Flow pattern analysis on sticky regime and effectiveness of volume chamber for milk production using CFD method

H Alwan¹ and Y Bindar²*
¹ Department of Chemical Engineering, University of Sultan Ageng Tirtayasa, Jl. Jenderal Sudirman Km. 3 Cilegon, Banten, Indonesia
² Department of Chemical Engineering, Faculty of Industrial Technology, Institut Teknologi Bandung, Jl. Ganesha 10, Bandung, Indonesia

*Email: ybybyb@fti.itb.ac.id

Abstract. The Computational Fluid Dynamics (CFD) method is used to evaluate the performance of the spray dryer operation in various geometry and operating conditions. Through this method, the design information needed in the cylinder-on-cone spray dryer construction can be obtained. Especially related to the milk drying process. The numerical solution solved through the CFD method using FLUENT ANSYS 19.0 with turbulent model RNG-kε. The spray drying chamber in this study is represented in 2-D geometry. Flow patterns that have strong backflow can cause high particle end temperatures. This flow pattern is created in the small size of space and wide spray angle. The problem that is often caused in the presence of particle deposits on the walls and product agglomeration. The result is particle deposition that often occurs in the walls of the cone and near the atomizer. While agglomeration occurs in the product collection area. The design of the spray drying chamber which is considered the best to be built is a spray dryer with 2 m diameter and spray angle of 60° and 100° in order to produce the final product with the low temperature and water content.

1. Introduction

Spray drying is a method for processing feed which is in the liquid phase, both the particles in the form of suspension and colloid, by atomizing liquid to create droplet and then drying into solid particles [1]. The drying medium that is commonly used is dry air with a certain humidity. Spray drying has been widely used in various industries to produce dry powder products, such as food, pharmaceuticals, and materials.

In the past few years the use of the Computational Fluid Dynamics (CFD) method in the food industry, especially in the spray dryer technology, has yielded quite accurate results, both on a pilot and industrial scale. The CFD method has been widely used by researchers in analyzing particle contacting flow patterns with a drying medium in the drying chamber. This pattern of contacting plays an important role in predicting the final product. Experimentally to observe the particle flow pattern is very complicated and need a reliable measuring instrument. Kuriakose et. al. in their study reported the use of CFD methods to predict gas flow patterns and observe the track record of particle parameters in the spray dryer chamber such as temperature, velocity, residence time, and particles trajectories [2]. On an industrial scale, the CFD method is used to analyze entropy production during the milk drying process and observe air flow patterns [3, 4]. Kieviet et. al. has conducted research in drying maltodextrin using a pilot scale spray dryer by observing operating parameters i.e. velocity.
magnitude, temperature and humidity of the drying medium in the drying chamber [5]. Data that has been obtained has been widely used by researchers as a basis for validating the spray dryer model using the CFD method included in this study as well [2, 6-7].

The use of CFD methods in analyzing flow patterns that are so complex in the drying chamber is very helpful for researchers in analyzing spray dryer performance, like in analyzing particle deposition on walls [8]. The factors that cause particle deposits on the walls are the shape of chamber and material of spray dryer. Different shape of drying chamber will produce different particle deposition fluxes [8]. Through the ability of the CFD method to solve problems comprehensively, the problems in designing a spray dryer to convert liquid milk into powdered milk can be solved without having to do experiments. The simulation results obtained can be used to map patterns and trends in the milk drying process.

2. Modeling Approach

The model approach used is the Eulerian-Lagrangian method to model the mass, energy and momentum balance between two phases (air and particles) in the spray drying chamber. Calculation of this model involves a numerical solution to discretize continuity and momentum equations with the right turbulence model, as well as energy and mass conservation equations. The general equation in this model with all the process variables involved is expressed in a partial differential equation [9].

\[
\frac{\partial \rho \Phi}{\partial t} + u \frac{\partial \rho \Phi}{\partial x} + v \frac{\partial \rho \Phi}{\partial y} + w \frac{\partial \rho \Phi}{\partial z} = \frac{\partial}{\partial x} \left( \frac{\partial \Phi}{\partial x} \right) + \frac{\partial}{\partial y} \left( \frac{\partial \Phi}{\partial y} \right) + \frac{\partial}{\partial z} \left( \frac{\partial \Phi}{\partial z} \right) + S_\Phi
\]

where the variable \( \Phi \) can be velocity \((u, v, w)\), concentration \((Y_i)\), energy \((\text{Temperature, } T \text{ or enthalpy, } H)\), turbulent kinetic energy \(k\), turbulent dissipation rate \(\varepsilon\), and other variables.

2.1. Equation of turbulent variables

The turbulent model is used to found a method of evaluating the value of turbulent viscosity \( (\mu_t) \) [9]. There are two turbulent variables in the RNG-\(k\varepsilon\) equation, that is turbulent kinetic energy \((k)\) and turbulent dissipation energy \((\varepsilon)\).

\[
\rho \frac{\partial k}{\partial t} + \rho u_i \frac{\partial k}{\partial x_i} = \frac{\partial}{\partial x} \left( \mu \frac{\partial k}{\partial x} \right) + \frac{\partial}{\partial y} \left( \mu \frac{\partial k}{\partial y} \right) + \frac{\partial}{\partial z} \left( \mu \frac{\partial k}{\partial z} \right) + P_k - \rho \varepsilon
\]

\[
\rho \frac{\partial \varepsilon}{\partial t} + \rho u_i \frac{\partial \varepsilon}{\partial x_i} = \frac{\partial}{\partial x} \left( \mu \frac{\partial \varepsilon}{\partial x} \right) + \frac{\partial}{\partial y} \left( \mu \frac{\partial \varepsilon}{\partial y} \right) + \frac{\partial}{\partial z} \left( \mu \frac{\partial \varepsilon}{\partial z} \right) + \frac{\partial}{\partial x} \left( C_\mu \rho \frac{\varepsilon^2}{k} \right) + C_\varepsilon \frac{\varepsilon}{k} P_k - C_\varepsilon \rho \varepsilon^2
\]

Turbulent viscosity \( (\mu_t) \) for the RNG-\(k\varepsilon\) turbulent model follows

\[
\mu_t = \mu_0 f \left( \alpha_s, \Omega, \frac{k}{\varepsilon} \right)
\]

where \( \mu_0 \) is the standard turbulent viscosity calculated without considering the existence of vortex flow, \( \mu_0 = C_\rho k^2 / \varepsilon \); \( \alpha_s \) is a vortex flow factor whose value is depending on the size of the vortex. \( \Omega \) is a vortex characteristic value. The values of the constants \( C_{\varepsilon2} \) and \( \lambda \) can be found through the following equation

\[
C_{\varepsilon2} = \tilde{C}_{\varepsilon2} + \frac{C_\rho \lambda^3 (1 - \lambda / \lambda_0)}{1 + \beta \lambda^3}
\]

\[
\lambda = \frac{k}{\varepsilon} \sqrt{2S_y S_z}
\]
The magnitude of the constants in the RNG-\(k\epsilon\) model is \(C_\epsilon = 1.42; \tilde{C}_{\epsilon 1} = 1.68; C_\mu = 0.085; \sigma_k = 0.72; \sigma_s = 0.72; \beta = 0.012\); and \(\Lambda_0 = 4.38\) [10].

2.2. Agglomeration and particle deposition

The Eulerian-Lagrangian approach provides the advantage that each trajectory droplet could be traced so that it could be discovered when the droplet hits the drying chamber wall. By knowing the water content and temperature of particles, it could be observed what happens to droplet when hits the wall, whether it sticks or bounces.

The temperature of the material under sticky conditions (\(T_{st}\)) can be determined by the following equation [11]

\[
T_{st} = \left[ X_0 \left( 1 - X_0 T_{gi} + X_0 T_{gw} \right) \right] + 23.3
\]

(7)

Where \(X_0\) is the final water content of the particle, \(T_{gi}\) is the temperature glass of component \(i\) (°C), \(T_{gw}\) is the glass temperature of water (°C). Glass temperature can be calculated through equation (8) for the value of water activity \((a_w)\) below 0.575 (0 < \(a_w\) < 0.575) [12].

\[
T_g = 530.66a_w^3 + 652.06a_w^2 - 366.33a_w + 99.458
\]

(8)

3. Methodology

The design of a spray dryer to drying liquid milk into powdered milk is done by investigating the performance using the CFD method. There are two variables in numerical investigation, the first variable is spray angle and diameter of the spray dryer \(\phi_{GA}\), the second variable is grid generation (meshing) with turbulent model RNG-\(k\epsilon\) \(\phi_{GT}\). The diameter chamber and spray angle used are 1.4 m, 1.6 m, 2.0 m, 2.2 m, and 20°, 60°, 76°, 100° respectively. In this study the grid generation variable used is the size and shape of the mesh. The mesh size used is 5 mm and 4 mm, and the mesh shape used is triangular and quadrilateral.

**Figure 1.** Algorithm for optimization of spray dryer chamber design for drying liquid milk using the CFD method.

The geometry of the spray dryer used is a cylinder-on-cone type and a co-current flow with rotary atomizer type. The dimensions of the drying chamber are taken from experimental data conducted by Kieviet et. al. [5]. Position the atomizer and the drying air inlet above the chamber. Air exit through a
channel located in the middle of the drying chamber cone and the particles exit through the area at the end of the cone. Figure 2 shows the spray dryer dimension adapted from Kieviet research.

![喷雾干燥器图片](a) 2D geometry (b) 2D-Axisymmetric. (adapted from Kieviet, 1997)

Boundary and initial condition were obtained from Kieviet experiment [5]. Wall material used is stainless steel with a thickness of 2 mm. The droplet that hit the wall in this study used reflect and escape boundary conditions. The reflect boundary conditions are used for all walls except the particle output wall. The boundary conditions and initial values used in this simulation are shown in table 1.

| Parameter                              | Value                  |
|----------------------------------------|------------------------|
| Liquid milk Mass flow [kg/s]            | 0.0139                 |
| Drying air Mass flow [kg/s]             | 0.3175                 |
| Liquid milk Total solid [% w/w]         | 42.5                   |
| Drying air Total solid [% w/w]          | -                      |
| Liquid milk Temperature [°C]            | 27                     |
| Drying air Temperature [°C]             | 195                    |
| Liquid milk Moisture content [kg water/kg dry air] | - 0.009 |
| Drying air Moisture content [kg water/kg dry air] | - -150 |
| Spray angle standard [°]                | 20°, 60°, 78°, 100°    |
| Wall thickness [mm]                     | 2                      |
| Heat transfer coefficient [W/m².K]      | 3.5                    |
| Ambient temperature [°C]                | 25                     |

### 4. Results and Discussion

#### 4.1. Model validation with experimental data

This research was built in a two-dimensional (2-D) and 2D-Axisymmetric field with the turbulent RNG-ke model. The results of both show that the data between simulation results and Kieviet
experiments are not much different [5]. Validated parameters are fluid velocity profiles for each segment in the drying chamber.

![Air velocity profile between experimental data and CFD simulation data on each spray dryer height (a) 0.6 m and (b) 1.0 m.](image)

**Figure 3.** Air velocity profile between experimental data and CFD simulation data on each spray dryer height (a) 0.6 m and (b) 1.0 m.

The fluid velocity profile is shown in figure 3, divided into two height segments, that is 0.6 m and 1 m (measured from top to bottom). At an altitude of 0.6 m the maximum gas velocity achieved from the simulation is 7 m/s while the experimental data are 7.23 m/s. The velocity profile from the start (z = 0.6 m) looks symmetrical to the end of the track (z = 1.0 m). This symmetrical profile proves and can be used as a justification that the model built using the CFD method with ANSYS FLUENT 19.0 software has sufficient accuracy.

4.2. **Geometry effects on milk drying**

The smaller volume of space decreases the amount of air in the drying chamber, which results in an increase in the mass fraction of water (Y) in the air. The fraction of water in the air rises sharply at the central radial position, the phenomena is caused by a backflow of air that meets its main flow. The mass fraction of water in the air decreases with changes in axial position.

Higher heating air temperatures in the drying chamber cause low thermal efficiency and not expected in the process of drying milk, because it can damage the structure, taste and aroma of the product. On the other hand higher air temperatures can increase the pressure of saturated vapor in the air, with the result that the equilibrium water content (X_{eq}) in the material gets smaller.

![Effect the diameter of spray dryer chamber on the drying air temperature (colored by the drying air temperature, °C).](image)

**Figure 4.** Effect the diameter of spray dryer chamber on the drying air temperature (colored by the drying air temperature, °C).
Keshani et al. reported that air flow patterns are influenced by the shape of the drying chamber [8]. In the small diameter of the drying chamber, the particles’ trajectories tend to be shorter than the larger. Figure 4 shows several dead zones in the spray dryer chamber, which is formed by backflow due to high jet velocity. Backflow in the drying chamber is formed in the area near the output in the cone section and in the area near the air inlet. When the particles are carried by the backflow, the particle residence time will be longer than other particles. Backflow provides better mass transfer and heat transfer processes, but too long residence time can cause damage to dairy products.

The drying rate of droplets into particles is influenced by the size of the chamber and droplet. The smaller droplet size, the faster the drying process will be. Droplet sizes varying from 250 microns to 50 microns causing the drying time required to be non-uniform. The shortest drying process indicates that the concentration gradient of water in particles with air is quite high. 1.4 meters drying chamber diameter has a temperature quite high compared to another chamber diameter (figure 4.). This conditions can cause the drying rate to be fast and can cause water to evaporate quickly. When the water has been completely evaporated the particles will undergo further heating which can cause damage to the final product. In this simulation droplet with a size of 220 microns has reached equilibrium water content ($X_{eq}$) just before entering the output area.

4.3. Effects of spray angles on milk drying

The spray angle in the drying chamber gives a significant impact in influencing the drying process. Spray angle that is too large will cause the droplet to hit the wall faster.

Figure 5. Particle trajectory profile at various spray angles with a constant diameter at 2.2 m (a) 20°, (b) 60°, (c) 78°, and (d) 100° (colored by particle velocity, m/s).

Figure 5 shows that the greater of spray angle can cause backflow on the drying chamber. However, the spray angle 20° will cause the particles to go directly to the output area which causes the particles to still contains high water content. Spray angle analysis proves that a spray angle that is too small can produce high water content. Conversely the spray angle that are too large can cause deposits of particles on the wall. So the optimum spray angle needs to be determined. From the results of this analysis the optimal spray angle at the 2.2 m drying chamber diameter is above 60° and less than 100° ($60° < \theta_{GA} < 100°$).
4.4. Particle deposition analysis

One of the factors that influence deposition of particles in the drying chamber wall is water activity ($\alpha_w$) and particle temperature. Small diameter drying chambers have a much greater tendency for particles to undergo deposition in the drying chamber wall.
Figure 6. The evolution curve of milk droplet into milk powder in spray dryer chamber at diameter (a) 1.4 m and (b) 2.2 m.

Figure 6 is a combination of the droplet drying curve and the droplet temperature along the droplet trajectory. The area between the glass temperature ($T_{\text{glass}}$) and the sticky temperature ($T_{\text{sticky}}$) is referred
to as the sticky region. In this area the particle viscosity reaches a critical point which is in the range 106 - 108 Pa.s. Adhesion force at a viscosity of this magnitude is very dominant [13]. When the particles are in a sticky area and its position is hit the wall, then the possibility of these particles will stick to the wall is very large. With the same spray angle but a small diameter of the drying chamber, the possibility of a collision with a wall getting bigger. Areas that allow particle deposition in the spray dryer chamber have been described by Master [14]. This area is the area near the atomizer and cone. In larger chamber, that is 2 meters and 2.2 meter in diameter, particle deposition does not occur.

To eliminate the deposition and agglomeration of particles in the milk drying process is very difficult to do. After going through the drying process the dominant composition of milk is carbohydrate, fat and protein. Carbohydrate component is the dominant component that causes deposition of particles. Some ways that can be done to reduce particle deposition and agglomeration include optimizing the operating conditions of drying (air temperature, water content in materials), manipulating the drying chamber geometry and replacing drying chamber materials. Materials that have high thermal conductivity and rough surfaces cause particles to be deposited in the drying chamber wall.

5. Conclusion
The performance of the spray dryer which is quantified through particle deposition in the drying chamber wall shows that many particles are deposited in the wall area near the atomizer and the cone wall. More particle deposition fluxes when the drying chamber diameter gets smaller and the spray angle is large. The sticky area on the droplet is predicted through a sticky curve. This curve is used to evaluate the droplet into particles and their position in the spray dryer chamber. This evaluation shows that to produce milk powder products according to quality requirements and its operation does not cause many problems, the drying chamber used must have a chamber diameter greater than 1.6 m and a spray angle of less than 100° and greater than 60°.

References
[1] Filkova I, Huang L X, and Mujumdar A S 2015 Handbook of Industrial Drying ed Mujumdar A S, Taylor & Francis Group, Singapore 4th ed pp 191–226
[2] Kuriakose R, and Anandharamakrishnan C 2010 Trends Food Sci. Tech. 21 383–398
[3] Jin Y dan Chen X D 2011 Int. J. Therm. Sci. 50 615–625
[4] Gabites, J R, Abrahamson J, and Winchester J A 2006 Fifth International Conference on CFD in the Process Industries CSIRO, Melbourne, Australia
[5] Kieviet F G 1997 Modeling Quality in Spray Drying, Doctoral Dissertation, Eindhoven University of Technology, Eindhoven, The Netherlands
[6] Mezhericher M, Levy A, and Borde I 2010 Chem. Eng. Process 49 1205–1213
[7] Huang L X, Kumar K, and Mujumdar A S 2006 Chem. Eng. Process 45 461–470
[8] Keshani S, Daud W R W, Nouroz M M, Namvar F, and Ghasemi M 2015 J. Food Eng. 146 152–162
[9] Bindar Y 2017, Rekayasa Komputasi Multidimensi Sistem Pembroses Dan Energi Industri ed Bindar Y Bandung, Forum Guru Besar ITB 1 pp 12–49
[10] Gupta A and Kumar R 2007 Int. J. Heat Fluid Fl. 28 249–261
[11] Langrish T A G 2009 J. Food Eng. 93, 218–228
[12] Walmsley T G, Walmsley M R W, Atkins M J, Neale J R and Sellers C M J. Food Eng. 127, 111–119
[13] Turchiuli C, Gianfrancesco A, Palzer S, and Dumoulin, E 2011 Powder Technol. 208 433–440
[14] Masters K 1991 Spray Drying Handbook – 5th edition, The Bath Press, United Kingdom pp 275–285