Simulation of the Drying Process of Polysaccharide Extract Solution in a Spray Dryer

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Abstract. The drying process of droplets into particles on a spray dryer is influenced by several factors, including the temperature and the flow rate of inlet air as a carrier gas and a drying media. The effects of temperature of the inlet air in the spray dryer system was elucidated in this study. A solution containing 35 w% polysaccharide extract and water as the solvent was injected into a spray dryer. The inlet air temperatures were varied at 135, 170, and 200 °C with 3 L/min. The geometry of spray dryer consisted of the tubular-conical with a length of 48.8 cm and 15.2 cm diameter cylinder. The spray dryer unit was simulated using CFD code, Fluent Ansys R15.0 with the second phase of droplets/particles was modelled by the Lagrangian discrete phase model (DPM). The inlet air temperature also affected the size of the particles. The increase of the air temperature led to the increase of the average particle diameter leaving the chamber with the smaller standard deviation. The air flow rate also affected the particle size. The higher the air flow rate, the smaller the size of the average diameter of the particles and smaller standard deviation would be. The evaporation rate increased with the increase of the flow rate and inlet air temperature. The resulting particles had an average size of 1.28~1.9 μm diameter to drying with hot air that flowed continuously. The simulation result was validated by the experimental work with discrepancy less than 20%.

Introduction

Increasing consumer demand for food, health, and the polymer industry makes the demand to improve the quality of products that can be stored for a long time and does not require a large place. One method used to improve product quality is by drying. The results of the drying process can be granules, lumps, and powder. The advantage that will be obtained if the product produced in powder form is that the product can be stored for a longer time, minimizing product distribution costs because the dried product has a lighter weight and smaller size thereby minimizing production costs (Patel et al., 2009).

One method used in the process of drying with powder products is to use a spray dryer. Spray dryers are widely used in the food industry, pharmaceuticals, biochemicals, plastics, resins, ceramic materials, detergents, pesticides, fertilizers, organic and inorganic chemicals, skim powder, milk, baby food, instant coffee, tea, dried fruits, juices enzymes and vitamins.

Spray dryer has several advantages, such as the rate of drying speed, a large range for operating temperatures, producing uniform products, and high capacity. Generally spray dryers are used in the final process because they are used to control the final quality of the product. Removal of water on the product affects the quality of the product.

However, the production of powder in the spray dryer cannot be controlled optimal conditions that can affect the final production of powder on an industrial scale. This is because the drying process in a spray dryer involves a complex turbulent flow and the interaction between large particles and air is difficult to observe in a spray dryer (Defraeye, 2014; Salem et al., 2011). Therefore, to observe the phenomena that occur in the spray dryer Computational Fluid Dynamics (CFD) is needed.

The CFD application to analyze the drying mechanism of the spray dryer with a rotary atomizer in three dimensions was carried out (Huang et al., 2003). The hot air co-current flow pattern system affects
the particle flow pattern on the spray dryer and affects the particle deposition (Rajashekhara and Raghavendra, 2015). The higher the flow rate of hot air will also make the average particle diameter bigger (Woo et al., 2008). CFD simulations can predict the whole phenomenon that occurs in a spray dryer. However, the complex interaction process of drying droplets by air makes simulation more difficult. CFD simulations still require a lot of important data from experiments such as speed, temperature and droplet characteristics selected in the operation of the spray dryer (Lee et al., 2013).

In the present study, the performance of spray drying system was studied. The simulation results were validated with the experimental work. The effect of air temperature and air flow rate was evaluated to have more understanding the performance of the spray drying system. The CFD can provide the detail condition in the whole system. Therefore, the flow pattern in the spray drying system was presented.

Simulation procedures
The simulation was carried out using software ANSYS® 15 Academic Package. The system geometry was modelled using DesignModeler® and the grid and node number was determined using Meshing®. The iteration procedure of Computational Fluid Dynamics (CFD) used FLUENT®.

The geometry system and grid generation
The spray dryer system was consisted of two fluid nozzle as atomizer and chamber. The chamber had two zones, i.e. cylindrical and conical zones. The spray dryer geometry was based on the experiment (Matsunaga et al., 2013). Figure 1(a) shows the detail geometry and the size of each part to be modelled in the spray dryer system. The two fluid nozzle was used as an atomizer. The detail geometry of the two fluid nozzle was shown in inset of Figure 1(a). The feed inlet was located on the center of the nozzle with diameter of 1.1938 mm. The air was flowed through a slit with a width of 0.0508 mm and a slope towards the center of 45°. The diameter of the cylindrical chamber was 48.8 cm. The outlet flow was located in the bottom of the chamber with cone diameter of 3.6 cm.

Grid generation of geometry system based on the tetrahedral cells consisting of 142,656 cells, 432,928 faces, and 147,684 nodes, as shown in Figure 1(b). The skewness was 0.078 indicating that the grid was excellently developed. The feed inlet was polysaccharide solution with concentration of 35 w%, temperature of 160 °C, and flowrate of 1 mL/min. The air temperature was varied at temperature of 135, 170, and 200 °C. The flow rate of air was maintained constant at 3 L/min.

Figure 1. Experimental set-up

Model selection
The three dimension simulation was carried out in steady state system. The turbulence flow of the system was modelled based on the Reynolds stress turbulent model using RNG $k – \varepsilon$ model. The droplet trajectory, the rate of mass and heat transfer between droplet and air was modelled using Lagrangian discrete phase model (DPM). In DPM model, the fluid phase is treated as a continuum by solving the Navier-Stokes equations, while the dispersed phase is solved by tracking the droplets through the
calculated flow field (Anonim, 2009). DPM disregards the interaction among droplets that the model was realizable for volume fraction of droplet less than 0.25 compared to the total volume. In the spray system, the droplet concentration is not more than 1 vol%. Therefore, the DPM can be applied in our system. The droplet size distribution was modelled using Rosin-Rammler parameter. The average droplet size distribution follows the following equation:

\[ d_d = \left( \frac{m_L \gamma}{\rho_A \Delta P_L} \right)^{1/3} \]  

(1)

where \( d_d \) is the droplet diameter, \( m_L \) is the liquid flow rate, \( \gamma \) is surface tension, \( \rho_A \) is the air density, and \( \Delta P_L \) is the difference of atomization pressure. The maximum and minimum diameter of droplet applied on the simulation were 1.66 and 5.88 μm, respectively, with the spread parameter was 3.5. The droplet distribution using Rosin Rammler parameter is stated as the following equation:

\[ Y_d = \left( \frac{d_d}{d} \right)^n \]  

(2)

where \( Y_d \) is the droplet mass fraction, \( d \) is the droplet diameter, \( d \) is the average droplet diameter, and \( n \) is the spread parameter.

Results and Discussion

Simulation validation

The simulation results were validated with the experiment conducted by Matsunaga et al. (Matsunaga et al., 2013). The polysaccharide extract was dried in spray dryer using air at flow rate of 3 L/min and varied temperatures of 135, 170, and 200 °C. Figure 2(a-c) shows the simulation results and the corresponding condition of the experimental results. The predicted particle size distribution by CFD simulation and the experimental results of temperatures of 135, 170, and 200 °C have discrepancy of 19.6, 13.5, and 18.3 %, respectively. The discrepancy less than 20 % indicates that the simulation results is good enough for particle size distribution prediction.

Effect of air temperature on the particle size distribution

Table 1 shows the detail drying characteristics for difference air temperatures and flow rate of 3 L/min. The mean particle diameters slightly decrease by increasing the air temperature at around 1.3 μm. Increasing temperature from 135 to 200 °C led to the increase of evaporation rate from 6.50×10^{-11} kg/s to 6.76×10^{-11} kg/s. Therefore, the drying time also decreases from 726 to 676 ms with increasing the temperature from 135 to 200 °C. The CFD simulation can also identify the particles that hit the wall before collected in the bottom and directly collected in bottom without hitting the wall. Two boundary condition that available the FLUENT® are escape and trap condition. Escape condition was applied in bottom outlet of the spray drying system. In this condition, when the particle through the boundary, the calculation of that particle was stopped. The second condition was trap that applied in the wall. When the particle through the wall boundary, that particle calculation was stopped but the mass and energy
was still calculated. The particles hit the wall was 57.34 % for air temperature of 135 °C. The percentage of particles hitting the wall decreases with increasing the temperatures. At air temperature of 135 and 200 °C, the particles hitting the wall were 57.10 and 56.90 %.

Table 1. The temperature effect on the drying characteristics using air flow rate of 3 L/min

| Temperature (°C) | 135   | 170   | 200   |
|------------------|-------|-------|-------|
| Total particles collected | 1.32  | 1.30  | 1.28  |
| Average particle diameter (μm) | 6.25  | 6.11  | 6.02  |
| Deviation standard (×10⁻7) | 726   | 693   | 676   |
| Average drying time (ms) | 6.50  | 6.52  | 6.76  |
| Evaporation rate (×10⁻11 kg/s) | 42.66 | 42.90 | 43.10 |
| Escaped particles (bottom chamber) | 1.63  | 1.74  | 1.84  |
| Percentage (%) | 57.34 | 57.10 | 56.90 |
| Average particle diameter (μm) | 1.25  | 1.24  | 1.23  |
| Trapped particles (hitting the wall) | | | |
| Percentage (%) | 42.66 | 42.90 | 43.10 |
| Average particle diameter (μm) | 1.25  | 1.24  | 1.23  |

In the bottom chamber, the average particle diameter increased with temperature. The average particle diameters were 1.63, 1.74, and 1.84 μm for inlet air temperature of 135, 170, and 200 °C. The results was in accordance with the most reported previous experiment results that by using higher inlet air temperature led to the production of larger particles (Tonon et al., 2008). On the other hand, the average particle diameter calculated from the particle hitting the wall decreased slightly with the increase of temperature. The experimental work by Matsunaga et al. resulted that the increase of the inlet air temperature led to the slight reduce of particle size (Matsunaga et al., 2013). The internal water in the drying droplet transferred slowly at a lower air temperature resulting in the larger particles compared to drying droplet at higher temperature.

![Figure 3. The flow pattern of air and path line of particle tracking at a flow rate of 3 L/min and temperature of 170 °C](image)

Increasing temperature resulted in the increase in evaporation rate. Larger and smaller droplets tended to locate at the center chamber and at around the wall chamber respectively. It is the reason why the smaller droplets tended to adhere in the wall. Therefore, the trapped boundary condition in the wall was appropriate to be selected. It is also supported by the flow pattern inside the whole chamber that the particle with higher velocity located in the center chamber and the particle with lower velocity resided approaching the wall chamber. The particles in the center chamber tended to directly downward to the outlet bottom chamber. The flow pattern and the path line of the particles tracking was shown in Figure 3.
The particle size distribution of particle that directly collected in the bottom corresponding to the escape boundary condition and particle that hit the wall stated by trap boundary condition are shown in Figures 4(a) and 4(b), respectively. The particle size increases with the air temperature but the deviation standard decreases with increasing temperature. The diameter of particle was in the range 0.9 to 5.88 μm for all air temperatures.

**Effect of air flow rate on the particle size distribution**

Table 2 shows the effect of the air flow rate on the average particle diameter, standard deviation, average drying time, and the evaporation rate in the spray drying system. In the overall particles collected, the average particle size was not influenced by the inlet air flow rate. However, for particles that directly collected in the bottom chamber without hitting the wall chamber, the average particle size decreased with increasing the inlet air flow rate. Increasing the inlet air flow rate also contributed on the increase of number percentage of escaped particle or particle that directly collected in the bottom chamber without hitting the wall chamber.

| Total particles collected | Inlet air flow rate (L/min) | 2  | 3  | 4  |
|---------------------------|----------------------------|----|----|----|
| Average particle diameter (μm) |                           | 1.30| 1.30| 1.30|
| Standard deviation (x10^-7) |                           | 6.19| 6.11| 6.10|
| Average drying time (ms)    |                           | 951 | 693 | 611 |
| Evaporation rate (x10^-11 kg/s) |                      | 6.50 | 6.52 | 6.68 |

**Escaped particles (bottom chamber)**

| Percentage (%)     | 40.36 | 42.90 | 47.01 |
|--------------------|-------|-------|-------|
| Average particle diameter (μm) | 1.78 | 1.74 | 1.73 |

**Trapped particles (hitting the wall)**

| Percentage (%) | 59.64 | 57.10 | 52.99 |
|----------------|-------|-------|-------|
| Average particle diameter (μm) | 1.24 | 1.24 | 1.24 |

Further investigation on the evaluating the particle size distribution affected by the inlet air flow rate is shown in Figure 5(a-b). It can be shown that increasing the inlet air flow rate led to decrease in particle size distribution for particle directly collected in the bottom chamber. On the other hand, the particle size distribution did not changed by increasing the inlet air flow rate for particle that preceded collected by hitting the wall chamber.
Conclusion

The computational fluid dynamics (CFD) simulation successfully predicted the experimental work of the spray dried of polysaccharide liquid extract. Three inlet air temperatures were evaluated, 135, 170, and 200 °C at constant flow rate of 3 L/min. Lagrangian discrete phase model was selected to model the second phase of droplets. Increasing the inlet air temperature led to the increase of the average particle diameter with smaller standard deviation. On the other hand, the increasing inlet air flow rate resulted in the decrease in the average particle size. The results suggested that the selected simulation model is good enough to predict the distribution particle diameter with the discrepancy less than 20%.

References

Anonim (2009). Ansys fluent 12.0 Theory Guide.
Defraeye, T. (2014). Advanced computational modelling for drying processes – A review. Applied Energy 131, 323–344. doi:10.1016/j.apenergy.2014.06.027.
Huang, L., Kumar, K., and Mujumdar, A. S. (2003). A parametric study of the gas flow patterns and drying performance of co-current spray dryer: Results of a computational fluid dynamics study. Drying Technology 21, 957–978. doi:10.1081/DRT-120021850.
Lee, I.-B., Bitog, J. P. P., Hong, S.-W., Seo, I.-H., Kwon, K.-S., Bartzanas, T., et al. (2013). The past, present and future of CFD for agro-environmental applications. Computers and Electronics in Agriculture 93, 168–183. doi:10.1016/j.compag.2012.09.006.
Matsunaga, Y., Wahyudiono, Machmudah, S., Askin, R., Qutain, A. T., Sasaki, M., et al. (2013). Hydrothermal extraction and micronization of polysaccharides from Ganoderma lucidum in a one-step process. BioResources 8, 461–471.
Patel, R. P., Patel, M. P., and Suthar, A. M. (2009). Spray drying technology: an overview. Indian Journal of Science and Technology 2, 44–47.
Rajashekhara, M. C., and Raghavendra, N. (2015). CFD Simulation of a Co – Current Spray Dryer for Silica Powder Production. International Advanced Research Journal in Science, Engineering and Technology 2, 105–109. doi:10.17148/IARJSET.2015.2623.
Salem, A., Ahmadlouiedarab, M., and Ghasemzadeh, K. (2011). CFD approach for the moisture prediction in spray chamber for drying of salt solution. Journal of Industrial and Engineering Chemistry 17, 527–532. doi:10.1016/j.jiec.2010.10.023.
Tonon, R. V., Brabet, C., and Hubinger, M. D. (2008). Influence of process conditions on the physicochemical properties of açai (Euterpe oleracea Mart.) powder produced by spray drying. Journal of Food Engineering 88, 411–418. doi:10.1016/j.jfoodeng.2008.02.029.
Woo, M. W., Daud, W. R. W., Mujumdar, A. S., Wu, Z. H., Talib, M. Z. M., and Tasirin, S. M. (2008). CFD evaluation of droplet drying models in a spray dryer fitted with a rotary atomizer. Drying Technology 26, 1180–1198. doi:10.1080/07373930802306953.

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