Conference Proceedings

EuroSun 2014
Aix-les-Bains (France), 16 - 19 September 2014

Numerical Modeling of Hot Air Multi-pass Solar Dryer

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Abstract

This article presents the investigation of modeling solar drying system using partial differential equation module of MATLAB to predict the thermal conditions of a drying system with pebble beds as heat storage medium. A 2-dimensional geometry of the air heater was examined using both Dirichlet and Neumann boundary conditions to define the heat transfer and temperature gradient at the walls of the system. Appropriate thermal equations were used to define the multi-layer drying system with specific properties of materials which have significant effect on the performance efficiency of the solar collector. Finite element method of meshing the system component was employed to solve the heat transfer equation. The dynamic simulation of the air heater was tested for 5000 s at the average maximum daily temperature of 318 K with solar irradiation of 800 Wm^{-2}. Despite five cabinet channels design, the temperature gradient of hot air distribution at various points was less than 1 K. The heat transfer simulation of the system has been achieved in good agreement with the reported studies. However, the mass transfer aspect of the model still needs to be improved upon for better and accurate collector characterization.

Key-words: Heat transfer; Hot air distribution; Multi-pass; Numerical; Solar collector

1. Introduction

Energy is a critical function of human survival on earth. The concomitant effects of using organic fuel pose serious challenges to sustainability. Hence, renewable energy remains the viable source of energy for all. No doubt that the United Nations and various governments are increasing their annual energy plan contribution, especially on the research and development of renewable energy sector. Hence, the researchers in the solar energy are now on their toes to achieve the vision 2030 of UN on renewable energy for all.

Heat transfer is defined by Kaviany (2011) as the transport of thermal energy due to spatial variation in temperature within the medium or with other surrounding media while Bejan (1993) said that mass transfer takes place in an environment with non-equilibrium in concentration of chemical species. It was stressed further that drying process remains the classical example of mass transfer. The thermal and mass transfers are two principal activities that form the solar drying process whereas solar thermal air heater was viewed as combination of heating, cooling and humidification processes that are evaluated by conservation laws (Akpinar et al. 2005, Midilli and Kaushik 2003, Panwar et al. 2012 and Prommas et al. 2010).

Crop drying is a means of reducing the moisture content of edible agricultural product such as grain and vegetable with the sole motive of extending its shelf span without compromising the quality. It is an economical technique used to preserve farm products in which moving hot air of temperature between 40°C and 60°C remove moisture from crops and medicinal herbs (Janjai et al. 2008, Midilli and Kaushik 2003 and Panwar et al. 2012). However, a range of temperature between 60°C and 80°C with air velocity of 1.0 ms^{-1}-1.5 ms^{-1} and relative humidity of 0.1-0.2 was reported as favourable condition for drying (Akpinar et al. 2005).

Solar air dryer is a simple and easily made system that harvests the energy from solar irradiance by a flat or

doi:10.18086/eurosun.2014.01.04 Available at http://proceedings.ises.org

curved collector. The collector releases the gained energy into the surrounding air by force or free convection. Porosity, air mass flow rate of hot air, pebble bed material and geometry are some of the factors that influence the performance of porous rock bed that are used as thermal storage in solar drying.

Several studies have been investigated on transient characterization of solar collector. Nayak and Amer (2000) have grouped them into nine different classes and brought out the theoretical and cost differences in each of the group with the Dynamic Solar Collector (DSC) method been the most economical. Dynamic evaluation of solar absorber is preferred base on economic reason and most importantly when focusing control problems (Villar et al. 2009). Kong et al. (2012) presented an improved transfer function technique under transient condition in which the fluid volume and time parameter were obtained as new indicators of solar collector thermal transfer. A numerical solution of partial derivative of first order for solar collector under transient mode was studied (Hilmer et al. 1999). The uniqueness of this developed model are that the non-equilibrium thermal transfer is estimated and the air mass flow rate is a function of time.

A 1-Dimensional numerical analysis of solar absorber has been investigated (Cadafalch, 2009) the model was configured with a pile of geometrical components and material specifications. Both real and imaginary data such as environmental temperature and radiant intensity were considered. Flat plate made of polymer was numerically optimized with an optimum result at 10mm separation distance between the absorber and transparent polymer cover (Do Ango et al. 2013). The absorption of solar radiation through the glass cover, quasi-dynamic condition, convective heating of the working fluid and thermal waste as a function of system temperature still remains the state of art of solar heater in accordance with the European standard EN 12975-2 (Fisher et al. 2012, Kong et al. 2012 and Osório and Carvalho, 2012). Different collector sizes have been investigated. Large collector of area 4.340 m^2 with thickness of 2.0×10^{-3} m was used in a modeling (Fisher et al. 2012), whereas small aperture dimension of 0.9 m by 0.4 m was used in reported investigation (Kurtbas and Durmuş, 2004). Hence, heat required from solar collector is a principal factor to be considered for proper sizing. Selection of coating of absorber is a fundamental aspect of optimizing the heat generation by the solar air heater. An efficient coating improves the solar energy absorbed into the solar system and minimize loss of energy mostly from infrared radiation by reflection (Joly et al. 2013).

Modeling with MATLAB/SIMULINK has been exhaustively been used in engineering control, mechanics, dynamics etc. But only few investigations in solar energy system have been reported using this robust tool. Da Silva and Fernandes (2010) affirmed the relevancy of this tool with good result in a hybrid modeling of solar energy systems. Several solar drying systems have been made. However, the gap of hot air even distribution, efficient and modeling optimization of dryer is still remaining unclosed. Therefore, this study is an attempt to use MATLAB tool to model a drying system with optimum design, operation and environmental conditions.

2. Assumptions used in the analysis

The following assumptions and approximation were made to simplify the analysis of the multi-pass solar collector drying system investigation.

- Working fluid was air with ideal gas properties.
- The thermal contribution of steel rod used for heating chamber reinforcement was considered insignificant.
- Collector surface harvested radiation with no tolerance for wavelength and direction.
- Vertical boundary layers were assumed to be perfect insulators.
- Material properties were isotropic.
- Moisture content of the material to be dried was considered.
- The system was considered under dynamic mode.

3. Theoretical concepts

The design of the required numerical model using partial differential equation solver was based on convective and radiation thermal transfer. These processes remain dominant in this model in which the moving hot air and heat energy were considered. Hence, Navier-Stokes Equations and energy laws were considered relevant in this study. The mass flow rate continuity is shown in Equation 1 while the momentum principle forms Equation 2. The useful heat flux generated by the system convective and radiation thermal transfer are depicted in Equation 3 and Equation 4 respectively.

$$\sum_{in} \dot{m} - \sum_{out} \dot{m} = \frac{\partial m}{\partial t} \qquad \text{(eq. 1)}$$

$$\frac{\partial}{\partial t}(vm) = \sum_{in} \dot{m}v - \sum_{out} \dot{m}v + \sum P \qquad \text{(eq. 2)}$$

Note that the air velocities and the convective forces in Equation 2 are vector quantities.

$$Q_c = h_{con}[T - T_a] \qquad \text{(eq. 3)}$$

$$Q_r = \sigma\varepsilon[T^4 - T_a^4] \qquad \text{(eq. 4)}$$

The convective and radiation heat transfer processes are the dominant thermal transfer involved in this investigation. Hence, Equation 5 reflects the thermodynamic operations within the solar dryer (Tiwari, 2002).

$$\psi\rho C_p \frac{\partial T}{\partial t} - \psi k\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2}\right) = Q_{con} + Q_r \qquad \text{(eq. 5)}$$

Equations 3 and 4 are substituted into Equation 5 to obtain the system energy balance equation as shown in Equation 6.

$$\psi\rho C_p \frac{\partial T}{\partial t} - \psi k \nabla^2 T = h_r[T - T_a] + \sigma\varepsilon[T^4 - T_a^4] \qquad \text{(eq. 6)}$$

Kalogirou (2004) emphasized that absorber performance efficiency was most paramount value in solar thermal system characterization. The system performance efficiency can be computed as the ratio of useful heat flux to the product of solar absorber plate area and the incident solar irradiance as shown in equation 7.

$$\eta_c = \frac{\dot{m}\rho C_p dT}{A_c G} \qquad \text{(eq. 7)}$$

Duffie and Beckman (2006) expressed the collector flow factor, F and thermal removal factor, F_r as shown in Equations 8-10.

$$F = \frac{\dot{m}C_p}{fA_cU_L}\left[1-\exp\left(-\frac{fA_cU_L}{\dot{m}C_p}\right)\right] \quad \text{(eq. 8)}$$

$$F_r = \frac{\dot{m}C_p}{U_LA_c}\left[1-\exp\left(-\frac{fA_cU_L}{\dot{m}C_p}\right)\right] \quad \text{(eq. 9)}$$

$$f = \frac{F_r}{F} \quad \text{(eq. 10)}$$

The mass transfer of water content of the crop to dry is governed by Equation 11.

$$\frac{\partial M_{db}}{\partial t} = C_d \frac{\partial^2 M_{db}}{\partial l^2} \quad \text{(eq. 11)}$$

Equation 12 shows the expression to evaluate the ratio of moisture content of drying crop using Fourier number of mass transfer (ω) which is a function of time and coefficient of mass diffusion. The number of grains or kernels subjected to drying operation (Pabis et al. 1998).

$$M_R(t) = \frac{M(t)-M_{eq}}{M_i - M_{eq}} = \frac{6}{\pi}\sum_{j=1}^{\infty}\frac{\exp\left(-j^2\pi^2\omega\right)}{x^2} \quad \text{(eq. 12)}$$

The granite porosity ρ was defined by Kaviany (2011) as the ratio of the fluid in the void to the sum of fluid-granite total volume. This is depicted in Equation 13.

$$\rho = \frac{f_v}{f_v + Gr_v} \quad \text{(eq. 13)}$$

4. Model description

Kalogirou (2004) stressed that solar collector modeling is a complicated and difficult task as it compose of both predictive and non-predictive data. It was emphasized that solar collector modeling should commenced by system structural representation which enjoys no one way rule. The popular technique of resolving transient heat transfer problem in recent time is through numerical modeling (Bejan, 1993).

The partial differential equation platform of MATLAB, version 8.1.0.604 (2013a) was employed in this modeling. Constructive body geometry approach was used to define in detail the size and shape of the system. This involves putting together of common plane figures such as rectangle and polygon to build the required 2D system as shown in Figure 1 while Figure 2 shows the flow of working fluid in the drying system

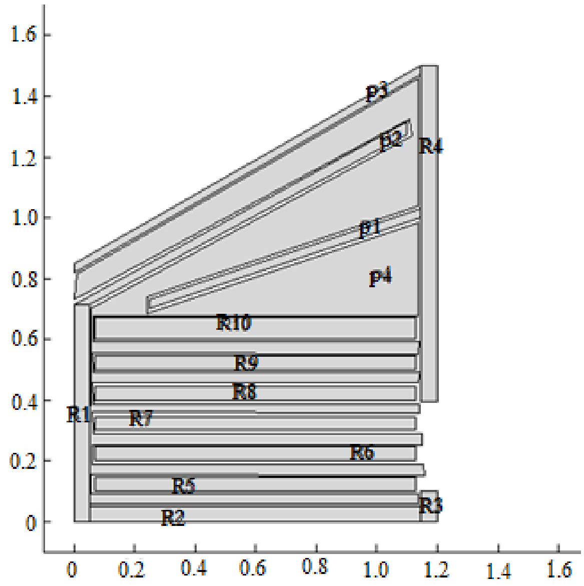

Fig. 1 : Hot air dryer in 2D geometry

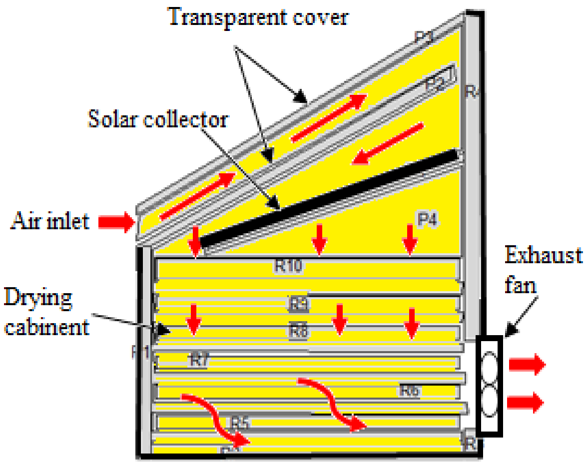

Fig. 2 : System thermo-fluid (air) flow path

The thermal properties of each elemental part must be defined before the simulation was run for accurate prediction. However, materials that have little or no influence were ignored for simplicity. Gray (2011) emphasized that a modeler must know the necessary parameters to consider as input in order to get the desire outcome. Fischer et al. (2012) affirmed that the adjustment of theoretical parameters to experimental data is an acceptable procedure to achieve the best fit parameters. Properties of six different materials were considered for simulation of this model. Table 1 shows some of the parameters and constants considered in this model. The detailed input variables used form the composition of all material that made up the drying system including air as thermodynamic fluid.

Table 1: Some of the parameters and constants used for modelling

Quantity	Symbol	Value	Unit
Ambient Temperature	T	304	K
Solar irradiance	I	800	W m^{-2}
Simulation time	t	5000	S
Collector area	A_c	0.90	m^2
S-Boltzmann constant	σ	5.669×10^{-8}	W $m^{-2}K^{-4}$
Air density	ρ	1.29	kg m^{-3}
Specific heat of water	C_p	4180	$Jkg^{-1}K^{-1}$
Conductance of Al	K	205	$Wm^{-1}K^{-1}$
Relative humidity	H	0.62	-
Granite porosity	ρ	0.302	-
Air mass flow rate	$\dot{m}$	0.035	Kgs^{-1}
Wood conductivity	K	0.17	$Wm^{-1}K^{-1}$

The mesh of the model geometry was achieved after all needed input variables were inserted and a refined mesh was done for better accuracy. However, refining of mesh inceased the computer memory and time required to run the simulation. The refined mesh topology in Figure 3. was achieved when further discretization has negligible effect on the simulation outcome. The elemental nodes covered the entire geometry which comprises of both inner and outer nodes. The ambient and operating parameters were employed to define the system boundary. Combination of Peter Dirichlet and Carl Neumann boundary conditions were used appropriately to define the entire system boundaries.

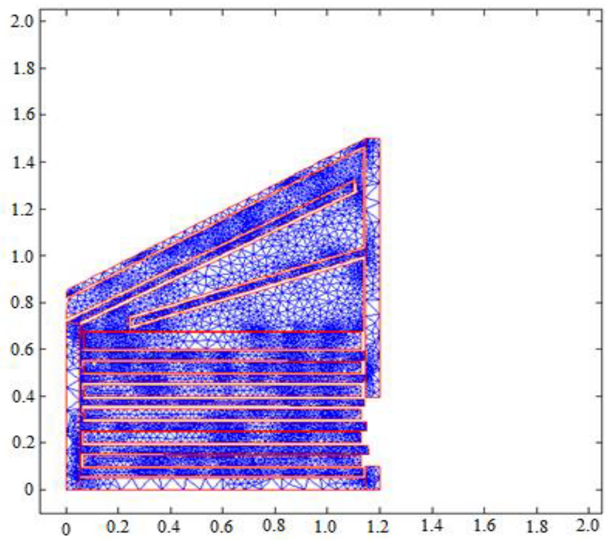

Fig. 3: System mesh topology

5. Results and discussion

Transient partial derivative was employed with 42 decompositions of both lower and upper triangular matrixes. A total of 454 solution of linear systems were obtained. The thermal transfer within the multi-channelled solar drying system is depicted in Figure 4. The harvested thermal flux by the solar collector was evenly distributed within the cabinents that contained the food crop to be dried. This was achieved with the help of laminar forced convection mode used for the model with air mass flow rate of 0.04 kgs^{-1} at system optimum performance which is in agreement with reported investigation (Sopian et al. 2009).

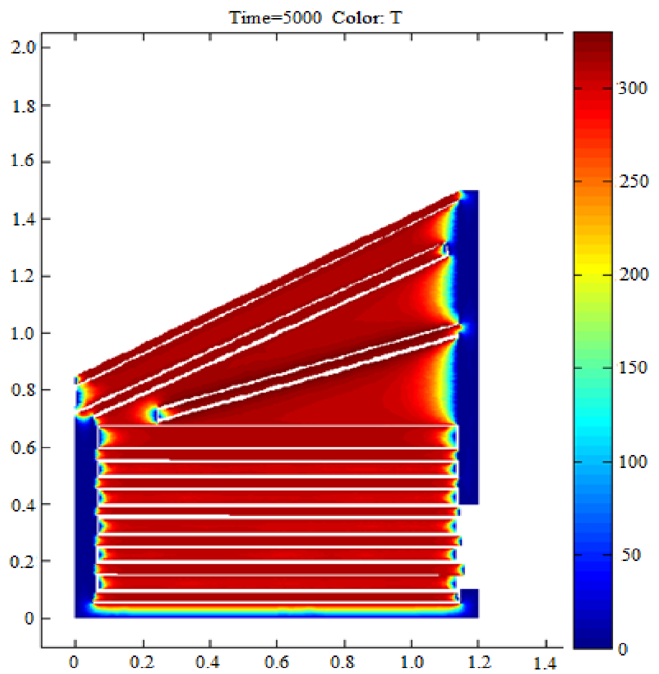

Fig. 4 : Distribution of hot air

6. Conclusion

The hot air distribution inside the drying system was evenly distributed. This has significant effect on performance efficiency of the drying system with the solar collector thermal efficiency of 6.2% at optimum air mass flow rate when compared with reported experiment on double pass collector mode (Sopian et al. 2009). However, improvement is still needed on the analysis of system mass transfer to make the partial differential equation technique a better tool for solar thermal modeling. The average error between the reported experimental result and the predictive outcome was lower than 0.04.

Nomenclature

$\dot{m}$	Air mass flow rate (kgs^{-1})
m	mass (kg)
t	time (s)
v	velocity (ms^{-1})
P	convective force (N)
Q	thermal source (J)
T	temperature (K)
C_p	specific thermal capacity at constant pressure ($KJkg^{-1}K^{-1}$)
k	conductivity ($Wm^{-1}K^{-1}$)
x	horizontal distance (m)
y	vertical distance (m)
h	thermal transfer coefficient ($Wm^{-2}K^{-1}$)
A	area (m^2)
G	global irradiance (Wm^{-2})
F	collector flow factor
F_r	thermal removal factor
U	heat flux (J)
M	moisture content (kg)
C_d	coefficient of diffusion (m^2s^{-1})
l	characteristic lenght (m)
Gr	granite
f	fluid, thermal transfer ratio
j	number of grains of crop
Greek letters	
ψ	thermal diffusivity
ρ	density (kgm^{-3})
ε	emisivity
σ	Stefan-Boltzmann constant ($Wm^{-2}K^{-4}$)
η	instantaneous performance efficiency
ω	Fourier number for mass transfer

Subscripts

con	convective
r	radiative
a	ambient
c	collector
L	loss
db	dry basis
v	volume
eq	equilibrum
i	initial

Acknowledgement

Authors indeed appreciate the Universiti Teknologi PETRONAS for financial support through University Research Internal Fund (URIF) grant No: 015 3AA B07 which was used for this investigation. The first author would like to acknowledge Universiti Teknologi PETRONAS for the award of Graduate Assistantship Scheme as support during the period of this investigation.

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