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Review on the Application of a Tray Dryer System for Agricultural Products

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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. Implementing the proper design of a tray dryer system may eliminate or reduce non-uniformity of drying and increases dryer efficiency. This paper discussed several design of tray dryer system for drying agricultural products and its performance. Most of the dryer systems have been developed are using solar energy because the systems run at low operating cost. Computational fluid dynamics simulation is a very useful tool in the optimization of the drying chamber configuration by predicting the airflow distribution and the temperature profile throughout the drying chamber.

Key words: Tray dryer · Agricultural drying · Solar dryer

INTRODUCTION

Drying has remained one of the popular methods for preserving food for many years. The drying process involves reducing water from the product to an acceptable level for marketing, storage, or processing. Given the absence of sufficient water, microorganisms are unable to grow and multiply. Many of the enzymes that cause food spoilage cannot function without water. The old method of food drying is executed by spreading the food material on the ground and exposing the food to sunlight. This method is practiced until today for certain products because of the advantages of simplicity and economy. However, open sun drying has some drawbacks. Open sun drying requires longer drying time and product quality is difficult to control because of inadequate drying, high moisture, fungal growth, encroachment of insects, birds and rodents and others. Open sun drying also requires a large space.

Drying is usually conducted by vaporizing water in the product. Thus, the latent heat of vaporization must be supplied. Airflow is also required to remove the vapor away from the product. The lower the humidity of hot air supplied to the drying chamber is, the better the drying rate, as the less humid air can carry more moisture from the product surface than the more humid air. Generally, increasing the temperature and velocity shortens the drying time. However, for heat-sensitive products, such as food and pharmaceutical products, high temperature decreases product quality. In this case, drying at low temperature and humidity is required to maintain the fresh color of the product using the desiccant system [1-3]. Without the use of the desiccant system, high temperature is required to obtain low humidity. Several advantages of using desiccant material in drying application have been discussed in detail by Misha *et al*. [4]. The same product dried with different techniques produces different levels of product quality [5]. An example, refractance-window (RW) drying method can maintain the antioxidant compounds such as L-ascorbic acid, total flavonoids and lycopene content except in phenolic compounds which was found to be more in tomato powder produced by convection drying [6].

Augustus Leon *et al*. [7] presented the parameters commonly used to evaluate solar dryers. The parameters include physical features of the dryer, thermal performance, quality of dried product, cost of dryer and payback period. These parameters are also suitable for any dryer system. Chua and Chou [8] evaluated low-cost drying methods used in developing countries. The selection criteria were based on the following considerations: (1) initial cost is low; (2) system is easy to

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install, operate and maintain; and (3) high drying rate and better product quality are produced. In the selection of dryer types, each item contributed at a different percentage to the final score. For most of the cases, especially food products, they more emphasize on the product quality characteristic compare to the remaining criteria.

Many dryer types have been used in the domestic and industry sectors. The dryers that are commonly used are tray dryers, tunnel dryers, drum dryers, fluidized bed dryers, spray dryers, flash dryers, rotary dryers, belt dryers, vacuum dryers and freeze dryers. Among these dryers, the tray dryer is the most extensively used because of its simple and economic design. The food is spread out on trays at an acceptable thickness so that the product can be dried uniformly. Heating may be produced by hot air stream across the trays, conduction from heated trays, or radiation from heated surfaces. In a tray dryer, more products can be loaded as the trays are arranged at different levels. The key to the successful operation of the tray dryer is uniform airflow distribution over the trays. The tray dryer may be applied to a solar dryer or any conventional dryer that uses fossil fuel or electrical energy. Good airflow distribution will ensure the final moisture content of the dried products on the trays are uniform. Normally the moisture content is determined by using electronic balance to get the difference between final and initial mass of the product. Bakhshipour *et al*. [9] used a machine vision system integrated with the neural networks to predict the moisture content of raisin.

Types of Tray Dryer: Generally, a tray dryer consists of several stacks of trays placed in an insulated chamber in which hot air is distributed by a fan or natural flow. Sometimes, part of the exhausted air is re-circulated within the drying chamber. The tray inside the chamber can be stationary or moving.

Stationary Tray Dryer: The stationary tray dryer is widely used because of its simple design. In this system, the trays are fixed at their positions. The uniformity of airflow distribution over the trays is crucial to obtain uniform product quality. The variation of the final moisture content of the dried product at different tray positions is commonly encountered because of poor airflow distribution. This problem also limits the volume of the product to be loaded in the dryer system. A good tray dryer system design eliminates or reduces the non-uniformity of drying throughout the drying chamber.

Mohanraj and Chandrasekar [10] designed and fabricated an indirect forced convection solar dryer combined with heat storage material for chili drying. The use of heat storage material extends the drying time by about 4 h per day. The chili moisture content of 72.8% (wb) was reduced to 9.7% and 9.2% (wb) in the top and bottom trays, respectively, during the drying process. The solar dryer thermal efficiency was estimated at about 21% and specific moisture extraction rate was estimated at about 0.87 kg/kW h. At the initial stages of drying, the outlet air humidity was higher by about 89% and it decreased as time increased. At the final stage of drying, the outlet air humidity became constant at about 60%. As drying time increased, the drying rate decreased. Syahrul *et al*. [11] study the effects of the inlet air temperature, the air velocity and the initial moisture content of the corn on the thermal efficiency. It was found that the thermal efficiencies of the fluidized bed drying decrease with decreasing moisture content of corn.

Hallak *et al*. [12] designed and built the staircase solar dryer for drying fruits and vegetables. The top surface is covered with a transparent polycarbon sheet to allow sunlight to pass through. The base of the dryer and the separation walls between the compartments have four holes for airflow. The result shows that the temperature increases in the higher compartment. Therefore, drying at a higher temperature can be achieved by increasing the number of dryer compartments, with the uppermost levels producing higher temperature. Samples can be placed initially at the lower levels and then moved to the higher ones later on until the desired moisture content is achieved. The mass of samples tested was reduced to less than 20% from the initial mass in around 2.5 days to 3.5 days, whereas samples using open sun drying took around 12 days to 15 days.

Torres-Reyes *et al*. [13] investigated the thermal performance analysis of the cabinet-type indirect solar dryer for mango slices drying by using semi-empirical models. A simplified method to design solar collectors based on the determination of minimum entropy generation during the thermal conversion of solar energy was introduced. The results show that the products positioned at the higher level experience high humidity compared with those at the lower position. The drying rate increases by increasing the flow rate of the inlet air.

A hybrid solar dryer was designed and developed by Amer *et al*. [14] using direct solar energy and a heat exchanger for drying ripe banana slices. The drying chamber is located under the collector. During sunny days, the dryer operates as a solar dryer and stores heat energy in water, whereas during days with less sunlight, the dryer works as a hybrid solar dryer. At night, the heat energy stored in water is used to continue drying, with electric heaters in the water tank supplying sufficient heat as backup energy. The dryer efficiency was improved by recycling approximately 65% of the drying air in the dryer system. The air temperature could increase from 30 °C to 40°C above the ambient temperature. The moisture content of banana slices was reduced from 82% to 18% (wb) within 8 h when drying during a sunny day. The use of open sun drying reduced moisture content by only 62% (wb) with the same duration. The color, texture and aroma of the products dried with the solar dryer were better than those of the open sun-dried products.

Gülþah Çakmak and Cengiz Yıldız, [15] designed and constructed an air solar collector with swirl flow to dry seeded grape. Additional air-directing elements on the wall of the drying chamber and a swirl element at the inlet of the drying chamber produced uniform flow of drying air over the grapes on a single tray and the dried products reached the desired moisture conditions more rapidly than the products subjected to open sun drying. The drying time of 200 h under open sun was decreased to 80 h with the developed dryer. The dryer air velocity was about 1.5 m/s. The drying rate increased with the increase in dryer air velocity. Thus, air velocity has a more significant effect on the drying process than does air temperature.

Salah *et al*. [16] investigated and evaluated the performance of the drying chamber of the forced convective solar-assisted drying system. The drying chamber has adjustable shelves to support wire-mesh trays. The dryer system can operate with or without the heater. In this work, standard equations of heat transfer analysis under steady state condition were applied to determine heat losses from the drying chamber and its efficiency. The well insulation of the drying chamber was found to increase the efficiency of the system.

Shawik Das *et al*. [17] designed and developed a re-circulatory cabinet dryer using a central air distribution system. The capacity of the dryer is 5 kg/batch. Hot air is fed from the center to avoid non-uniform drying and to reduce the heat loss to the surroundings. A blanched potato chip was tested in the dryer. The results show that the velocity of both chambers is in the range of 1.5 m/s to 1.7 m/s. The initial heating time of air is 25 min and 12 min with no re-circulation and 100% re-circulation, respectively. The experiments were conducted at loading capacities of 5, 6 and 7 kg/m^2 of potato chips and drying temperatures of 55, 60 and 65°C. The thermal heat efficiency and the heat utilization factor are in the range of 21% to 24% and 17% to 20%, respectively. The drying times of different loading capacities are in the range of 180 min to 225 min. Drying products with a loading capacity of 7 kg/m^2 is more economic because product quality is maintained despite differences in loading capacity.

Pelegrina *et al*. [18, 19] developed a rotary semi-continuous dryer for drying vegetables and investigated the effect of air recycling. Recycling of exhaust air and mixing with fresh air reduced the energy consumption. However, lower recycle fractions must be applied for quality retention. Neslihan Colak and Arif Hepbasli [20] investigated the performance of green olives in a tray dryer using the exergy analysis method. The drying process was conducted at four different drying air temperatures in the range of 40°C to 70°C, with a constant relative humidity of 15%. Lower exergy loss and higher exergy efficiency were obtained by decreasing the boundary temperature of the drying chamber. The drying process at a temperature of 70°C showed the highest exergy efficiency.

Sukhmeet *et al*. [21] designed and constructed a solar dryer for drying farm products called the "PAU portable farm solar dryer". The dryer exhibits high efficiency because of its inclined absorber and the airflow passing through the product. Drying can be conducted with or without shade. All the trays should be fully occupied by the product. If some spaces are void of the product, the thermal efficiency drops because of the hot air bypassing the product. If the amount of the product is less than the capacity of the dryer, the top tray should be loaded first, followed by the lower tray. For drying under shade, a shading plate must be placed over all trays, including the empty trays if any. During subsequent drying days, if there are some void spaces in any of the trays, the product must be transferred from the lower tray to higher tray to remove the void space.

The drying process can be conducted in batch mode or semi-continuous mode. In batch mode, the fresh products are loaded after the dried product from the previous batch that has been removed. In semi-continuous mode, the partially dried product is transferred to another tray and the empty tray is filled with fresh product. The fresh product with high moisture content is loaded on the top trays, whereas the partially dried product is transferred to the lower trays. Otherwise, moisture from the fresh product will be carried by hot air to the partially dried product, potentially increasing the moisture again. The drying rate is uniform in all the trays because of air in between the trays being heated by solar energy. Moisture evaporation on the first, second and third days of drying fenugreek leaves was 1.4, 0.9 and 0.4 kg/m^2, respectively.

Parm Pal Singh *et al*. [22] designed and constructed a multi-shelf natural convection solar dryer called the "PAU domestic solar dryer" which consists of three perforated trays for drying various products. It has an adjustable inclination angle to capture more solar energy. Most of the dryer features and operation are the same as those of the PAU portable farm solar dryer. Moisture evaporation on the first, second and third days of drying fenugreek leaves was 0.23, 0.18 and 0.038 kg/m^2 h, respectively. The drying time for drying chilies and fenugreek leaves was 86 and 204 drying days, respectively. A semi-continuous mode was implemented to maintain the efficiency on all drying days. In open shade drying, the drying rate was more than double, causing low-moisture content of the product (7.3% wb). The drying efficiency is slightly less for indirect mode dryers, but the quality is good for sensitive products that require drying under shade. The cost of drying fenugreek leaves using this solar dryer is approximately 60% compared with that of the electric dryer. The payback period is only about two years, but the life of the dryer is about 20 years. Therefore, the dryer operates at no cost during almost its entire life period.

Bennamoun and Belhamri [23] investigated a solar batch dryer for drying agriculture products. The result shows that increasing the collector surface area and the temperature of the drying air reduces the drying time. The capacity of the dried products does not produce a significant effect. The use of a heater improves the drying performance. Drying using this system is more economical. The collector surface with an area of 3m^2 and a heater at 50°C can dry approximately 250 kg per day.

Smitabhindu *et al*. [24] studied the simulation and optimization of a solar-assisted drying system for drying bananas to minimize the drying cost. The drying chamber consists of 10 trays. The simulation model shows good agreement with the experimental data. Optimization was studied on the geometrical and operational parameters of the drying system. The optimum values of the recycle factor and collector area are 90% and 26 m^2, respectively. The minimum drying cost obtained is about USD 0. 225 per kg.

Komilov and Murodov [25] designed and developed a greenhouse-type solar dryer with pebble accumulator. The walls are constructed from brick except the south-facing inclined wall, which is covered with window glass. The heat accumulator in a cylindrical shape filled with pebbles and an air heater are installed. A black metallic sheet is mounted under the glass, functioning as a heat collector and shade. The humid warm air at the top part of the chamber is directed by a fan to the accumulator through a pipe. Part of the heat from the humid warm air is transferred to the pebbles before being exhausted to ambient. The air pipe below the chamber is connected to the air heater to provide hot air to the drying chamber. Hot air flows through the product in each tray to the upper part. The dryer can be loaded with 500 kg to 600 kg of apricots, tomatoes, fruits, or vegetables per drying cycle.

A hybrid solar dryer with 3600 kg capacity for drying fruits and crops was designed and built at the Solar and other Energy Systems Laboratory of the National Center for Scientific Research "Demokritos," as reported by Belessiotis and Delyannis [26]. The cross section of the dryer and the air circulation is shown in Figure 1. The trays are installed at both sides of the drying chamber wall, with hot air coming from the center. The dryer system uses propane as an auxiliary energy source.

Al-Juamily *et al*. [27] designed and developed an indirect-mode forced dryer for vegetable and fruit drying. The cabinet consists of five shelves with a distance of 0.3m between the shelves except for the upper one, which is 0.5m from the roof. Grapes, apricots and beans were selected as the products to be dried. The moisture content of apricot was reduced from 80% to 13% in one day and a half, that of grapes was reduced from 80% to 18% in two and a half days and that of beans was reduced from 65% to 18% in 1 day only. The result shows that drying air temperature is the most important factor in drying rate. The velocity of air in the drying cabinet has less influence on the drying rate. The relative humidity of air between 25% and 30% was recorded at an outlet of the cabinet. The high air velocity in the cabinet is not necessary because of the low relative humidity at the outlet.

Ayensu and Aseiedu-Bondizie [28] designed and constructed a mixed-mode natural convection solar dryer (Figure 2). The dryer is integrated with collector-cum-rock to store the energy. The drying chamber made of plywood sides with a glazed top holds three layers of wire-mesh tray inside it. The chimney, which has a diameter of 30 cm and height of 1.9 m, is required to increase the airflow velocity. Hot air passes through the product in each tray and carries the moisture by natural convection.

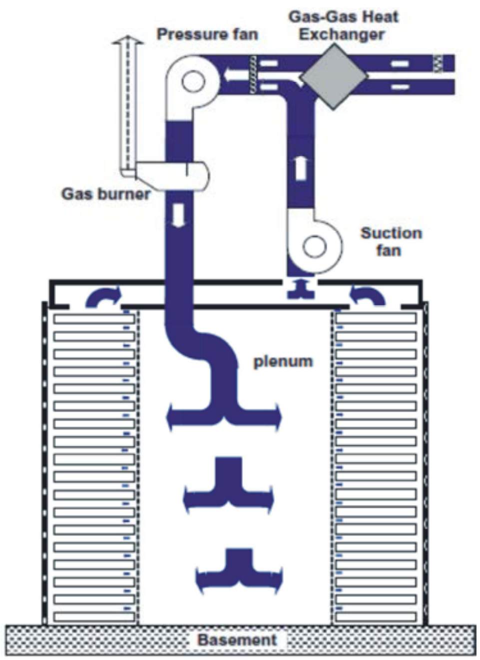

Fig. 1: Air circulation inside the hybrid solar dryer [26]

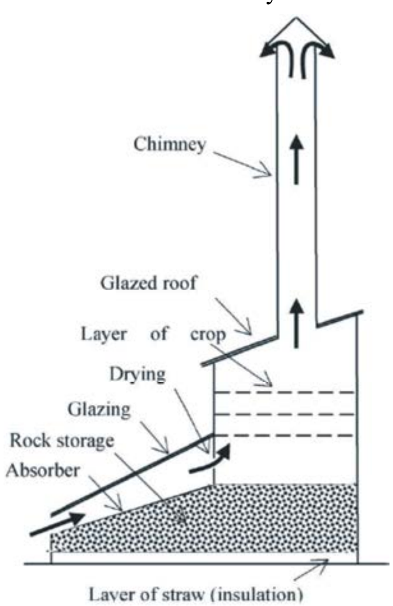

Fig. 2: Indirect-type natural convection solar dryer [28]

Li *et al*. [29] designed and constructed a forced convection dryer for drying salted greengages using the V-groove air collector absorber. A silica photovoltaic module is installed to power three fans that are used in the dryer system. The drying period of salted greengages using traditional sun drying was reduced from 48 days to 15 days using solar drying. The regained moisture by the semi-dry product at night or on rainy days can be avoided during the drying period using a solar dryer. Thermal efficiency can be improved by spreading wet salted greengages on the two trays from the top and semi-dry ones on other trays.

Vlachos *et al*. [30] developed and investigated a solar-assisted indirect dryer integrated with a heat storage cabinet. At night, heat is supplied by the heat storage cabinet with natural convection. The result shows that the drying process occurs at night but at a lower rate. Faster drying occurs for products in the lower drawer than for those in the higher drawer. Therefore, variation occurs in the moisture removal for the dried product in the drying chamber. Interchanging the position of the drawer may be done to avoid this problem.

Tarigan and Tekasakul [31] reported on a natural convection solar dryer combined with a burner and bricks for heat storage as back-up energy. The dryer capacity is about 60 kg to 65 kg of unshelled fresh groundnuts. The drying efficiency of using solar energy and a burner with heat storage is 23% and 40%, respectively. The acceptable thermal efficiency and uniform drying air temperature through the trays are due to the insulation and gap enclosing the drying chamber and bricks that store heat.

Numerous solar dryer systems have been designed using the tray dryer type, which consists of several perforated trays arranged at different levels, one above the other inside the drying chamber [32-42] as reported by Fudholi *et al*. [43]. However, the drying air distribution and the dried product uniformity in the drying chamber are not described in detail.

Moving Tray Dryer: The moving tray dryer was designed to overcome the obstacle of poor drying air distribution, as encountered in most stationary tray dryer systems. The movement of the trays helps increase the drying rate and produce uniform product quality. However, this type of dryer is more expensive because more energy to move or rotate the tray and a more complex design are required. Therefore, the moving tray dryer is seldom used even if it can produce more uniform drying.

Sarsilmaz *et al*. [44] developed and investigated the rotary column cylindrical dryer (Figure 3) for drying apricots. The rotary column contains holes at the center of the drying chamber for the flow of outlet air. The column was rotated by a 12 V DC motor with adjustable speed through voltage control. The rotary column is divided into four equal levels and five plates are attached at each level. Each plate can be loaded with approximately 2 kg to 3 kg of fresh apricots. The result shows that the developed dryer system increases the

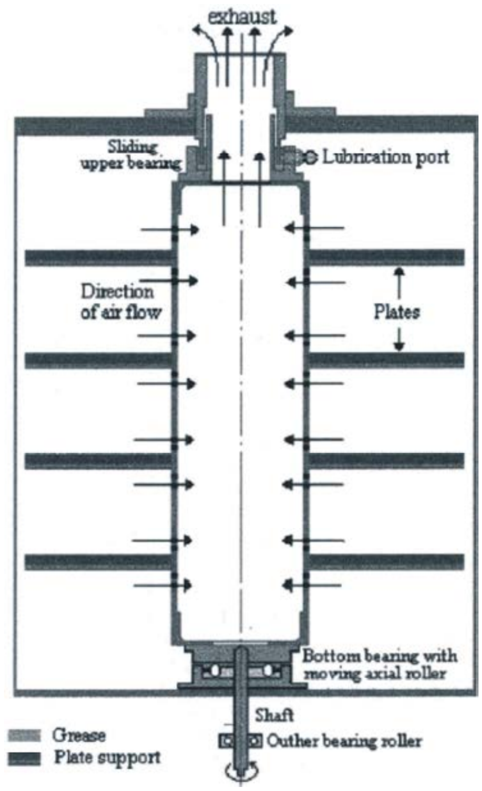

Fig. 3: Vertical cross-section of the drying chamber [44]

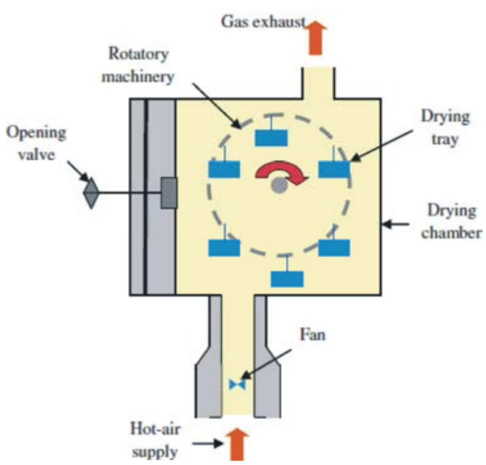

Fig. 4: Rotating tray dryer [45]

drying rate of Sugarpiece-type apricots about twice than that of drying on an open sheet to achieve a 25% moisture level. The rotation of the drying chamber produces uniform and high-quality dried apricots.

Norma Francenia *et al*. [45] designed and developed a rotating tray dryer (Figure 4) for tomato drying. The dryer operates at a temperature range of 20°C to 60°C and air velocity between 0 ms^{-1} and 1.2 ms^{-1}. The tray can be rotated at 20 rpm using a 186.5 W motor. The oven consists of four stainless steel trays, each with a dimension of 0.36m x 0.10m. Each tray has 2 mm-diameter holes for ventilation. An 850W resistor and 10.6W fan supply circulate hot air through the drying chamber. Temperature and air velocity can be controlled using a microcontroller. The use of a rotating tray for tomato drying significantly increases the drying rate and improves product quality. Generally, the drying time is significantly influenced by temperature, tray rotation and air velocity.

Tunnel dryers are considered as developments of the tray dryer. The trays are attached on the trolleys and move through a tunnel. The product direction can be concurrent or countercurrent to the airflow. Sometimes, the cross-flow may also be applied. An example of the tunnel dryer is reported by Kiranoudis *et al*. [46]. The dryer contains a number of trucks/trolleys, each of which behaving as a separate batch tray dryer. Products are placed uniformly on each tray. The air is blown over the trays in the tunnel. When the first truck reaches the desired moisture content, it is removed from the dryer and a new truck is loaded at the end of the train. The tunnel dryer can produce uniform drying. Re-circulated air is heated by a conventional burner. The temperature and humidity of the hot air are controlled by adjusting the fuel induction valve and fresh air dumper, respectively.

The simple and common design of the tray dryer consists of several perforated trays or wire mesh arranged at different levels, one above the other inside the drying chamber. As the drying air passes over the trays, it carries more moisture and loses its heat. Thus, the drying air has low capability of removing moisture from the next product. Good air flow distribution throughout the drying chamber can improve the drying uniformity. In some cases, the semi-continuous mode or exchange of tray position may be done for the stationary tray dryer to obtain uniform product quality. For the natural convection solar dryer, a chimney is required to increase the buoyancy force imposed on the air stream and to provide higher airflow velocity. The moving tray dryer produces better flow distribution of drying air and more even drying.

Design Optimization of the Tray Dryer: Implementing a better design of tray dryers can eliminate poor drying air distribution in the drying chamber. The measurement of drying parameters in the drying chamber is expensive, difficult and time consuming, as sensors and data loggers have to be installed in many positions, especially in a large-scale dryer. Currently, computational fluid dynamics (CFD) simulation is used extensively because of its capability to solve equations for the conservation of mass, momentum and energy using numerical methods to predict the temperature, velocity and pressure profiles in the drying chamber.

Mathioulakis *et al*. [47] designed and constructed an industrial batch-type tray dryer for drying fruits. CFD is used to simulate the air pressure profiles and the air velocity distribution in the drying chamber. The result shows that a variation of final moisture content occurs in several trays and non-uniformity is present in some areas of the chamber. Comparison of the simulation result by the CFD and experimental data shows a strong correlation between drying rate and air velocity.

Dionissios and Adrian-Gabriel Ghious [48] studied the numerical simulation inside a drying chamber with hundreds of trays. A set of measurements was obtained experimentally above one single tray to validate the model. The validation between the measured data and the simulation results by CFD shows that the standard k-e model is the most adequate turbulence model.

Amanlou and Zomorodian [49] designed, constructed and evaluated a new cabinet dryer with a side-mounted plenum chamber for fruit drying. The experimental results show that the developed dryer produces uniform airflow and temperature distribution in the chamber. The experimental and CFD simulation data show very good agreement with the correlation coefficient of 86.5% and 99.9% for air velocity and temperature in the drying chamber, respectively.

Chr. Lamnatou *et al*. [50] developed and investigated a numerical model of heat and mass transfer during convective drying of a porous body using the finite-volume method. The results show that the aspect ratio of the drying plate and the flow separation influence the flow field and heat/mass transfer coefficients, affecting the quality of the dried product. The thinner plate combined with the blockage effect can lead to better heat/mass transfer coefficients.

Jacek Smolka *et al*. [51] investigated a numerical model of a drying oven using the CFD simulation. The simulation results show very good agreement with the experimental data. Several new configurations were simulated to improve uniformity of temperature throughout the chamber. A new shape and position of the heater and baffle directing the airflow were found as the most effective.

Cronin *et al*. [52] developed a simulation tool to analyze industrial batch timber drying. The simulation result from the integrated model with a customized CFD code is used to generate a macroscopic representation of the product. The validated macroscopic model is used as a component in a drying installation model. The developed system model can be applied to represent accurately a new drying material or different drying conditions. Application of CFD has also been used extensively in modeling the spray dryers to predict complex flow patterns and moisture profile. A number of studies pertaining to the application of CFD in spray drying have been reported by Rinil Kuriakose and Anandharamakrishnan [53].

Design optimization of a drying chamber is necessary to achieve higher heat/mass transfer rates and uniform drying by avoiding an unfavorable aerodynamic phenomenon in the chamber. Optimization using CFD can produce better performance of the tray dryer system, high quality of dried products and uniform drying at minimum cost.

CONCLUSION

The objective of this review is to emphasis the important of tray dryer design in drying of agricultural product. Several designs can be implemented to improve tray dryer performance, increases quality of dried product and produces uniform drying. For the stationary tray dryer, the semi-continuous mode or exchange of the position of the tray can be executed to obtain uniform drying. The rotating/moving tray dryer can also produce more uniform drying. In general, re-circulation of drying air and mixing with fresh air reduces energy consumption. However, for certain products, it may decrease the product quality and thus appropriate recycle fractions must be applied. The use of solar energy for drying agricultural product will make the dryer system run at low operating cost. Therefore the solar dryer is widely use for drying agricultural product and will be the future trends. The drying chamber configuration can be optimized by CFD simulation to predict the airflow distribution throughout the drying chamber. Nowadays, given the increase in computing power, the application of CFD can be a valuable tool for engineering design and analysis of solving complex fluid flow, addressing heat and mass transfer phenomena, aiding in the better design of tray dryers and produce high quality of dried product.

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