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Research Article

Drying Uniformity Analysis in a Tray Dryer: An Experimental and Simulation Approach

[1]S. Vargas Natalia, [1]Caicedo Mauricio, [1]A. Martínez-Correa Hugo and [2]F. Lobaton Hugo
[1]Grupo de Procesos Agroindustriales, Universidad Nacional de Colombia, Palmira 763533,
[2]Facultad de Ingeniería, Universitaria Agustiniana-Uniagustiniana, Bogotá 111156, Colombia

Abstract: This study aimed to use a Computational Fluid Dynamics (CFD) simulation of a tray dryer to investigate the possible causes of non-uniformity in the absolute final product humidity after the drying process in an empirically constructed tray dryer. In the experimental part, turmeric, which is the rhizome of a perennial herbaceous plant with interesting properties for the cosmetic and food industries, was dried. Pieces of turmeric with identical dimensions were placed in different zones of the dryer and their initial and final humidity values were empirically measured. In the simulations, the momentum and energy equations were solved with ANSYS software (Student v.17.2). The K-epsilon model was used to model the turbulence and the boundary and process conditions were identical to those used in the experiment. Although the steady-state CFD simulations show a homogenous local temperature distribution in the dryer, the local turbulence intensity profiles display dead zones with low turbulence values. Furthermore, these dead zones are consistent with areas where the product exhibits higher humidity. Low local turbulence values can negatively affect the local mass transfer coefficient, which may explain the experimental results of this study.

Keywords: Computational fluid dynamics (CFD), jet-type flow, turbulence intensity, tray dryer, turmeric

INTRODUCTION

Drying, a complex operation that involves the removal of water from natural or industrial materials to achieve a specific moisture content, is applied in various industries, such as food, pharmaceuticals and biotechnology (Defraeye, 2014). To improve consumer acceptance, factors such as the drying uniformity related to product quality should be analyzed when a food drying operation is designed (Margaris and Ghiaus, 2006).

A common type of dryer used industrially to dry food-type materials is the tray dryer, wherein air is usually introduced on one side of the dryer and then passed through the trays. This geometrical configuration can cause homogeneity problems in the final moisture content of the dried products (Amanlou and Zomorodian, 2010).

This problem is even more noticeable in large batch drying systems such as those used to dehydrate agricultural products. Nevertheless, the uniformity of the moisture content can be improved with a suitable distribution and orientation of air inside the drying space (Margaris and Ghiaus, 2006).

In convective drying, the dehydration rate is directly related to the temperature and air velocity in the process (Amanlou and Zomorodian, 2010). Thus, identifying the air flow and air velocity in the drying chamber is very important for adequate drying. However, air flow and velocity are difficult to measure during the operation of the equipment because several sensors, each in different airflow directions and locations, are required (Xia and Sun, 2002).

An alternative way to predict difficult-to-measure process variables is to use computational simulation tools. Computational Fluid Dynamics (CFD), one of the most advanced and well-known modeling methods for drying processes, has been applied in recent years to different types of dryers, such as convective dryers and spray dryers (Defraeye, 2014).

In drying operations, CFD numerical simulations are often used to significantly reduce experimentation times without incurring costs. In addition, CFD simulations are highly correlated with experimental data and therefore provide reliable and verifiable information (Amanlou and Zomorodian, 2010). The application of CFD to drying processes can help improve the final quality of the products, ensure product uniformity and optimize the drying operation and energy consumption during operation (Defraeye, 2014).

A study published by Amanlou and Zomorodian (2010) addressed the problem of non-uniformity in drying operations. They studied the airflow in different

Corresponding Author: Lobaton Hugo F., Facultad de Ingeniería, Universitaria Agustiniana-Uniagustiniana, Bogotá 111156, Colombia

geometries of a convective cabinet dryer using CFD and found high correlations with the experimental data of the process. Similarly, studies carried out by Margaris and Ghiaus (2006) showed that experimental investigations in conjunction with CFD numerical simulation can predict configurations that optimize the drying spaces in convective tray dryers to obtain more uniform air flows. Studies by Mathioulakis *et al*. (1998) extended the application of CFD simulations to industrial facilities, helping obtain a better understanding of the problems associated with products dried with poor uniformity in a 5-ton industrial dryer.

This study uses CFD simulations to understand aspects related to the lack of homogeneity in the final moisture content in turmeric-drying processes. Moreover, it seeks to identify the possible causes of this phenomenon by providing information that can be used by the industry as a starting point to improve the process conditions of the process by better designing the equipment.

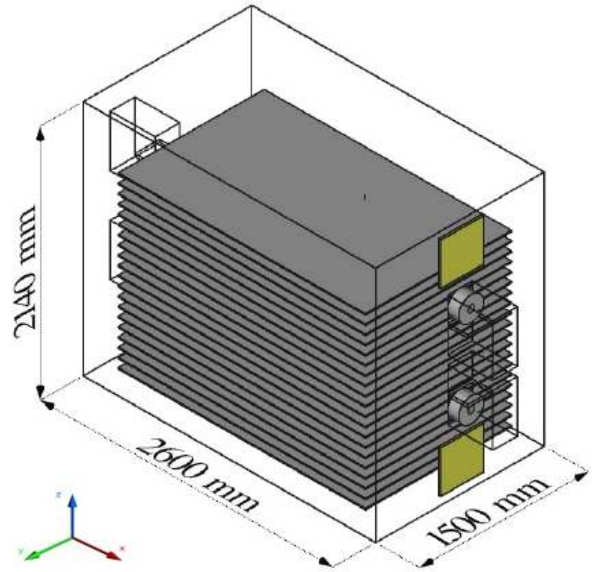

Fig. 1: Geometry of the tray dryer. The yellow squares are the air inlet and outlet

MATERIALS AND METHODS

The experiments were performed in the Biovalle dehydration plant in the municipality of Ginebra, Valle Del Cauca, Colombia. Selected turmeric (*Curcuma longa* L.) grown in the area was used to investigate the drying process. The sample was randomly selected from lots destined for the dehydration process. *Curcuma*, a genus in the family Zingiberaceae, contains approximately 80 species of herbaceous plants that are cultivated in the tropical regions of Asia, Australia and South America. Some species of turmeric are currently used as nutritional supplements because of their pharmacological properties (anti-inflammatory, antioxidant and anticancer) (Awin *et al*., 2016). Additionally, their commercial value is derived from the production of natural pigments and oleoresins (Martinez-Correa *et al*., 2017).

Description of the equipment: The equipment, which was initially empirical designed, consists of an industrial drying unit manufactured by Didacontrol (Cali, Colombia) that has trays with the capacity to dry 120 kg of material. The equipment has a turbine that drives the air and an automatic temperature control board. Its dimensions are 2.140 m in height, 2.60 m in width and 1.5 m in depth. (Fig. 1). The maximum operating temperature is 68°C. The dryer is packed with 20 trays distributed evenly along the height. They trays have a uniform distribution of diamond-shaped perforations across the surface.

The air is heated by the combustion of natural gas in a chamber outside the drying equipment. A turbine supplies hot air to the dryer through a duct connected to the bottom of the drying equipment. Inside the drying chamber, the hot air is redistributed by a series of fans and extractors on the sidewalls of the equipment. The air outlet is located at the top of the drying equipment.

Pretreatment of the sample: The sample was initially disinfected by immersion in a 2% sodium hypochlorite solution. Then, the material was cut into slices with a thickness of 3 mm. A blanching treatment was performed by immersing the material in an aluminum pot for 45 min at 90°C.

Drying operating conditions: The temperature in the air inlet was set to 60°C and the drying process was stopped after 9 h of drying. The air velocity in the parallel flow was set to 3.5 m/s. The configuration of the equipment does not permit air recirculation.

Design of the experiment: The experimental design consisted of a 3^2 design of 2 factors corresponding to the spatial coordinates X and Z, which represent the location of the sample in the dryer chamber with respect to these coordinate axes at three levels per coordinate. The design was run in a single block for 6 experimental points. The selected levels were high (1) and low (-1) for the position along the X axis and high (1), middle (0) and low (-1) for the position along the Z axis.

Analysis of the samples: The initial moisture content of the sample was 84% with a margin of error of 0.1%. After the stipulated drying time, the humidity of the samples was measured using a Precisa Model XN 160 scale with an accuracy of 0.001 g. Random samples were measured in triplicate.

Analysis of the samples: After 9 h of drying time, the humidity of the samples was measured using a {g. The

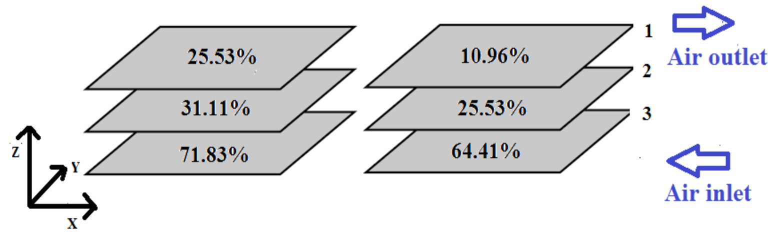

Fig. 2: Schematic of the moisture percentage results at different points of the equipment. The arrows represent the air inlet and outlet. The numbers identify the level which the trays are located

samples were assumed to be homogeneous and their humidity was determined before they entered the dryer using an identical moisture balance. The initial moisture content of the sample was 84% with a margin of error of 0.1%. Random samples were measured in triplicate.

CFD simulations: The continuum, momentum and energy equations were solved for air in the described geometry (Fig. 1). ANSYS software (Student v.17.2) was used to perform the simulations.

Turbulence model: The turbulence approach was performed using the K-epsilon model, which comprises two equations with constants C1-epsilon of 0.142 and C2-epsilon of 1.68.

Boundary conditions: The boundary conditions were identical to those in the experimental stage. An air inlet at the bottom left was defined by a fixed velocity inlet parameter of 3.5 m/s and a temperature of 60°C. The air outlet face was modeled as a pressure outlet boundary condition (atmospheric pressure).

RESULTS AND DISCUSSION

The experimental measurements for the drying process using turmeric show that the product does not have uniform humidity. Figure 2 illustrates the moisture percentage of the selected samples that were analyzed after 9 h of drying.

The average moisture percentage in the product is 38.23% with a standard deviation of 24.21%, which is much higher than the standard deviation of approximately 5% reported by other authors (Mathioulakis *et al*., 1998). Thus, the final moisture obtained depends on the location of the material in the dryer.

According to a statistical analysis of the experimental data (Fig. 3), the location of the material with respect to the Z axis significantly affects the moisture content of the product (significance level: 5%). Evidently, the samples at the top of the dryer have the lowest percentages of humidity, while the lower zone possibly exhibits flow stagnation with low x and z values.

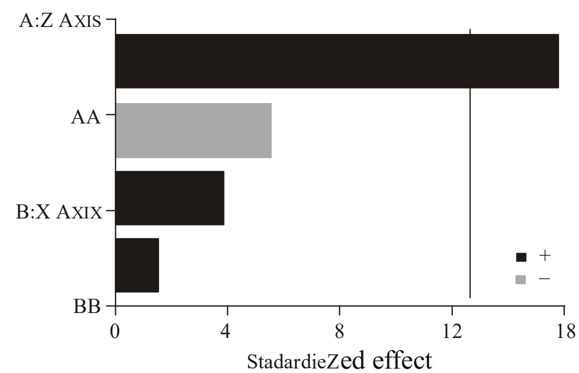

Fig. 3: Standardized Pareto chart of the significant effect of sample location in the equipment

The simulation shows a homogeneous temperature profile distribution. Therefore, it prioritized the evaluation of the effect of the air flow. Figure 4 shows the velocity vectors in an XZ plane in the middle of the Y axis. The air velocity has a notably uneven distribution and is higher in the areas near the inlet of the dryer with jet flow behavior (yellow vectors).The experimental results show low water product removal (64 and 72%, level 3) in the trays located in level 3 (Fig. 2),which are located in the same area as a jet-type flow. The air velocity is low along the height (z-axis) because of the pressure drops. Figure 5 shows the total pressure when the flow is distributed along the X and Z axes. According to Mathioulakis *et al*. (1998), this behavior can be attributed to the density and quantity of trays, which represent a notably large obstacle to the flow, thereby generating stagnation zones in the dryer.

A jet flow regime is characterized by fluid flows in parallel layers with no disruption between the layers and no eddies or swirls of fluids. The turbulence eddies carry mass across the flow. In laminar flow, the mass has to diffuse across the flow. Diffusion is there in both cases, but in the turbulence case, the mass gets carried as well as diffusing.

An important factor in the analysis of the drying operations is the relation between the flow regimen and the effect of the mass and heat transfer coefficients. Several reports have stated that increasing the turbulence increases the local mass and heat transfer coefficients (Kaya *et al*., 2008). Local mass transfer

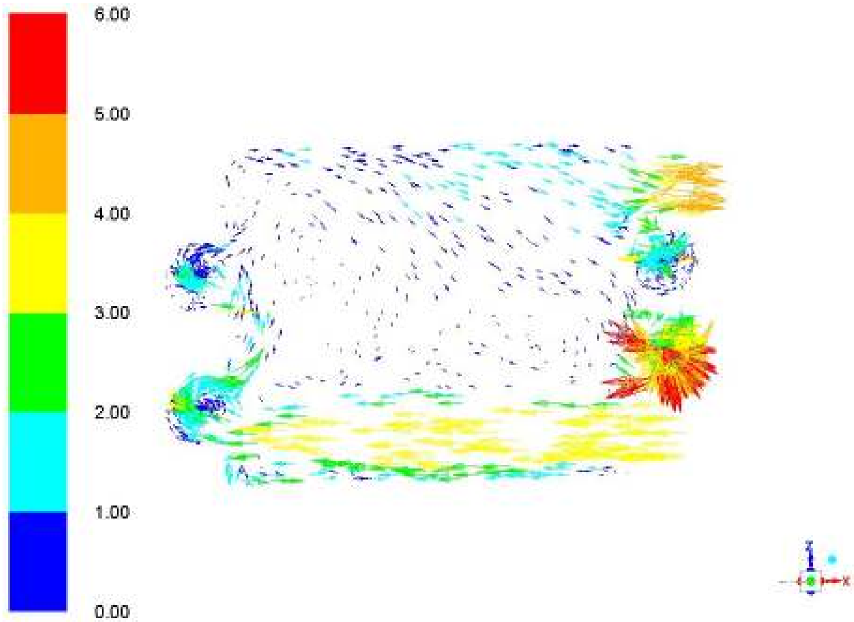

Fig. 4: Velocity vectors (m/s) in an XZ plane in the middle of the Y axis.

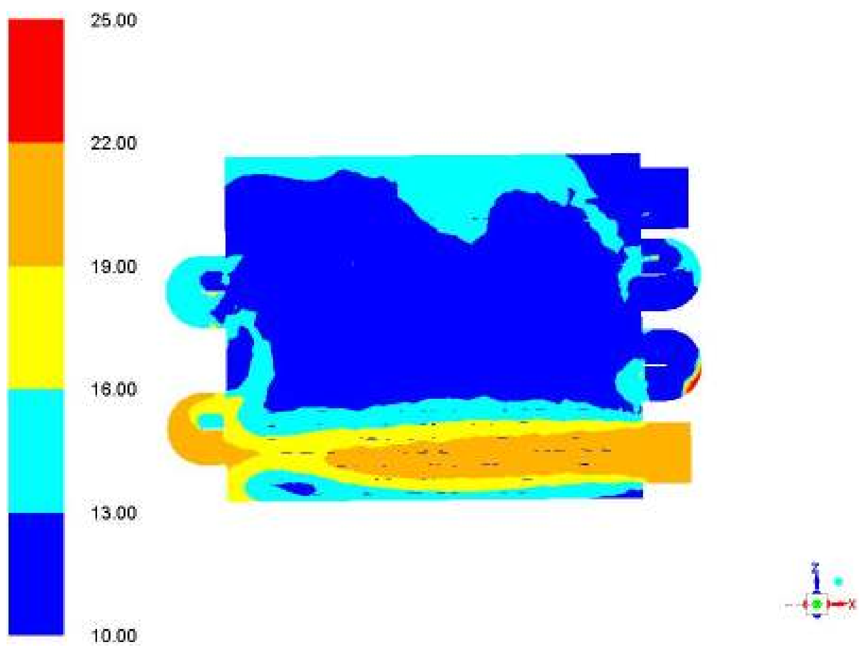

Fig. 5: Contours of total pressure in an XZ plane in the middle of the Y axis (Pascal)

coefficients are high in regions where small eddies are dominant. For example, a stronger turbulence distribution in the equipment indicates that less drying time is required due to improved mass and heat transfer coefficients (Ryu *et al*., 2013). Variables such as the tray geometry and arrangement affect the turbulence in the equipment.

Figure 4 shows a jet-type flow behavior in the area near the inlet (yellow vectors), whereas Fig. 6 shows low turbulence intensity in the same area (values between 5 and 15%). The turbulence intensity is defined as the ratio of the root-mean-square of the velocity fluctuations to the mean flow velocity. A turbulence intensity of 1% or less is generally considered low and turbulence intensities greater than 10% are considered high (Chakrabarti and Brebbia, 2007).

Figure 6 shows high values of turbulence in the central part of the dryer. According to the literature, higher turbulence corresponds to a better mass transfer

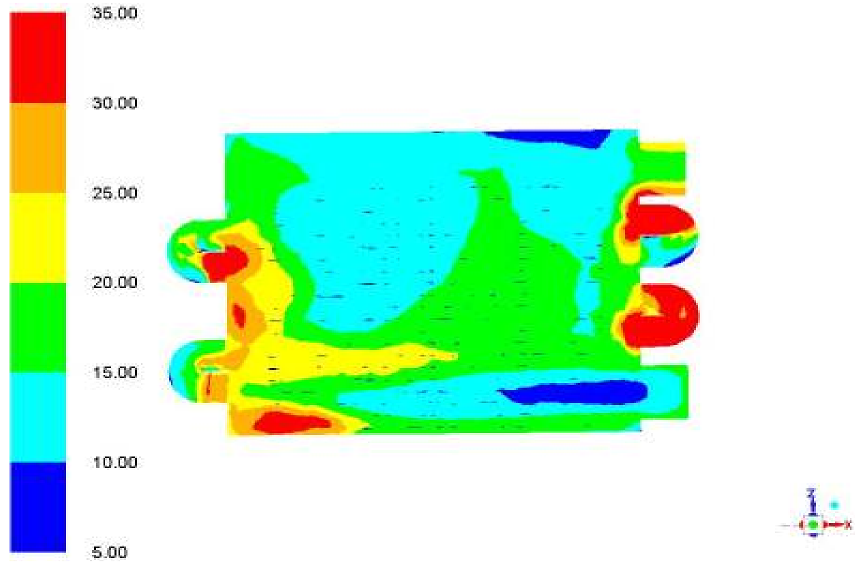

Fig. 6: Contours of turbulence intensity in an XZ plane in the middle of the Y axis (%)

coefficient (Lin *et al*., 1953) and this enhancement is due to velocity fluctuations as results of the eddies. This outcome is consistent with the lowest percentages of humidity being at the center and top of the dryer (25% and 11% in the trays located in level 2 and level 1, respectively). The mass transfer process controls the diffusion of the humidity from the product to the air; thus, the low turbulence arguably causes low mass transfer, thereby leading to insufficient drying in the bottom zones of the dryer.

CONCLUSION

The evaluated tray drying equipment, which was empirically designed, cannot perform a uniform drying process as result of two factors: first, the jet flow behavior in the inlet does not favor the formation of eddies (low turbulence intensity), which negatively affects the residence time and mass transfer coefficient between the product and the air and second, the current configuration has a high density of trays, which causes large pressure drops. This decrease in pressure generates dead zones with low air velocities.

Finally, CFD simulation has been proven as a powerful computational tool that enables the corroboration of experimental data, reduces testing costs and generates an approach to phenomenologically describe the process and the causes of the presented problems, thereby facilitating the analysis and increasing the opportunities for improvement.

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