CFD Modelling and Simulation of an Indirect Forced Convection Solar Dryer

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Abstract. Solar dryer is a conventional device used for solar drying products. There are several types of solar dryers being employed for drying fruits and vegetables. In this research, the indirect type solar dryer is studied and computational fluid dynamics is employed to simulate the process. Ansys fluent CFD software is used to simulate and obtain dynamic and thermal performance of the dryer at different operating conditions (mass flow rate). The predicted results are validated with the help of experimental results. The average velocity at the exit of the collector was 2.89 m/s for 0.0872 kg/s mass flow rate, while for a mass flow rate of 0.0447 kg/s was 1.36 m/s. The maximum temperature at the collector outlet was 44.6°C and the maximum absorber plate temperature was 69.57°C for a magnitude of 0.0872 kg/s mass flow rate. The temperature profiles of the trays are also analysed and the tray closest to the collector is found to have the maximum average temperature. The results also revealed that CFD simulations are a reliable method to predict and design solar dryers.

1. Introduction
The depletion of natural resources of Earth, have made it necessary to shift towards the renewable resources alternative for the energy extraction purposes. Solar energy is one of the free, abundant renewable resources. It has several productive applications like concentrated solar power plants for generating high amounts of energy, while low energy generation devices like solar furnaces, solar dryers etc., are used. A solar dryer is a conventional device used to dry food products and vegetables to preserve and maintain the integrity for a longer period [1]. The fruits and vegetables are dried using direct or indirect solar irradiance. A flow of dry air is allowed to pass through a closed chamber containing the products, the moisture is extracted from the food product and a dry output is obtained. For increasing the efficiency and making the dryer operational at night and in all weather conditions, an integration is added with a secondary heater like an electric heater, biomass stove, etc. [2].

Solar dryer is preferred over the sun drying processes. The food product is placed in a closed chamber situated at a certain height, away from biological reactions, insects and dust [3]. In a solar dryer, depreciation in relative humidity content was observed while the drying temperature was increased, resulting in less moisture content [4]. The solar dryer application includes the drying of agricultural products and textile materials, dehydrating vegetables, preservation of dairy products, etc. [5]. Lingayat et al. (2020) [6] reviewed the different models of ITSD used for agricultural purposes. The dry air flowing through the solar dryer can be due to nature’s convection; in case of insufficient wind flow, a blower fan can be used to produce forced convection. A glass surface is present on the front side of the solar dryer to allow the solar radiation to penetrate the product and heat the inner part, and dry the outer cover; this amplifies the heat transfer process. The factors affecting the solar drying
operation include solar radiation absorptance, thermal conductivity of crops, and excessive temperature [1].

Solar dryers are broadly categorized into passive solar drying systems (natural air circulation) and active solar drying systems (forced air convection), which are further divided into direct, indirect, mixed, and hybrid solar dryers. Prakash et al. (2016) [5] have reviewed and discussed the numerous types of solar dryers and the development and condition of solar dryers in India. This includes the usage of solar panels for operating the fan to induce forced air flow, which operates entirely on solar resources. The pharmaceutical and nutritional value of any crop can be preserved by drying if a wide range of controllable parameters of drying are present [7].

Many studies have shown the experimental work on drying agricultural products like vegetables and fruits. Vijayan et al. (2020) [8] analyzed the environmental and exergy impact by constructing an active type indirect solar dryer for drying slices of food products like bitter gourd. The mass flow rate’s effect on solar dryer’s pickup and exergetic efficiency in drying slices of bitter gourd were calculated.

Lingayat et al. (2020) [9] developed an indirect type solar dryer and analyzed the drying kinetics of watermelon and apple. The results showed that overall thermal efficiency of the dryer came out to be 28.76% for watermelon and 25.39% for apple slices. The depreciation in the moisture content of apple slices was 5.361 kg/kg of db and 10.264 kg/kg of db (dry basis) for watermelon slices. Jiskani et al. (2020) [4] conducted the experiment on chilies and grapes using passive-direct type solar dryer and observed a reduction in the moisture content of around 75% in grapes & 85% in green chilies, while examining for 15 hours. Hamdi et al. (2018) [10] analyzed energy and exergy involved in drying tomatoes using solar greenhouse dryers. A reduction in moisture of around 19.91g water/g dry matter resulted in drying upto 48h and overall dryer efficiency 42%. Apart from the agricultural applications, solar dryers can dry different materials based on their absorptivity property. Luo et al. (2010) [11] did an experimental study on solar drying the ignite (brown coal) material and observed the characteristic property of the material. Direct type solar dryer was used. The results concluded that the optimal condition for the solar drying process requires a thin layer having small particles of material with high strength solar radiation.

![Figure 1. Detailed diagram of solar dryer setup [8]](image)

Computational fluid dynamics (CFD) develops a mathematical model based on the governing equations & boundary conditions and provides the numerical solution [12]. The 3D air flow field and temperature variation over the drying setup can be predicted by using the CFD analysis [13]. CFD analysis software develops the result contours and graphs by applying the boundary conditions on a
virtual model. It can help in optimizing the design and help researchers to analyze different characteristics of CFD simulation.

Jain et al. (2018) [14] developed a CAD model of a shelf direct solar dryer and simulated the drying process using ANSYS Fluent. The energy variation and heat flux contours were obtained and compared with the experimental work. M. et al. (2019) [15] analyzed the optimal shape of the roof for a greenhouse solar dryer. Different roof shapes (hemispherical, triangle, trapezoidal) were virtually designed and temperature variation was observed using the analysis software. Results showed that the trapezoidal shaped roof achieved the maximum temperature.

Meenakshi Reddy et al. (2018) [16] developed a solar crop dryer having a recovery mechanism of exhaust’s waste heat. The results were compared with the normal solar dryer and the flow field & temperature distribution within the solar dryer was demonstrated using CFD analysis. Moghimi et al. (2020) [17] proposed an optimal solar dryer design for household purposes. The experiment was conducted on a physically designed device, and the air flow and temperature contours were obtained by modeling and analyzing the design on the CFD software.

This current research work demonstrates the CFD simulation of active type indirect solar dryer operated at different mass flow rates. The tentative temperature distribution and flow field is simulated, which can help the researchers visualize different features of the indirect solar dryer. A brief review of solar dryer and the methodology involved in simulation is presented in this paper and the simulation results are compared with the experimental data provided by [8].

2. Design and material of solar dryer

The solar dryer’s design and construction require considering certain variables like solar irradiation, humidity and ambient temperature [18]. An active type indirect solar dryer was constructed by [8] at Coimbatore, India. The solar dryer consisted of a drying chamber having four trays at a specified distance on which the product was placed. Figure 1 shows the experimental setup of an active type indirect solar dryer with different parts annotated separately. The air flow is transferred by the blower fan, which gets heated up by solar radiations while traveling through the collector and is released through the chimney, drying the products in the drying chamber.

| Table 1. Solar dryer’s component dimensions & materials |
|------------------------------------------------------|
| S. No. | Component | Material | Dimensions (lxbxh) |
|--------|-----------|----------|--------------------|
| 1       | Drying Chamber | Galvanized iron | 750×750×1050 |
| 2       | Flat plate collector | - | 2000×1000×150 |
| 3       | Tray ×4 | Aluminium | 750×750×1.2 |
| 4       | Corrugated absorber plate | Galvanized iron sheet | 2000×1000×6 |
| 5       | Window glass cover | Glass | 2000×1000×4 |
| 6       | Glass wool insulation | Glass wool | 25 mm thick |
| 7       | Chimney | Galvanized iron | 150 mm diameter |
| 8       | Convergent section | Galvanized iron | 1000×400×60 |

The tray’s area was 0.5625 m², placed at a distance of 0.2m from each other. For ensuring maximum collection of solar radiations, the collector was aligned to 11° to the horizontal, in the latitude’s direction of the corresponding area. For reducing the heat losses due to convection and conduction, insulation of glass wool is provided in the whole setup.
The setup is shown in Figure 2 (a) was developed as a CAD model in Solidworks 2020. All the solar dryer parts were developed and assembled separately according to the dimensions given in (Table 1). The collector and drying chamber consisting of four trays were designed and connected with a convergent part. The drying chamber consisted of a vent at the top, which acts as the chimney outlet and an inlet vent was provided at the opening of the collector part.

![Figure 2](image)

**Figure 2.** (a) solar dryer’s 3D CAD model developed in Solidworks 2020; (b) refined mesh generated on the symmetric solid model.

3. Simulation

3.1. Methodology

Simulating a model on ANSYS, requires the implementation of correct governing equations and applying appropriate boundary conditions. In CFD, a finite volume method is used to resolve the governing equations of flowing fluid. This method involves dividing the flow domain into several control volumes and applying the fundamental laws of conservation on them [19].

For determining the characteristic properties of the fluid domain, several conservation laws are considered. The laws involved are stated below [13]:

Continuity equation: \( \frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0 \) \hspace{1cm} (1)

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

Energy conservation equation: \( \frac{\partial}{\partial t} (\rho E) + \nabla \cdot (\mathbf{v}(\rho E + p)) = 0 \) \hspace{1cm} (3)

where ‘\( \rho \)’ is the fluid’s density, ‘\( \mathbf{v} \)’ is the velocity with which the fluid flows, ‘\( \rho g \)’ is the gravitational force, ‘\( F \)’ being the external force applied, static pressure is represented by ‘\( p \)’ and ‘\( E \)’ is the fluid’s total energy.

CFD is applied to determine the airflow and temperature variation within the solar dryer. A mathematical model is generated by providing the necessary boundary conditions, and result data and contours are obtained. The flow of the CFD simulation process is depicted (Figure 3).

![Figure 3](image)

**Figure 3.** Flowchart representing CFD simulation process [14]
3.2. Meshing

Meshing is done for calculating the governing equations at the required points and defining the domain. To simulate the result on the analysis software, a refined tetrahedral shaped mesh with 120649 nodes and 621106 elements were generated over the completely assembled solid model [Figure 2(b)].

3.3. Simulation setup

For conducting simulation on ANSYS all the prerequisite information of the boundary conditions and variables should be known. As this study is demonstrating the simulation of experimental work presented by [8], the conditions are analyzed before setting up the model.

The solar dryer setup was constructed in Coimbatore Institute of Engineering and Technology, India, with latitude and longitude as 11.028831373336152 and 77.0272806. A realizable k-ε model was selected to carry out turbulent computation as it produces accurate and satisfactory results. Similarly, energy equations were also turned on to account for thermal calculations. The conditions were applied considering 1300 hours of the day at the experiment location, which corresponded to maximum solar insolation of 996 W/m² and the ambient temperature of 32°C. The simulations were carried out for the mass flow rate of 0.0872, 0.0636, and 0.0447 kg/s.

| Region      | Boundary condition | Value         |
|-------------|--------------------|---------------|
| Inlet       | Mass flow-inlet    | 0.0872 kg/s   |
| Walls       | No-slip, convection| 5 W/m²        |
| Absorber plate | Heat flux      | 996 W/m²     |
| Outlet      | Pressure-outlet    | 0 Pa          |
| Ambient temperature | -               | 32°C         |

4. Results and Discussions

The airflow velocity contours for the maximum mass flow rate are depicted in Figure 4(a) on the symmetry plane. It shows the novel design of ITSD to supply drying airflow in the dryer chamber. Figure 5 shows the velocity streamlines of the air flowing within the model. It is evident that the airflow travels smoothly through the collector before passing through the convergent passage and speeding up the flow. The porous aluminium trays with the agricultural products act as a barrier for the airflow and drastically slows it down. It is evident from Figure 4(a) that after passing through tray 1 the air velocity is reduced drastically. The airflow then speeds up again after passing through tray 4 to exit through the chimney. The average velocity at the collector's exit for 0.0872 kg/s mass flow rate is calculated at 2.89 m/s, while for a mass flow rate of 0.0447 (Figure 4(b)) is 1.36 m/s. From the experimental work carried out by [8], the average velocity at the exit of the collector was recorded as 3.09 m/s and 1.58 m/s for the mass flow rate of 0.0872 kg/s and 0.0447 kg/s, respectively. This helps to validate the results obtained from simulations with experimental results.
Figure 4. (a) Velocity contour corresponding to 0.0872 kg/s rate (b) Velocity contour for mass flow rate of 0.0447 kg/s.

Figure 5. Velocity streamlines.

Utilizing and providing the right amount of heat to the dryer chamber is very important for an efficient ITSD. Figure 6 shows the temperature contours on the symmetry plane for different values of mass flow rates. It is evident that as the wind velocity is increased, a depreciation in the temperature in the collector and dryer chamber is observed (Figure 7). This trend is observed because as the velocity increases, the airflow has less time to absorb heat from the absorber plate and increase its temperature. The maximum collector outlet temperature and the maximum absorber plate temperature for the 0.0872 kg/s mass flow rate was observed as 44.6°C and 69.57°C, respectively (Figure 6(a)), which also helps to verify the simulation results (Figure 8). Table 3 represents the variation in velocity & temperature at collector outlet and absorber plate with different mass flow rates input.

Table 3. CFD simulation results corresponding to different mass flow rate

| Mass flow rate of air (kg/s) | Average velocity at the outlet of collector (m/s) | Maximum absorber plate temperature (°C) | Maximum collector outlet temperature (°C) |
|-----------------------------|-----------------------------------------------|----------------------------------------|----------------------------------------|
| 0.0872                      | 2.89                                          | 69.57                                  | 44.6                                   |
| 0.0636                      | 2.12                                          | 73.72                                  | 46.2                                   |
| 0.0447                      | 1.36                                          | 76.02                                  | 48.5                                   |
Figure 6. Temperature contours for various inlet mass flow rates (a) Flow rate = 0.0872 kg/s; (b) Flow rate = 0.0636 kg/s; (c) Flow rate = 0.0447 kg/s.

Figure 7. Average temperature rise for different air mass flow rates.

Figure 8. Solar insolation and temperature of several elements [8].

Figure 9. Pressure contour for inlet mass flow rate of 0.0872 kg/s

Figure 7 shows the comparative graph plot between the CFD simulation and the experimental results conducted by [8]. The results gained from the simulation resemble the experimental results. From gauge pressure contours as evident from Figure 9, it can be concurred that the pressure remains more or less the same inside the dryer chamber. Figure 10 displays the temperature contours of the 4 trays in
the dryer chamber. As evident from the figure, tray 1 (bottom most) temperature is maximum since it is the first tray to interact with the high temperature airflow from the collector. After passing the first tray, a considerable amount of heat is absorbed by the agricultural products, and the tray itself obstructs some flow. Therefore, the trend of lower temperature for higher placed trays is observed. The average temperature of tray 2 is considerably lower than tray 1 and trays 3 and 4 are at lower values than tray 2. Figure 11 shows the temperature distribution in four trays, corresponding to different mass flow rates.

![Image of temperature contours](image.png)

**Figure 10.** Temperature contours of trays developed at 0.0872 kg/s mass flow rate.

![Image of temperature distribution](image.png)

**Figure 11.** Average temperature of trays developed at different mass flow rates.

### 5. Conclusion

A CFD modelling and simulation on an active type indirect solar dryer was attempted. The temperature variation and flow velocity at different mass flow rates (0.0872, 0.0636 & 0.0447 kg/s) were predicted and compared with the experimental data. The velocity contours and streamlines were obtained and the results showed that the average velocity at the exit of the collector was 2.89 m/s for 0.0872 kg/s mass flow rate, while for a mass flow rate of 0.0447 kg/s was 1.36 m/s. The maximum collector outlet temperature was 44.6°C and the maximum absorber plate temperature 69.57°C for 0.0872kg/s mass flow rate. The average temperature rise difference was around 4°C for the two flow rates (0.0872 & 0.0447 kg/s). The temperature contours in the trays were analysed and it was observed that the bottom most tray attained the maximum temperature, while the uppermost tray had the lowest temperature. The CFD simulation provided an insightful output of the temperature distribution and velocity profile within the solar dryer.

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