CFD Analysis of Water Content and Minimum Droplet Temperature of Spray Drying Product with Inlet Temperature and Air Flow Direction Variation

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Abstract. This study aimed to analyze the effect of inlet temperature and airflow direction variation of a spray dryer on the product's water content and minimum droplet temperature using the means of computational fluid dynamics (CFD). The airflow direction types were mixed and co-current. The k-ω SST and standard k-ε models were used to simulate the flow, and the Eulerian-Lagrangian approach was used to predict the motion of particles. The simulation results showed that water content decreased as temperature increased for both airflow directions and vice versa for the minimum droplet temperature. A mixed flow spray dryer produced the lowest water content (0%) product with droplets diameter of 10 μm and 30 μm and an inlet temperature of 180 °C. The lowest minimum droplet temperature (32.73 °C) occurred in the mixed flow spray dryer with an inlet temperature of 100 °C.

Keywords: Spray dryer · Water content · Droplet temperature

1 Introduction

Spray drying is a widely used commercial drying process for products such as tea, powdered milk, instant coffee, and vitamins [1, 2]. The low product temperature and short drying time allow the spray-drying method to be used to dry products that are highly sensitive to heat and maintain product qualities such as color, taste, and nutrition [3]. For example, the process of drying tea into powder products generally involves spray drying technology.

A study by Anandharamakrishnan *et al.* [4] and Habtegebriel *et al.* [5] showed that CFD analyses yielded reasonably good predictions of the temperature and velocity

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distributions in the spray dryer compared with the experimental approach. In addition, drying air temperature has been shown to influence the water content of the dried product of the spray dryer—higher drying air temperature results in a product with lower water content [6, 7].

Based on previous descriptions, it has been shown that the inlet temperature of a spray dryer influences the water content of the dried product. Therefore, this study aimed to gain a deeper understanding of inlet temperature and airflow direction variations of a spray dryer on the product's water content and minimum droplet temperature using Computational Fluid Dynamics (CFD) method.

2 Method

2.1 Basic Theory

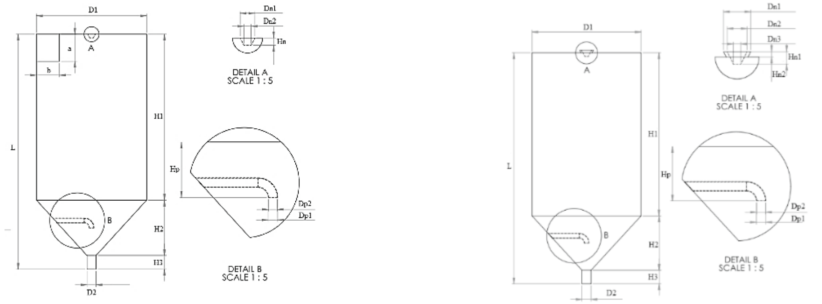
This study used a three-phase flow solution with the Eulerian-Lagrangian approach to predict particle tracking in a spray dryer. The continuous phase is air, while the discrete phase is particles [5]. The particle movement was analyzed using the Eulerian approach by solving the Navier-Stokes equation. The forces acting on particles include drag and gravity. For incompressible fluid flows, the continuity, momentum, and energy equation were used. Finally, the particle trajectory in a stream was calculated using the discrete phase model (DPM) to track individual particles [8].

2.2 CFD Model

The present work used the k-ω SST turbulence model and standard k-ε turbulence model for mixed flow and co-current flow spray dryer to produce more accurate fluid flow characteristics [4, 5, 9, 10]. Figure 1 shows the shape and geometric dimensions of the spray dryer created with SOLIDWORKS. The co-current flow spray dryer design is based on the research of Anandharamakrishnan *et al.* [4]. The dimensions of mixed flow (co-current flow) spray dryer are: body diameter D1 = 600(600), cylinder diameter D2 = 50(50), nozzle diameter Dn1 = 40(81), nozzle diameter 2 Dn2 = 20(55), nozzle diameter 3 Dn3 = (20), inlet dimension a × b = 147 × 125, spray dryer length L = 1275(1275). All dimensions are in millimeters.

Mesh generation of the spray dryer geometry was performed based on the element size using ANSYS Mesh. The body sizing feature with the curvature size function was added to the meshing of the geometry, with tetrahedral cells being the shape of the element. Grid independence analysis was conducted in grid size varied from 0.015 m (coarse mesh) to 0.013 m (fine mesh), shown in Table 1. Gride size of 0.0145 m (medium mesh) was adopted for all following simulations because it gives an acceptable level of grid independence with feasible computational time.

The boundary conditions for the inlet and outlet were the inlet velocity and the outlet pressure. Meanwhile, the boundary condition specified at the spray dryer surface is wall pressure with the following settings: "DPM escape" condition for the spray dryer surface and "reflect" for pipe wall. Drying air intake speed was 8 m/s, the hydraulic diameter is 0.1351 m, the turbulence intensity is 3.94, the initial temperature is 100 °C, 120 °C,



(a) Mixed Flow Spray Dryer (b) Co-current flow spray dryer

Fig. 1. Spray dryer shape and geometric dimensions.

Table 1. Grid independence test results.

Grid	Outlet temperature (°C)
0.0130	32.39
0.0135	33.09
0.0140	32.89
0.0145	32.73
0.0150	34.56

140 °C, 160 °C, and 180 °C, the mass loading value of 0.0015 kg/s, the particle density is 816.4 kg/m^3, and the gas density is 1.225 kg/m^3. Rosin-Rammler distribution was used for the analysis of Particle Size Distribution (PSD), with particle diameter ranging from 10 µm to 130 µm and average diameter $\overline{d}$ of 50 µm [11].

The governing equations were solved numerically using ANSYS Fluent, and SIMPLE scheme was used for pressure-velocity coupling to achieve convergence. The second-order scheme was chosen for pressure discretization to precisely predict velocity and temperature distribution under actual conditions. The first-order upwind scheme was used for the momentum, dissipation rate, and kinetic energy. For discretization of the energy equation, the first-order upwind scheme was adopted to avoid numerical instability and achieve better convergence. The convergence criteria of 1×10^{-4} were applied to all solution variables, and the convergence criteria of 1×10^{-6} was used for the energy equation.

The simulation results in this study were compared with the results of experimental research done by Habtegebriel *et al.*, which showed good agreement with the reference; therefore, the present methodology was adopted for all following simulations [5].

3 Results and Discussion

In this study, the water content in the final product is examined by plotting the simulation results into a graph. Product with lower water content is preferred as it is less likely to be contaminated by microbes, thus increasing the quality of the product [6]. In general, a mixed flow spray dryer resulted in droplets with lower water content than a co-current flow spray dryer. The higher inlet temperature of a mixed flow dryer results in a higher probability of mass flow changes; thus, the water content in the droplets decreases [5].

Figure 2 shows the comparison of the water content in the final dried product between the spray dryer with the mixed and co-current flow. The droplet diameter of 50 µm is given the emphasize as it is the average droplet diameter in this study. It can be seen that in a mixed flow spray dryer, droplets with diameters of 10 µm and 30 µm and inlet temperature of 180 °C have the lowest water content (0%) compared with other droplets diameters. Droplets with the highest water content (58.15%) are 130 µm in diameter and have an inlet temperature of 100 °C. For the spray dryer with the co-current flow, droplets with diameters of 10 µm and 30 µm and an inlet temperature of 180 °C have the lowest water content (0%) compared with other droplet diameters. A droplet with 130 µm has the greatest water content (59.32%) with an inlet temperature of 100 °C.

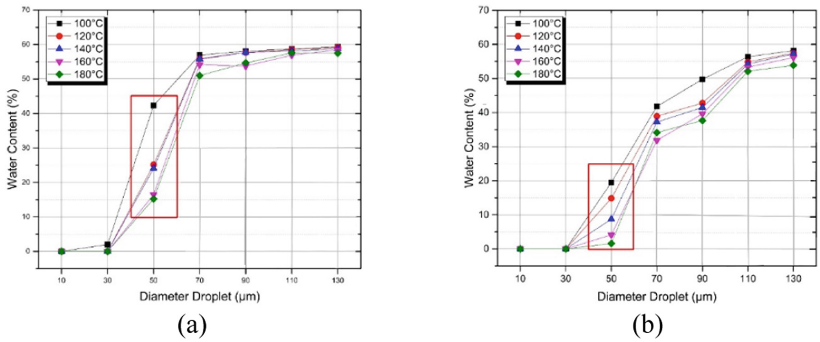


Fig. 2. Comparison of water content in droplets in the drying chamber of (a) Mixed Flow Spray Dryer and (b) Co-Current Flow Spray Dryer.

The minimum temperature of particles that exit the spray dryer influences the product quality and post-drying processes. Increasing the inlet temperature can increase the minimum droplet temperature that exits the spray dryer [12]. Figure 3 shows the comparison of the minimum droplet temperature produced by each spray dryer. The lowest minimum droplet temperature (32.73 °C) occurred in the spray dryer with the mixed flow with an inlet temperature of 100 °C, and the highest (62.85 °C) occurred in the spray dryer with the co-current flow with an inlet temperature of 180 °C.

Co-current flow spray dryer had a higher average minimum droplet temperature compared to the mixed flow spray dryer. This is due to the high-temperature airflow in the co-current flow spray dryer that is concentrated in the center of the drying chamber, which pushes the droplets directly to the outlet [5]. Figure 4 shows the difference in temperature contour and the temperature distribution along the radial direction at several elevations for the mixed flow and co-current flow spray dryer at an inlet temperature of 180 °C.

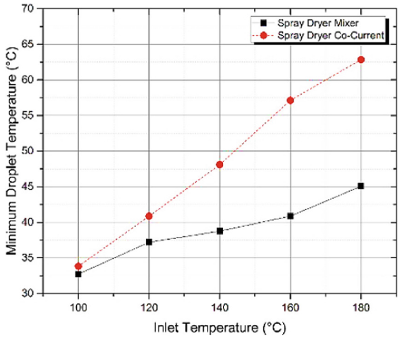


Fig. 3. Minimum droplet temperature in the drying chamber.

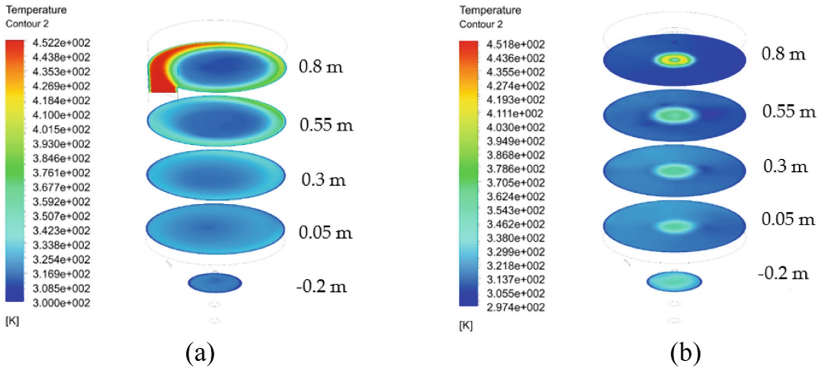


Fig. 4. Temperature contour and temperature distribution of (a) Mixed Flow Spray Dryer and (b) Co-Current Flow Spray Dryer at an Inlet Temperature of 180 °C.

4 Conclusion

This paper presents a study of water content and minimum droplet temperature analysis of spray drying products with inlet temperature and airflow direction variation. It can be concluded that inlet temperature plays a significant role in water content and minimum droplet temperature of spray drying products. Therefore, a mixed flow spray dryer produces a product with lower water content and minimum droplet temperature than a co-current flow spray dryer.

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