

Simulation of Solar Heat Pump Dryer Directly Driven by Photovoltaic Panels

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Abstract. This paper investigates a new type of solar heat pump dryer directly driven by photovoltaic panels. In order to design this system, a mathematical model has been established describing the whole drying process, including models of key components and phenomena of heat and mass transfer at the product layer and the air. The results of simulation at different drying air temperatures and velocities have been calculated and it indicate that the temperature of drying air is crucial external parameter compared to the velocity, with the increase of drying temperature from 45°C to 55°C, the product moisture content (Kg water/Kg dry product) decreased from 0.75 Kg/Kg to 0.3 Kg/Kg.

1. Introduction

Solar energy represents the largest source of renewable energy supply. It can be converted into electrical energy using photovoltaic panels (PV), concentrating solar thermal power (CSP) and concentrating photovoltaic (CVT) [1]. It can be also converted into thermal energy using non-concentrating solar collectors such as flat-plate, hybrid photovoltaic-thermal (PVT) and concentrating solar collectors[2]. Nowadays solar thermal energy is used in great fields as generation of electricity with heat engines, domestic hot water production, heating buildings and drying food and vegetables. Solar drying system has been used for thousands years and developed basing on the good understanding of drying process and the different parameters controlling it[3] and [4], In the aim of improving its efficiency, the noticed development was the combination of the solar energy with the heat pump system[5]. In literature we cite[6], who presented a review about studies on the advances in solar assisted heat pump dryers for agriculture and marine products. Another review of heat pump systems for drying application was done by[7]; where the authors explain that improving coefficient of performance (COP) of heat pump leads to improve the efficiency of drying system with considering the drying condition. Moreover, in the design of the drying systems, we need to pay attention to the energy requirement for drying a mass of product generally characterized by the high initial moisture content. Several researchers have developed simulation models for solar convective drying systems [8]-[10]. Our study focus on building a mathematical model of the heat and mass transfer of the drying air and the product that simulates the operation of the drying process.



2. System description

The main parts of the proposed system are the dryer (drying chamber) and the heat pump system (condenser, evaporator, compressor and the expansion valve). This system contain two different cycles

2.1. The Vapor-Compression Refrigeration Cycle

The Vapor-Compression Refrigeration Cycle is comprised of four steps (figure 1):

- **Compression:** In this stage, the refrigerant enters the compressor as a gas under low pressure and having a low temperature. Then, it will be compressed adiabatically.
- **Condensation:** The high pressure, high temperature gas will go through a condensation phase and releases heat energy that will be absorbed by the drying air.
- **Throttling:** The liquid refrigerant is pushed through a throttling valve, which expands it. As a result, the refrigerant now has low pressure and lower temperature.
- **Evaporation:** The refrigerant enters the evaporator, which is in contact with the drying air. Since, low pressure is maintained the refrigerant will be able to boil at a low temperature, and then will be driven to the compressor (back to the beginning of the cycle).

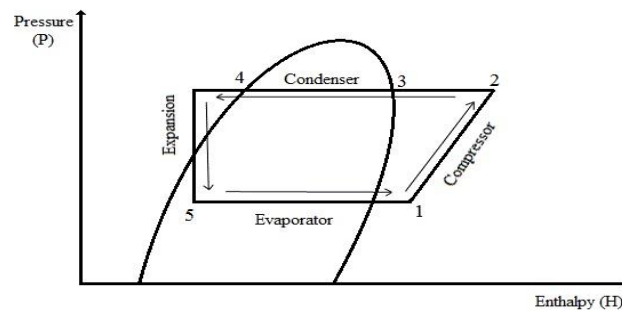


Figure 1. Vapor-Compression Refrigeration Cycle.

2.2. Drying air cycle

The drying air heated by the condenser goes into the drying chamber to heat and extract moisture of the product (grape). The moist air leaving the drying chamber will be used to maintain the temperature of the evaporator to achieve a better Coefficient of Performance (COP) and finally return into the condenser. Repeatedly, the condenser heats up the drying air to reach the desired temperature of the drying process (figure 2).

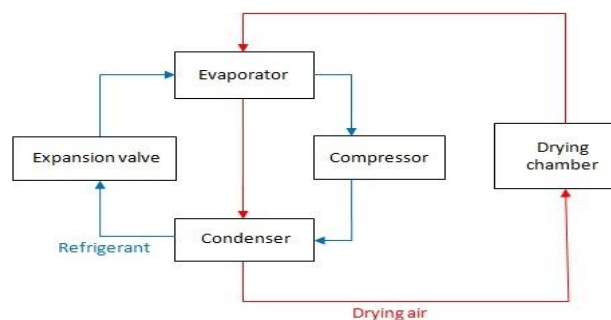


Figure 2. Description scheme of the heat pump dryer system.

3. Heat and mass transfer analyses at the drying chamber

Inside the drying chamber the various transfers are:

- Convection heat and mass transfer between the product and the air.
- Convection heat transfer between the air coming into the drying chamber and insider air.

- Convection and conduction heat transfer between internal and outsider air through the walls (thermal loose).

For what's next we give the mathematical equations describing the heat and mass transfer at the drying chamber.

3.1. Heat and mass transfer coefficients

The mass transfer coefficient can be calculated using and Chilton-Colburn analogy [11] with the dimensionless Lewis number:

$$h_m = h_{c1} (\rho_a c_{p,a})^{-1} (Le)^{-2/3} \quad (1)$$

For the air ($Le \cong 1$).

$h_{c1} (W / m^2 \circ C)$ Is the convective heat transfer coefficient between the air and the product it can be determined by the following equation:

$$h_{c1} = Nu \lambda_a D^{-1} \quad (2)$$

Nu : is the Nusselt number; we use the following correlation to calculate it [12]:

$$Nu = 0.023 Re^{0.8} Pr^{0.4} \quad (3)$$

Re : is Reynolds number:

$$Re = u L \nu^{-1} \quad (4)$$

Pr : Is the Prandtl number ($Pr = 0.7$ for the air).

$h_{c2} (W / m^2 \circ C)$ Is the convective heat transfer coefficient between the air and inner walls, taking Nusselt number as [12]:

$$Nu = 0.036 Re^{4/5} Pr^{1/3} \quad (5)$$

The conductive heat transfer coefficient $K (W / m^2 \circ C)$ between the internal air and the outside air through the walls is:

$$K = \lambda_i d_i^{-1} \quad (6)$$

3.2. Mass balance

The change in the amount of water inside the product is:

$$m_p (dX / dt) = -\dot{m}_v \quad (7)$$

Where $\dot{m}_v (kg / s)$ is mass of water evaporated from the product:

$$\dot{m}_v = A_p h_m \left(X_p (1 + X_p)^{-1} + Y_a (1 + Y_a)^{-1} \right) \quad (8)$$

The change in the amount of water in the air is:

$$m_a (dY_a / dt) = \dot{m}_{a,i} Y_{a,i} + \dot{m}_v - \dot{m}_{a,o} Y_a \quad (9)$$

3.3. Heat balance

The energy balance equation for the product is:

$$m_p c_{p,p} (dT_p / dt) = -\dot{m}_v L_v + A_p h_{c1} (T_a - T_p) \quad (10)$$

The energy balance equation for the air is:

$$\begin{aligned} m_a c_{p,a} (dT_a / dt) = & \dot{m}_{ai} ((c_{p,a} T_{a,i}) + (Y_{in} (2500.9 + 1.82 T_{a,i}))) - \dot{m}_{ao} ((c_{p,a} T_a) \\ & + (Y_a (2500.9 + 1.82 T_a))) + \dot{m}_v c_{p,v} T_a - A_p h_{c1} (T_a - T_p) - A_{wa} h_{c2} (T_a - T_{wa}) \end{aligned} \quad (11)$$

3.4. Thermal losses

The energy balance equation of the wall of the drying chamber is written as:

$$\rho_{wa} c_{p,wa} (dT_{wa} / dt) = h_{c2} A_{wa} (T_a - T_{wa}) - K A_{wa} (T_{wa} - T_{am}) \quad (12)$$

4. Results and discussion

A MATLAB program was built to calculate the different parameters for solving the heat and mass balance equations according to the system of parameters in the table (1).

Table 1. Descriptions and values of the parameters used in the MATLAB program.

Parameters	Descriptions	Values
A_p	Surface of the product	0.5 (m ²)
A_{wa}	Surface of the wall	3 (m ²)
C_{pp}	Specific heat of the product	4180 (J/Kg °C)
C_{pa}	Specific heat of the air	1005 (J/Kg °C)
C_{va}	Specific heat of the air	717 (J/Kg °C)
C_{pwa}	Specific heat of the wall	860 (J/Kg °C)
D	Characteristic diameter of the layer of product	0.80 (m)
d_i	Thickness of the insulation wall	0.20 (m)
L	Characteristic length	1 (m)
m_p	Mass of the product	10 (Kg)
X_{in}	Initial moisture content of the product	4 (kg water/kg dry product)
ρ_a	Density of the air	1.06 (Kg/m ³)
ρ_{wa}	Density of the wall	2700 (Kg/m ³)
λ_i	Conductivity of the insulation wall	0.022 (W/m °C)

The temperatures and the moisture contents of the product and the air inside the drying chamber were calculated and plotted for different temperatures and velocities. The influence of these parameters in the drying process is shown in the following figures.

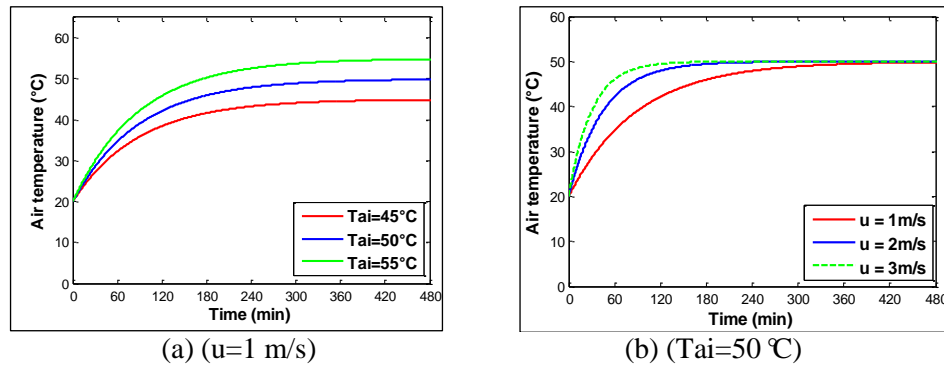


Figure 3. Influence of drying air temperature (a) and velocity (b) on the variation of air's temperature.

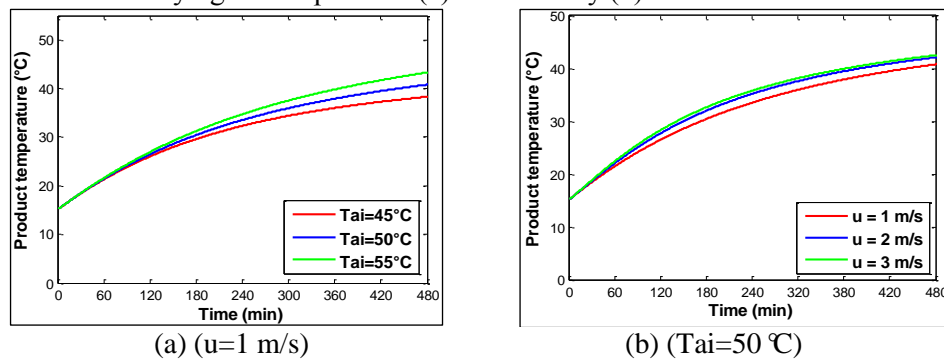


Figure 4. Influence of drying air temperature (a) and velocity (b) on the variation of product's temperature.

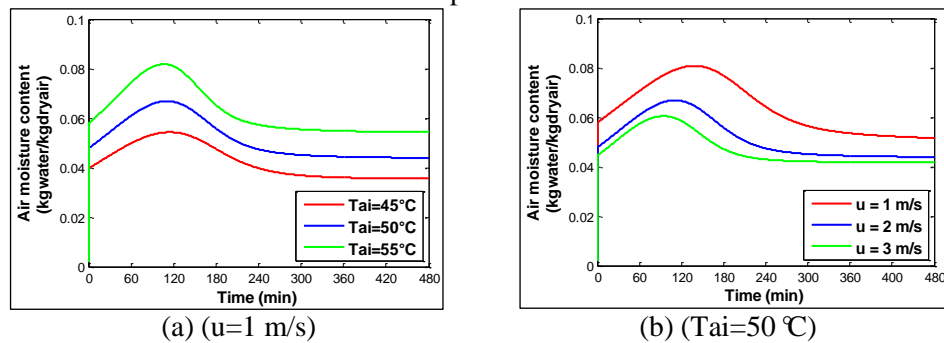


Figure 5. Influence of drying air temperature (a) and velocity (b) on the variation of air's moisture content.

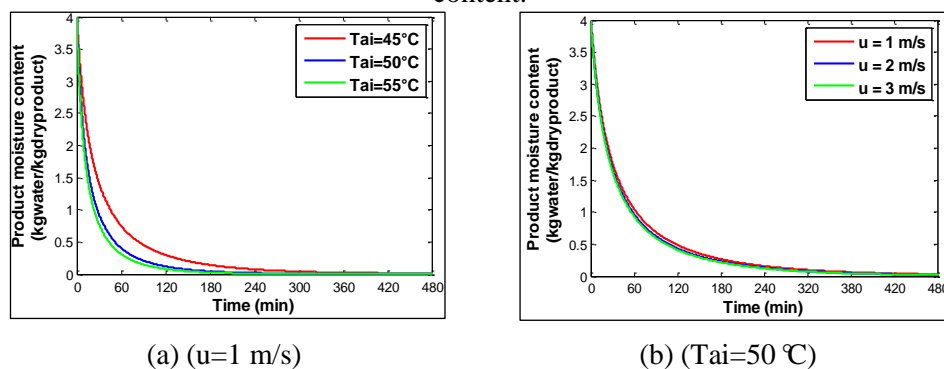


Figure 6. Influence of drying air temperature (a) and velocity (b) on the variation of product's moisture content.

Figure 3 shows the influence of the drying air temperature (a) and velocity (b) during the drying process as we can see that the influence of the temperature is more important than velocity which is the same case for the temperature of the product figure 4. This result agrees with the previous work [13] and [14]. Also for the variation of the moisture contents of the air and the product inside the drying chamber figure 5 and figure 6 the temperature of drying air is crucial parameter compared with its velocity.

5. Conclusion

In this work the simulation of the heat and mass balance equations using MATLAB software shows that the drying air temperature is an important influential parameter in the drying process. Through this simulation; the temperature and the moisture content of the hot wet air leaving the drying chamber goes into the evaporator is calculated. The influence of this hot wet air in the variation of the evaporation temperature must be handled in the design of the heat pump drying system to get higher efficiency and high value of the coefficient of performance (COP).

6. References

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