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Numerical modelling of multi-pass solar dryer filled with granite pebbles for thermal storage enhancement

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Abstract. In this paper, a theoretical modelling of a cheap solar thermal dryer for small and medium scale farmers with multi-pass approach has been investigated. Comsol Multiphysics modelling tool was employed using numerical technique. The rock particles were used to enhance the thermal storage of the drying system. The local weather data were used during the simulation while parameters and coefficients were sourced from literature. An improvement on efficiency of up to 7% was recorded with error of 10^{-5} when compared with the reported double pass solar collector. A fair distribution of hot air within the cabinets was also achieved. Though the modelling tool used was robust but the characterization of the system materials need to be done to improve the system accuracy and better prediction.

1. Introduction

The United Nations has constantly monitoring its targets set for renewable energy sector under renewable energy for all by the year 2050 [1]. Therefore effort to improve the efficiency of the renewable energy systems is a major concern for researchers and this has made the use of latest modelling tools a must in the research on solar energy, in order to accomplish the noble goal of reducing the carbon content of our atmosphere due to the frequent usage of energy sourced from fossil fuels.

Carbonell et al. [2] examined both modified correlation model and an improved Duffie-Beckman model under a transient condition. Unsteady parameters such as solar irradiance, mass flow rate and inlet temperature of fluid were employed to get better system performance. These models were validated by virtual test approach that was based on numerical technique. However, it was difficult to determine the physical behaviour of the system through this approach.

Wu and Wang [3] developed a model using numerical technique to study the dynamic behaviour of volumetric solar thermal air absorber when subjected to different working conditions. A two dimensional discretization of solar absorber made of ceramic material was generated and analysed using CFD software. This dynamic model was confirmed to be accurate in predicting the volumetric solar hot air absorber. It was also affirmed that the ceramic solar absorber has smooth reaction to variation in thermal flux during the cause of operation. Ceramic porous absorber was investigated

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numerically by Wu et al. [4] to determine the pressure drop of the air and the flow field pattern inside the porous material. A pressure drop of up to 70% at air velocity of 5ms^{-1} was achieved. A model based on non-equilibrium local temperature of both fluid and porous matrix was studied by Wu et al. [5] to determine the characteristics of thermal transfer that exist between both the air and the ceramic porous material. They developed a thermal transfer coefficient correlation as a function of porosity, velocity and the cell geometry by using CFD modelling tool.

Significant increase in rate of drying was reported with solar dryer that has pebble bed as energy storing material with energy charging at the early hours of operation and discharge the heat energy at the later period. This extends the drying period after sunset, though the geometry of the porous matrix, air mass flow rate, porosity, physical and thermal characteristics are functions of thermal storage [6]. Pebble bed material was introduced in 1970s to address energy shortage that was frequent. Recent report shows that porous matrixes has improved thermal application technique, cost effective and reliable means of storing thermal energy [7].

Interest in solar drying is gaining momentum as a result of shifting the energy source from hydrocarbon based to renewable energy sources. Hence, solar energy source remains the most economical and eco-friendly option suitable for food preservation methods such as drying technique. This was emphasised by Fudhoil et al [8] that solar energy source remains the best option to ensure all year round food security for fast growing global population. They remarked that solar drying is gaining more attention of researchers than ever based on its present and future relevance in global food security. Kareem et al. [9] reported the advantages of drying applications and emphasised the solar energy as the clean source of drying agricultural crops.

Many solar dryers have been reported in literature but a cost effective multi-pass dryer has been left undone. Hence, a robust tool that captures all relevant physics of the solar drying system was utilised to model a cost effective dryer for small and medium scale farmers.

2. Theoretical Analysis

The system model was based on the fundamental principle of thermodynamics as shown in equation (1), while equation (2) and equation (3) are the extension of equation (1). The velocity field (U) at a point (x,y) and other thermo physical variables were declared during simulation based on local weather data using heat transfer platform of Comsol Multiphysics modelling tool.

$$C_p\rho\frac{\partial T}{\partial t} + C_p\rho U.\nabla T = \nabla.[k\nabla T] + Q \quad (1)$$

$$C_p\rho\left[\frac{\partial T}{\partial t} + U.\nabla T\right] = k\nabla^2 T + Q \quad (2)$$

$$\nabla^2 T = \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} \quad (3)$$

The performance efficiency of the drying system can be computed by equation (4) [10].

$$\eta_d = \frac{\dot{m}\rho C_p dT}{IA_c} \quad (4)$$

The wet crop temperature or material to be dried can be modelled by expression proposed by Pabis et al. [11] as shown in equation (5).

$$\frac{\partial T}{\partial t} = \frac{dM}{dt} \left(\frac{h_v \rho_d}{C \rho_w} \right) - [T - T_a] A \left(\frac{h}{VC_p \rho_w} \right) \quad (5)$$

Oliveira and Haghghi [12] presented a detailed expression that models the drying mechanisms of porous media such as transportation of water capillarity, diffusion and convection as depicted in equation (6)

$$\lambda \frac{\partial \Omega_i}{\partial t} = \sum_{n=1}^m \nabla \cdot (P_{in} \nabla \Omega_n) + Q_i \quad i = 1, m \quad (6)$$

3. Geometrical System Model and Discretization

A two dimensional approach was employed in this investigation. Figure 1 shows the combinations of fourteen basic plane figures used to define the geometry of the drying system on Comsol geographical user interface. The model boundary conditions were implemented through the selected physics module that has the capability of analysing and numerically solved the problem.

The composition was made of seven different materials such as air as the thermodynamic fluid, aluminium as solar collector, granite as sensible energy storage, water properties of material library was conditioned to model mass transfer of moisture, while the rest materials were used to replicate the system casing.

Surface to surface and porous thermal transfers were considered during the simulation. The outcome of dryer finite element discretization is shown in figure 2 in which 77379 degree of freedom was achieved. This was obtained after various boundary conditions were defined and meshing was performed under a time dependent situation.

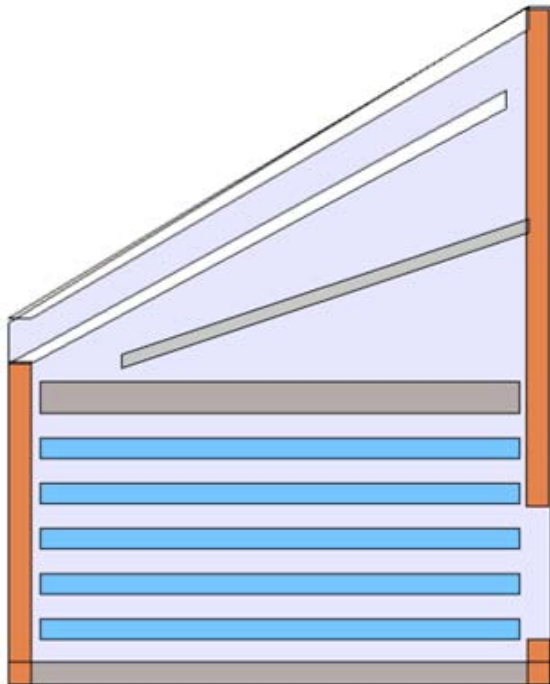


Figure 1. Drying system geometry

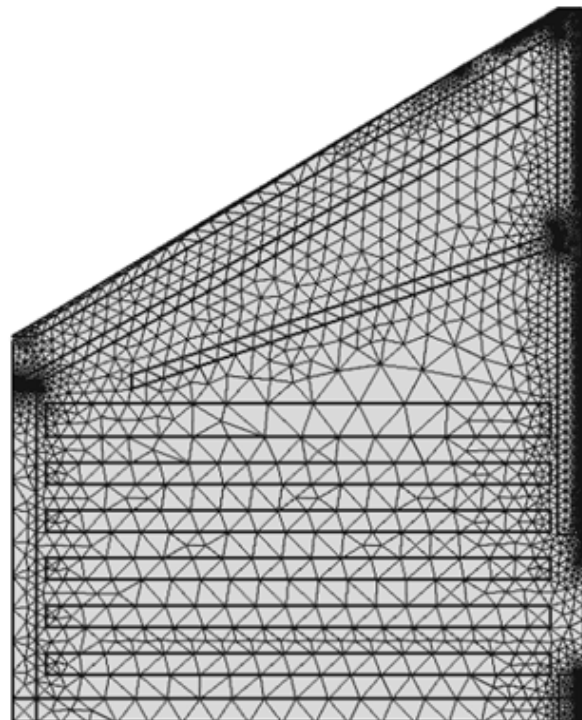


Figure 2. Discretization of the system geometry

4. Results and Discussion

The modelling was simulated for a period of 32 s and the convergence of the numerical iteration was achieved within this period. The drying chamber mean temperature of about 348.50K was recorded which is suitable for drying of common crops. The surface temperature in figure 3 shows the distribution of temperature within the modelled system while the isothermal graph in figure 4 shows the areas with equal temperature value.

The force convective source imposed at the base of system influenced the rate of drying which reached the peak value when the air mass flow rate was at 0.042 kgs^{-1} . The granite material used as alternative heat source has prolonged and enhanced the thermal transfer within the drying system, especially during the discharge period. The economic value of all materials used for modelling was considered for cost optimization of the drying system. This made it affordable for the small and medium scale farmers.

It was also noticed that the system operating conditions were suitable for drying of medicinal herbs which its demand is currently on the increase since Beijing Declaration of World Health Organization in 2008.

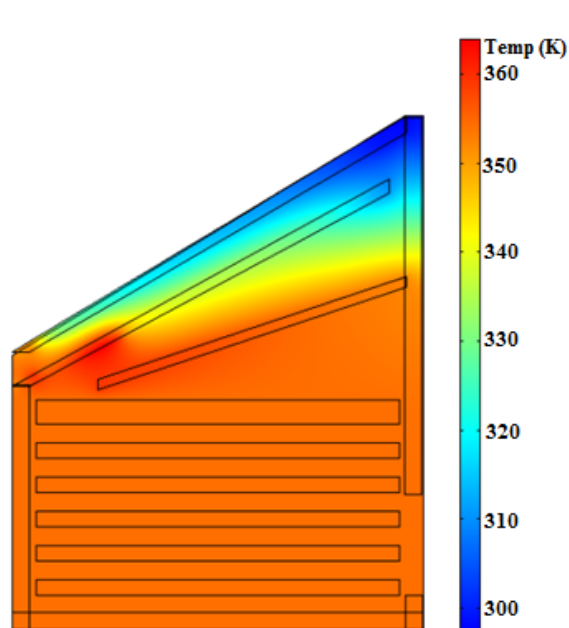


Figure 3. System surface temperature

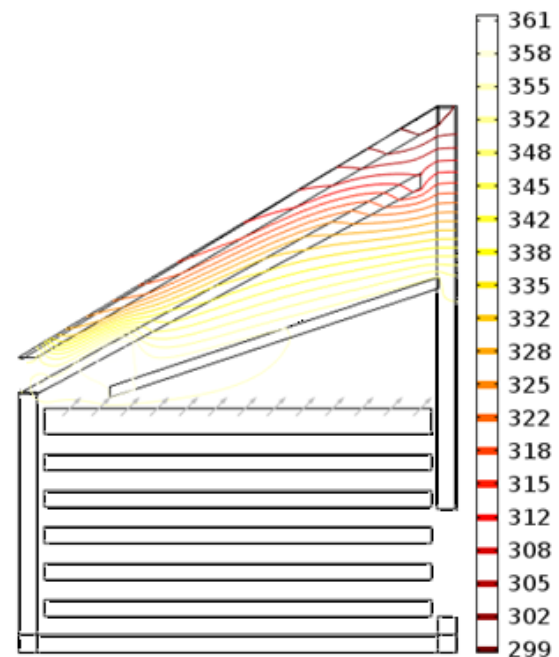


Figure 4. System isothermal curve

The trend of simulation convergence is depicted in figure 5. The error value was plotted against the number of iterations for the nonlinear solver which reflects the relevance of the modelling tool for solar thermal drying system. The numerical solver was able to give solution after the seventh iterative procedure with moderate computer memory usage.

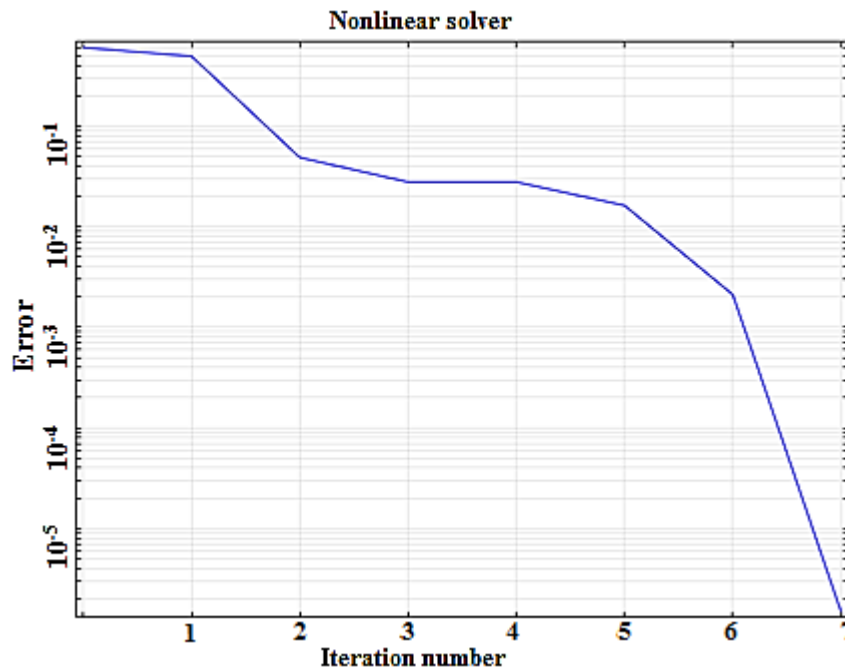


Figure 5. System error-iteration profile

5. Conclusion

The modelling of solar drying system has been done with heat transfer module of Comsol Multiphysics. The results indicate the relevance of the tool employed in solar energy system modelling with inclusion of porous media. The error recorded at the end of iterations was 10^{-5} . Granite was imposed as a sensible thermal storage matrix which acted as heat source during discharge period. This has positive contribution on system performance efficiency which was improved by 5-7 % when compared with a reported study on double pass solar dryer [13]. Despite the result obtained, there was still need to do specific thermal characterization for each material that constitutes the system for better accuracy.

Nomenclature

Symbol	Description	Unit
C	Specific heat capacity	$\text{kJkg}^{-1}\text{C}^{-1}$
ρ	Fluid density	Kgm^{-3}
T	Temperature	$^{\circ}\text{C}$
U	Velocity field (x,y)	ms^{-1}
t	Time	S
k	Thermal conductivity	$\text{W(m.}^{\circ}\text{C)}^{-1}$
Q	Heat flux	W
A_c	Collector aperture area	m^2
I	Solar Irradiance	Wm^{-2}
V	Volume	m^3
A	Crop surface area	m^2
h	Heat transfer coefficient	$\text{Wm}^{-2}.^{\circ}\text{C}^{-1}$
\dot{m}	Mass flow rate	Kgs^{-1}
M	Moisture content	Kg

λ	Capacity coefficient of drying material
P	Kinetic coefficient of drying material
Subscripts	
p	Constant pressure
c	Collector
d	Dry, drying
w	Wet
a	Ambient

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