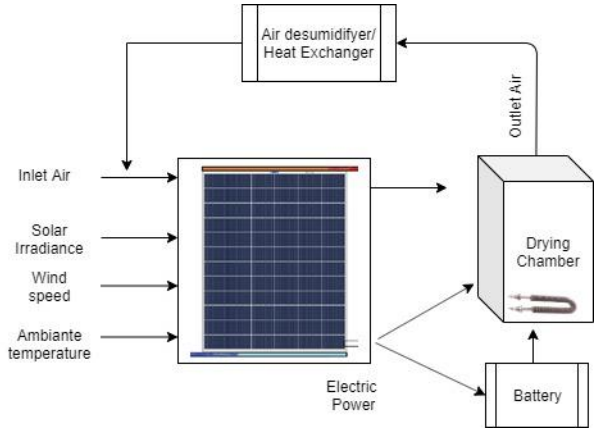

Fig. 3: The solar dryer with air recirculation

Recycling scenario: Let us now consider that the outlet air is recycled from the output to the input of the PV/T (Fig. 3), obviously by using a process or a treatment that avoids recycling the moisture. Further, let us assume that the input temperature T_{fi} of the air flow is proportional to the output air temperature T_{fo}, namely

$$T_{fi} = \eta_{ra} T_{fo} \tag{10}$$

where η_{ra} is the efficiency of the temperature air recycling. Then, there exists a control in terms of air flow if (9) is positive, which translates to the condition

$$T_{fo} < \frac{T_t + T_i}{(1+\eta_{ra})} \tag{11}$$

If 50% (resp. 90%) of the outlet temperature is injected to the input air, then one can already reach a high bound for the output air temperature, namely $T_{fo} < T_t + T_i$ (resp. $T_{fo} < 5(T_t + T_i)$.

Under recycling scenario, the expression (7) becomes

$$T_{fo} = \frac{h_v A_c (T_t + T_i)}{\dot{m}_f C_f (1-\eta_{ra}) + h_v A_c (1+\eta_{ra})} \tag{12}$$

While equation (9) becomes:

$$\dot{m}_f = \frac{h_v A_c \left(T_t + T_i - T_{fo}^{ref} (1+\eta_{ra}) \right)}{C_f T_{fo}^{ref} (1-\eta_{ra})} \tag{13}$$

It can be seen from (12) that the output air temperature can be close to its maximum depicted in (11) if:

- The recycling efficiency is high
- The air flow rate is low.

This means that it is only needed to set the air flow rate to a low value that allows

i) The collection of the heat from solar energy
ii) The moisture removal
iii) The heat recovery from the outlet air.

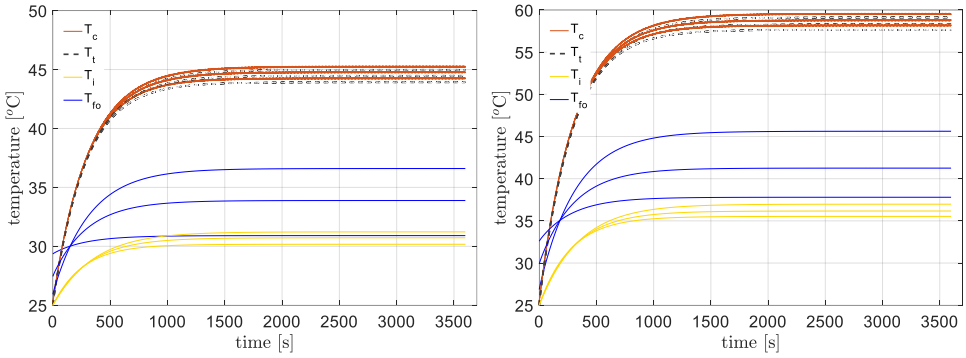

Fig. 4: [(a) – left] Temperature evolution of cell layer, tedlar layer, fluid and insulator at T_a = 30° and I_{sun} = 500 (for mass flow = 0.005, 0.01 and 0.025). [(b) – right] Temperature evolution of cell layer, tedlar layer, fluid and insulator at T_a = 35° and I_{sun} = 800 (for mass flow = 0.005, 0.01 and 0.025).

4. Simulation results

Simulations have been performed to analyze the system behavior using numerical values in the Annex. First, we study the influence of the air mass flow rate on the PV/T temperatures using equation (7) under different conditions for ambient temperature (30 and 35°C) and solar radiation (500 and 800 W/m^2). The obtained results with the mass flow (0.005, 0.01 and 0.025kg/s respectively.) are as follows:

Fig. 4(a) is obtained using ambient conditions (30°C and 500W/m^2) whereas Fig. 4(b) is obtained using conditions (35°C and 800W/m^2). It can be seen that low values of $\dot{m}_f$ implies higher temperatures for all the layers (PV cell, tedlar, insulator, and fluid).

Now, let us consider a reference value for the outlet air temperature, for instance T_{fo}^{ref}= 50, 55 and 60°C with a solar radiation of 800 W/m^2 and ambient temperature of 35°C. Then one can use equation (9) to compute the mass airflow as a control action to ensure the given T_{fo}^{ref}. In fact, the above equation (9) (resp. (13)) can be considered for an open-loop control without air recirculation (resp. with air recirculation). This control is very useful for simulation analysis and also in a process with relatively stable environment. However, it may be sensitive to changes in external variables and to parameters variations that are better attenuated with closed-loop control.

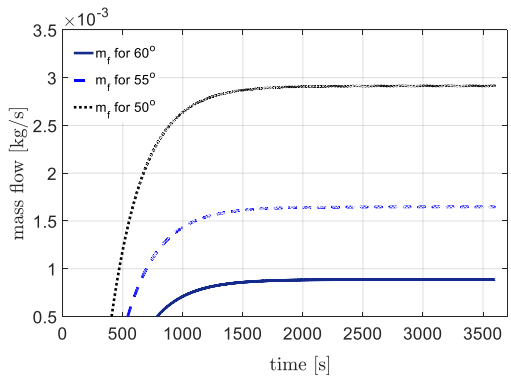

Fig. 5: Mass flow required to achieve a desire output temperature (50, 55 and 60°C)

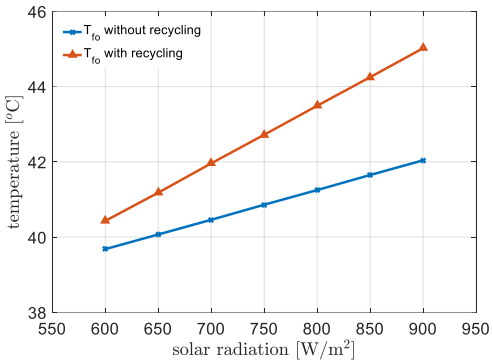

Fig. 6: With and without recycling profile for air outlet temperature and solar radiation

The results indicate that to achieve (50, 55 and 60ºC) outlet temperature from the duct and with ambient and inlet temperatures to the duct kept as 35ºC and solar radiation as 800 W/m^2, then one has to reduce the mass flow rate to (0.0029, 0.0016 and 0.0009 kg/s) in order to get the desired temperature. This means a lower mass flow is required to get higher output temperature as presented in Fig. 5.

If the ambient temperature and inlet temperature injected to the duct is 35ºC with solar radiation set to 900 W/m^2, then the outlet temperature of the duct goes to 42.04ºC with a mass flow rate of 0.01 kg/sec (see Fig. 6).

Recycling scenario: It is assumed that the input temperature T_{fi} of the air flow is proportional to the output air temperature T_{fo} given in (10) and under the recycling scenario, the air output temperature and air flow rate expression becomes (12) and (13). Using (12), the air output temperature rises to 40.43ºC from 39.68 ºC with solar radiation set to 600 W/m^2. Similarly, with the solar radiation of 900 W/m^2 and inlet temperature injected to the duct is 35ºC, the temperature rises from 42.04ºC to 45.02ºC under the recycling scenario. Fig. 6 shows the increase of the outlet temperature when solar radiation increases, including the recycling case. An interesting observation is that at lower solar radiation, the outlet temperature difference is small whereas it gets bigger with an increase in solar radiation.

5. Conclusions

This paper presented an analysis of PV/T solar dryer with air recirculation. An open-loop control has been proposed to ensure a specified drying temperature. Further developments can be considered such as closed-loop control synthesis and experimental results on a concrete dryer with a quantity of product to dry. Also, an economic analysis would be useful to evaluate the profitability of investment in such technology considering the capacity of drying which depends on the product.

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6. Nomenclature

Symbols		β	*packing factor*
		β_p	*temperature coefficient*
A_m	*module Area of a PV panel*	δ	*solar radiation coefficient*
A_c	*horizontal area of duct & collector area*	ε	*emissivity*
C	*heat capacity*	λ	*thermal conductivity*
D_H	*hydraulic diameter*	η_{ref}	*reference efficiency*
I_{sun}	*solar radiation*	ρ	*density*
l	*thickness*	τ	*transmissivity*
M	*mass*	μ	*dynamic viscosity of air*
T	*temperature*	ψ	*PV module area= A_m/A_c*
V_w	*wind velocity*		
V_f	*velocity of fluid (air)*	*Subscripts*	
$h_{r/v/c}$	*radiative/convective/conductive coefficient between 2 layers*	a	*ambient*
		c	*PV cell*
		f	*fluid,*
Greek letter		f_i	*inlet air*
		f_o	*outlet air*
		g	*glass cover*
		i	*thermal insulator*
α	*absorptivity*	t	*tedlar*

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Annex: Numerical values for the parameters used in simulation

A_m	1.28x0.32 m^2
α_g	0.06
C_g	500 J/kg-K
M_g	3.93 kg
σ	5.67×10^{-8} W/m^2-K^4
ε_g	0.93
l_g	0.0032 m
l_c	0.0003 m
λ_g	1.8 W/m-K
λ_c	148 W/m-K

l_t	0.001 m
M_c	0.28 kg
C_c	677 J/kg-K
τ_g	0.84
α_c	0.85
β	0.88
M_t	0.49 kg
C_t	1250 J/kg-K
λ_t	0.2 W/m-K
ρ_f	1.184 kg/m^3

μ_f	1.849×10^{-5} kg/m-s
λ_f	0.0242 W/m-K
λ_i	0.035 W/m-K
C_p	1007 J/kg-K
M_i	2.253 kg
C_i	1030 J/kg-K
β_p	0.0045
δ	0.052
η_{ref}	12 %

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