

Numerical simulation of secondary air inlet swirl addition on drying process characteristics and spray dryer performance

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ABSTRACT

Tea (*Camellia sinensis*) is one of the most widely consumed beverages, popular for centuries globally, including in Indonesia. The productivity of tea processing is supported by equipment, such as spray dryers, which produce tea in powdered form. This study investigated the effect of adding a secondary air inlet swirl in the drying chamber using computational fluid dynamics (CFD) to analyze its impact on heat and mass transfer, temperature distribution, and overall droplet drying rate. The drying chamber model employed co-current airflow with a swirl effect, simulating three variations of secondary air inlet swirl positions and three inlet air temperature variations (60 °C, 70 °C, 80 °C) to analyze mass transfer processes, distribution of water vapor mass fraction, tea droplet drying, and drying chamber performance. The Realizable k- ϵ turbulence model was used in fluid flow simulation within the drying chamber. Based on the CFD simulation results, adding a secondary inlet swirl at the uppermost position produced a uniform swirling flow from the top to the bottom of the drying chamber. The highest thermal efficiency of 87.52% was achieved with the secondary inlet swirl in the topmost position at an inlet temperature of 60 °C, yielding a droplet evaporation rate of 88.64%.

Keywords: computational fluid dynamics, drying chamber, secondary inlet swirl, evaporation.

INTRODUCTION

Spray drying is a widely used drying method in industrial plants, including food [1, 2]. The working principle of spray drying is to remove moisture by applying heat to the product and controlling the humidity of the drying medium [3]. It can produce dry powder by drying sprayed

(atomized) droplets using hot or drying air [4]. The advantages of spray drying include ease of operation, suitability for continuous and mass production, simple quality control, and the possibility of processing heat-sensitive materials using relatively short times and relatively low temperatures [5]. The shape of the dried powder can vary depending on the operating conditions, for

example, spherical, hollow, circular, or unshaped particles can be obtained [4].

One of the important and main parts of spray drying is the drying chamber, because in this part, the hot air flow will evaporate the moisture from the atomized droplets and change them into powder form [6]. There are two types of flow directions commonly used in the spray drying process, namely co-current flow and counter-current flow. In addition to these two types of flow, there is another type of flow that is generally used to assist the drying process in the drying chamber, namely swirl flow. In co-current flow, droplets are sprayed in the same direction and axis as the hot air inlet, resulting in relatively low drying time characteristics but requiring a fairly high hot air temperature [7–9]. In counter-current flow, droplets are sprayed in the opposite direction to the hot air inlet, resulting in slightly longer drying time characteristics and greater contact of the solution with hot air [10–13]. The use of co-current flow is more suitable for products that are sensitive to heat, including tea products [6]. In addition, the use of swirl flow in the drying chamber produces even contact between droplets and hot air [14, 15]. The selection of the hot air temperature used in the drying chamber has a large influence on the drying process, so it needs to be adjusted to the type of flow to be used [16, 17].

To the best of the authors' knowledge, there is limited research on spray drying with a combination of co-current flow with swirl. The main novelty of this work lies in the structural modification of an existing lab-scale drying chamber by introducing an adjustable secondary air inlet swirl located at different vertical height positions. In this study, a combination of two types of flow, namely co-current and swirl, was carried out to be able to carry out the drying process with a short drying time and still be able to use low temperatures, as well as a minimal agglomeration of particles. The swirl flow in this study is a swirl hot air flow formed due to the influence of the contour or shape of the spray dryer geometry, as given in the research of Poozesh, Lu, and Marsac [18]. Drying analysis in the drying chamber was carried out using the computational fluid dynamics (CFD) method, which can provide more detailed information about the particle drying process in the drying chamber, which is difficult to realize by experimental methods [19].

Based on the explanation above, the main purpose of this research was to analyze the effect

of adding three variations of secondary air inlet swirl position in a spray dryer on the heat and mass transfer that occurs. In addition, there were three variations of the inlet hot air temperature of 60 °C, 70 °C, and 80 °C in the drying chamber. The temperature distribution, mass fraction distribution, and particle drying rate produced by the drying chamber were analyzed.

METHODOLOGY

Simulation model

The drying chamber model analyzed in this study was a newly conceptualized design aimed at overcoming the limitations of standard co-current spray dryers. The geometric dimensions were established based on standard scaling principles from previous literature [4], whereas the placement of the secondary air inlet swirl is a unique feature proposed in this research to combine the advantages of co-current flow and swirl motion. Figure 1 explains the 3D drying chamber model used for simulation. This model has three variations of secondary inlet swirl positions with height variations (C) 1D, 2D, and 3D, as shown in Figure 1 and Table 1.

Gas-liquid flow modeling

The mathematical modeling in the drying chamber flow simulation has been defined in Ansys Fluent Solver. There are several building equations to define the hot air flow and droplet spraying. The mass conservation equation is shown in Equation 1 where ρ is the density and $\vec{u}$ is the velocity vector.

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{u}) = 0 \quad (1)$$

Table 1. Geometric dimensions of the drying chamber

Notation	Dimension (mm)
ϕA	1160
ϕB	101.6
C	150, 300, 450
D	150
E	1820
F	2720.65
G	644.5
ϕH	114

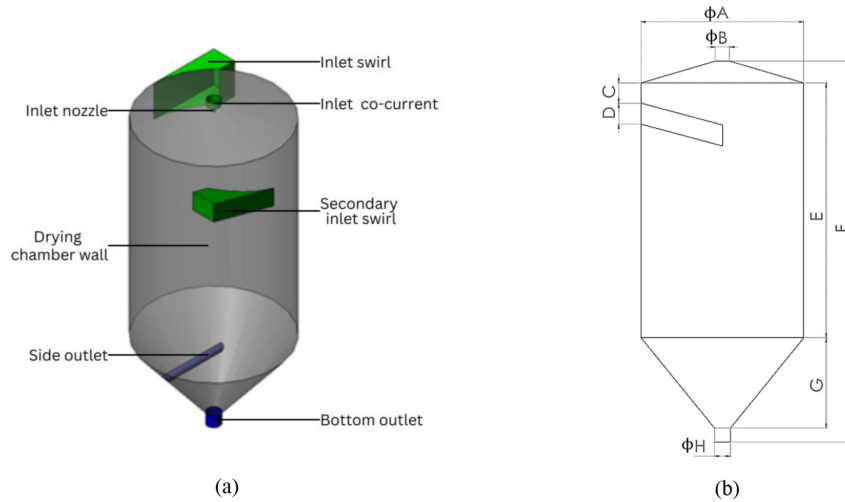


Figure 1. Drying chamber (a) 3D model, (b) model dimensions

The momentum conservation equation for the simulation is shown by Equation 2, where μ is the viscosity of the fluid, $\vec{g}$ is the acceleration of gravity, and $\vec{F}$ is the external force.

$$\frac{\partial(\rho\vec{u})}{\partial t} + \nabla \cdot (\rho\vec{u}\vec{u}) = -\nabla P + \nabla \cdot (\mu(\nabla\vec{u} + \nabla\vec{u}^T)) + \rho\vec{g} + \vec{F} \quad (2)$$

The energy equation for the simulation is described in Equation 3, where E denotes the average energy value, P denotes pressure, T denotes absolute temperature, and S_E denotes volumetric heat source.

$$\frac{\partial(\rho E)}{\partial t} + \nabla \cdot (\vec{u}(\rho E + P)) = \nabla \cdot (k_{eff}\nabla T - \sum h_k J_k) + S_E \quad (3)$$

Turbulence modeling in the flow simulation in the drying chamber uses Realizable k- ϵ because it produces a suitable flow distribution in the drying chamber [20]. This model has the ability to model turbulent viscosity. The model predicts good observations on flows involving rotation, separation, recirculation, and boundary layers with large pressure gradients. In addition, the Realizable k- ϵ model is also suitable for use in modeling impinging jets or jet flows [21]. The transport equations for the realizable k- ϵ turbulence model are given by Equations 4 and 5 [22].

$$\frac{\partial}{\partial t}(\rho_l k) + \frac{\partial}{\partial x_i}(\rho_l k u_i) = \frac{\partial}{\partial x_j} \left[\left(\mu_l + \frac{\mu_t}{\sigma_k} \right) \frac{\partial k}{\partial x_j} \right] + G_k + G_b - \rho_l \epsilon - Y_M + S_k \quad (4)$$

$$\frac{\partial}{\partial t}(\rho_l \epsilon) + \frac{\partial}{\partial x_i}(\rho_l \epsilon u_i) = \frac{\partial}{\partial x_j} \left[\left(\mu + \frac{\mu_t}{\sigma_\epsilon} \right) \frac{\partial \epsilon}{\partial x_j} \right] + \rho_l C_1 S_\epsilon - \rho_l C_2 \frac{\epsilon^2}{k + \sqrt{v_l \epsilon}} + C_{1\epsilon} \frac{\epsilon}{k} C_{3\epsilon} G_b + S_\epsilon \quad (5)$$

where,

$$C_1 = \max \left[0.43, \frac{\eta}{\eta + 5} \right],$$

$$\eta = S \frac{k}{\epsilon}, s = \sqrt{2S_{ij}S_{ij}}$$

where: k denotes the turbulent kinetic energy value, and ϵ denotes the turbulent dissipation rate. σ_k , σ_ϵ , are the Prandtl numbers for k and ϵ . G_k indicates the generation of turbulent kinetic energy due to the mean velocity gradient. G_b denotes the generation of turbulent kinetic energy due to buoyancy. Y_M denotes the contribution of fluctuating dilatation in compressible turbulence to the overall dissipation rate. C_2 and $C_{1\epsilon}$ are constant. S_k and S_ϵ are user-defined source terms.

The Realizable k- ϵ model was selected due to its mathematical formulation for turbulent viscosity, which accounts for rotational and swirling effects better than standard two-equation models. While Reynolds stress models (RSM) capture anisotropic turbulence fully, Realizable k- ϵ provides sufficient accuracy for core recirculation zones and droplet transport at significantly lower computational cost. Near-wall treatment was modeled using Enhanced Wall Treatment, as the primary phenomena of interest (droplet

evaporation and core airflow distribution) occur away from the immediate wall boundary layer.

Boundary condition

A tea solution with air is sprayed through a nozzle with boundary conditions as a pressure inlet that has a temperature of 26.85 °C. The composition of the tea solution is 0.68, and air is 0.32. Hot air flows from above through the co-current inlet, swirl inlet, and secondary inlet swirl with boundary conditions as a velocity inlet. The turbulence intensity at the air inlet is 5%. The hydraulic velocity and diameter of hot air at each inlet are shown in Table 2. The discrete phase interaction with the drying chamber walls was set to the reflect boundary condition. This setup allows the particles hitting the wall surface to rebound back into the fluid domain with a specified restitution coefficient, enabling continuous calculation of full particle trajectories until they exit through the outlets [23]. While this boundary condition is a simplified numerical representation that does not account for potential wall deposition, particle sticking, or agglomeration commonly observed in real spray drying of cohesive materials like tea extracts, it provides a consistent baseline for comparing particle residence time and spatial distribution across the proposed geometric variations. The potential impact of this assumption on residence time overestimation and outlet collection fractions represents a known limitation of the current discrete phase model (DPM) setup. A comprehensive summary of the computational parameters, DPM settings, particle injection conditions, and convergence criteria used in this study is consolidated in Table 3.

Grid independent test

Mesh generation was performed using ANSYS Mesh with tetrahedral elements. Five grid configurations were generated by varying the global element size from 0.00225 m to

0.00475 m, corresponding to an estimated element count ranging from approximately 2.08×10^6 to 19.62×10^6 elements. The grid independence test evaluated the outlet bottom temperature across these variations. Based on the results, Mesh 3 (element size = 0.00325 m, consisting of 6,507,829 elements) was selected for all final production simulations, as it achieved numerical convergence with a relative error below 0.3% relative to the finest grid resolution while maintaining computational efficiency. The results of the meshing structure can be seen in Figure 2. The values of skewness and orthogonal quality can be seen in Table 4. It can be seen that the maximum value of skewness and minimum orthogonal quality obtained has entered the acceptable class.

The grid independence test is conducted to obtain stable simulation results, but not to burden the computer hardware. Grid independence test can guarantee that the meshing done is good and does not cause errors in simulation results. Grid tests were conducted for element sizes of 0.00225, 0.00275, 0.00325, 0.00425, and 0.00475 m. The grid independence test results of the drying chamber geometry are shown in Figure 3. The parameter used as a comparison in this grid test is the outlet temperature. From Figure 3, it can be seen that there is no significant error value, where all error values are below 5%. The grid independence test results show that the simulation results will not produce significant errors.

The application of the near-wall mesh in this simulation needs to be verified for the turbulence model. The influence of the wall boundary layer is considered so that the meshing of the drying chamber is perfect. The average y^+ value in the drying chamber is required to be close to 1 [24]. Figure 4 shows the y^+ contours of the simulation in the drying chamber. The y^+ value in the drying chamber is basically maintained close to 1 except for a small change in the outlet section, with a y^+ value that is still below 10, so it is considered that the boundary layer inflation is reliable [25].

Table 2. The inlet velocity and hydraulic diameter of each inlet

Inlet	Velocity (m/s)	Hydraulic diameter (m)
Inlet co-current	12.848	0.1
Inlet swirl	2.604	0.24
Secondary inlet swirl	5.208	0.171

Table 3. Summary of CFD simulation parameters, discrete phase model (DPM) settings, and numerical boundary conditions

Parameter category	Numerical setting	Value or details
Convergence criteria	Scaled residual monitors	$\leq 10^{-6}$ (Energy equation) $\leq 10^{-3}$ (Momentum, continuity, turbulence, species)
	Balance checks	Global mass and energy balance checks
Particle injection conditions	Nozzle orifice diameter	0.5 mm
	Spray cone angle	60°
	Liquid mass flow rate	0.0012 kg/s
	Tracked particle streams	2,500 parcels
Droplet size distribution	Distribution model	Rosin-Rammler
	Droplet diameter range	15–35 μm
	Mean diameter	24.5 μm
	Spread parameter	3.2
Evaporative model	Heat and mass transfer	Spalding convective evaporation model
	Coupling	Two-way phase momentum, energy, and moisture coupling
Wall boundary conditions	Continuous gas phase	Stationary, non-slip wall condition
	Discrete phase (Droplets)	Reflect boundary condition

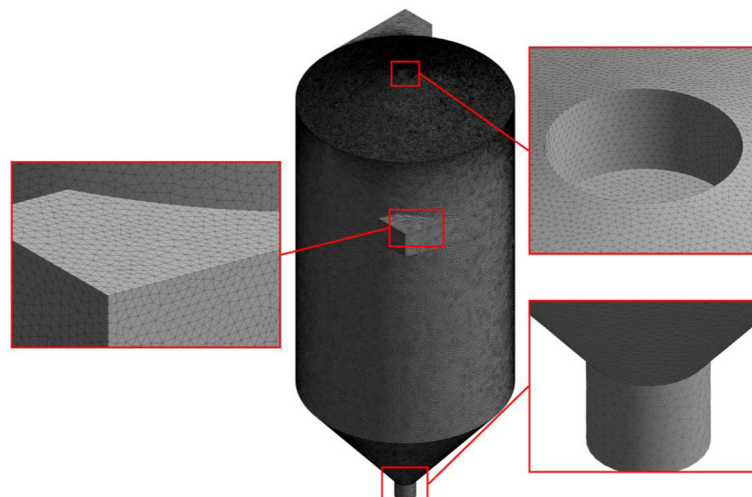


Figure 2. Drying chamber meshing structure

Table 4. Skewness and orthogonal quality mesh values of drying chamber geometry

Skewness	Value	Orthogonal quality	Value
Minimum	6.5315e-005	Minimum	0.15604
Maximum	0.89396	Maximum	0.99795
Average	0.21551	Average	0.78325
Standard deviation	0.11705	Standard deviation	0.11548

Simulation validation

The numerical simulation setup must be validated to verify solver settings, grid dependency, and physical model accuracy. In this study, a

baseline simulation model was validated against the numerical data published by Okada et al. [4]. To ensure comparability between the two numerical studies, equivalent geometric scaling, boundary conditions (inlet air velocity and temperatures),

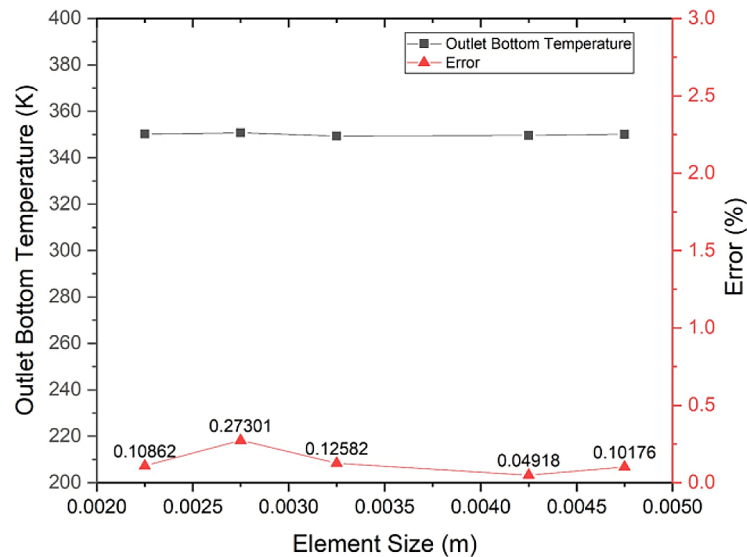


Figure 3. Grid independence test

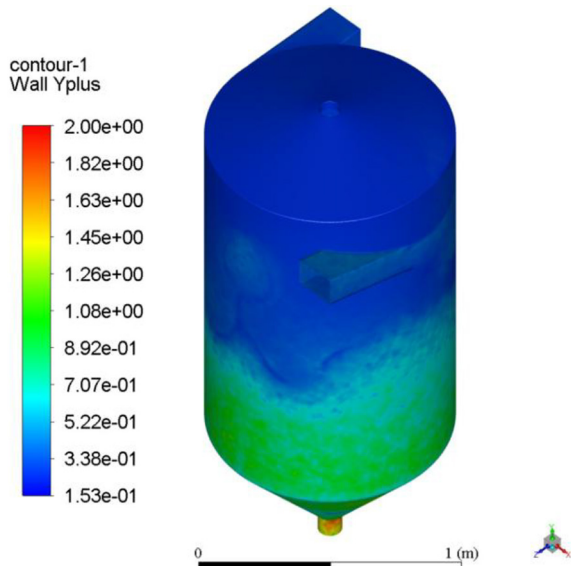


Figure 4. Contour y+ meshing drying chamber

discrete phase properties, and injection parameters were applied in the baseline validation setup. As shown in Figure 5, the predicted outlet temperatures show strong agreement with the benchmark results of Okada et al. [4], yielding a maximum relative error of 2.381% at 435 K, which is well within the acceptable limit of 10% [26].

Due to physical equipment and experimental testing limitations, direct empirical validation on the physical lab-scale prototype could not be conducted in this work, which represents a limitation of the present study. However, the close alignment with established numerical literature [4] confirms that the selected numerical schemes,

turbulence models, and discrete phase setups are reliable for evaluating the proposed drying chamber modifications.

RESULT AND DISCUSSION

Simulation result data collection position

The position of the qualitative data observations was carried out on a horizontal cross-section at each drying chamber elevation, determined according to Table 5. The elevation positions used were selected based on the analysis needed to observe the droplet drying phenomenon at the inlet area, the center of the drying chamber, the side outlet area, and the bottom outlet area. The variations in this study are the inlet air temperature of 60 °C, 70 °C, 80 °C, and the position of the secondary inlet swirl with 1D, 2D, and 3D heights.

Flow characteristics in drying chamber

One of the main parameters discussed in this study is the flow pattern in the drying chamber due to the presence of co-current flow and swirl flow, which is strengthened by the addition of a secondary inlet swirl. The streamlined flow pattern in the drying chamber is shown in Figures 6 and 7 to make it easier to see the flow pattern formed. Figure 6 qualitatively illustrates the full 3D swirling path and spatial flow coverage inside the chamber, while the detailed internal recirculation zones and local velocity behavior are further

Table 5. Elevation position

Code	Position of Y axis
Y1	-0.20615 m
Y2	-1.11212 m
Y3	-2.01615 m
Y4	-2.52065 m

detailed in the 2D cross-sectional view in Figure 7. In the 1D variation where the secondary inlet swirl position is at the top, the flow from the secondary inlet swirl rotates towards the top of the drying chamber uniformly before being pushed down by the co-current flow. In the 2D variation, most of the flow from the secondary inlet swirl produces a dense vortex near the top wall of the drying chamber and is then pushed down

by the co-current flow as well. Meanwhile, most of the flow from the secondary inlet swirls in the 3D variation is pushed down the drying chamber and triggers a backflow from the bottom to the top of the drying chamber. In general, the swirl flow in the drying chamber is quite widespread in the drying chamber, but is still weak at the top of the drying chamber. The swirl flow in droplet drying is very suitable for drying tea, which cannot be exposed to hot air at high temperatures and relies on the length of contact time [27].

Temperature distribution characteristics

Temperature is one of the important parameters in the drying process. Temperature observations in the drying chamber are presented in the form of elevation graphs ranging from Y1 to Y4,

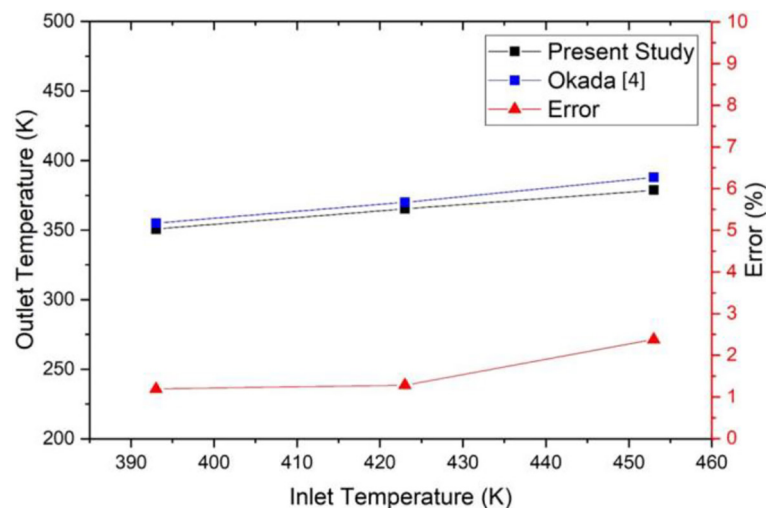


Figure 5. Simulation validation with Okada et al. [4] of bottom outlet temperature parameters

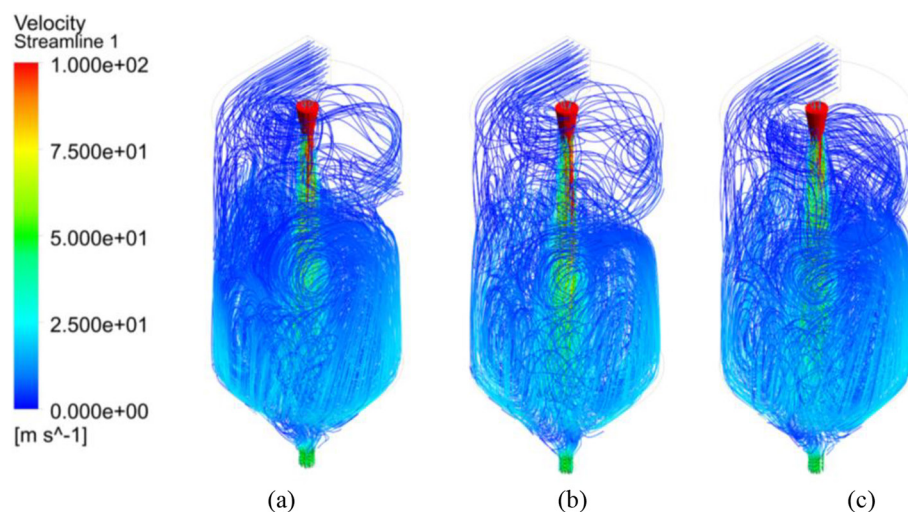


Figure 6. Velocity flow streamline drying chamber (a) 1D variation (b) 2D variation (c) 3D variation

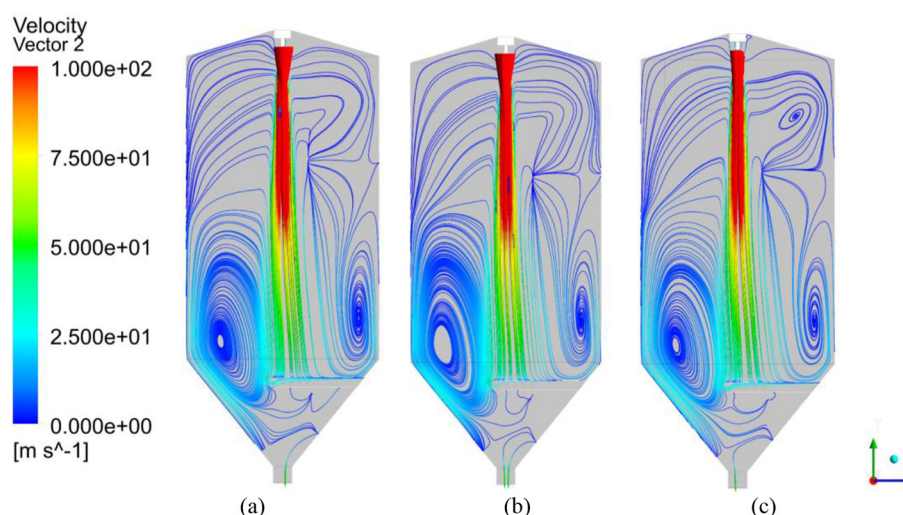


Figure 7. Velocity flow streamline drying chamber in x-center (a) 1D variation (b) 2D variation (c) 3D variation

shown in Figure 8. From all variations, it can be seen that the air temperature will decrease when it reaches the low elevation point of Y4; this happens because there has been a heat transfer process from hot air to droplets during the evaporation process [28]. From all conditions, it can be seen that the temperature on the radial center side has a lower value than the surrounding side due to the injection of droplets in the area, which makes the temperature value low. At elevation Y2, the temperature value starts to fluctuate due to the influence of swirl flow. At radial positions -0.3 m to -0.14 m , the temperature distribution at elevation Y3 approaches the temperature value at elevation Y2. This occurs because at elevation Y3 on the negative side of the radial center has a continuous swirling flow, causing a fast temperature distribution and a fluctuating graph. In turn, on the positive side of the radial center, there are side outlets that cause obstructed flow so that the temperature distribution is more stable. Low outlet temperature is one of the desirable things in a spray dryer. Low outlet temperature indicates that the heat from the inlet air is used better to evaporate the water content of the droplets; besides that, the high particle temperature can trigger the absorption of water vapor again due to the relatively higher particle temperature from the ambient air.

Distribution characteristics of H_2O mass fraction

The distribution of the H_2O mass fraction in the drying chamber for each variation is presented in the form of a graph at each elevation, which

can be seen in Figure 9. The drying air used must have a small H_2O mass fraction value to maximally release water vapor content from the droplets. From the figure, it can be seen that the H_2O mass fraction value at the Y1 elevation position at the radial center or the position below the inlet nozzle has the highest value. This is different from the Y1 elevation position, which is not at the radial center, where the H_2O mass fraction value is very low because this is the area of hot air inflow, which has a very low humidity value. The figure shows that the H_2O mass fraction value will be more stable and flat when approaching the outlet position, which occurs due to the transfer of heat and mass from the droplets to the hot air, which is approaching equilibrium conditions. At the radial position of -0.3 m to -0.22 m , the H_2O mass fraction value at elevation Y3 is close to elevation Y2 because at elevation Y3, at the negative position of the radial center, there is a continuous swirling flow, which causes the evaporation process to be faster, so that it has a high H_2O mass fraction value. At elevation positions Y3 and Y4, the H_2O mass fraction value is stable at each variation, which indicates that the droplet evaporation process is optimal so that the H_2O mass fraction content at each position does not have a significant difference, even though it has different hot air temperature variations [16].

Distribution characteristics of $\text{H}_2\text{O(l)}$ mass fraction

Observation of the distribution characteristics of $\text{H}_2\text{O(l)}$ mass fraction is important in the droplet

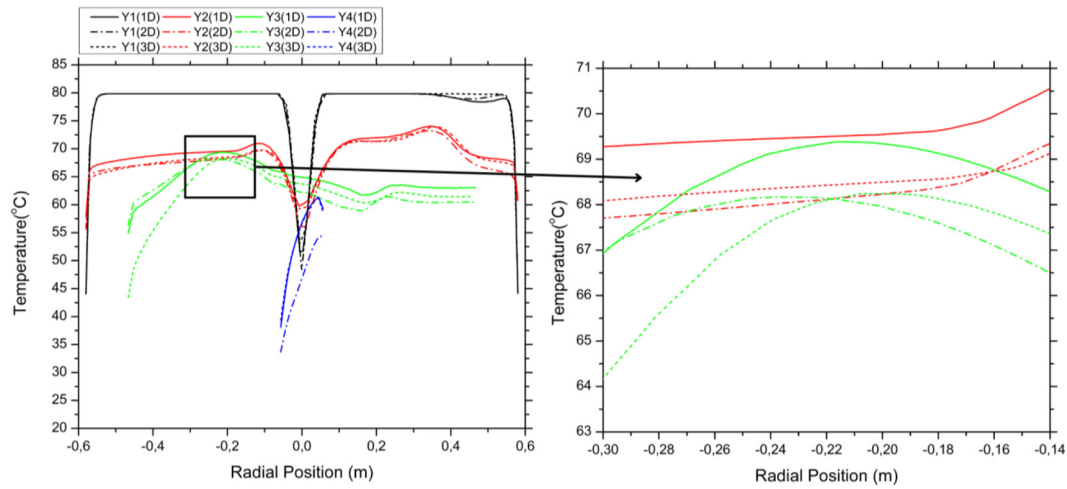


Figure 8. Temperature plot at each elevation

drying process. Droplets sprayed from the nozzle contain 60% $H_2O(l)$ mass fraction, and it will be observed how variations in the secondary inlet swirl and hot air temperature can affect the $H_2O(l)$ mass fraction in the air due to mass transfer from the droplets. Observation of the distribution characteristics of $H_2O(l)$ mass fraction is presented in a graph at each elevation in the drying chamber shown in Figure 10. The figure shows the distribution of the $H_2O(l)$ mass fraction across different elevations in the drying chamber. While the evaporation process continuously reduces the liquid mass fraction of individual droplets, the $H_2O(l)$ mass fraction near the outlet position (Y4) exhibits higher localized values. This increase is not caused by evaporation, but rather by the flow dynamics and swirling air pattern, which induce droplet entrainment and transport fine unevaporated droplets upward toward the exit zone [29]. The

$H_2O(l)$ mass fraction value continues to fluctuate, especially at the side outlet or at Y3. At elevation Y3, the $H_2O(l)$ mass fraction value on the positive side of the radial center has a more stable value compared to the negative side of the radial center because the stagnation point above the side outlet pipe causes droplet accumulation, making the $H_2O(l)$ mass fraction more stable. On the other hand, on the negative side of the radial center, the $H_2O(l)$ mass fraction value fluctuates and decreases at positions -0.3m to -0.14m because there is a continuous swirling hot air flow from the hot air inlet, so that the evaporation process is faster.

Particle diameter

One of particle parameters that can be used as a basis to describe how the flow occurs in the drying chamber is the diameter of the particles. In

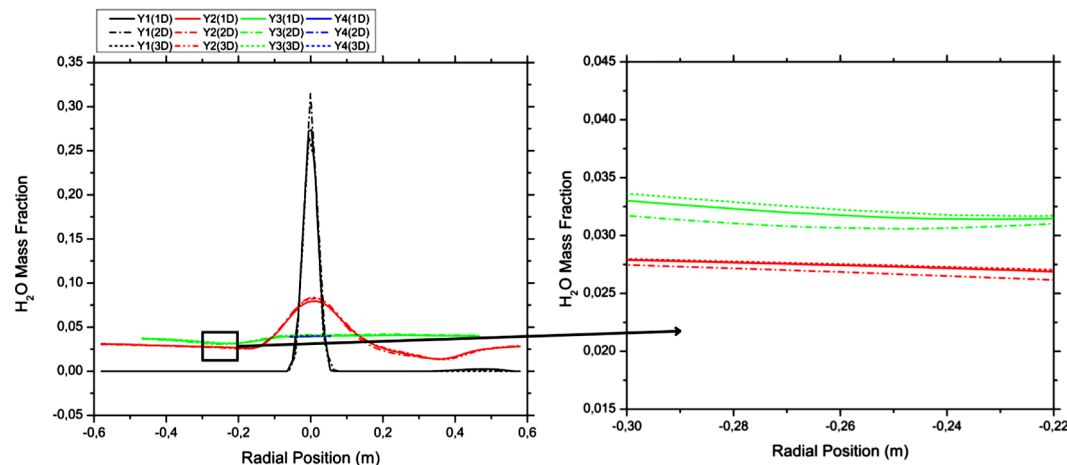


Figure 9. Plot of H_2O mass fraction at each elevation

this study, the injection droplet diameter size used was $15\ \mu\text{m}$ - $35\ \mu\text{m}$, where these particles will experience a change in diameter during the drying process in the drying chamber, as seen in Figure 11. Particles experience a decrease in diameter over time of contact with hot air, so there will be a decrease in diameter that varies for each particle [30]. The particle diameter is also related to the evaporation that occurs in the droplet. Droplets that are well evaporated will have a smaller diameter compared to their initial diameter. In Figure 10, it is known that dry particles with large diameters will immediately exit through the bottom outlet because they are difficult to carry with the drying air [27], but particles with small diameters will follow the air recirculation flow, so that these small particles that are blue to green in color are carried back to the top

of the drying chamber due to the air recirculation flow and continue to rotate in the drying chamber until they finally exit through the side outlet or exit through the bottom outlet.

Particle end position

The particle end position shows the percentage of particles exiting each outlet. This value indicates the characteristics of the particle flow exiting the drying chamber. Particle end position data and the total mass of particles exiting each outlet are presented in the form of a graph shown in Figure 12. The figure shows that the percentage of particles exiting the bottom outlet is much greater than the percentage of particles exiting the side outlet. This happens because heavier particles will fall more easily and exit through

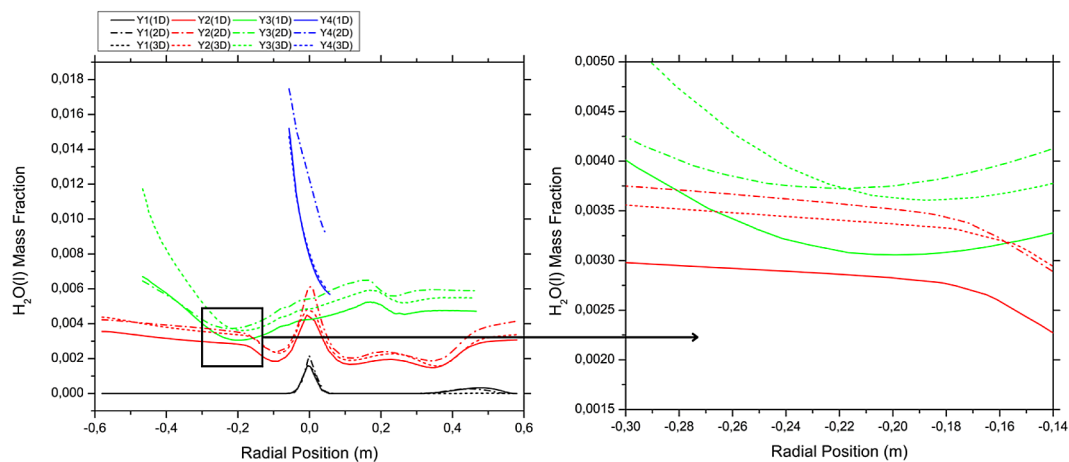


Figure 10. Plot of $\text{H}_2\text{O}(\text{l})$ mass fraction at each elevation

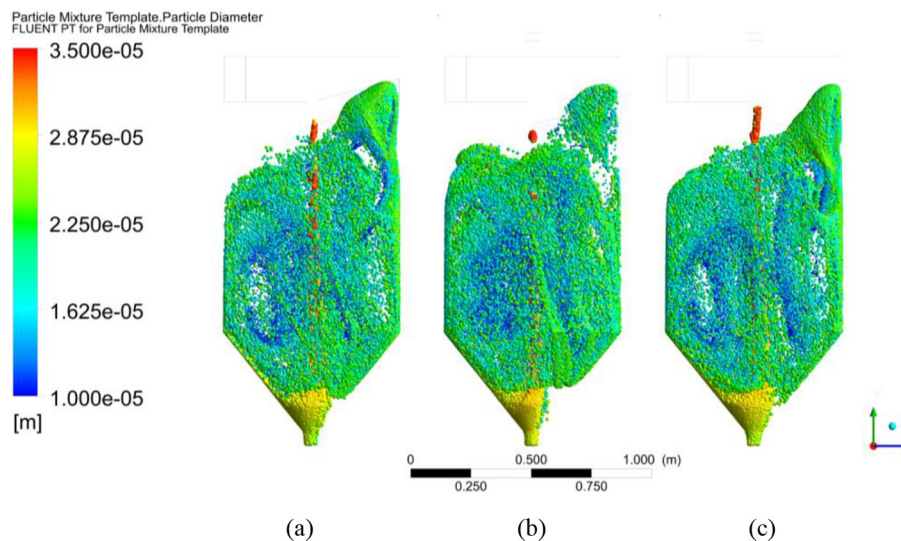


Figure 11. Particle diameter (a) 1D variation (b) 2D variation (c) 3D variation

the bottom outlet [31]. At the same temperature variation, it appears to follow the same pattern, where the 1D variation has a higher percentage of particles exiting the bottom outlet, and the 3D variation has a higher percentage of particles exiting the side outlet. The graph also shows that the 1D variation produces the lowest particle mass exiting the bottom outlet, while the 2D variation is the highest. In addition, at a temperature variation of 80 °C, the total particle mass is the lowest, while the temperature variation of 60 °C has the highest total particle mass.

Particle H₂O(l) evaporation

The last parameter describes the evaporation of water content in the particles. The data shows the percentage reduction of H₂O(l) mass fraction in particles from each variation, and the average residence time of particles in the drying chamber is explained in Figure 13. From the graph, it can be seen that the percentage of evaporation at the side outlet is always higher than at the bottom outlet. This is also in line with the average residence time of particles at the side outlet, which is longer

than at the bottom outlet. In the 1D variation, it can be seen that particle drying, especially at the bottom outlet, has a higher evaporation of compared to the 2D and 3D variations. This occurs in all variations of inlet air temperature, which indicates that the 1D variation has better particle drying performance. The swirl flow in the drying chamber will increase the particle residence time so that the particles can contact the hot air longer, then produce a drier final product. The residence time for each variation of the secondary inlet swirl is consistent with the results of research by Zhang et al., explaining that the time for particles to be fully exposed to hot air in the swirl flow is from 0.05–0.3 s [18]. Another study by McDonagh and Tajber also supports this where the droplet drying time for particles measuring 15 µm to 30 µm is from 0.03 s to 0.15 s [32], so it can be seen that for particles with a size of less than 25 µm, it will be Substantially evaporated when the particles exit the drying chamber with the highest average residence time occurring at the bottom outlet in the 1D flow variation of 0.0723 s. However, the drying of some particles with a larger size is still not optimal, so the maximum evaporation that

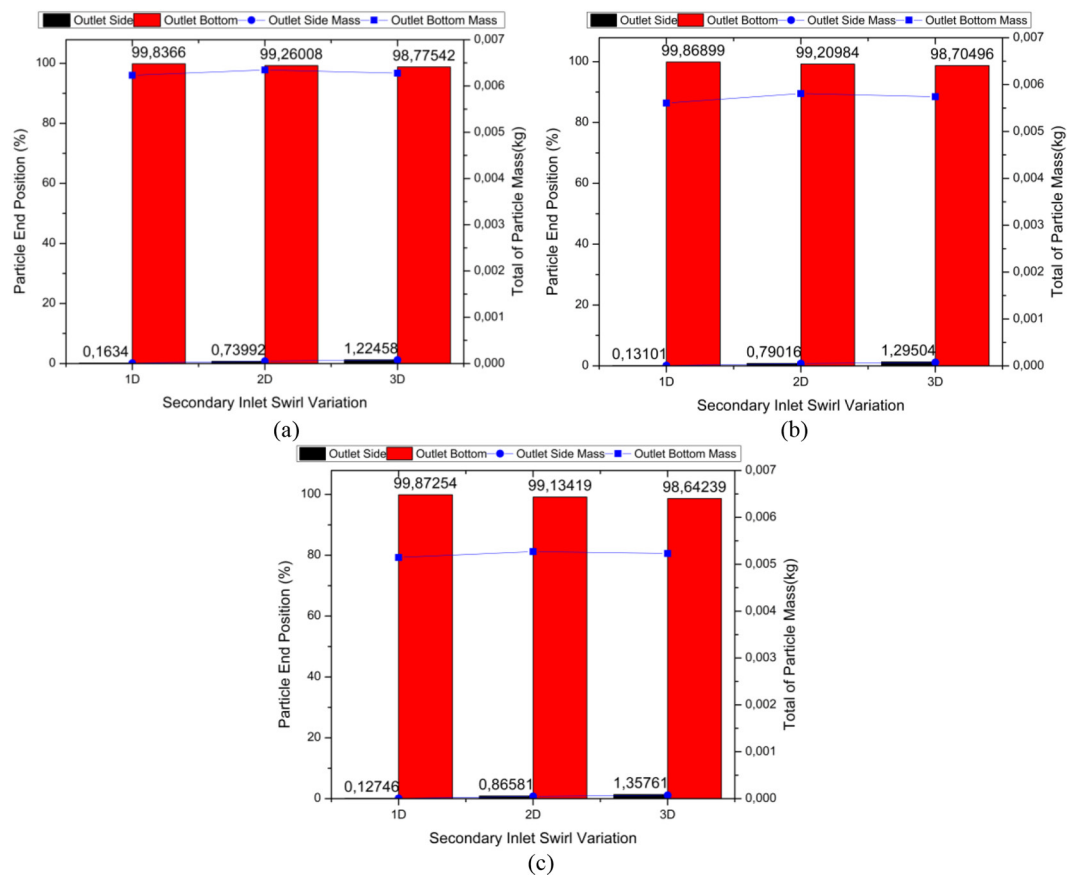


Figure 12. Particle end position at (a) 60 °C (b) 70 °C (c) 80 °C

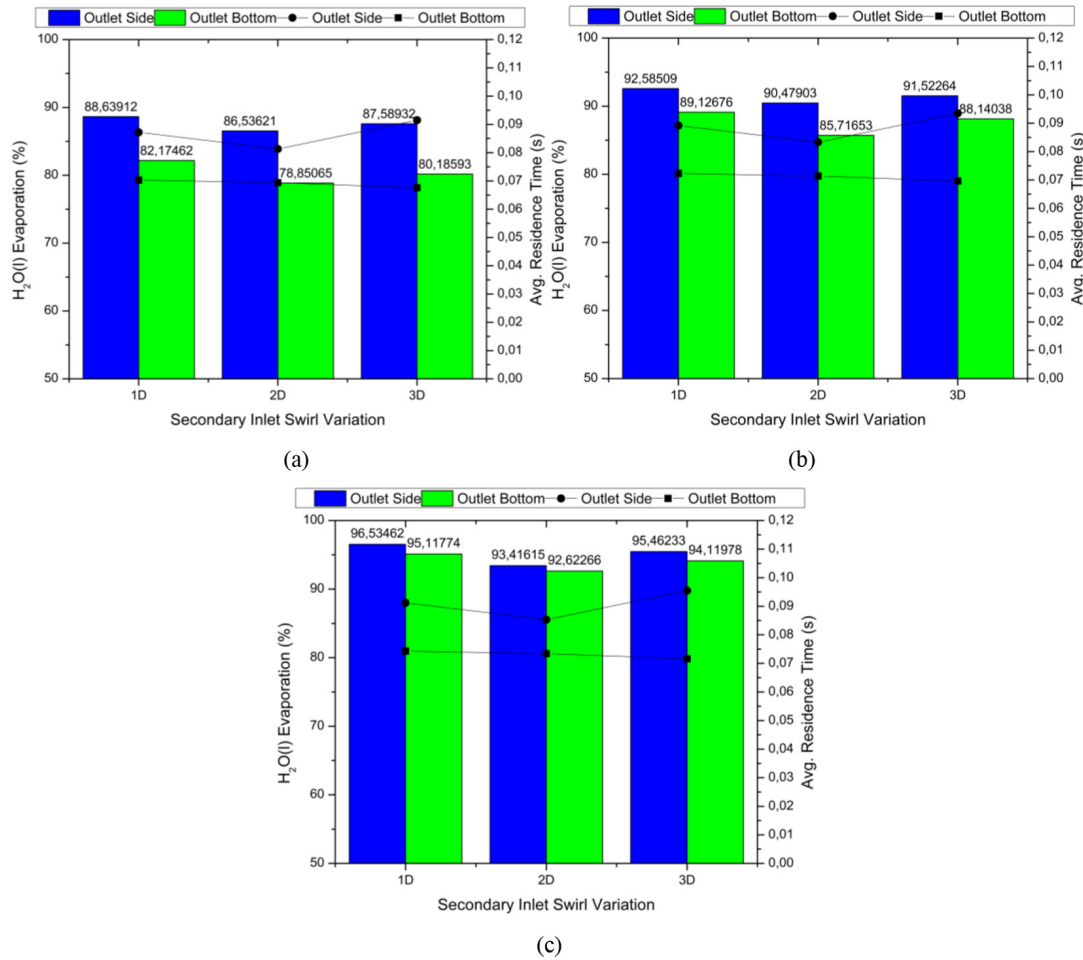


Figure 13. Particle H₂O evaporation at (a) 60 °C (b) 70 °C (c) 80 °C

can be achieved is only 96.53% at the bottom outlet. The final product results from the spray dryer in each variation can be said to have met the dryness standards for powdered food ingredients, as stated in the research of Opaliński, Chutkowski, and Hassanpour (2016) that for food and beverage products, they must have a maximum.

In addition to particle drying data, the parameter used to see the characteristics of the drying chamber outlet is the temperature, which can be seen in Figure 14. The outlet temperature affects the final water content and surface topography of the resulting product [34]. If the outlet temperature is too high, the particles that come out will also have a high temperature, and if the particle temperature is much higher than ambient conditions while the water content in the particles is low, then the particles will most likely reabsorb water content from the ambient air [35]. The decrease in the lower outlet temperature is approximately 30 °C from the inlet hot air temperature, according to the research by McDonagh

and Tajber [36]. The large temperature decrease indicates that the heat in the hot air is transferred or used very well toward the particles to release the water content in the particles [37]. The highest temperature decrease was achieved in the 1D variation with an inlet temperature of 80 °C, with a decrease of 35.7 °C.

By using the outlet air temperature data, the simplified temperature-based thermal efficiency indicator (η_T) of the drying chamber can be estimated using Equation 6 as follows [38]:

$$\eta_T = \frac{T_{Ai} - T_{Ao}}{T_{Ai} - T_{amb}} \times 100\% \quad (6)$$

where: T_{Ai} is the air inlet temperature, T_{Ao} is the air outlet temperature, and T_{amb} is the ambient air temperature.

It should be noted that η_T represents a simplified temperature-based indicator of thermal effectiveness, rather than the overall thermodynamic efficiency of the spray dryer. A comprehensive

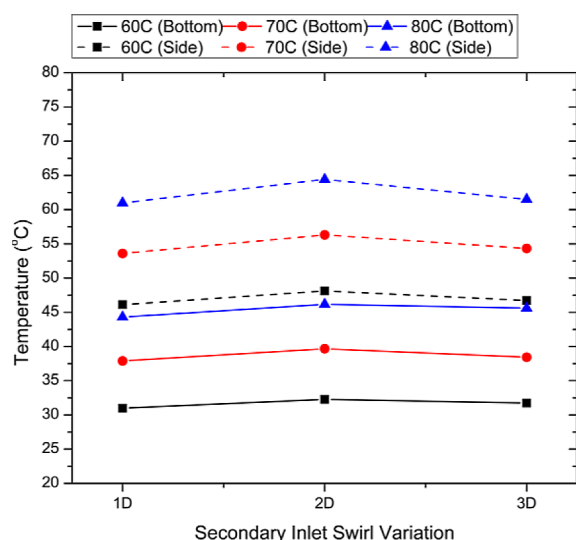


Figure 14. Outlet temperature

efficiency assessment would require accounting for feed and air mass flow rates, wall heat losses, latent heat of vaporization, and overall auxiliary energy consumption.

Using this comparative approach, the estimated thermal efficiency indicator for an inlet temperature of 60 °C with variations of 1D, 2D, and 3D is 87.52%, 83.61%, and 85.27% , respectively. For an inlet temperature of 70 °C with variations of 1D, 2D, and 3D, the values are 74.41%, 70.28%, and 73.16%, respectively. Finally, for an inlet temperature of 80 °C with variations of 1D, 2D, and 3D, the resulting indicators are 67.16%, 63.66%, and 64.70%, respectively.

CONCLUSIONS

This study investigated the effects of secondary inlet swirl position (1D, 2D, and 3D) and inlet hot air temperature (60 °C, 70 °C and 80 °C) on the airflow dynamics, thermal behavior, and droplet evaporation performance inside a spray drying chamber using CFD simulations. The main conclusions drawn from this research are as follows:

- Airflow patterns and recirculation: The vertical position of the secondary inlet swirl significantly influences the internal vortex structure. The 1D configuration establishes a strong central swirl near the top, promoting extended particle transport toward the lower chamber. In contrast, the 3D variation pushes the main flow downward, triggering a central upward

backflow that alters droplet paths toward the upper region.

- Particle exit distribution and residence time: The 1D position directs the highest fraction of particles toward the bottom outlet while extending particle residence time (≈ 0.09 s) due to deep recirculation in the lower cone. Conversely, the 3D configuration leads to a higher proportion of particles exiting through the side outlet.
- Evaporation and thermal performance: Increasing the inlet air temperature enhances moisture evaporation across all geometric variations. Among the configurations tested, the 1D variation at an inlet temperature of 60 °C achieved the highest temperature-based thermal efficiency indicator ($\eta_T = 87.52\%$) with a droplet $H_2O(l)$ evaporation percentage of 88.64%. Overall, positioning the secondary inlet swirl at 1D provides superior thermal effectiveness and improved particle collection at the bottom outlet.

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REFERENCES

1. Sim J. W., Lee H., Jo S., Oh S., Kim S., and Kim D. R., Increasing energy saving of pilot-scale spray dryers with enhanced yield by low-adhesive surfaces, *Case Stud. Therm. Eng.*, 2023, 49, April, 103218, <https://doi.org/10.1016/j.csite.2023.103218>
2. van Boven A. P. et al., Investigating the impact of air distribution on spray dryer operability using CFD simulations and pilot-scale experiments, *Powder Technol.*, 2024, 440, no. March, 1–15, <https://doi.org/10.1016/j.powtec.2024.119779>
3. Anandharamakrishnan S. P., C.; Ishwarya, *Spray Drying Techniques for Food Ingredient Encapsulation*-Wiley-Blackwell 2015.
4. Okada S., Ohsaki S., Nakamura H., and Watano S., Estimation of evaporation rate of water droplet group in spray drying process, *Chem. Eng. Sci.*, 2020, 227, 115938, <https://doi.org/10.1016/j.ces.2020.115938>

5. de Melo Ramos F., Ubbink J., Silveira Júnior V., and Prata A. S., Drying of Maltodextrin solution in a vacuum spray dryer, *Chem. Eng. Res. Des.*, 2019, 146, 78–86, <https://doi.org/10.1016/j.cherd.2019.03.036>
6. Gunjal S. D. and Shirolkar S. V., An overview of process parameters and spray drying agents involved in spray drying of herbal extracts, *Paid. J.*, 2020, XIII(Vii), 102–118.
7. Jin Y. and Chen X. D., Entropy production during the drying process of milk droplets in an industrial spray dryer, *Int. J. Therm. Sci.*, 2011, 50(4), 615–625, <https://doi.org/10.1016/j.ijthermalsci.2010.10.013>
8. Salem A., Ahmadelouiedarab M., and Ghasemzadeh K., CFD approach for the moisture prediction in spray chamber for drying of salt solution, *J. Ind. Eng. Chem.*, 2011, 17(3), 527–532, <https://doi.org/10.1016/j.jiec.2010.10.023>
9. Cotabarren I. M., Bertín D., Razuc M., Ramírez-Rigo M. V., and Piña J., Modelling of the spray drying process for particle design, *Chem. Eng. Res. Des.*, 2018, 132, 1091–1104, <https://doi.org/10.1016/j.cherd.2018.01.012>
10. Jaskulski M., Wawrzyniak P., and Zbiciński I., CFD model of particle agglomeration in spray drying, *Dry. Technol.*, 2015, 33(15–16), 1971–1980, <https://doi.org/10.1080/07373937.2015.1081605>
11. Shakiba S., Mansouri S., Selomulya C., and Woo M. W., The role of the intermediate stage of drying on particle in-situ crystallization in spray dryers, *Powder Technol.*, 2018, 323, 357–366, <https://doi.org/10.1016/j.powtec.2017.10.018>
12. Olufemi B. A. and Ayomoh M. K., Parametric optimization and statistical evaluation of a spray dryer for the evaporation of caustic soda solution, *Heliyon*, 2019, 5(7), e02026, <https://doi.org/10.1016/j.heliyon.2019.e02026>
13. Jubaer H. et al., Computationally inexpensive simulation of agglomeration in spray drying while preserving structure related information using CFD, *Powder Technol.*, 2020, 372, 372–393, <https://doi.org/10.1016/j.powtec.2020.05.111>
14. Hernandez B., Fraser B., Martin De Juan L., and Martin M., Computational fluid dynamics (CFD) modeling of swirling flows in industrial counter-current spray-drying towers under fouling conditions †, *Ind. Eng. Chem. Res.*, 2018, 57(35), 11988–12002, <https://doi.org/10.1021/acs.iecr.8b02202>
15. A. G. Suárez J., Mejía A. G., and Uruña C. H. G., Low-cost eddy-resolving simulation in the near-field of an annular swirling jet for spray drying applications, *ChemEngineering*, 2021, 5(4), 1–22, <https://doi.org/10.3390/chemengineering5040080>
16. Ren W. et al., Effects of spray-drying temperature on the physicochemical properties and polymethoxyflavone loading efficiency of citrus oil microcapsules, *Lwt*, 2020, 133(July), 109954, <https://doi.org/10.1016/j.lwt.2020.109954>
17. Tan S., Zhong C., and Langrish T., Encapsulation of caffeine in spray-dried micro-eggs for controlled release: The effect of spray-drying (cooking) temperature, *Food Hydrocoll.*, 2020, 108(June 2019), 105979, <https://doi.org/10.1016/j.foodhyd.2020.105979>
18. Poozesh S., Lu K., and Marsac P. J., On the particle formation in spray drying process for biopharmaceutical applications: Interrogating a new model via computational fluid dynamics, *Int. J. Heat Mass Transf.*, 2018, 122, 863–876, <https://doi.org/10.1016/j.ijheatmasstransfer.2018.02.043>
19. Chen K., Bachmann P., Bück A., Jacob M., and Tsotsas E., CFD simulation of particle residence time distribution in industrial scale horizontal fluidized bed, *Powder Technol.*, 2019, 345, 129–139, <https://doi.org/10.1016/j.powtec.2018.12.086>
20. Habtegebriel H., Edward D., Motsamai O., Wawire M., Seifu E., and Daniel S., The potential of computational fluid dynamics simulation to investigate the relation between quality parameters and outlet temperature during spray drying of camel milk, *Dry. Technol.*, 2021, 39(13), 2010–2024, <https://doi.org/10.1080/07373937.2019.1684317>
21. Qi J., Yin J., Yan F., Liu P., Wang T., and Chen C., Liquid–solid flow characteristics in vertical swirling hydraulic transportation with tangential jet inlet, *J. Mar. Sci. Eng.*, 2021, 9(10), <https://doi.org/10.3390/jmse9101091>
22. Shih T. H., Liou W. W., Shabbir A., Yang Z., and Zhu J., A new $k-\epsilon$ eddy viscosity model for high reynolds number turbulent flows, *Comput. Fluids*, 1995, 24(3), 227–238, [https://doi.org/10.1016/0045-7930\(94\)00032-T](https://doi.org/10.1016/0045-7930(94)00032-T)
23. Xiao J., Yang S., George O. A., Putranto A., Wu W. D., and Chen X. D., Numerical simulation of mono-disperse droplet spray dryer: Coupling distinctively different sized chambers, *Chem. Eng. Sci.*, 2019, 200, 12–26, <https://doi.org/10.1016/j.ces.2019.01.030>
24. Yu J., Jin S., and Xia Y., Experimental and CFD investigation of the counter-flow spray concentration tower in solar energy air evaporating separation saline wastewater treatment system, *Int. J. Heat Mass Transf.*, 2019, 144, 118621, <https://doi.org/10.1016/j.ijheatmasstransfer.2019.118621>
25. Ahsan M., Numerical analysis of friction factor for a fully developed turbulent flow using $k-\epsilon$ turbulence model with enhanced wall treatment, *Beni-Suef Univ. J. Basic Appl. Sci.*, 2014, 3(4), 269–277, <https://doi.org/10.1016/j.bjbas.2014.12.001>
26. Sirisomboon K. and Arromdee P., A computational fluid dynamics study of gas–solid distribution of Geldart Group B particles in a swirling fluidized

- bed, *Powder Technol.*, 2021, 393, 734–750, <https://doi.org/10.1016/j.powtec.2021.08.020>
27. Benavides-Morán A., Cubillos A., and Gómez A., Spray drying experiments and CFD simulation of guava juice formulation, *Dry. Technol.*, 2021, 39(4), 450–465, <https://doi.org/10.1080/07373937.2019.1708382>
28. Kieviet F., Modelling quality in spray drying, vol. 16, no. 5. Nederland: Jaarlijkse bijeenkomst SON-werkgemeenschap Procestechnologie, 1996. <https://doi.org/10.2298/TSCI121205224E>
29. Saleh S. N., CFD simulations of a co-current spray dryer, *World Acad. Sci. Eng. Technol.*, 2010, 62, 772–777.
30. Zafiryadis F. L., Numerical modeling of droplet trajectories in pilot plant spray dryer fitted with rotary atomizer, Technical University of Denmark, 2019.
31. Pinto M., Kemp I., Bermingham S., Hartwig T., and Bisten A., Development of an axisymmetric population balance model for spray drying and validation against experimental data and CFD simulations, *Chem. Eng. Res. Des.*, 2014, 92(4), 619–634, <https://doi.org/10.1016/j.cherd.2013.12.019>
32. Zhang T., Tang Q., Pu C., and Zhang L., Numerical simulation of gas-droplets mixing and spray evaporation in rotary spray desulfurization tower, *Adv. Powder Technol.*, 2022, 33(2), 103420, <https://doi.org/10.1016/j.appt.2021.103420>
33. Opaliński, I. Chutkowski M., and Hassanpour A., Rheology of moist food powders as affected by moisture content, *Powder Technol.*, 2016, 294, 315–322, <https://doi.org/10.1016/j.powtec.2016.02.049>
34. Maas S. G. et al., The impact of spray drying outlet temperature on the particle morphology of mannitol, *Powder Technol.*, 2011, 213(1), 27–35, <https://doi.org/10.1016/j.powtec.2011.06.024>
35. Thi Anh Dao D., Van Thanh H., Viet Ha D., and Duc Nguyen V., Optimization of spray-drying process to manufacture green tea powder and its characters, *Food Sci. Nutr.*, 2021, 9, 12, 6566–6574.
36. McDonagh A. F. and Tajber L., The control of paracetamol particle size and surface morphology through crystallisation in a spray dryer, *Adv. Powder Technol.*, 2020, 31(1), 287–299, <https://doi.org/10.1016/j.appt.2019.10.021>
37. Xu F. et al., Research on atomization evaporation characteristics and parameter optimization of a novel spray evaporation desalting system, *Desalination*, 2022, 542, no. May, <https://doi.org/10.1016/j.desal.2022.116057>
38. Mujumdar A. S., *Handbook of Industrial Drying*. CRC press, 2014.