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A review on computation fluid dynamics studies in drying processes

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ABSTRACT

The drying is a useful technique to preserve food for long time against microbial contamination. Since it is a simultaneous heat and mass transfer operation it finds versatile applications. There are different types of drying operations but in this article an endeavour has made to explain in-detail about tray drying with an aid of CFD (Computational fluid dynamics). There are several designs of tray dryer system with CFD. To implement proper design of tray drier there is a need to optimize variables that are influencing drying operation such as drying chamber configuration, air velocity and air temperature. Also, the equations that are pertinent to drying operation have been explained. In a nut-shell, this article provides an extensive review of the variables that are affecting the tray dryer system.

INTRODUCTION

There are a great number of different types of dryers for various applications. Drying is an operation which involves both heat transfer and mass transfer. We use drying for removal of solvents or water from the solids. The end product is a dry solid. Sometimes even the liquids are dried by removing the last traces of moisture contained in them. Drying is a useful technique for preservation of food materials over a period of time against microbial contamination. Many different foods can be prepared and preserved by drying.

Computational Fluid Dynamics (CFD) is a popular modelling approach which utilizes numerical methods and computer simulations to solve and analyze problems that are related to fluid flow. CFD can provide essential information regarding system design. Many scenarios including the positioning of air inlets and outlets, and the influence of flow obstructions also can be simulated reviewed by Norton et al.[1]. The CFD-based modelling deals with variety of engineering problems involving macroscopic transport phenomena (fluid/gas dynamics, turbulence, heat transfer and mass transfer) which optimise the amount of necessary experiments, time and overall cost of solution of many engineering and scientific problems Mezhericher[2]. Several researchers made noteworthy contributions in the area of drying using CFD. There are numerous studies related to spray drying. CFD simulations were carried out with the aim to find the optimum conditions for the drying air, and the heat and mass transfers between the droplets and the air stream as one such contribution, the effects of the air flow pattern on droplet trajectories, residence time distribution of droplets and deposition of the droplets on the wall were reported in a study[3].

Ali et al.[4] simulated a spray drying process to develop a model for particle collision with rough walls and also studied the importance of the particle trajectories and the overall heat and mass transfer. It was found that the particle-wall interaction was one of the critical factors that significantly influenced the average dried powder characteristics. Misha et al.[5] investigated the drying uniformity of new design of the commercial tray dryer for agricultural product and also the temperature and velocity profiles. Streamline and velocity on each tray were analyzed. Besides the experimental investigations on the effects of various process parameters, CFD simulation for optimal design of fixed bed dryer are carried out by Prukwarun et al.[6].

Jang et al[7] aimed to develop the CFD model that would be used to optimize the performance and assist in the scale-up of bubbling fluidized bed. The studies on modelling a heat flow in tray and fluidized bed dryers using CFD techniques have been very limited. So it is intended in the present review to mainly focus on heat flow analysis in a tray drier. In addition, the study also stresses the need of optimization of drying chamber to achieve considerable improvement in the drying characteristics of any materials during drying operation.

Based on the above literature information it was evident that only a few works were concentrated on the effects of various variables on tray drying. In this regard this review provides in depth discussion on the drying variables such as dryer geometry, air velocity and air temperature in tray drying.

METHOD OF DRYING OPERATION

Drying can be carried out by various methods namely batch, continuous and semi batch operations both with the direct contact and indirect contact of air with the drying solids. Here we restrict our discussion to batch operation.

Batch or semi batch equipment is operated at regular intervals under unsteady state conditions and the drier is fed with the substance, which remains in the chamber until it dries. Subsequently the drier is emptied and is charged again with a fresh batch. Continuous drier are usually operated in steady state manner where capacities of production are very high.

There are equations which can be used in the field of drying process to assess the effects of various process variables, such as drying rate, rate of heat transfer, drying time, diffusivity coefficients and also the influence of temperature on drying process. The following equations are pertinent and can be applied for drying operations.

The rate of evaporation is given by[8]

$$k'_g A(Y_s - Y_a) \quad (1)$$

where, k'_g mass-transfer coefficient, kg m^{-2} s^{-1}, A evaporation area, m^2, y_a humidity of air, kg kg^{-1}, y_s humidity of saturated air kg kg^{-1}.

Rate of heat transfer in air drying is given by[8]

$$q = h_c A(T_a - T_s) \quad (2)$$

where, q heat flow rate, J s^{-1}, h_c heat transfer coefficient, J m^{-2} s^{-1} °C^{-1}, T_a dry bulb temperature of air, °C, T_s wet bulb temperature (at food surface), °C.

Time taken to bring down moisture content from initial moisture content (X_1) to final moisture content (X_2) is given by[9]

$$t_d = \frac{M_S}{A} \int_{X_2}^{X_1} \frac{dX}{N} \quad (3)$$

where, t_d drying time, s (or h), X_1 initial moisture content, kg water/kg dry solid, X_2 final moisture content, kg water/kg dry solid, M_S mass of dry solids, kg, N rate of water evaporation, kg m^{-2} h^{-1}. The diffusivity of moisture can be found by using fick's second law for spherical particles and is given by[10]

$$(c/(t = D_{\downarrow}(v)((^{\uparrow}2/(c/t + 2/r (c/(t) \quad (4)$$

Where, D_v diffusivity coefficient m^2/s, r radius of spherical particle, mm.

The effect of temperature on diffusivity can be found by using Arrhenius type equation and is given by [10]

$$D_v = D_0 e^{\frac{-E}{RT}} \quad (5)$$

Where, D_0 is a constant, E is the activation energy in J/mole, R is universal gas constant = 8.3144 J/mole K, *T* is temperature in degrees Kelvin.

Methods of heat supply

In direct driers the heat is supplied fully by direct contact of the substance with the hot gas in to which the moisture evaporates. In indirect driers, the heat is supplied quite independently of the gas used to carry away the vaporized moisture.

Cabinet tray dryer is one of the most flexible and most frequently used dryer in food processing. The cabinet tray dryers are usually operated in a batch manner. It is generally used for drying of low cost foods. It is frequently used for removing initial moisture before shifting the product to some other dryer. A schematic diagram of the dryer is shown in Figure 1. which consists of a heating chamber, heated by steam or electrical coils or by flue gases by combustion of agro waste or by any

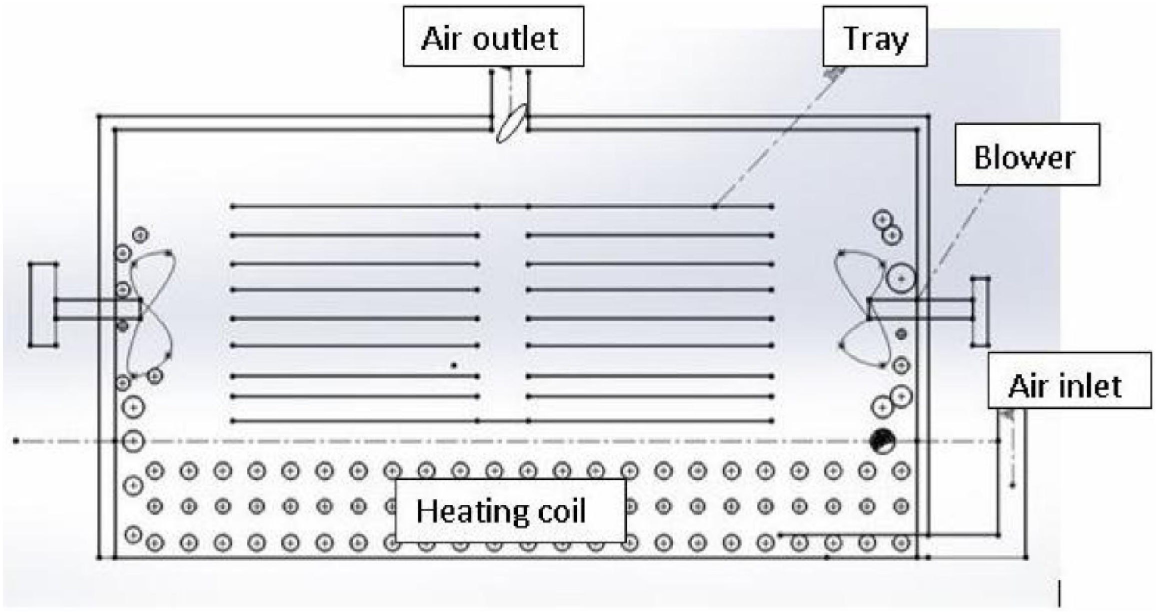

Figure 1 : Schematic representation of a tray drier

other heating source. The drying air is drawn into the chambers by a blower, and the air is heated by contact with the heating elements. It consists of a number of trays, usually multiples of 12, and are made out of stainless steel or aluminium. They may be perforated or plain and are usually of the size 40 cm × 100 cm × 2.5 cm[10]. The food material to be dried is filled into these trays. For 12 and 24 tray dryer, the trays are stacked directly into the heating chamber. If the number is more (viz., 48, 96 and 192), the trays are stacked into a trolley which is later pushed into the heating chamber. The hot convective air currents either pass on the food materials (cross flow) or pass through the food material (through flow), and dry the food material. Usually a part of the air is recirculated, and the rest is drawn afresh through the air inlet, which usually consists of a filter screen to filter the air before entering into the dryer

VARIABLES INFLUENCING DRYING PERFORMANCE

While designing any drying chamber, the drying rate will be evaluated by varying the design and operating variables. The emphasis here is on drying chamber geometry. Apart from this, there are more factors that will influence the rate of drying. The factors affecting the rate of drying will vary slightly with the type of drying system used. However, in general, the following factors must be considered[11]

i. Nature of the material, physical and chemical composition and moisture content, etc.
ii. Size, shape, and arrangement of the substance to be dried;
iii. Relative humidity, or partial pressure of water vapor in the air medium
Iv. Air conditions, namely; air temperature and air velocity

Another factor that must be considered in drying of solid materials is case hardening. This problem can occur if the initial stage of drying occurs at low relative humidity and high temperature. Under these conditions, moisture is removed from the surface of the material much faster than it can diffuse from or within the material. The result is the formation of a hardened relatively impervious layer on the surface of the material. Formation of such a layer will lower subsequent drying rates.

The numerical simulation methods will help us to evaluate temperature, velocity, and pressure profiles inside dryer or system. It is aimed to study the air temperature and air velocity distribution in a typical drier which would enhance the rate of moisture removal in a given set of conditions.

Drying chamber geometry

The drying rate generally depends on the air flow rate, temperature and design of geometry. To assist the above fact, several noteworthy experimental investigations on the effects of varying air velocity;

temperature and geometry configurations were demonstrated by many researchers. Misha et al.[6] studied the effects of varying temperature and air flow rate in a typical tray dryer and the simulation was carried out. The outcomes of these studies revealed that the difference in temperature of about 1.2°C among the trays is considered small, and it can be assumed that the design has successfully achieved the reasonable uniform air temperature in the drying chamber. The average air velocity above the tray is about 0.38 m/s. Misha et al.[12] also performed the simulation to evaluate the drying performance by varying the drying chamber geometry. The simulation was carried out on a tray dryer system using porous and solid products. The simulation outcomes proved that the difference of temperature among the trays for both cases (i.e., porous and solid product) is considered to be small, and it can be assumed that all requirements for a successful design has been achieved in the reasonable uniform air temperature in the drying chamber. It also proved that good air flow distribution throughout the drying chamber can improve the drying uniformity.

Likewise Ghiaus and Gavriliuc[13] investigated the flow parameters for different geometrical configuration and their interpretation led to the optimisation of the tray arrangement, size and position of the inlet opening to achieve the uniform inlet air in the drying space. Besides the experimental investigations on parameters such as the rotational speed of the device fan, the effectiveness of the distribution gaps and the rate of heat generated in the electrical heaters have been tested by Smolkato et al.[14] to improve the temperature uniformity within the chamber. Several changes of the device configurations, such as the location of the heaters, the fan and the fan baffle, have been considered. As a result, the temperature uniformity has been significantly improved. Amanlou et al.[15] has also investigated experimental result with predicted results, their data revealed a very good correlation coefficient of 0.999 and 0.865 for drying air temperature and air velocity respectively in the drying chamber

Drying air temperature

The temperature is one of the important operating parameters to ensure drying characteristics of any drying chamber which has great influence on rate of drying. Chinenye[16] investigated the effect of drying temperature on drying rate. He analysed for three levels of temperatures (55, 70 and 81 °C) for drying rate of cocoa beans. The results showed that the drying rate increased with increase in temperature. Hence it was concluded that the temperature has positive influence on the rate of drying. Galvez et al[17] investigated the effect of temperature and air velocity on drying kinetics. Experiments were conducted at 40, 60 and 80^{0}C, as well as at air velocities of 0.5, 1.0 and 1.5 m/ s. The experimental results showed that the dehydration was faster when air temperature and air velocity increased, which was also reflected in the values obtained for effective moisture diffusivity.

Drying air velocity

Chinenye et al.[16] evaluated and calculated drying rates at different air velocity of 1.3m/s, 2.51m/sand 3.7 m/s, and observed that the draying rate increased with increase in air velocity. Dimitrios et al.[18] developed a new correlation relating the Nusselt number as a function of Prandtl and Reynolds numbers which was intended to correlate for the specific geometric flow configuration. This model is validated against experimental data for different air velocities (1 and 2 m/s) and temperatures (40, 50 and 60 ^{0}C). The model was found to be very useful, computationally proficient and able to capture with sufficient accuracy. Simpson[19] investigated the basic drying rate of individual boards which was found to vary with air velocity at different temperatures. Results showed that drying rate increased with air velocity for moisture contents above approximately 40% to 50%. The results of his study gave guidelines for selecting experimental air velocities in test runs to optimize air velocity for full kiln loads.

CONCLUSION

CFD, research in drying will enhance the design process and understanding of heat, mass and moment transfer. The drier geometry configuration, air velocity and air temperature have much influence on the rate of effective drying. If we can optimize these parameters, we can optimize the industrial drying process easily. The benefits of CFD to the food processing industry in the area of drying are many. In the recent years great development has taken place in these areas.

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