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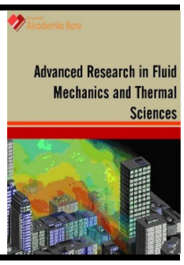

A Study of Drying Uniformity in a New Design of Tray Dryer

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ABSTRACT

Application of tray dryer is widely used in agricultural drying because of its simple design and capability to dry products at high volume. However, the greatest drawback of the tray dryer is uneven drying because of poor airflow distribution in the drying chamber. This study investigates kenaf core drying uniformity in a tray dryer through Computational Fluid Dynamics (CFD) simulation. The simulation focused on air velocity above the products and was conducted under steady state condition to simplify the analysis. The experimental and simulation data exhibit very good agreement. The drying rate of dried products in each tray predicted based on average air velocity from the simulation. The result shows that, the higher the air velocity, the higher the drying rate of the products. The alternate arrangement of tray position adopted to ensure that all trays are exposed directly to drying air and to improve airflow distribution in drying chamber. There was a variation of final moisture content for product at different columns. However, the uniformity of air flow distribution to each level of product at the same column are acceptable. Drying using semi-continuous mode was recommended to improve drying time and uniformity.

1. Introduction

Tray dryers are the most widely used dryers for various drying applications because of their simple design and low cost. The variation of the final moisture content of the dried product at different tray positions commonly encountered because of poor airflow distribution [1]. Generally, drying air temperature and velocity significantly affect drying rate [2]. Computational Fluid Dynamics (CFD) simulation is used extensively in drying analysis because of its ability to solve systems of differential equations for the conservation of mass, momentum, and energy with the use of advanced numerical methods to predict temperature, velocity, and pressure profiles in the drying chamber.

Mathioulakis *et al.,* [3] developed an industrial batch-type tray dryer for drying fruits. They used CFD simulation to predict the air velocity profiles in the drying chamber and found that the final

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moisture content in several trays was not uniform. Margaris and Ghious [4] studied the numerical simulation inside a drying chamber. A set of measurements was obtained experimentally above a single tray to validate the model. The validation of the measured data and the simulation results through CFD showed that the standard k–e model is the most adequate turbulence model. Tzempelikos *et al.,* [5] predicted the three dimensional (3D) flow problem through the solution of the steady-state incompressible, Reynolds-Averaged Navier-Stokes (RANS) equations with the incorporation of the standard k-ε turbulence model.

Kenaf application is an alternative for wood-based application. In producing the kenaf fiber, it need to be dried. The drying kinetic of thin layered kenaf core at different drying conditions has been studied by Misha *et al.,* [6], who found that the Two-Term model is the best model in describing the drying curves of the kenaf core. This study aims to design and evaluate an industrial-scale tray dryer for chipped kenaf core. CFD is used to predict airflow distribution in the drying chamber to study drying uniformity. Uniform airflow distribution in a drying chamber is very important because it strongly influences dryer efficiency and the homogeneity of the products being dried [7]. CFD also has been extensively used in the food industry to investigate the airflow pattern in drying chambers [8,9].

2. Method and Simulation

The industrial scale of solar assisted solid desiccant dryer was designed and developed to investigate system performance and drying uniformity in the drying chamber. The experiment setup has been discussed by Misha *et al.,* [10]. The design of the drying chamber is shown in Figure 1, and includes seven layers of trays, with each layer comprising six trays with dimensions of 64 cm x 92 cm each, for a total of 42 trays. When viewed from the side, only 21 trays are visible, with the remainder visible on the other side. The drying chamber is designed symmetrically from the top view.

The sensors are installed only at the right side, assuming that values from the left side are the same, owing to this symmetry. The volume of the drying chamber is 1.7 m (height) x 2 m (width) x 3 m (length). The wall of the dryer system constructed using 6-cm thick hollow polycarbonate with a hollow space in the middle, 4 cm deep. The top roof is made of glass. The middle trays positioned between the trays in the first and third columns. This tray arrangement adopted to ensure that all trays exposed directly to drying air and to improve airflow distribution throughout the drying chamber. The position of trays in existing tray dryer are at the same height for each column of tray. The second column of tray blocked by the first column of tray and produce poor air flow distribution for existing design.

Five random positions (A10 to A14) in the drying chamber, inlet (A4) and outlet (A5) of the drying chamber were selected to be installed with velocity, temperature and humidity sensors, as shown in Figure 2. The load cell installed to trays number 4, 9, 11, 13, and 18 to monitor weight loss. The actual picture of drying chamber and dryer system as shown in Figure 3. The kenaf core fiber was supplied by Lembaga Kenaf and Tembakau Negara (LKTN). The sample of the kenaf core fiber is a very light material with a density of approximately 100 kg/m3. The total weight of the sample in all trays is approximately 155 kg. The core fiber is dried without the outer layer and was chipped. The thickness of the product on the tray is approximately 6 cm. The initial moisture content was determined by oven-drying at 105 °C until constant weight was obtained [11]. The average initial moisture content of the sample was approximately 55% wet basis.

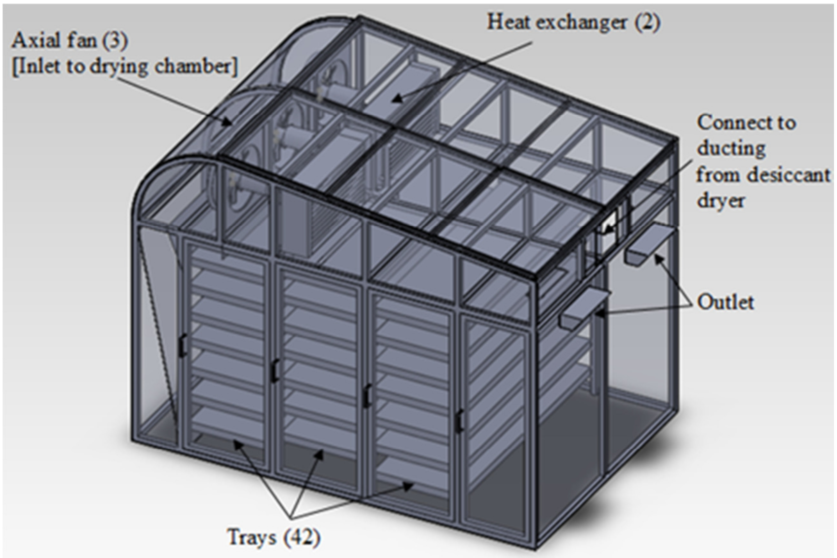

Fig. 1. Drying chamber design

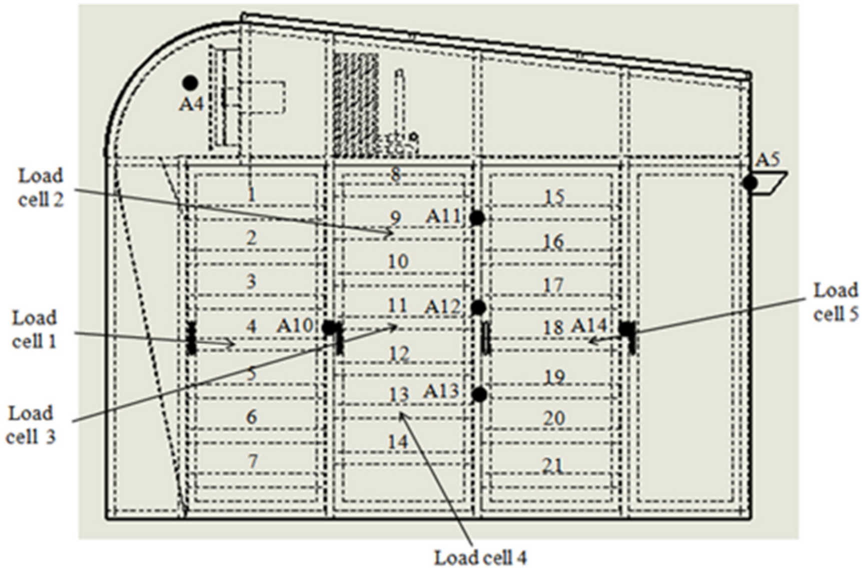

Fig. 2. Sensors position

The boundary conditions are shown in Figure 4. The boundary conditions were set up as follows.

- Inlet 1: The air mass flow rate was 0.29 kg/s (approximate velocity of 1.5 m/s normal to air inlet), and the air temperature was 56 °C.
- Inlet 2: The air mass flow rate was 0.145 kg/s (50% of inlet 1 but has the same velocity of 1.5 m/s), and the air temperature was 56 °C.
- Outlet: The gauge pressure was assumed to be equal to 0 at the outlet.
- Porous media: The trays were assumed to be porous with 10% porosity.
- Wall: The heat transfer coefficient of the chamber wall is 4 W/(m^2K) and environmental conditions were defined. The environmental temperature was assumed to be 34 °C.

Fig. 3. Drying chamber and dryer system

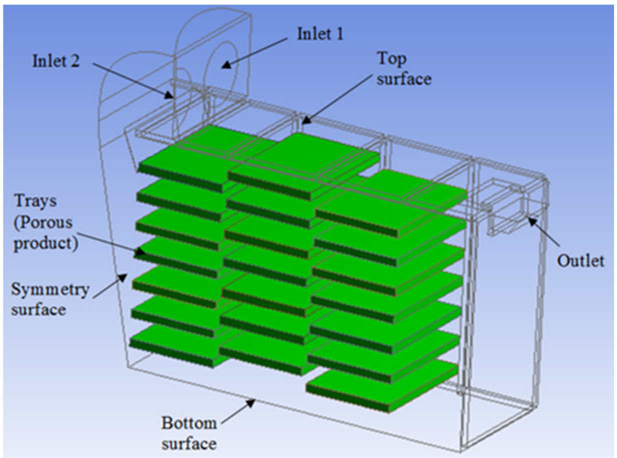

Fig. 4. Boundary condition

3. Results and Discussion

3.1 Drying Experiment

The drying experiment conducted in one days with average solar radiation of 834 W/m^2. The drying was begun at approximately 10.30 am and was stopped at 2.15 pm. The experiment stopped when the samples in first column of samples achieved moisture content below 15% wet basis. Actually, the experiment was continuing until all samples in the drying chamber achieve moisture content below 15% by remove the dried sample (first column) and shift the second and third column of samples to the first and second column, respectively. However, for the validation purpose, only the first experiment data required because at the initial stage all the products have similar moisture contents. The graph of moisture contents against time for five trays as shown in Figure 5.

Variations of final moisture content observed along the experiment. The highest drying rate was at tray 4, followed by trays 13, 11, 9, and 18. The average inlet air velocity at point A4 is 1.5 m/s and the average outlet air velocity at point A5 is approximately 8.9 m/s. The sensors were installed approximately 3 cm from the product level in the tray and the position can't be adjusted. The drying air in this region should carry moisture because of its proximity to the product.

Tray 18 only achieved 39% moisture content at the end of the experiment. The variation of final moisture contents for selected trays as shown in Table 1. Semi continuous mode is required to dry product in second and third column. The dried product in the first column should be removed and shifted the product in second and third column to first and second column, respectively. However, for validation purpose with CFD simulation, only the first experiment was reported. This study focused on drying uniformity; thus, the performance of the dryer system is not discussed in this paper.

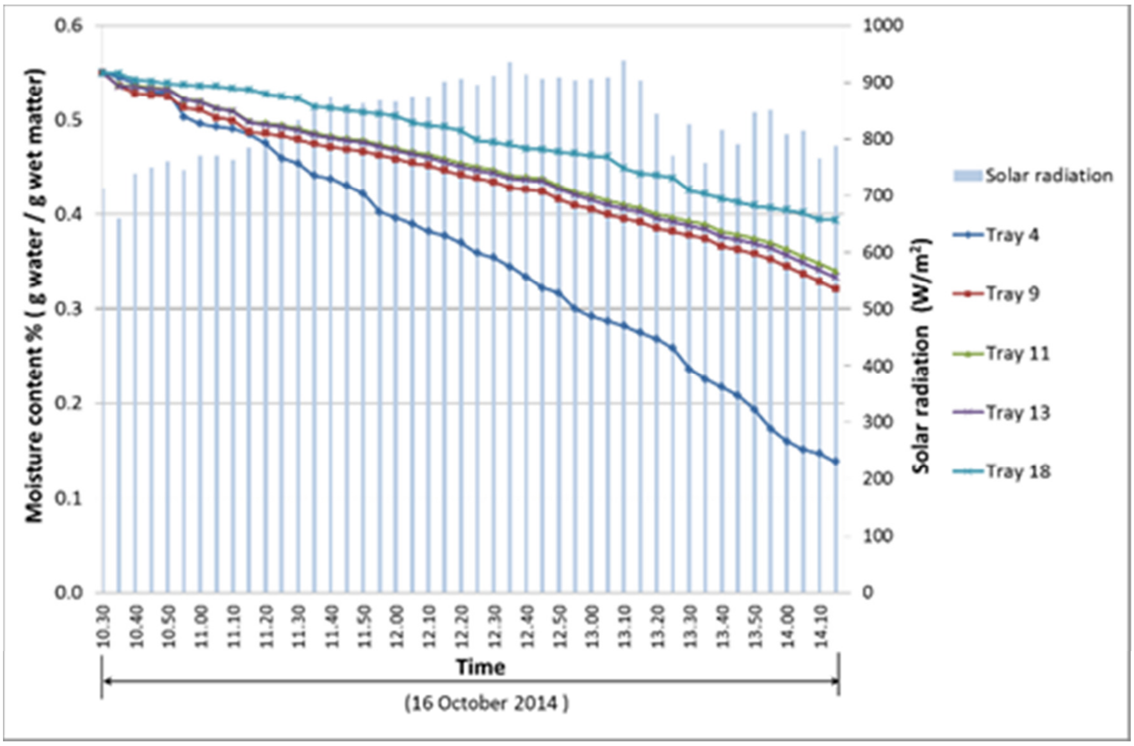

Fig. 5. Moisture contents against time

Table 1
Final moisture content

Tray position	Moisture content, % (wet basis)
4	14
9	32
11	34
13	33
18	39

3.2 Simulation

Three dimensional (3D) CFD simulation was conducted to predict the airflow distribution in the drying chamber because the result of a two dimensional (2D) simulation would not represent the real problem, as discussed by Misha *et al.,* [12]. The product was assumed to be porous with 10% porosity. Misha *et al.,* [13] studied the comparison between porous and solid product and, it was found that by using porous product the overall velocities in the drying chamber are lower than solid product since some of the hot air stream passes through the porous product. However, the porous media is more appropriate to represent the product. Tzempelikos *et al.,* [14] investigated the airflow distribution inside the batch-type tray air dryer through a commercial CFD package. In the simulation, the tray used inside the drying chamber, was modeled as a thin porous media of finite thickness.

Manual measurements were carried out at the fronts of trays in column one (parallel to the center of fan 1) as shown in Figure 6 to validate the simulation result. These positions are located in the middle between upper and lower trays. However, the value of velocity at tray 2 and 3 cannot be measured because the value is below 0.4 m/s. The value of measurement data and simulation result for all locations are shown in Table 2. The simulation values for all points were within the range of anemometer accuracy. Therefore, the simulation results are highly consistent with the experimental data.

In this current simulation, a plane was created 2 cm above each tray as shown in Figure 6 to find the average air velocity above the trays. The velocity at this region was necessary to carry the moisture from the product. The drying rate of the product at trays 4, 9, 11, 13, and 18 was determined (Table 3) from the experimental result. As shown in the Figure 7, the product with higher drying rate has higher average air velocity above the tray as expected. The drying rate has strong correlation with average velocity above the trays. The straight line represents the relation between these two parameters, with a high R-squared value of 0.96. The equation for the straight line is given by

$$y=2.705x-0.235 \quad (1)$$

where y is the predicted drying rate and x is the air velocity from the simulation result.

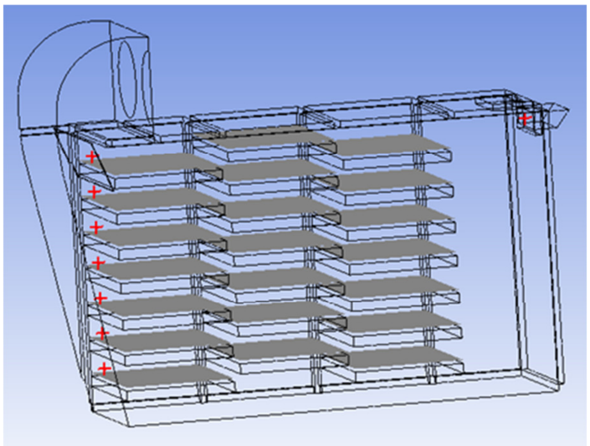

Fig. 6. Position of air velocity measurement and plane above the trays

Table 2
Velocity of experimental and simulation result

No	Anemometer Positions	Velocity (m/s)	
		Experiment	Simulation
1	Tray 1	0.8	0.80
2	Tray 2	-	0.15
3	Tray 3	-	0.27
4	Tray 4	0.4	0.41
5	Tray 5	0.6	0.62
6	Tray 6	0.6	0.64
7	Tray 7	0.7	0.73
8	Exit channel	8.9	9.02

The values of the actual and predicted (using equation) drying rates are shown in Table 3. The average percentage error was extremely small and acceptable. Therefore, the drying rate at the other tray positions can be predicted by using Equation (1). The graph in Figure 8 shows the air velocity from the simulation and the predicted drying rate. The simulation result shows that the highest air velocity was at tray 1 and 7 because of the additional baffle and incline wall that channels the air to each tray level. The simulation without a baffle was conducted to predict air flow in the drying chamber [15]. Without the baffle, less air was channelled to the top tray and lower air velocity was produced. The drying rate of the dried products are depending on the air velocity. The product with higher average air velocity has lower moisture content (Table 1).

Such findings also show that the incline wall at the inlet contributed to the uniform distribution of drying air to each tray level at the same column. The 3D simulation result of the air stream is shown in Figure 9. In this study, air flow was produced by the axial fan at 1.5 m/s, which is considered high velocity and not influenced by temperature. Therefore, the simulation was conducted under steady state condition. In a natural flow, air flow is depending on the temperature gradients in the air.

Table 3
Prediction of drying rate

Tray positions	Average velocity from simulation result (m/s)	Drying rate (kg/h)	Prediction of drying rate (kg/h)	Percentage of error (%)
4	0.26	0.48	0.47	2.08
9	0.22	0.34	0.36	5.88
11	0.20	0.32	0.31	3.13
13	0.21	0.32	0.33	3.13
18	0.18	0.26	0.25	3.85
Average percentage of error				3.61

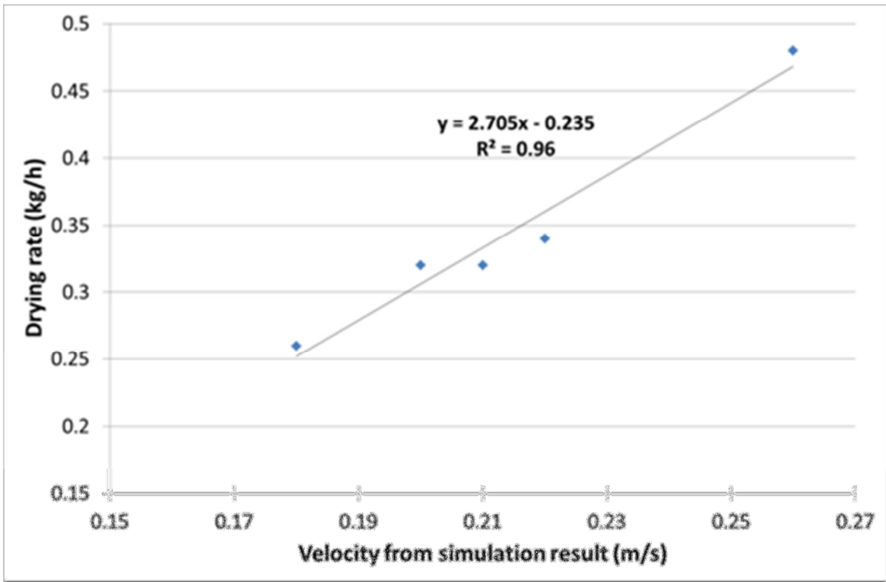

Fig. 7. Drying rate against velocity from simulation

The simulation was simplified by assuming that the product temperature was in equilibrium with the drying air at the final stage of drying. In actual experiment the drying was stopped before this stage because the products were dried only at certain final moisture content, in this case below

15% wet basis. This simulation did not include humidity because two phases of air material are required in the process, which will result in a more complicated equation and time-consuming simulation.

Based on the experimental result the airflow rate can be considered as constant along the experiment. Therefore, the CFD simulation was carried out under steady state condition. Temperature was not analyzed in simulation because the temperature is not constant, fluctuate depending on solar radiation and moisture content of the dried product. Temperature analysis only can be done using transient condition which is more complicated and time consuming.

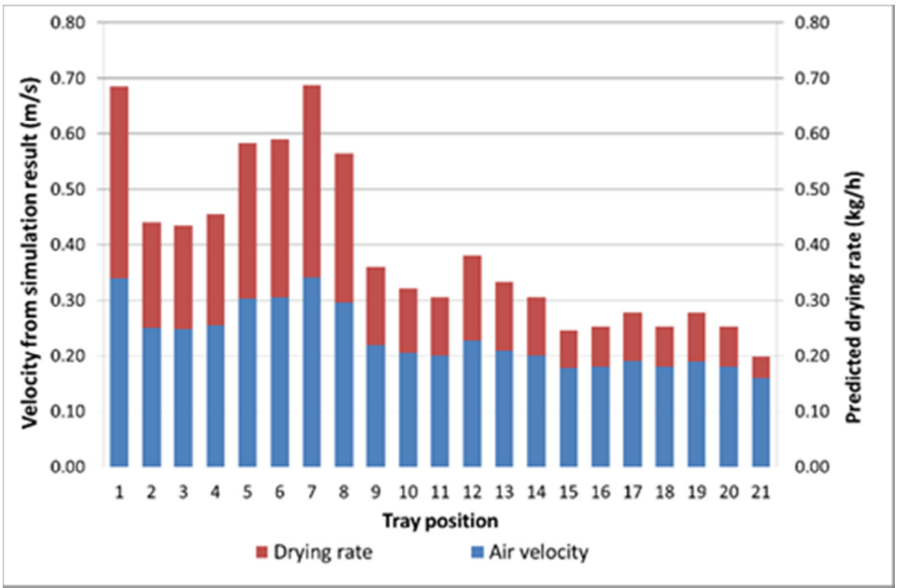

Fig. 8. Velocity from simulation and predicted drying rate for each tray

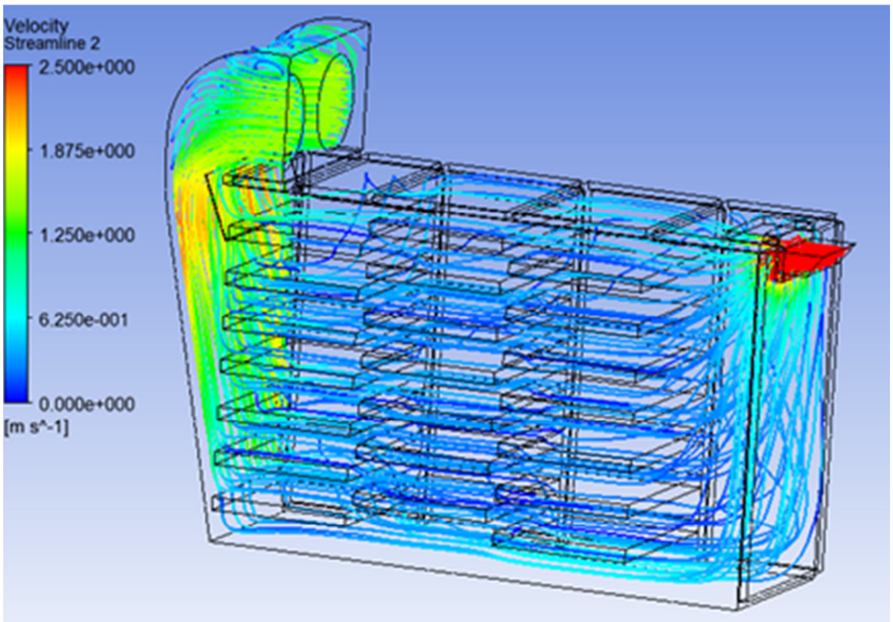

Fig. 9. 3D streamlines in the drying chamber

4. Conclusions

A kenaf core drying experiment using a solar-assisted solid desiccant dryer was performed under average solar radiation of 834 W/m2. CFD simulation was used to predict air flow distribution in the drying chamber by considering the product as porous media. The experimental and simulation data were in good agreement. The drying rate of the product was significantly influenced by the average air velocity above the tray. The higher the average air velocity, the higher the drying rate of the products. The correlation between average air velocity above the trays and drying rate at some trays is very useful to predict the drying uniformity throughout the drying chamber. As the distance of product far from the air inlet the air velocity decreased. However, the uniformity of air flow distribution to each level of product at the same column are acceptable. The alternate arrangement of tray position was adopted to ensure that all trays are exposed directly to drying air. Since the products that close to the air inlet were dry earlier, drying using semi-continuous mode was recommended to shorter the drying time and improve drying uniformity.

Acknowledgments

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