Analysis of temperature and velocity distributions in a solar drying box coffee beans

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Abstract. In this study the fluid flow and velocity distribution in a solar drying box which is used to dry coffee beans are studied numerically. The solar box receives the hot air from flat-plate collector. The hot air is flowed by using an electric fan which is powered by a photovoltaic. The objective of this study is to explore the temperature and velocity distributions in the box. The dimension of the drying box is 100 cm \times 90 cm \times 50 cm. Several experimental are carried out. The experimental results are used as boundary value in the numerical simulation. The commercial code CFD is used to perform the analysis. The results show that the temperature of the hot air entering the solar drying box varies from 29.29\degree C (at 9.00 AM) to 59.98\degree C (at 14.00 PM). By using these data, the numerical simulations are carried out. The temperature and velocity distributions are plotted and discussed. It is recommended to use the results to design an optimum solar drying box.

1. Introduction

The cabinet drying system is the most popular equipment for drying fruit and agricultural products [1]. A drying system with a cabinet or shelf is the most favorite equipment used in drying fruit including coffee beans. Because these dryers are simple in structure, low-cost installation and can be used in almost any environmental condition. Non-uniformity in the moisture content of the final product is the inherent weakness in applying the dryer cabinet then the manufacturer is usually not interested in utilizing this drying system [2]. The dehydration rate of decreasing moisture content indicates a very strong relationship with drying air temperature and airflow velocity [3]. The uniform air flow distribution in the dryer is important because it determines the efficiency and homogeneity of the dried product [4]. To control all experimental parameters on drying is often tedious and difficult. There are two methodologies usually used to analyze drying cabinet. They are experimental method and numerical one by using computational fluid dynamics technique. In fact, experimental method can’t be replaced by fluid dynamics computational techniques (CFD), but it can reduce the amount of time required for experimental work. The CFD is able to analyze the flow patterns of the air performance system in a short span of time, which was previously impossible from...
the experimental and theoretical methods [5]. Computational fluid dynamics (CFDs) have been widely used to predict airspeed and temperature in drying chambers. With the development of low cost needs, powerful computers, and commercial software packages such as Current, Star-CD and CFX in the past decade, CFDs have been increasingly deployed in the food and agricultural products industry [6].

Indonesia has a big potency of solar radiation and it is suitable as an energy source for drying agricultural product [7]. Authors are developing continuous solar drier that suitable for agricultural products. A prototype continuous solar drier has been tested for drying cocoa [8]. It was shown that the drying time can be reduced and the quality was better in comparison with forced convection drying and direct sun drying. In this work, we develop a solar drier for coffee beans. Siagian et al [9] have been reported a survey on the drying methods of coffee beans in Indonesia small holder farmers. It was reveled that the drying methods need to be improved. In order to provide a better design of drying cabinet of solar drier for coffee, CFD tool is applied. This is the focus of the present work. The main objectives of this research are: to know the flow characteristics and temperature distribution in CFD based coffee driers. The results are expected to supply the necessary information on development of continuous solar drier for coffee beans.

2. Methods
A drying box has been designed and fabricated. The schematic diagram of the drying box is shown in Figure 1. The drier consists of drying chamber, solar thermal collector and Photovoltaic. The racks are placed in the drying chamber. The thermal solar collector is a flat-plate collector. In order to circulate drying air a blower is employed. It is powered by using photovoltaic.

![Figure 1. Schematic of drying box and heat source system.](image)

The drying box is made of several layers of the outermost layer insulating material composed of a 3.5mm zinc plate, 30mm Styrofoam, 3.5mm Aluminum plate and the deepest
layer of Aluminum foil. Shelves of coffee beans consist of lower shelf and upper shelf. Each shelf is hung with a distance of 30cm each. The hot air stream sourced from the solar collector is passed into the dryer through a flexible aluminum pipe. The heat is flowed with fan at a constant speed of 1m/s. Hot conditions in the box are measured with a thermocouple device so that the data temperature data present in the box can be known every minute and stored in the data logger.

2.1. Governing equations
In the CFD method, the governing equations are solved iteratively. The governing equations consists of continuity, momentum and energy equations. Since the flow is assumed to be turbulent, $k$-epsilon model is employed. The transport equation for $k$ is derived from the exact equation, whereas the transport equation for $\varepsilon$ is obtained by using physical reasoning and has little resemblance to its precise mathematical counterpart. The turbulent kinetic energy, $k$ and the dissipation rate $\varepsilon$ are obtained from the following transport equations.

\[
\frac{\partial}{\partial t}(G\rho k) + \frac{\partial}{\partial x_i}(\rho ku_i) = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_k}\right) \frac{\partial k}{\partial x_j}\right] + G_k + G_b - \rho \varepsilon - Y_M + S_k \tag{1}
\]

\[
\frac{\partial}{\partial t}(\rho \varepsilon) + \frac{\partial}{\partial x_i}(\rho \varepsilon u_i) = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_\varepsilon}\right) \frac{\partial \varepsilon}{\partial x_j}\right] + C_{\varepsilon}\varepsilon \left(G_k + C_{\varepsilon}G_b\right) - C_{\varepsilon}^{\prime}\varepsilon^2 + S_\varepsilon \tag{2}
\]

The governing equation for heat convection and mass transfer in the $k$-epsilon model is given by the below equation.

\[
\frac{\partial}{\partial t}(\rho E) + \frac{\partial}{\partial x_i}(\rho E u_i) = \frac{\partial}{\partial x_j}\left[\left(k + \frac{c_p \mu_t}{Pr_t}\right) \frac{\partial T}{\partial x_j} + \mu_t \left(\tau_{ij}\right)_{ij} + S_h\right] \tag{3}
\]

2.2. Meshing
Domains are discredited with unstructured tetrahedral mesh elements using ANSYS Meshing. After the test results obtained mesh with Nodes 43192 and Element 188491 has ensured the state of the results for geometry and without the distance of each buffle.

The source of heat coming from the solar collector is fed into the box ranging from at 9 am to 5 pm. The fan works to flow heat through 2 pieces of channel on the left and right with a constant speed of $1\text{m/s}^2$. The power source to drive the fan is sourced from Potovoltaic. The constant heat flow rate is expected to distribute the heat more uniformly and evenly across the drying chamber.
Figure 2. Meshing of the computational domain

3. Results and Discussions
Several experiments have been carried out by exposing the solar drier with solar irradiation at Medan city of Indonesia. The location of the experiment is at coordinate 3°34' North and 98°40' East.

3.1. Solar Irradiation
Solar radiation is measured by thermocouples for 8 hours continuously. The temperature in the dryer box is measured at several points as in Table 1.

Table 1. Time and Temperature in dryers.

| Time (hour) | Bottom Rack (°C) | Door Box (°C) | Top Rack (°C) | Air tunnel left (°C) | Chimney (°C) | Wall rack bottom (°C) | Wall rack Top (°C) | Air funnel Right (°C) |
|-------------|------------------|--------------|--------------|---------------------|-------------|-----------------------|-------------------|---------------------|
| 09.00       | 28.82            | 31.80        | 27.03        | 32.29               | 29.15       | 28.07                 | 30.55             | 31.86               |
| 09.30       | 32.83            | 34.20        | 29.24        | 36.53               | 34.70       | 33.76                 | 35.59             | 36.12               |
| 10.00       | 36.69            | 38.48        | 30.65        | 45.95               | 40.14       | 37.78                 | 43.21             | 43.58               |
| 10.30       | 41.79            | 43.64        | 32.38        | 52.47               | 45.67       | 42.92                 | 49.05             | 50.80               |
| 11.00       | 43.28            | 44.43        | 32.28        | 54.89               | 46.13       | 46.19                 | 50.38             | 52.88               |
| 11.30       | 46.94            | 48.76        | 41.54        | 56.09               | 51.23       | 48.60                 | 52.31             | 57.78               |
| 12.05       | 48.17            | 48.05        | 40.39        | 53.01               | 49.88       | 49.00                 | 49.97             | 52.01               |
| 12.30       | 47.84            | 50.53        | 42.84        | 59.18               | 52.81       | 49.03                 | 51.59             | 58.81               |
| 13.00       | 46.21            | 48.30        | 42.84        | 56.62               | 50.42       | 46.32                 | 48.44             | 56.14               |
| 13.30       | 45.23            | 49.96        | 43.18        | 56.03               | 51.83       | 47.34                 | 49.87             | 58.37               |
| 14.00       | 28.82            | 52.30        | 43.64        | 59.98               | 54.35       | 48.90                 | 51.81             | 62.79               |
| 14.30       | 38.56            | 48.12        | 41.17        | 49.57               | 49.18       | 47.71                 | 48.41             | 52.27               |
| 15.00       | 31.66            | 47.83        | 39.78        | 51.38               | 48.93       | 44.94                 | 46.63             | 55.93               |
The flow kinetics and the magnitude of the temperature are discussed by using the ratio of the magnitude of the temperature to time, the magnitude of the temperature entering the drying chamber through the right and left air ducts with the exhaust flue at the top of the dryer box to the wasted temperature through the chimney shown in figure 3. At 09.00 the temperature on the incoming air funnel of 31.33°C continues to increase until at 14.00 reaches a maximum of 62.79°C and gradually decline up to 17.00 at 37.86°C. At the funnel portion the remaining air condition from the initial temperature of 32.29°C increased steadily to 59.98°C at 14.00 and gradually decreased to 37.10°C at 17:00 or the initial average of the temperature at 09.00 was 31.8°C and the maximum at 14.00 of 61.38°C and decreased until 17:00 at 37.57°C. At the sewer funnel, at 9.00 the initial temperature of 29.15°C gradually rises up to a maximum temperature of 54.67°C at 14.10. The highest efficiency of the temperature occurring in the drying box when distributed in the dryer box is 91.14%. These facts suggest that the solar drier system works perfectly. The system can provide hot drying air in the drying chamber. The high drying air will provide sufficient energy to overcome latent heat for evaporation. Thus, the moist content of the object dried will decrease. The evaporation on the surface of the object will drive mass transfer from the inner of the object to the surface. After the moist is evaporated, the drying air need to be replaced by using the new hot fresh air.

![Temperature history in the drier box](image-url)
3.2. *Fluid Flow Characteristics*

Figure 4 shows velocity vector in the drying chamber. It consists of three-dimensional view and two-dimensional view. It can be seen the fresh air entering from the bottom of the drying chamber. It will follow the flow passage within the drying chamber. The minimum and maximum value in the computational domain is 36°C and 60°C, respectively.

![Image](figure4.png)

**Figure 4.** Temperature distribution in the drying chamber

Figure 5 shows the path line within the drying chamber. The flow direction and distribution can be examined using this path line.

![Image](figure5.png)

**Figure 5.** Pathline in the drying chamber
4. Conclusions
The heat generated from the solar collector enters through the left and right funnel from the dryer box. The flow conditions occur horizontally or laminar constant conditions moving continuously to touch the vertical wall of the box with a temperature of 48°C (3210 K) up to 54°C (3270 K). The flow rotates upward and partially exits through the chimney on the section with a temperature of 54.67°C (327.6 K). On the bottom shelf it is seen that the higher temperature content of the upper shelf at the beginning of the hot flow moves. The larger inlet coming from the solar collector is partially discharged through the upper chimney which over time tends to become uniform because turbulent flow occurs with a continuous flow rate of 1 m/s. The flow direction that occurs initially follows the contour of the drying box so that the longer the heat is evenly distributed due to the turbulent flow in the center position of the box. Due to the turbulent flow that occurs around the box, the temperature is distributed evenly toward the bottom shelf and upper shelf.

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