CFD Modeling of An Even-Span Greenhouse Dryer Under Natural and Forced Convection Modes

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Abstract. In this study an even-span greenhouse dryer was designed and simulated under two different drying modes, natural and forced convection modes. The CFD simulation was carried out taking into consideration the weather conditions at the mean day of January (winter season) in Marrakech, Morocco. CFD was employed to predict the air velocity, temperature and relative humidity distribution inside the greenhouse dryer. Under forced convection mode the air temperature and relative humidity were uniformly distributed inside the dryer. The highest air temperature and lowest air relative humidity was recorded at the mean hour of the simulation day, under forced convection mode. They were 37 °C and 12%, respectively. These results reveal that under forced convection mode the greenhouse exhibited significant thermal performances.

1. Introduction

Solar drying has attracted much attention as a cost-effective technique for food, grains and medicinal plants preservation and biomass pretreatment to produce bio-combustible [1], through a free and environmentally friendly source of energy. Various solar drying systems have been wildly studied [1, 3, 4]. Their classification is based on the direct or indirect solar radiation interception and natural or forced convection air circulation inside the dryer. The direct and natural convection based solar drying system characterized by low efficiency, non-drying uniformity, low product quality and low drying rate. Whereas the direct forced convection drying system is the most efficient in terms of high drying rate and good product quality. Ameri et al [2] made a kinetic comparison between the direct and indirect solar dryers operated under natural convection. They found that under the same operating conditions, the indirect system gives high temperatures and efficiency compared to the direct dryer; thus reducing the drying time and increasing the drying rate. Rodríguez et al [3] studied the thermal behavior and evaluated the drying kinetic of natural rub sheets under two solar drying technologies: direct under natural convection (passive mode) and indirect under forced convection (active mode) under the same weather conditions. They found that under the active indirect solar drying mode, the moisture content of the natural rub sheets was reduced by 48.9% in 9 days, while it was reduced by 45.2% in 12 days in case of passive direct solar drying.

Greenhouse dryer is a drying system which has the ability to combine all cited drying modes. It is made of a transparent cover to the incident short wavelength radiation and it has the ability to trap reradiated radiation from the greenhouse components, thus creating the greenhouse effect. Compared
to other drying systems, the greenhouse drying system efficiency and solar radiation interception is significantly influenced by the greenhouse shape, orientation, and structure. Jitjack et al [4] made a comparative study between two greenhouse dryer structures for rubber drying. The first system had a parabolic shape (PG), while in the case of the second system an additional area was added to the lateral section of the parabolic greenhouse (PGEP). They found that under no load conditions the PGEP system inside air temperature and thermal efficiency were higher than those of the PG system. In addition, the drying period of rubber sheets in the PGEP system was 3.3 time less than the drying period in the PG system. The additional area had a significant effect on the greenhouse thermal and drying performances.

Several studies were conducted in the objective to optimize the greenhouse shape and orientation [6-8]. However, the majority of those studies only evaluate the solar radiation received by the air within the greenhouse system for different shapes and orientations. Chen et al [6] evaluated the amount of global solar radiation captured by different greenhouse shapes at different latitudes. They developed a Matlab code based on the solar radiation interception equations by different slopped and oriented surfaces. However, no attention was paid to the air temperature, humidity and velocity distribution inside the dryer, in order to improve the drying uniformity and consequently the product quality. Only few researches were devoted to this optimization type. Vivekanandan et al [8] made a CFD investigation of six greenhouse shapes in no load conditions to determine the ideal dryer shape. They found that the ideal greenhouse shape is the Quonset as it had the ability to warm the inside air to 66°C in winter. However, they only evaluated the temperature distribution inside the greenhouse dryer under natural convection mode.

The present work overcomes the above limitations by using CFD to model and simulate a greenhouse solar dryer by the CFD, with the aim of developing an adequate model for air flow, temperature, and humidity distribution. Computational Fluid Dynamics (CFD) has emerged as one of the efficient and promising tools to model and to simulate drying phenomena [8]. It has the advantage of reducing the experimentation time and cost. Moreover CFD can be used for the analysis and investigation of air flow inside the dryer, humidity and temperature patterns through appropriate simulation of momentum and energy equations and heat and mass transfer.

In this work CFD software ANSYS FLUENT was used for the thermal performances evaluation of an optimal even span greenhouse shape oriented under the optimal orientation in Marrakech, Morocco (31.6295° N, 7.9811° W and 466 m). The main objectives of this study are: I) develop a 3D model of the even-span greenhouse II) to evaluate the greenhouse system thermal performances under natural and forced modes in a chosen day in winter season (mean day of January), and III) to predict the air velocity, temperature and humidity distribution inside the greenhouse dryer.

2. Methodology

2.1 Description of the greenhouse system

ANSYS subsoftware DesignModeler was used to construct a 3-D model of the greenhouse system. As fig. 1 shows the greenhouse system has an even-span shape, oriented 15° from the south, in order to intercept the maximum of solar radiation during winter season. The dimensions of the greenhouse dryer are 6 m X 4 m X 5 m (length X width X height). The height of the side walls is 2 m, and the roof tilt angle is 60°. The greenhouse system is equipped with 3 inlets of 0.3 m2 each, for the circulation of air by natural convection. Those inlets are located in the North-West side of the greenhouse, since the wind direction is North-West in Marrakech. Two outlets were fixed in the top of the east and west walls of the greenhouse system, for the exit of the moist air, their dimensions are 0.5 m2 each. The floor was covered by asphalt for efficient solar energy absorption and storage and to reradiate the heat during the hours of low solar radiation. Polycarbonate with a transmittance of 84% and a thickness of 6 mm was used to cover the greenhouse system.
2.2 Governing equations
In this study ANSYS FLUENT ver.20 was used to evaluate the air velocity, temperature, and humidity distribution inside an even-span greenhouse dryer under natural and forced convection mode. The governing equation of fluid flow and heat transfer are considered as mathematical formulations of the conservation laws of fluid mechanics which are referred to as the Navier-Stockes equations. Those equations in ANSYS Fluent are written as follows [9]:

- Mass conservation equation
  \[ \frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{V}) = 0 \]  
  \hspace{1cm} (1)

- Momentum conservation equation
  \[ \frac{\partial}{\partial t} (\rho \mathbf{V}) + \nabla \cdot (\rho \mathbf{V} \mathbf{V}) = -\nabla p + \rho \mathbf{g} + \mathbf{F} \]  
  \hspace{1cm} (2)

- Energy conservation equation
  \[ \frac{\partial}{\partial t} (\rho E) + \nabla \cdot (\rho \mathbf{V} E + p \mathbf{V}) = \nabla (K_{eff} \nabla T) + S_h \]  
  \hspace{1cm} (3)

2.3 Turbulent model
The realizable k-\( \varepsilon \) model was adapted during this study to describe the air flow behavior inside the greenhouse dryer. This model was chosen due to its ability to provide better prediction of the velocity distribution [9]. It is based on a model transport equations for the turbulence kinetic energy (k) and its dissipation rate (\( \varepsilon \)). The equation of the realizable k-\( \varepsilon \) model can be found in [9].

2.4 Radiation Model
The DO model was adapted to radiative transfer equation inside the greenhouse dryer. It writes the radiative transfer equation (RTE) in the direction \( \mathbf{s} \) as a field equation. Thus, the RTE is written as follows [9]:

\[ \nabla \cdot \left( I(\mathbf{r}, \mathbf{s}) \mathbf{s} \right) + (\alpha + \sigma_s) I(\mathbf{r}, \mathbf{s}) = a n^2 \frac{\sigma T^4}{\pi} + \frac{\sigma n}{4\pi} \int_0^{4\pi} I(\mathbf{r}, \mathbf{s}') \phi(\mathbf{s}, \mathbf{s}') \, d\Omega' \]  
\hspace{1cm} (4)

where \( I \) is the intensity, \( \mathbf{r} \) is the position vector, \( \mathbf{s} \) is the scattering direction vector, \( \sigma \) is the Stefan-Boltzmann constant, \( \alpha \) is the absorption coefficient of air, \( \sigma_s \) is the scattering coefficient, \( n \) is the refractive index of air, \( \phi \) is the phase function and \( \Omega' \) is the solid angle (radian).
2.5 Boundary conditions

The solar load model was adapted to evaluate the solar radiation received by the greenhouse system. Measured weather condition data were used in this study. Fig. 2 shows the solar radiation and ambient air temperature and relative humidity during the mean day of January. These data were used as boundary condition, applied to the computational domain during the CFD simulation. Under natural convection mode the pressure boundary condition was applied at the inlet and outlet of the greenhouse dryer, as they are exposed to the surrounding atmosphere. While under forced convection mode the velocity inlet boundary condition was applied in the inlet of the greenhouse dryer.

![Figure 2](image_url)

**Figure 2.** Boundary condition, a) solar radiation and b) ambient air temperature and humidity at the mean day of January.

2.6 Mesh dependency

To ensure the accuracy of the simulation, a grid density test was performed for the considered even-span greenhouse dryer through repeated grid adaptation. Fig. 3 depicts the variation of the greenhouse floor temperature as a function of the mesh number. The mesh size was varied from a coarser mesh of 468,691 to a finer size of 6,118,616. Reducing the mesh size increased the greenhouse floor temperature. However after the second mesh density, the floor temperature remains constant. Therefore a mesh size of 1,158,116 was adapted for this study for further computations. It is associated to minimum mesh quality of 0.17 and a maximum skewness value of 0.82.
3. Results and discussions

In this study an even-span greenhouse dryer under the optimal shape and orientation [Article paper under preparation] was numerically simulated using the ANSYS FLUENT software. The air temperature, velocity, density and humidity contours were visualized at the mean hour of the chosen day (13h: 00) for two different convection modes (natural and forced convection). Moreover the temperature and humidity variation during the simulation day from 8h: 00 to 18h: 00 were compared for both convection modes.

3.1 Velocity distribution

The velocity vectors inside the greenhouse dryer under natural and forced convection are depicted on fig. 4 (a) and (b), respectively. Under natural convection mode the air velocity ranged from 0.01 m/s to 0.57 m/s. Its distribution inside the greenhouse dryer is between 0.05 m/s and 0.16 m/s with average magnitude of about 0.08 m/s. Such a distribution is deemed adequate for drying purposes [10]. Under forced convection mode, the air velocity ranged from 0.08 m/s to 0.8 m/s. The velocity distribution is good inside the even-span greenhouse and the average magnitude is about 0.35 m/s. This elevated velocity magnitude for forced convection mode compared to the natural mode has a significant effect on the drying process as stated by [10]. Not only the increase in the temperature contributes to a fast drying, but also the air must have an elevated velocity in order to increase the moisture removal from the product and to guaranty a high drying rate.

Figure 3. Effect of mesh density on the greenhouse’ floor temperature.

Figure 4. Velocity vectors inside the greenhouse dryer under (a) natural and (b) forced convection modes.
3.2 Temperature distribution

Fig. 5 (a) and (b) depicts the temperature distribution inside the even-span greenhouse dryer under natural and forced mode, respectively. It can be visualized that the air near the greenhouse walls (polycarbonate) has higher temperature than the air in other regions of the greenhouse. Moreover the air temperature progressively increases from the bottom towards the top of the greenhouse dryer. Atmospheric air enters the greenhouse dryer from the bottom of the north-west side. Once it enters the greenhouse dryer it starts absorbing direct solar radiation and stored heat in the greenhouse floor, which leads to an increase in the air temperature. The air temperature ranges from 14.2 °C to 60.7 °C and from 26.9 °C to 60.8 °C under natural and forced modes, respectively. The average inside air temperature under natural convection is 1.1 times lower than the air temperature under forced convection. This difference in temperature can be justified by the fact that under forced convection the heat transfer coefficient between the floor and the air is higher than under natural convection mode.

![Temperature contours](image1)

(a) ![Temperature contours](image2)

(b)

Figure 5. Temperature contours in the middle of the greenhouse dryer under (a) natural and (b) forced convection modes.

![Relative humidity contours](image3)

(a)

![Relative humidity contours](image4)

(b)

Figure 6. Relative humidity contours in the middle of the greenhouse dryer under (a) natural and (b) forced convection modes.
3.3 Humidity distribution

One of the most important parameters in the drying process is the air relative humidity. Under low air relative humidity the air has the aptitude to absorb more moisture from the product, while at high relative humidity the air is rapidly saturated, and the moisture removal from the product is low. Fig. 6 (a) and (b) depicts the air relative humidity distribution inside the even-span greenhouse dryer under natural and forced mode, respectively. As these figures show, the air relative humidity progressively decreases from the bottom towards the top of the greenhouse dryer. This is due to the heat accumulated inside the greenhouse dryer, absorbed by the flowing air which by consequence increases its temperature and reduces its relative humidity. The average air relative humidity is 15% and 12% under natural and forced convection mode, respectively. This difference in relative humidity can be explained by the ability of forced air to absorb more heat inside the dryer, leading to a decrease in its relative humidity.

3.4 Comparison of hourly results of the temperature and humidity under the two convection modes

Fig. 7 shows the variation of air relative humidity and temperature along the hours of the CFD study day, under both natural and forced convection mode. The inside air temperature is inversely proportional to the air relative humidity, while it is proportional to the solar ratio of the site. It is clear from the graph that the air temperature under forced convection mode is higher during all the hours of the day than under natural convection mode, whereas the air relative humidity under natural convection mode is higher during all the hours of the day than under forced convection mode. The highest air temperature was recorded at 13h: 00 under the highest solar radiation for both convection modes, associated to the lowest air relative humidity. Both air temperature and relative humidity have a significant effect on the drying process. Under relatively high air temperature and low air relative humidity, the drying rate is important.

4. Conclusion

In this work, the optimal even-span greenhouse dryer was numerically investigated under the natural and forced convection modes, by the mean of ANSYS FLUENT software, under the weather conditions of Marrakech, Morocco. A comparative study was conducted between the two drying modes. The air relative humidity and temperature were found to be low and high, respectively, under the forced convection mode. The highest air temperature and lowest air relative humidity obtained are 12 % and 37 °C, respectively. These results reveal that the forced convection mode has a significant effect on the air temperature and the relative humidity, compared to the natural convection mode. As a consequence, the forced convection drying process will leads to an increase in the drying rate and a decrease in the drying time.

Figure 7. Inside air temperature and humidity variation along the simulation day.
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