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Three-Dimensional Simulation of Solar Greenhouse Dryer

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This study investigates internal conditions of the solar greenhouse dryer with drying agricultural products. The operating conditions inside the solar greenhouse dryer were analysed by ANSYS Fluent software using mathematical models. Additionally, the moist air outside changed according to the climatic conditions of the day. Specifically, moist air enters the dryer through two front doors and exits through three exhaust fans installed in the back, and the flow was considered unstable and tumultuous. Agricultural products inside the solar greenhouse dryer were modelled as a porous material, and the radiation was modelled according to the radiation model. The simulation results show the distribution of temperature and humidity inside the solar drying greenhouse by the influence of heat exchange, turbulent flow, and the process of removing moisture from the drying material to the outside. The simulation results show that indoor drying temperature ranges from 303.15 K to 323.1 K at each time from 7:00 AM to 6:00 PM. The drying house reached its highest temperature at 2:00 PM. Variations of relative humidity in GHSD are between 23.70% and 79.55%. The airflow velocity inside the drying house is almost independent of time and varies based on location.

1. Introduction

Solar energy is the most popular energy source used for the drying process; in addition to being clean, solar energy has large reserves and does not pollute the environment (Sanmartin et al., 2017). Based on the radiation intensity, the method of solar drying by the solar greenhouse dryer (SGHD) helps increase the energy intensity of sunlight to the surface of drying materials through the greenhouse effect. Products in the SGHD can be dried while it rains outside (Chabane et al., 2018). The operation of SGHD is based on the characterisation of airflow and temperature distribution. This is due to the fact that inconsistent temperature distribution inside the SGHD causes non-uniform product quality. To overcome this problem, computational fluid dynamics (CFD) is one of the tools used to design, calculate, and analyse SGHD (Patil and Gawande, 2016).

Several studies have been conducted on the SGHD. In these studies, various types of programming software (e.g., MATLAB, C/C++, and Fortran) simulated the relationship between temperature profile and location and time (Picón et al., 2013). However, very few studies have researched this problem using ANSYS Fluent software. Most published CFD studies are based on the use of a two-dimensional (2D) model to analyse the velocity and temperature inside the solar greenhouse. This approach ignores the climate distribution characteristics inside the dryer according to three-dimensional (3D) space (Prashant et al., 2015). Some studies on the drying that use the 2D model only provide the temperature and velocity distribution without moisture distribution, and results from the 2D model do not cover all positions such as the 3D simulation model. Furthermore, the movement of dew droplets is complicated and can result in unsatisfactory moisture distribution (Román-Roldán et al., 2019). Consequently, use of 3D-dimensional simulation is necessary.

The primary objective of this work was to simulate the influence of time on the temperature and humidity distribution inside the SGHD. The daily meteorological aspects were taken into consideration in the simulation result, and the model was validated through experimental field solar drying data and representing an advance for the accurate prediction of the drying. This contributed to the design of a more efficient processes.

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2. Materials and methods

2.1 Experimental setup

The SGHD used in this study consists of a parabolic roof structure made from polycarbonate sheets on a concrete floor and is located in the An Giang province of Vietnam (10°23'25.1"N 105°26'12.7"E). The dryer was 8m long, 6m wide, and 3.5m high, and the air was drained from the solar greenhouse by three exhaust fans arranged on the wall. Solar radiation was measured by a Kipp and Zonen pyranometer placed on the roof of the dryer. Thermocouples (type K) and a digital probe Bioblock thermohygrometer with ± 3% precision were used to measure air temperatures and ambient air relative humidity in the dryer.

2.2 Modelling and analysis

2.2.1 Geometry model

Figure 1 shows the basic dryer with two rectangles (1.0m long and 0.2m wide) below and three circles (0.25 m diameter) above it represents the input windows and ventilating fans exit. The geometry of SGHD was built by a Design Modeler module, and the computational domain was discretised by mesh generation. In this case, the Hex Dominant method gave better results. However, the high-performance computational requirement was used with 129.803 nodes and 132.597 elements to ensure simulation accuracy.

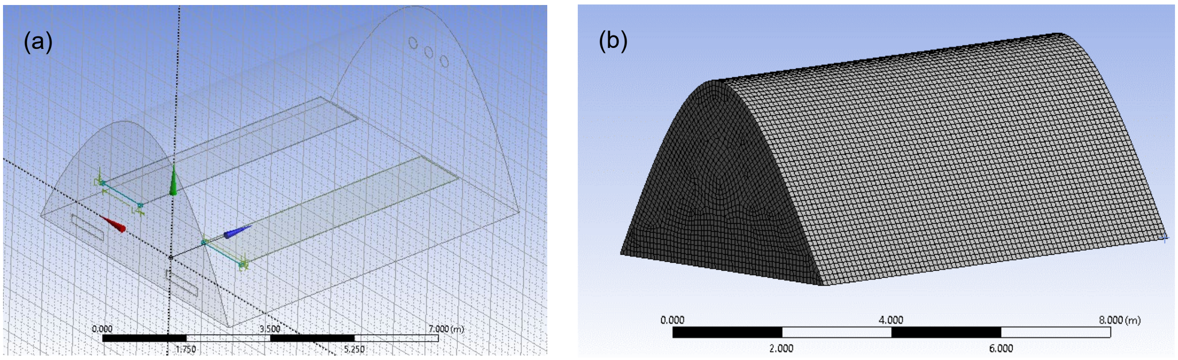

Figure 1: (a) Geometric model and (b) mesh domain of the SGHD

2.2.2 Turbulent model

Flows in ventilation systems are usually associated with turbulent movements. This is mainly due to the high flow rates and the heat transfer interactions involved in the flow field. The realisable turbulence model κ-ε is based on the transport model of turbulent kinetic energy (κ) and its dissipation speed (ε). In addition, the Boussinesq model had been applied to treat density as a constant value in all equations.

2.2.3 Radiation model

The light time and intensity of sunlight depend on the time of year, weather conditions, natural and geographical location. In order to simulate the effect of solar radiation inside the dryer, this study used the discrete ordinates (DO) radiation model. The DO model answers the radiative transport equation to solve the irradiance at semi-transparent walls. This model may be used with participating environments whose α_λ spectral absorption coefficients vary across the spectrum.

2.2.4 Species transport

This model represents air as a mixture of dry air and water vapour. Hot airflow through two dryer trays can be interpreted as flow through the porous zone. The porous area with defined parameters can be represented as dried material. This allows for modelling the process of moisture transfer in objects. When choosing to preserve the equation for chemical components, the software will predict the local mass fraction of each substance (Yi) by solving the convective diffusion equation for the i^{th} substance in the mixture.

2.2.5 Boundary conditions

In order to numerically obtain the solution to a problem, boundary conditions at streams must be defined, and the solution depends on values given at boundary conditions. Values of the model’s boundary conditions are tabulated in Table 1.

Table 1: Operating conditions

The operating conditions	Governing Equations
Solver	3D simulation Implicit formulation Absolute velocity formation Transient state analysis
Energy equation	Activated
Viscous model	Realisable k-ε model Standard wall function
Radiation model	Discrete Ordinate (DO)

Table 2: Boundary conditions

Boundary conditions	Material	Parameters	Value	Source
Wall	Polycarbonate	Thickness [m]	0.001	User-defined
(semi-transparent)		Emissivity	0.9	Román-Roldán et al. (2019)
	Concrete	Thickness [m]	0.2	User-defined
Inlet	Moist air	Temperature [K]	303.15	User-defined
		Velocity [m/s]	0.5	User-defined
		Mass fraction	0.021	User-defined
Outlet	Moist air	Pressure [at]	1.0	User-defined

3. Result analysis and discussion

A series of 3D numerical computations, achieved using the commercially available ANSYS Fluent CFD (Fluent Inc, 2018) code, produced results including temperature and velocity profiles relative to the time in a dryer. Figure 2 shows the simulation results of the humid air temperature with the variation over time. The simulated maximum temperature inside the drying house is 339.1 K at 2:00 PM, and the temperature inside the dryer in the range of 11:00 AM to 4:00 PM remains above 328 K. For the experimental results in Figure 3, the highest temperature is 335.3 K at 11:00 AM and 334.1 K at 2:00 PM. In addition, the experimental temperature provides more uniform results than simulation. Although the simulation results are slightly higher than the experimental values, the numerical results are generally consistent with the experimental data. The simulation model of SGHD can fully predict the behaviour of the experimental design understudy.

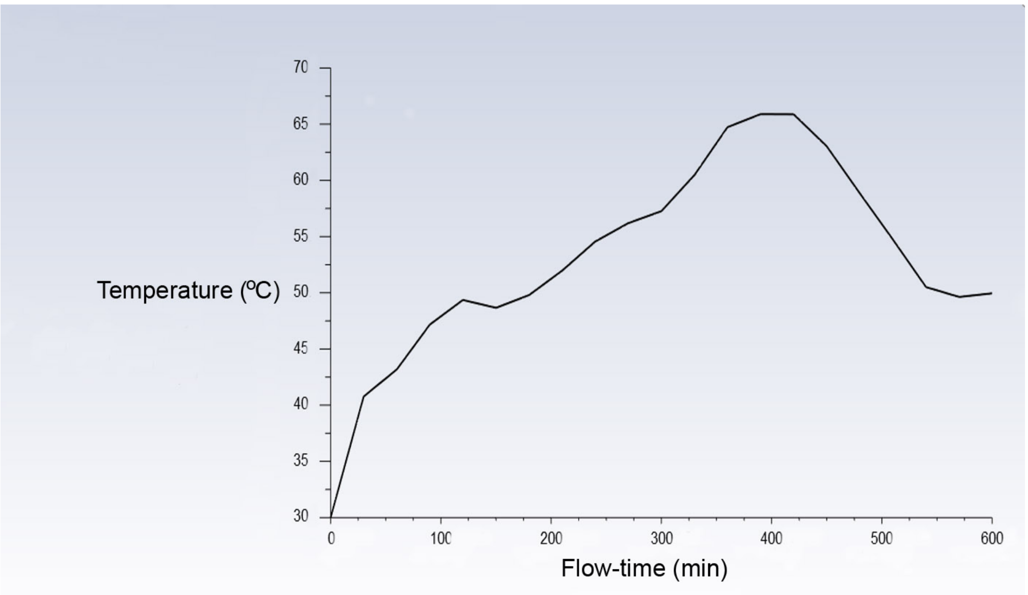

Figure 2: Simulation temperature profile inside the SGHD from 7:00 AM to 6:00 PM

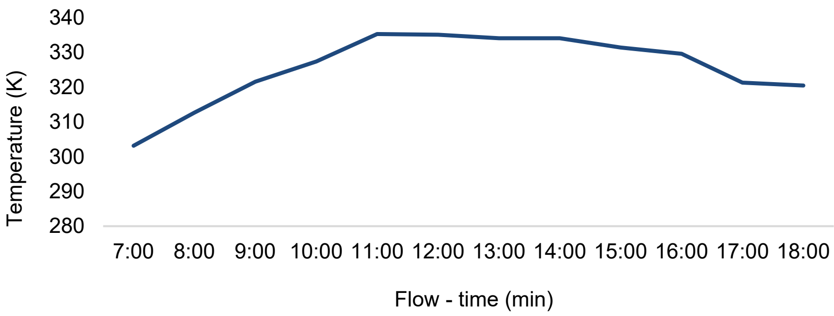

Figure 3: Experimental temperature inside the SGHD from 7:00 AM to 6:00 PM

3.1 Profile temperature inside SGHD

From sunrise (7:00 AM) to sunset (6:00 PM), the roof and inside of the dryer absorb solar radiation and are heated. As this heated air rises and exits the dryer through three fans, fresh air will be drawn in from the other end of the dryer. This causes a change in temperature of the humid air in the dryer, making the temperature in the dryer higher than that of the environment. Figure 4 shows the typical temperature distribution inside the dryer across three locations at 9:00 AM. Dark blue represents the lowest value while red represents the highest value. Green, yellow, and orange lie in the middle, showing the range between the lowest and highest values. The figure below demonstrates the strong relation of solar irradiation through the polycarbonate wall on the distribution of the temperature. The lowest temperature is near the region of inlet air because ambient temperature was the lower (303.1 K) than the temperature inside the dryer. According to the simulation result, the temperature of moist air is almost identical in the exhaust area.

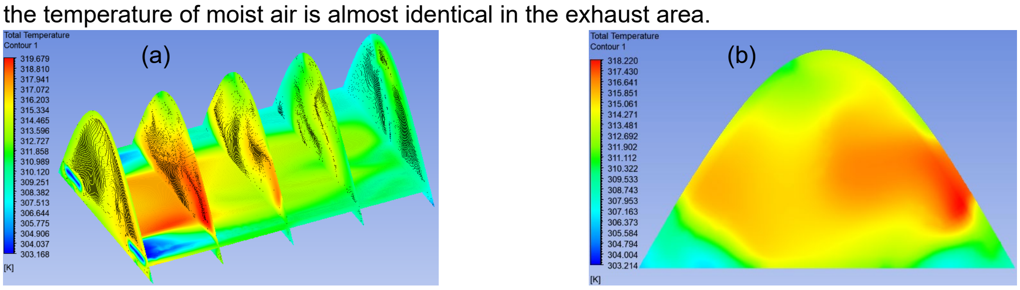

Figure 4: Temperature distribution of moist air in the volume (a) at various location and (b) in the middle of the SGHD

In order to investigate the effect of times on the profile temperature of moisture air inside the SGHD, this study includes an investigation of the distribution temperature of moist air inside the SGHD. The results of this analysis are presented in Figure 5 and the prove that the profile temperature is closely related not only to location but also to time.

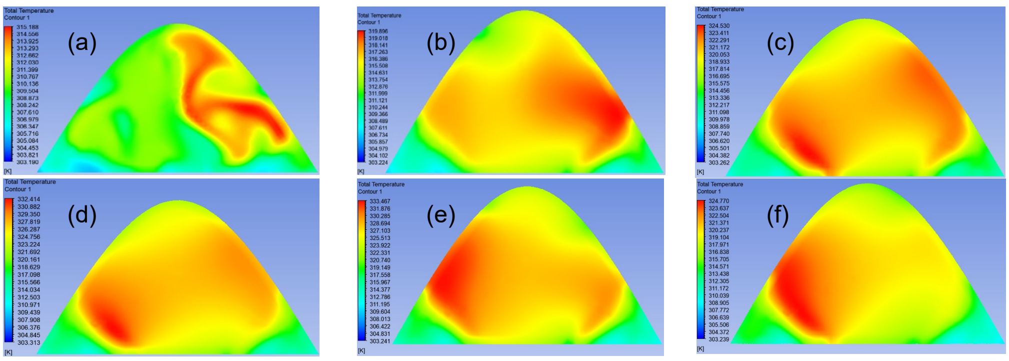

Figure 5: Temperature distribution of moist air in the volume of the SGHD at various times: (a): 8:00 AM; (b): 10:00 AM; (c): 12:00 PM; (d): 1:00 PM; (e): 2:00 PM; and (f): 4:00 PM

As shown in Figure 5, through the effect of heat transfer associated with solar irradiance through the upper semi-transparent wall, the temperature of moist air increases in the large volume of the SGHD, and the highest temperature area depends on the solar direction. This result is also similar to the experimental results measured at the dryer located in the An Giang province. When the air temperature in the dryer is fairly high, the temperature distribution in this section is relatively homogeneous, and the low-temperature zone accounts for a relatively small proportion area. When the indoor air temperature is not high, the temperature distribution of moist air on the surface containing the drying material is still greater than the outside air temperature. This means that the greenhouse understudy is suitable for a better drying process.

3.2 Profile moisture inside SGHD

In the SGHD, the properties of moist air change not only the temperature but also the relative humidity. The relative humidity of moisture was a strong effect by the energy which SGHD absorbed and the amount of fresh air was flown to SGHD. The velocity vector of the airflow is one of the effects of the important factors on the properties of the dryer, and the behaviour of the air movement inside the dryer is presented in Figure 6.

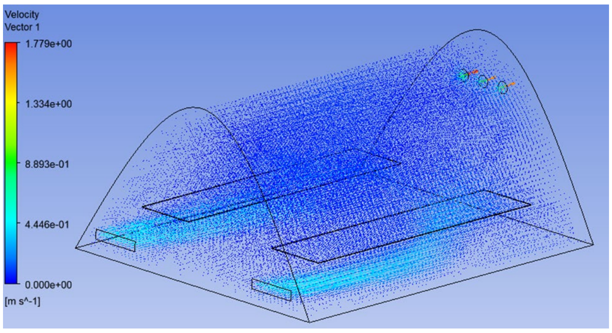

Figure 6: Velocity vectors of the airflow inside the SGHD

It can be realised that air can circulate throughout the whole dryer and the speed of air is independent of time. The velocity distribution of moist air inside the SGHD is similar at the highest and lowest temperatures. The simulation results demonstrate that the internal velocity value ranges 0.5 m/s and the highest point at the outlet is 1.7 m/s. Further, in order to probe the properties of moist air inside the dryer, a relative humidity simulation was conducted inside the SGHD for a one-day experimental run. The results of this investigation are illustrated in Figure 7. Relative humidity decreases with time inside the dryer from the sunrise to sunset, which is caused by decreased relative humidity of the ambient air and increased water-holding capacity of the drying air due to temperature increase. The relative humidity of the air inside the dryers is always lower than that of the ambient air and the lower relative humidity (RH ≤ 40%) inside the SGHD. This normally occurs from 11:00 AM and can carry on for 6 h. The air leaving the dryer has lower relative humidity than that of the ambient air, which indicates that the exhaust air from the dryer still has drying potential.

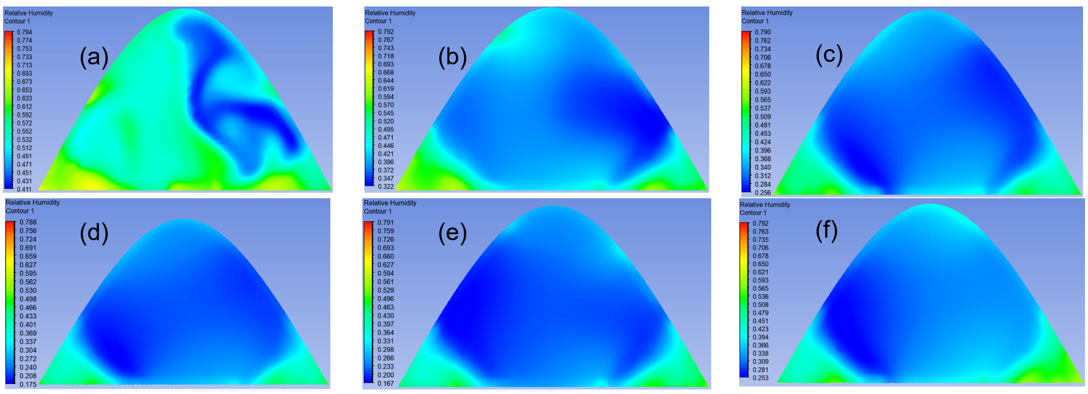

Figure 7: RH distribution of moist air in the volume of the SGHD at various time: (a): 8:00 AM; (b): 10:00 AM; (c): 12:00 PM; (d): 1:00 PM; (e): 2:00 PM; and (f): 4:00 PM

The relative humidity of the humid air inside the SGHD is very different in space. 3D numerical computation was applied to simulate RH values across various locations at the same time in order to investigate RH distribution inside the dryer. Figure 8 shows the RH variation of the humid air at different positions in the dryer during typical test runs. The configured RH value can be explained by the temperature distribution of the humidity air in the SGHD volume. The lowest air temperature, which results in the highest RH, can be demonstrated at the air inlet position and decreases inside the dryer as the air temperature increases.

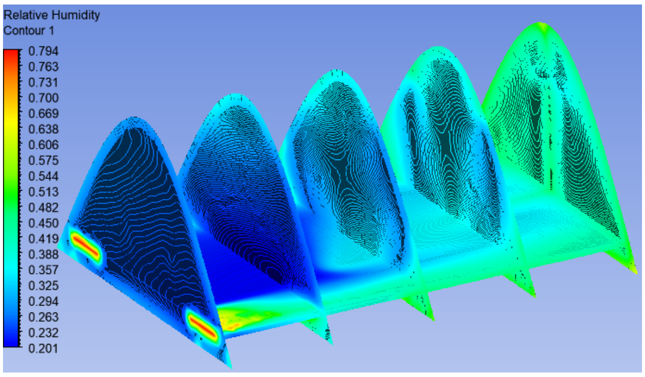

Figure 8: RH distribution of moist air in the volume of the SGHD at various location

4. Conclusions

This study created a computational model of SGHD in Design Modeler with simulation using ANSYS Fluent. Our results indicate that the complex models in which 3D geometry is suitable for predicting the performance of the dryer in various weather conditions with several incident solar radiations. The temperature distribution, as well as the velocity of moist air inside the dryer from sunrise to sunset, has been simulated. Additionally, numerically obtained results are consistent with experimental results. The highest temperature and lowest RH at 2:00 PM are 66.1°C (339 K) and 23.70%. Moreover, the velocity distribution of the air is more uniform. The simulation results also present the relation of RH inside the dryer at the location and time at which the maximum value of RH is 79.55% and the minimum value is 23.70%. The results of the simulation distribution temperature and distribution RH prove that the SGHD could be operated throughout an entire day and that it can be as a prime for building dryer in agricultural country.

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