Simulation On Natural Convection Semi-Glazed Flat Plate Solar Collector For Green Bell Pepper Drying Application

Leopold O. Nelwan¹, Yulfi N. Maulia¹, Delymi Oktariski¹

¹Departemen Teknik Mesin dan Biosistem Fateta IPB, Gedung Fateta IPB, PO Box 220, Bogor.

email: lonelwan@ipb.apps.ac.id

Abstract. A simulation on semi-glazed flat plate solar collectors under natural convection mode used for green bell pepper drying has been conducted. The solar collector has a 60% glazed area which was installed to the drying chamber with a 45° slope. The simulation consisted of the heating and drying process. For the heating process, a semi-empirical model of the buoyancy effect and heat balance was proposed. To determine the constants of the model, the non-linear least square method based on the experimental data of irradiation, ambient air temperature and the drying chamber temperature for no-load operation was used. Furthermore, for the drying process simulation was carried out based on the mass and energy balance of the product and the drying air as well as the drying characteristics of green bell pepper. The simulation results showed that in clear weather conditions, the temperature and air flow rate produced by the collector can be used to dry a stack of ten trays within effective time less than 20.6 hours or equal to less than three days sunshine.

1. Introduction

Drying with flat plate solar collector is one of the solar drying technologies that is often used for drying agricultural products. In this drying method, air is heated and then passed through to the product for the drying process to take place. In general, air flow through the product is performed by using a fan that requires a mechanical energy source. Certainly, this increases energy requirements while also causing the dependence of the dryer’s operation on mechanical / electrical energy sources.

To eliminate the use of blower, it is often to utilize free convection (passive mode) phenomena of the solar flat plate collector. This can be done by arranging the flat plate solar collector and drying container in such a way that a sufficient amount of hot air flow can occur. The arrangement is generally carried out by installing a flat plate solar collector mounted on the bottom of the dryer at a certain angle. The obstacle of this type of dryer is its low capacity. In addition, the drying rate is very dependent on weather conditions so that the quality may be poor [1].

Flat plate solar collectors generally use transparent cover in reducing radiative and convective heat loss. However, the use of cover actually reduces solar energy entering into the collector especially at large solar angles. Some results of the unglazed type collector (without transparent cover) testing indicate that the performance of this type of collector is quite good [2-3], [4], [5].

Testing of semi-glazed collectors with some levels of transparent-coverage area and various slope angles of the collector have been carried out by Nelwan et al. [6]. The result showed that the 60% transparent-coverage with 45° slope has the useful energy which was almost the same as the collector with 100% coverage, even better at a steeper collector slope.
The potential of the drying system for drying agricultural products such as green bell pepper drying is interesting to be investigated. The purpose of this study was to simulate the potential of the semi-glazed flat plate solar collector for green bell pepper drying. The simulation was based on buoyancy models of the system with heat input only from solar radiation as well as the energy and mass balance of the drying process.

2. Method
2.1 Drying system design

The flat plate solar collector designed in this study was the back-pass type in which the heated air flows below the absorber plate. The size of the solar collector was 1 m long, 0.3 m wide with 0.05 m thickness. The insulation used was flexible elastomeric foam with a thickness of 0.01 m. The channel cross section size was 0.02 x 0.3 m. The transparent cover was made of glass with a thickness of 5 mm. The inlet and outlet of the collector was located in the shorter side. The absorber used in the collector is a zinc-plated iron plate and painted black. The insulation applied at the bottom of the collector had a thickness of 25.4 mm. The solar collector designed in this drying system was a semi glazed solar collector where part of the collector closer to the inlet was left without transparent cover while the other part was equipped with transparent cover where the coverage area was 60% of the collector absorber area.

The drying chamber was designed with a length and width of 0.3 x 0.3 m and a height of 0.3 m. There was one stack of 4 trays where the distance between trays was 0.05 m. The drying chamber was also insulated with flexible elastomeric foam. The solar collector outlet was mounted to the drying container inlet at an angle of 45° in accordance with the results of experiment in the previous study to utilize the buoyancy force of air flow into the collector [6].

![Image of drying system](image_url)

**Figure 1.** The semi-glazed solar collector assembled with drying chamber (1: unglazed part of the semi-glazed solar collector, 2: the glazed part, 3: the drying chamber)

2.2 Testing of the drying system

The collector that had been assembled with drying chamber were tested without load from morning to evening. During testing, measurements of the ambient air temperature and air temperature inside the drying chamber were carried out using T-type thermocouples while
solar irradiation was measured using a pyranometer. Both temperature and irradiation were recorded at 15-minute intervals.

2.3 Drying system simulation

2.3.1 Air heating

The model used for the simulation included the energy balance at the collector and the mass flow rate due to the buoyancy effect. With the ambient air temperature (T_{amb} in K) used as the incoming air temperature into the collector, the quasi-steady energy balance in solar collectors can be expressed as:

\[
m c_p (T_o - T_{amb}) = I A R \tau a - U A_f \left( T_{avg} - T_{amb} \right)
\]  

(1)

where m is mass flow rate, \(c_p\) is specific heat of air, \(T_o\) is collector outlet temperature (K), I is solar irradiation (W/m^2), A is the collector area (m^2), R is the ratio of the incident solar irradiation on the tilted collector to that on a horizontal surface (dimensionless), is the effective transmittance-absorptance product of the collector (dimensionless), U is the overall heat loss coefficient of the collector (W/m^2-oC), AT is the total area of the collector (m^2). The air temperature in the collector (T_{avg} in K) is defined as the arithmetic mean of the air temperature (environment) with the outlet air temperature.

The mass flow rate due to buoyancy effects in the collector was determined by:

\[
m = C A_D \frac{P}{R_t \ T_{avg}} \sqrt{\frac{2 g H}{T_{avg} - T_{amb}} T_{amb}}
\]  

(2)

where C is the shrinkage coefficient ranged between 0 and 1, H is the total height of the drying system (m), P denotes the atmospheric pressure (Pa), R_t is the ideal gas constant for air (kJ/kg°C). The coefficients C and U are very dependent on the conditions of the flow and geometry of the system while are different between covered and opened areas. Because the cross-sectional areas (A_D) are different in the drying chamber and the collector, the product of C and A_D is defined as one coefficient K_1. For simplification UA_T was combined into one coefficient, K_2 and the coefficient R was also combined into K_3. Therefore equations (1) and (2) are expressed as:

\[
m c_p (T_o - T_{amb}) = K_1 I - K_2 \left( T_{avg} - T_{avg} \right)
\]  

(3)

and

\[
m = K_3 \frac{P}{R_t \ T_{avg}} \sqrt{\frac{2 g H}{T_{avg} - T_{amb}} T_{amb}}
\]  

(4)

To determine the three coefficients (K_1, K_2 and K_3), the non-linear least square method of with equations (3) and (4) was used by using the data of temperature of the drying chamber, solar irradiation and ambient air temperature. The method was performed by using a Microsoft Excel solver based on Generalized Reduced Gradient Algorithm.

2.3.2 Drying

The drying model is developed based on heat balance and energy and the drying characteristics of paprika with 2.5 cm in diameter and 3–4 mm in thickness. Since the direction of air flow is assumed to be uniform upward and it is assumed that no heat leakage from the chamber’s wall, then the rate of change of water vapor and the heat balance in the drying air and the rate of energy change in the product are approached from the deep bed equation by Bala (1999) which is expressed in the following equations:

\[
0 = G_a \frac{\partial H}{\partial x} + \rho_d \frac{\partial M}{\partial \theta}
\]  

(5)
\begin{equation}
0 = G_a \left( c_{pg} + c_{ps} H \right) \frac{\partial t}{\partial x} + \left( - \rho_d c_{ps} \frac{\partial M}{\partial \theta} + h_{ab} \right) \left( t_a - t_g \right) \tag{6}
\end{equation}

\begin{equation}
\rho_d \left( c_{pg} + c_{ps} M \right) \frac{\partial t}{\partial \theta} + \rho_d t_g c_{ps} \frac{\partial M}{\partial \theta} = h_{ab} \left( t_a - t_g \right) + \rho_d \left( h_{fg} + c_{pg} t_g \right) \frac{\partial M}{\partial \theta} \tag{7}
\end{equation}

where \( G \) is the air mass flux (kg/s-m\(^2\)) generated from free convection, \( M \) is the moisture content (%d.b.), \( C_p \) is the specific heat (kJ/kg-K), \( H \) is the absolute humidity (kg/kg dry air), \( h \) is the heat transfer coefficient (kW/m\(^2\)-K), \( h_{fg} \) is the latent heat of evaporation (kJ/kg), \( A \) is the contact area (m\(^2\)), \( t \) is the temperature (K), whereas subscript a denotes air, amb is ambient air, g is for the product.

A thin layer drying model was applied to predict the moisture content of the product in each tray during the drying process, which is expressed as:

\begin{equation}
\frac{dM}{d\theta} = -k(M - M_e) \tag{8}
\end{equation}

where \( k \) is the drying constant (1/hour) and \( M_e \) is the equilibrium moisture content (% d.b.). The drying constant of green bell pepper used was obtained from the results of Faustino et al. [7], while the equilibrium moisture content as the functions of temperature and humidity was obtained from Kiranoudis et al. [8].

The heat transfer coefficient (\( h \)) between air and green-bell pepper slice was approximated from the equation:

\begin{equation}
\frac{hD}{\lambda} = 0.228 \left( \frac{c_p \mu}{\lambda} \right)^{1/3} \left( \frac{\rho \nu D}{\mu} \right)^{0.731} \tag{9}
\end{equation}

where \( c_p, \mu \) and \( \lambda \) are the specific heat, viscosity (kg/m-s) and thermal conductivity of air (W/m-oC), respectively, while \( \nu \) denotes the air velocity and \( D \) denotes the diameter of the green-bell pepper slice (m).

### 3. Results and discussion

#### 3.1 Performance test and model validation

Figure 2 shows the data of irradiation, ambient air temperature and drying air inside the chamber during the experiment used to obtain the K1-K3 values in equations (3) and (4). The range of irradiation values was at 300 to 900 W/m\(^2\), while the ambient air temperature was between 33 and 40oC. By using the non-linear least squares method, the obtained values of K1, K2 and K3 were 0.2417, 0.0053 and 0.0115 respectively. Figure 2 also shows the calculated drying chamber temperature and air flow rate, which ranges from 32-470C and 0.0039-0.0111 kg/s, respectively. It can be seen that the fluctuating temperature of the drying chamber and the fluctuating air flow rate are affected by the solar irradiation. The plot between the data and the calculated air temperature drying in Figure 3 shows that the model could predict the air temperature quite well.
Figure 2. Irradiation, ambient temperature and drying chamber (data) with respect to time in day

Figure 3. Calculated drying chamber temperature and air mass flow rate with respect to time in day
3.2 Drying

The conditions of solar irradiation used for simulation during the drying process are assumed to be identical every day with a total reaching 5.8 kWh per day with an average ambient air temperature of 32.3°C and RH of 50-70%. The sliced green-bell pepper was spread on ten trays arranged in a vertical direction. With the dimensions of the drying rack and the thickness of 1 layer for each tray, the total of fresh product slices was 0.9765 kg. In such conditions, the simulated temperature of the drying air from the collector was in the range of 37-48°C or 7-9°C above the ambient air temperature.

The evolution of moisture content of the product during drying is shown in Figure 4. Products located at the bottom of the tray experience the fastest decrease in moisture content, i.e. within about 5 hours the lowest moisture content of the product has reached 60% w.b. while the top one was still above 80% w.b. However, the difference in moisture content decreases with respect to the drying time. After approximately 14 hours of effective drying, the moisture content of the bottom green-bell pepper slightly increases due to the occurrence of readsorption because the equilibrium moisture content of the condition was quite high. Furthermore, the moisture content in all trays was almost the same and the average reached 14% w.b. after 20.6 hours.

The simulation results show that the total solar energy consumed reached 19 MJ / kg of water evaporated. Such the energy consumption is quite high compared to the drying method in general. The drying potential is still quite high, because the difference in moisture content between the top / bottom shelf was not too large. An increase of the amount of the load can still be applied, but the increase in pressure drop must be taken into account.
Figure 5. Evolution of the moisture content (% w.b.) during the drying process

Conclusion
A drying simulation using a flat collector with natural convection mode for cabinet green bell pepper slices drying has been developed. Simulation on the air heating section was based on the buoyancy model and the energy balance on the flat collector. Assuming solar irradiation of 5.8 kWh per day and the average ambient air temperature of 32°C the temperature of the drying air from the collector produced is in the range 37-48°C or 7-9°C above the ambient air temperature. With a load of 0.9765 kg of green bell pepper slices, drying can be accomplished within effective time of 20.6 hours.

REFERENCES
[1] Mustayen A.G.M.B., S. Mekhilef and R. Saidur. 2014. Performance study of different solar dryers: A review. Renewable and Sustainable Energy Reviews 34 (2014) 463–470
[2] Burch, J., Salasovich, J. and Hillman T. 2005. An Assessment of Unglazed Solar Domestic Water Heaters. ISES Solar World Congress, Florida August 6–12, 2005
[3] Chan H.Y., S. Riffat, and J. Zhu. 2011. Experimental performance of unglazed transpired solar collector for air heating. World Renewable Energy Congress, Sweden, 8-11 May 2011.
[4] Leon, M.A., and S. Kumar. 2007. Mathematical modeling and thermal performance analysis of unglazed transpired solar collectors Solar Energy 81 (2007) 62–75.
[5] Van Decker, G.W.E., K.G.T. Hollands, and A.P. Brunger, 2001. Heat exchange relations for unglazed transpired solar collectors with circular holes on a square or triangular pitch. Solar Energy 71 (1), 33–45.
[6] Nelwan, L. O., Y. N. Maulia, D. Oktariski. 2012. Thermal study of a semi-glazed solar collector for various tilt angle. (in Indonesian). Prosiding Seminar Nasional Perteta, Denpasar, 13-14 Juli 2012.
[7] Faustino, J. M. F., M. J. Barroca and R. P. F. Guine. 2007. Study of the drying kinetics of green bell pepper and chemical characterization. Food and Bioproducts Processing, Trans IChemE, Part C, September 2007. Vol 85 (C3) 163–170
[8] Kiranoudis, C. T., Z. B. Maroulis, E. Tsami & D. Marinos-Kouris. 1993. Equilibrium Moisture Content and Heat of Desorption of Some Vegetables. Journal of Food Engineering 20 (1993) 55-74 circular holes on a square or triangular pitch. Solar Energy 71 (1), 33–45.