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Computational Fluid Dynamics (CFD) Simulation of a Solar Agricultural Dryer

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Abstract - Solar drying is an environmentally-friendly and cost-effective method for drying agricultural products. To design a proper solar agricultural dryer for specific products, thermodynamic relations for the agricultural dryer system need to be considered. CFD simulations are commonly used for the design of a dryer. This study presented a simulation of a solar agricultural dryer with the dryer systems divided into two parts, including a solar collector of 2.0 m width, 2.0 m length and 0.2 m height, and a drying chamber of 1.0 cm width, 2.0 m length and 0.6 m height. The temperature distribution and airflow pattern in the drying chamber and solar panel were accomplished by CFD. The results showed that the average drying air temperature in the drying chamber depended on the initial air velocity. As the initial air velocity increased, the average drying air temperature in the drying chamber decreased. In addition, the average drying air temperature and air velocity in the drying chamber at the low initial inlet air velocity were more uniformly distributed compared to the higher initial inlet air velocity. Concerning the simulation results, it can generally be concluded that the simulated dryer conditions are appropriate for drying agricultural products and suitable for transferring to farmers in the community.

Index Terms - CFD Simulation; Agricultural products; Solar dryer

INTRODUCTION

The drying technique that is used has a significant impact on the quality of a product. The most common drying method is sun drying, which is traditionally practiced in many countries. This traditional method has the advantages of simplicity and low initial investment. However, it requires large areas and high labour costs. To improve the quality, traditional sun-drying techniques can be replaced by industrial drying methods such as spray dried [1-2], hot-air mechanical and solar drying. It has been reported in literature that work on solar and hot-air drying of agricultural food products has been carried out by many researchers [3]. For example, Limpaiboon and Wiriyaumpaiwong [4] dried steamed glutinous rice using a free convective solar dryer. They showed that a solar dryer provided a higher air temperature and higher drying rate than open sun drying. Tirawanichakul et al. [5] dried shrimp by using hot-air convection and hybrid infrared radiation/hot air convection. The results showed that the moisture content of shrimp decreased exponentially with drying time, while increasing drying temperature significantly affected the drying kinetics and quality of the shrimp. Meanwhile, Limpaiboon [6] dried pumpkin slice on a lab-scale using a tray dryer, which showed that the drying time decreased with increasing drying temperature, but increased with increasing pumpkin slice thickness. Moreover, Limpaiboon [7] studied dried bird's eye chilies in a convective hot-air dryer. The results showed that operating temperature enhanced the kinetics of the drying of chilies. The red bird's eye chilies dried at a lower temperature and had higher Hunter L (lightness), a^* (redness) and b^* (yellowness) values. The Wang and Singh model satisfactorily described the drying kinetics of chilies.

Drying is a processing technique used for food product preservation. Drying by solar energy is an ancient food preservation technique. Solar dryers of various sizes, capacities, and designs are available for drying applications in agricultural industries. An indirect type solar dryer (ITSD) is one of the prominent dryers used to dry food products. This type of dryer has unique features, types, and different techniques incorporated to improve its performance, though it has not been investigated so far in any detail [8]. A few recent works have developed solar drying models that are based on fundamental mathematical concepts. The application of computational fluid dynamics (CFD) models to solar drying systems has advanced over the last 15 years [9]. CFD models can be built on finite difference time domain (FDTD) or finite element analysis (FEA) models; the latter is proving to be more popular for the analysis of solar drying systems. In the FEA approach, the software program divides a two- or three-dimensional virtual object into discrete elements. The partial differential equations that describe heat, mass, and/or momentum balances are set up for each element; the resulting system of equations is solved by the software, and the results are visualized for the user.

CFD models can be categorised according to the scale of the fundamental geometry of interest: an individual piece of food being dried, a tray or other collection of food pieces, the cabinet of the dryer, or the entire dryer system. These models can also be categorised by the mode(s) of heat, mass, and momentum transfer that are included. Standard hot-air convection dryers can be modelled considering the conduction and convection modes of heat transfer. However, solar drying presents an added modelling challenge in that the radiation mode of heat transfer must also be included. Furthermore, radiative heating from the sun [W/m^2] is inherently time-varying, and the radiation that reaches the dryer collector and/or cabinet consists of both direct and scattered radiation. Gago and Mesa [10] designed a simulation of a solar dryer for dried botanical seeds of pastures and forages by using the SolidWorks software (2020 version). Moreover, Dhanushkodi et al. [11] constructed and experimentally tested a solar biomass hybrid dryer without any trays or any load. The temperature distribution of airflow inside the dryer was performed with SolidWorks 2020. The results might be acceptable when compared with the experimental value.

The use of CFD as a tool to manage the temperature and air velocity in the solar agricultural dryer chamber can be carried out to design a dryer system. The CFD is used as a tool to predict the temperature and airflow distribution in the drying chamber to obtain uniform drying. CFD has also been widely used in the food industry to investigate the flow pattern of the air in the drying chamber. Uniform temperature and airflow distribution in the drying chamber are very important because they have a significant effect on the efficiency and homogeneity of the products being dried. The objective of this research is to design a solar agricultural dryer for food and agricultural products.

MATERIALS AND METHODS

I. *Design of a solar agriculture dryer*

The wall of the dryer system will be constructed of a structure by galvanized steel welded together. The drying chamber dimensions are approximately 1.0 m x 2.0 m x 0.6 m in width, length and height, respectively. The solar collector dimensions are approximately 2.0 m x 2.0 m x 0.2 m in width, length and height, respectively, as shown in Table 1. The dryer system consists of 2 levels of the tray placed horizontally inside the drying chamber. All the walls of the drying chamber are made from poly M-PE Alu-Max insulation with 0.01 m thickness, which is covered by a thin sheet of galvanized metal except at the top of the drying chamber. The solar collector is covered with 0.002 m polycarbonate sheets. The drying chamber was drilled with a 0.05 m diameter hole on both sides, while the front of the solar collector has 2 holes with 0.08 m diameter to allow ambient air flow inlet. The layout of the drying chamber is shown in Figure 1.

Table 1. Design parameters of the solar agricultural dryer.

Parameters	Value (m)
Drying chamber	
Length (L)	2.0
Height (H)	0.6
Width (W)	1.0
Solar collector	
Length (L)	2.0
Height (H)	0.2
Width (W)	2.0

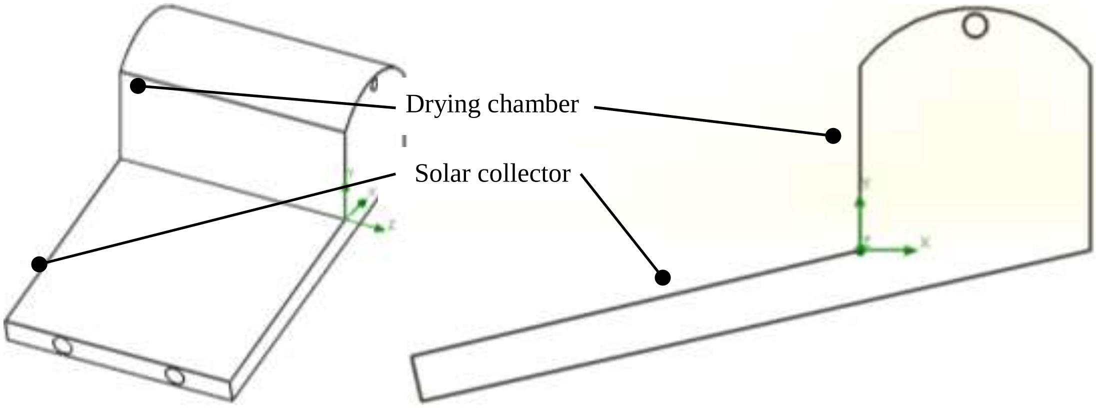


Figure 1. Illustration of the solar agricultural dryer.

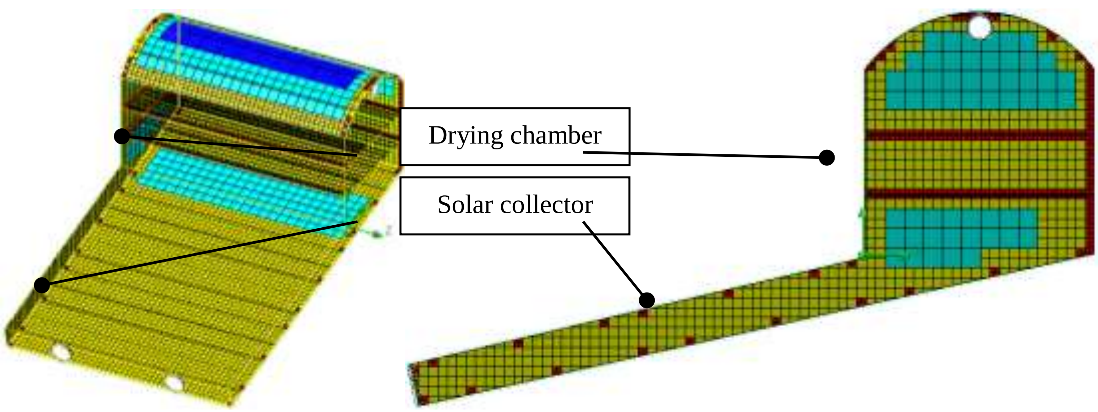


Figure 2. 3D model of the solar agricultural dryer.

II. Simulation details

A 3-D model of solar agricultural dryer geometry was created using SolidWorks software (2021 version) with an Intel(R) Core(TM) i5-7200U CPU, 64-bit Operating system, speed 2.5 GHz, 8.0 GB ram and 9.3 GB hard disk. Air velocity and temperature, a solar collector with a heat source at the bottom (for calculating the heat generated from the solar collector instead of the actual solar intensity) and boundary conditions are specified at models inlets and outlets. Time-dependent Reynolds-averaged 3D Navier-Stokes equations for flow simulation using SolidWorks involve the following procedure. A3D model of the solar agriculture dryer is shown in Figure 2. The following simulation procedures are used in this study.

The numerical finite volume method, as used in SolidWorks 2021, has been used for solving the equations. All the geometrical configurations are displayed in Figure 2. They were used to build up a numerical model based on an unstructured three-dimensional mesh by a tetrahedral cell of 47,946 (total cells) with global mesh settings resolution level 3 (mesh adaption was performed in the simulation until mesh independence is achieved). The simulation was carried out in the steady-state condition. The setup for initial and boundary conditions can be defined as follows: inlet air velocity of 0.3, 1.0 and 2.0 m/s (approximate air mass flow rate of 1.744, 5.816 and 11.631 kg/s, respectively), Outlet assuming gauge pressure is zero at the outlet, wall assuming with an adiabatic wall and roughness is zero were defined. The environment temperature is assumed to remain constant at 32^{o}C. Meanwhile, the bottom surface of the drying chamber and solar collector is assumed to have no heat loss.

RESULTS AND DISCUSSION

I. Simulation of the solar dryer without a heat source

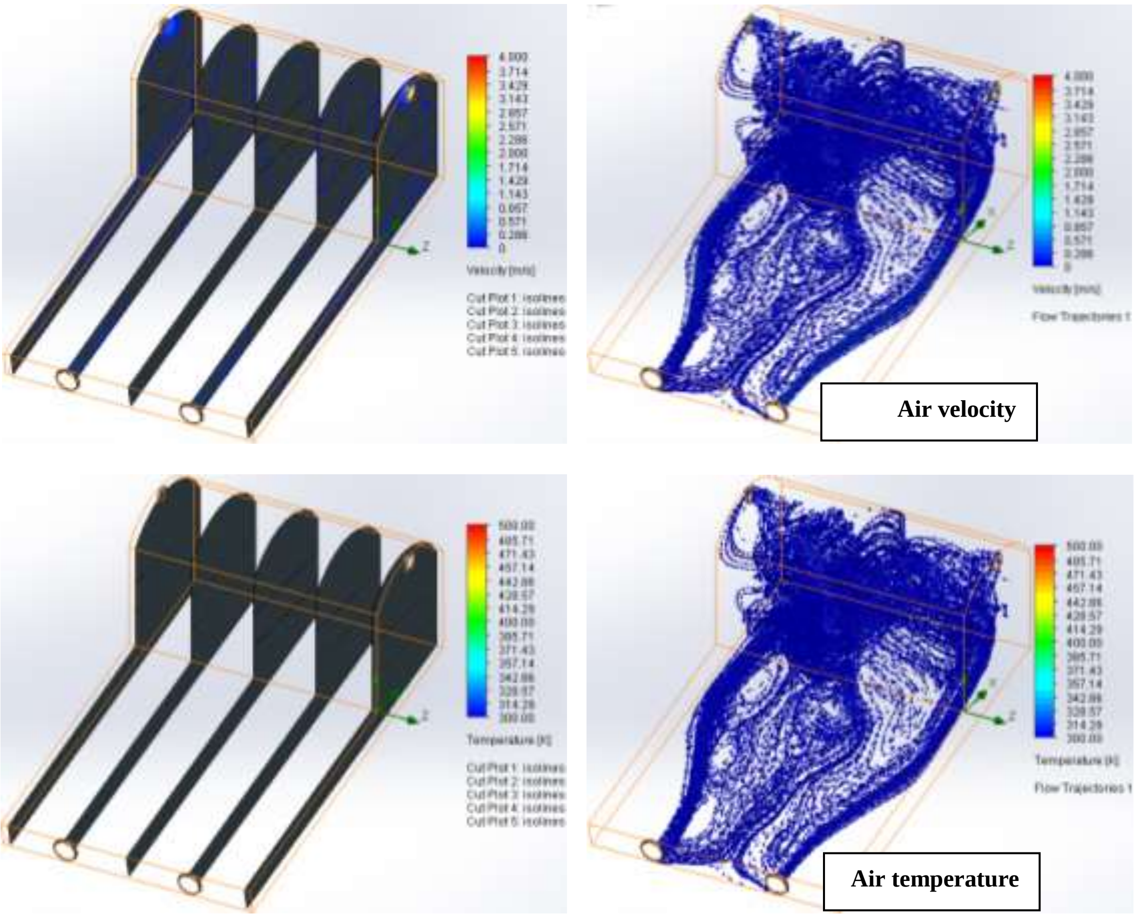


Figure 3. Distribution of air velocity and air temperature in the solar agriculture dryer at an inlet air velocity of 0.3 m/s without a heat source.

The simulation was carried out and the average air velocity distribution obtained from the drying chamber and solar collector without heat source at an initial inlet air velocity of 0.3, 1.0 and 2.0 m/s is presented in Figures 3 – 5. It can be seen that air enters the solar collector at an ambient temperature (the temperature at the solar collector and drying chamber of the dryer is equal to that of the ambient, this is because the heat source from the solar panel is not considered). Figure 3 shows a uniform motion of air movement pattern from the solar collector until it flows through the drying chamber and finally flows out through the holes on both sides of the drying chamber. Besides, the air stream distribution pattern does not spread to beside near the walls of both the solar collector and the drying chamber due to the initial inlet air velocity being as low as 0.3 m/s.

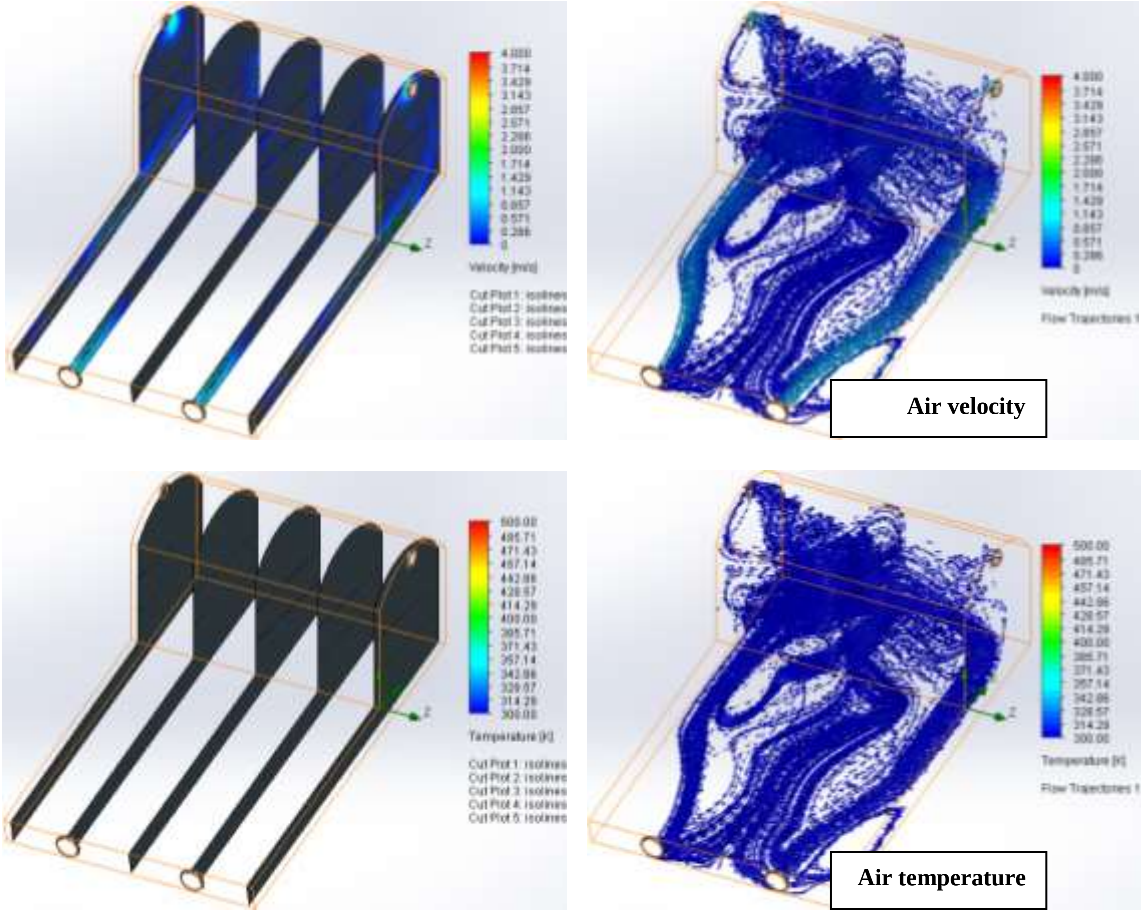
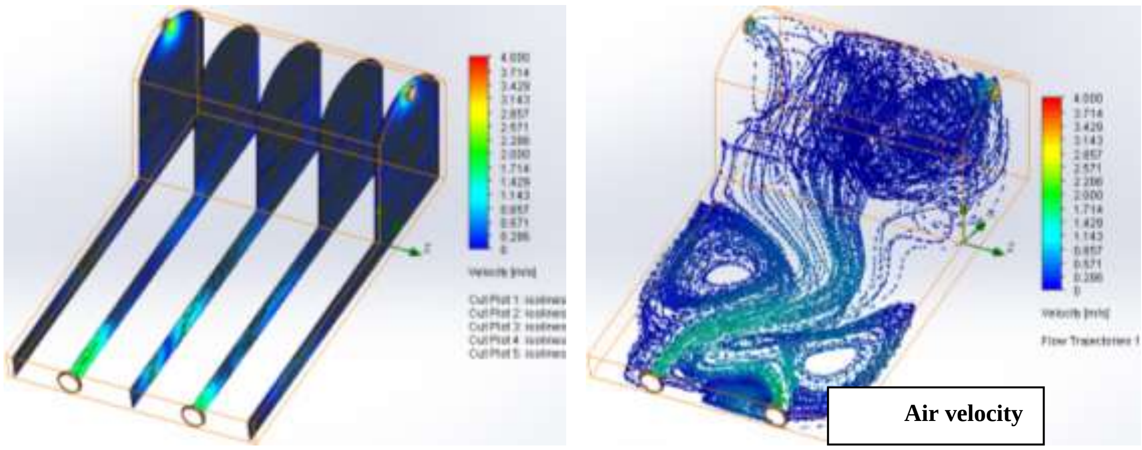


Figure 4. Distribution of air velocity and air temperature in the solar agriculture dryer at an inlet air velocity of 1.0 m/s without a heat source.

Considering that the initial inlet air velocity increases from 0.3 m/s to 1.0 m/s, the air stream distribution pattern in the solar collector and drying chambers increases. The distribution of air stream to the side of solar collector and drying chambers with a vortex of air occurs at the corner of the solar collector, as shown in Figure 4. When the initial inlet air velocity increases to 2.0 m/s, the air stream distribution is highly turbulent by dispersing in the solar collector and creating a clear air vortex. However, the air stream distribution pattern in the drying chamber is reduced due to the excessive air velocity (2.0 m/s), causing the air to move rapidly towards the outlet of the drying chamber, as shown in Figure 5. Likewise, Maia et al. [12] also used ANSYS to model an indirect hybrid type solar dryer. The results showed that velocity increased towards the exit section. It can also be observed that the velocity is homogeneous in a vertical plane in the solar collector and drying chamber, denoting a small turbulent Reynolds number flow in almost the entire drying section (approximately 9.0×10^3). In addition, they observed that a small velocity at the drying chamber centre, while in the last plane, located near the drying chamber exit the smaller velocity values are encountered at the walls.



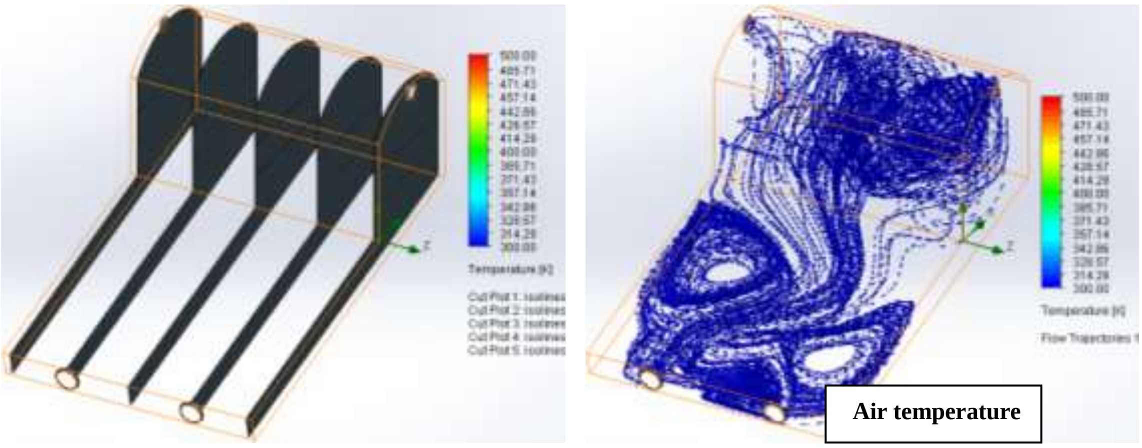


Figure 5. Distribution of air velocity and air temperature in the solar agriculture dryer at an inlet air velocity of 2.0 m/s without a heat source.

III. Simulation of the solar dryer with a heat source

The simulation was carried out and the average air velocity and temperature distribution pattern obtained from the drying chamber and solar collector with a constant heat source power of 5,000 W/m^2 of the solar collector (by placing the heat source on the inside surface at the bottom of the solar collector for calculating the heat generated from the solar collector instead of the actual solar intensity) at an initial inlet air velocity of 0.3, 1.0 and 2.0 m/s is presented in Figures 6 – 8. It can be seen that air enters the solar collector at an ambient temperature (the temperature at the solar collector and drying chamber is equal to that of the ambient of 32ºC at the start). Figure 6 shows the air movement pattern from the solar collector through the drying chamber and finally flows out through the holes on both sides of the drying chamber. An air stream distribution pattern does not spread to beside or near the walls of the solar collector, but most are gathered in the drying chamber due to the initial inlet air velocity being as low as 0.3 m/s. The result is that the air in the solar collector shows uniform heat transfer and then moves into the drying chamber up to the exit region. As expected, this recirculation region is formed by the buoyancy and forced convection effects, which are present in the flow at the same time. This be haviour of the temperature and velocity is desirable for dryer purposes since it guarantees a high-quality and homogeneous drying process [12].

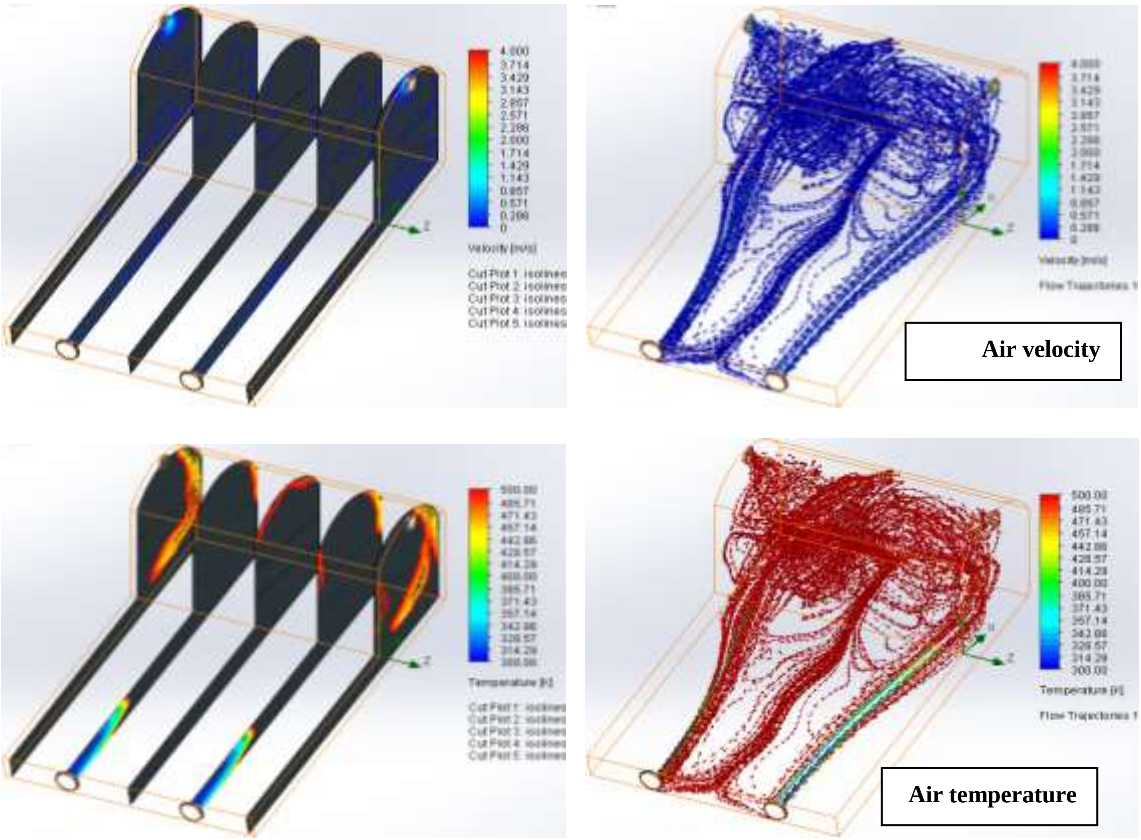


Figure 6. Distribution of air velocity and air temperature in the solar agriculture dryer at an inlet air velocity of 0.3 m/s with a heat source.

In Figure 7, it can be seen that the temperature pattern in the drying chamber is lower than that in the solar collector; it increases the initial inlet air velocity from 0.3 m/s to 1.0 m/s. It could be seen that the highest temperature is concentrated at the bottom of the solar collector due to the increased initial inlet air velocity; less heat transfer between the solar collector and airflow occurs. Therefore, the airstream temperature flowing through the drying chamber is lower than at low initial airspeed. As a result, the airstream flowing through the drying chamber has a lower temperature than at low initial inlet air velocity. Moreover, when the initial inlet air velocity is increased by 2.0 m/s, the heat source from the solar collector has no effect on producing hot air distribution. Even though the airflow pattern in the solar collector and drying chamber is extremely turbulent, as shown in Figure 8, which corresponds to Rigit and Low [13], who performed a simultaneous heat and mass transfer analysis of hybrid solar dryer was simulated to predict the optimum operating temperature and air velocity profiles for both natural and forced convection mode within the drying chamber during the drying process. It was found that the highest velocity was attained near the chimney outlet and the lowest was at the centre. The temperature profile of the drying system in natural convection conditions was shown to be higher than that of the forced convection mode. The natural convection condition provided more uniform heat distribution within the chamber due to the longer retention time of hot air inside.

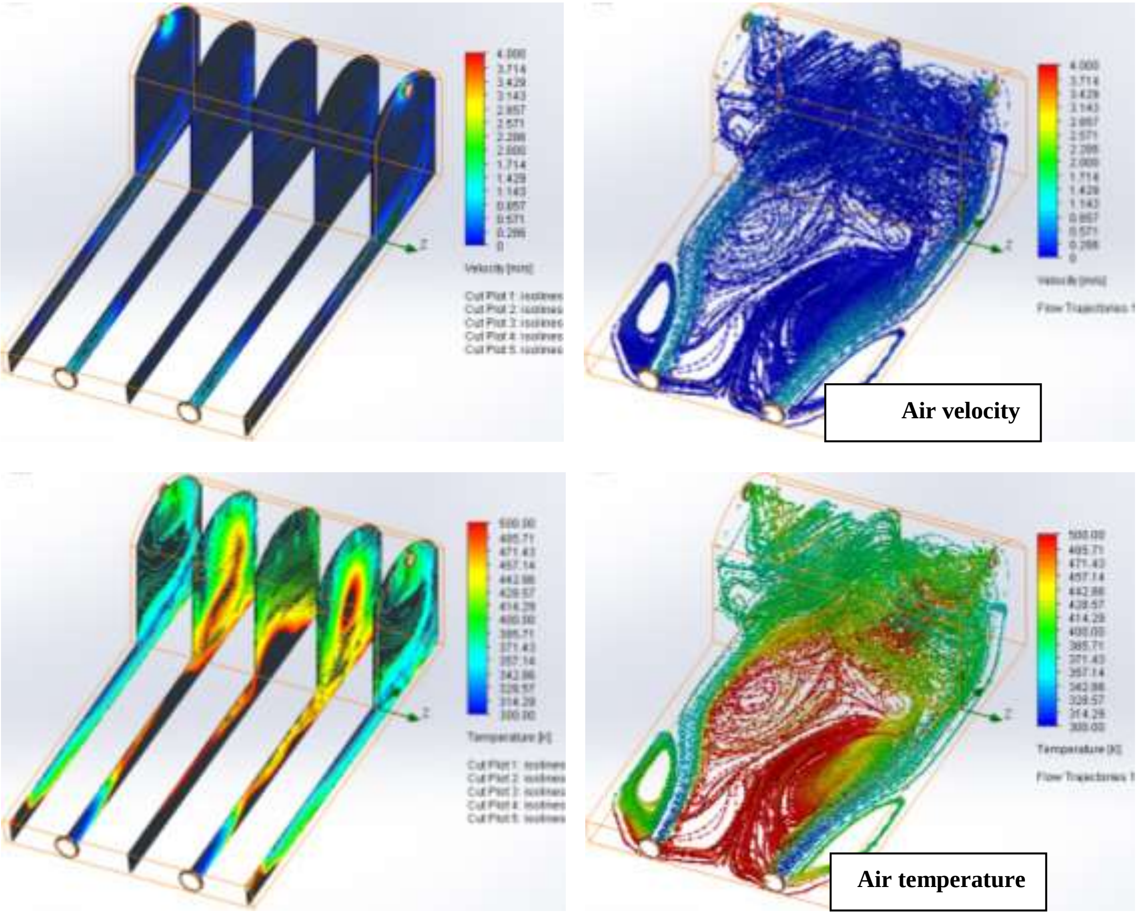
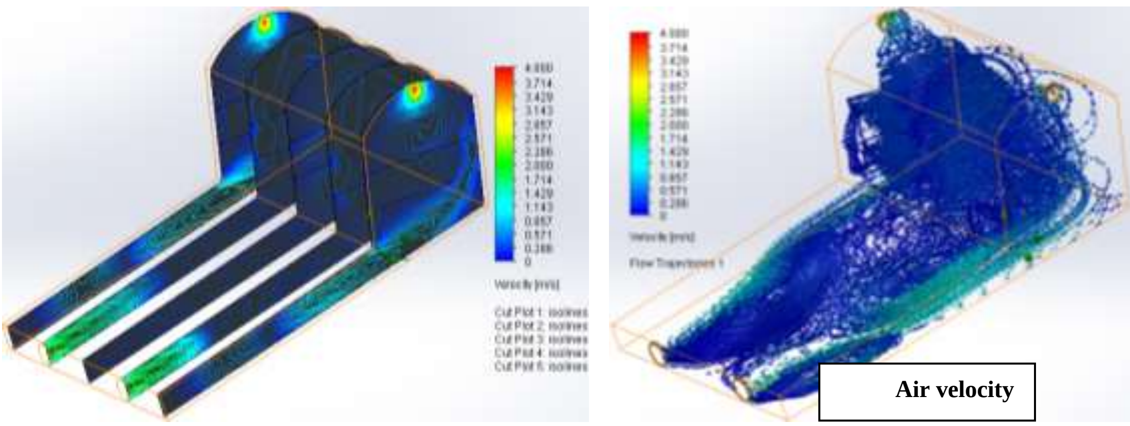


Figure 7. Distribution of air velocity and air temperature in the solar agriculture dryer at an inlet air velocity of 1.0 m/s with a heat source.



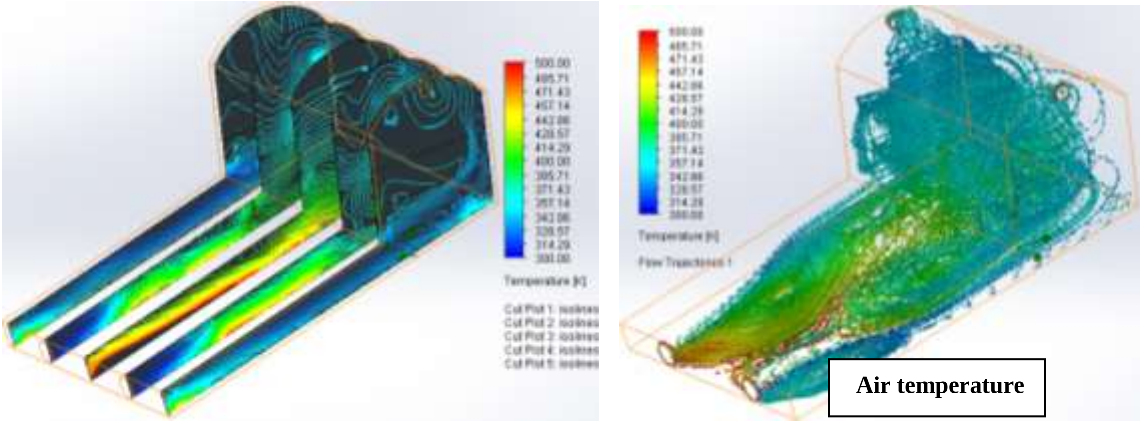


Figure 8. Distribution of air velocity and air temperature in the solar agriculture dryer at an inlet air velocity of 2.0 m/s with a heat source.

CONCLUSIONS

ACFD simulation of a solar agricultural dryer was performed, and air velocity flow and temperature distribution inside the dryer chamber were analysed. The computational domain considered was three-dimensional. The study focused on the effect of the initial inlet air velocity on the airflow and temperature distribution pattern inside the solar collector and drying chamber. It can be concluded that air distributions are more uniform when the initial inlet air velocity is low, whereas air distributions are extremely turbulent with higher initial inlet air velocity. While temperature distribution patterns are more uniform and have higher values when the initial inlet air velocity is low, whereas temperature distribution patterns are lower with higher initial inlet air velocity. The actual dryer will be developed in the future and experimental work will be conducted to validate the simulation data.

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