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Theoretical Analysis of the Wall Deposition of Particles in Spray Dryers

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A spray drying is an important process in food, healthcare and pharmaceutical industries. However, spray dryers normally face a difficulty in operation when some particles with high moisture content (stickiness) have collected contacts with the metal surface of a dryer chamber, which is called a wall deposition problem. In this study, a computational fluid dynamic model of the spray dryer is developed based on momentum, mass and heat equations of the fluid and solid phases and employed to analyze an effect of the addition of a drying agent material on the fluid flow pattern within the spray dryer and the percentage and position of particle deposition. The wall deposition of particles is predicted by considering glass transition temperatures using the sticky-point concept. The feed solution of anthocyanin using maltodextrins as the drying agent material is considered. The simulation results indicate that most particles are deposited on the conical wall more than cylindrical wall. Use of maltodextrin with a higher dextrose equivalent (DE) value lowers the glass transition temperature of particle, causing the particles attached on the wall.

1. Introduction

Drying is the process of removing liquid (usually water) from solids. It helps reduce transport load and increase the storage life of products. A decrease in the water content of products reduces a water activity, which is the cause of a product degradation (Chiou et al., 2006). Among the various drying technologies, the spray drying is widely used due to its advantage of obtaining final powder products with desired specific particle size and moisture content regardless of the dryer capacity and product heat sensitivity (Atkins et al., 20120 and further information in (Oi et al., 2013).

In spray dryers, a liquid-product feed is first atomized by an atomizer and the obtained liquid droplet is then contacted with hot dried air. At this step, liquid water is evaporated out of the droplet; more than 95 % of the total moisture is removed. In general, type and position of the atomizer have an effect on the evaporation and the particle size of final powder products (Southwell and Langrish, 2001). During spray drying operation, some particles with high moisture content (stickiness) have collected in contacts with metal surface of a dryer chamber, known as the wall deposition problem (Kieviet, 1997). This problem causes a product contamination and affects a quality of the final product (Kuriakose and Anandharakrishnan, 2010).

Among the different methods proposed to capture a sticky behavior, the indirect approach has been widely used. In this approach, sticky temperatures (Ts) are correlated with glass transition temperatures (Tg) of the substance. In principle, Tg can be taken as a reference parameter to predict the spray drying system and characterize its properties, such as product quality and stability. Ozmen and Langrish (2003) investigated the wall deposition effect in a pilot-scale spray dryer unit and developed the deposition model based on the glass transition and sticky point concept. However, it is noteworthy that using the glass transition as the cut-off point does not account for the effect of impacting velocity and angle on the collision outcome.To minimize the stickiness and wall deposition problems in the spray dryer, an addition of drying agent materials in product feeds is an alternative option (Dolinsky et al., 2000).

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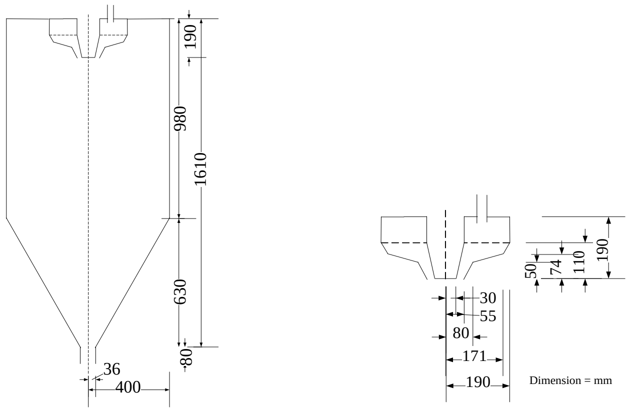

Figure 1: Schematic diagram of the spray dryer

This study is focused on a theoretical analysis of the wall deposition of particles in spray dryers. A computational fluid dynamic model of the spray drying of an anthocyanin solution is used to investigate the effect of introducing the drying agent material on the fluid flow pattern within the spray dryer and the percentage and position of particle deposition.

2. Introduction

Figure 1 shows the schematic diagram of the spray dryer used in this study. Feed solution and hot air enter the chamber in the same direction. With this flow pattern, hot air can contact droplets of the feed solution at its maximum moisture content. Thus, a final product does not suffer from heat degradation effect. A computational fluid dynamic model based on momentum, mass and heat equations is used to describe the fluid and solid phases in the spray dryer.

2.1 Continuous phase (air)

Continuity equation:

$$\frac{\partial \rho}{\partial t}+\frac{\partial}{\partial x}(\rho u_x)+\frac{\partial}{\partial r}(\rho u_r)+\frac{\rho u_r}{r}=S_m \tag{1}$$

where ρ represents the fluid density, u_x and u_r are the velocities in axial and radial directions and S_m is the source term of droplet phase.

Momentum equation:

$$\frac{\partial}{\partial t}(\rho v_x)+\frac{1}{r}\frac{\partial}{\partial x}(\mathrm{r}\,\rho u_x u_r)+\frac{1}{r}\frac{\partial}{\partial r}(\mathrm{r}\,\rho u_x u_r)=-\frac{\partial P}{\partial x}+\frac{1}{r}\frac{\partial}{\partial r}\left[r\mu\left(2\frac{\partial u_x}{\partial x}-\frac{2}{3}(\nabla\cdot u)\right)\right]+\frac{1}{r}\frac{\partial}{\partial r}\left[r\mu\left(\frac{\partial u_r}{\partial r}+\frac{\partial u_r}{\partial x}\right)\right]+F_x \tag{2}$$

$$\frac{\partial}{\partial t}(\rho u_r)+\frac{1}{r}\frac{\partial}{\partial x}(\mathrm{r}\,\rho u_x u_r)+\frac{1}{r}\frac{\partial}{\partial r}(\mathrm{r}\,\rho u_r u_r)=-\frac{\partial P}{\partial x}+\frac{1}{r}\frac{\partial}{\partial x}\left[r\mu\left(\frac{\partial u_r}{\partial x}+\frac{\partial u_x}{\partial r}\right)\right]+\frac{1}{r}\frac{\partial}{\partial r}\left[r\mu\left(2\frac{\partial u_r}{\partial r}-\frac{2}{3}(\nabla\cdot u)\right)\right]-2\mu\frac{u_r}{r^2}+\frac{2}{3}\frac{\mu}{r}(\nabla\cdot u)+F_r \tag{3}$$

where P is the pressure, μ is the fluid viscosity and F_x and F_r are the forces acting in axial and redial directions. The velocity gradient (u) in the momentum equations is described by following equation:

$$\nabla\cdot u=\frac{\partial u_x}{\partial x}+\frac{\partial u_r}{\partial r}+\frac{u_r}{r} \tag{4}$$

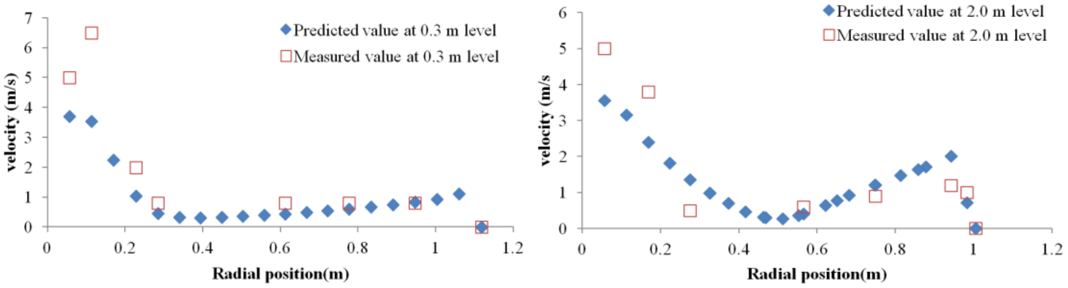

Figure 2: Model validation

Energy conservation:

$$\frac{\partial}{\partial x}(\rho_g u q)+\frac{1}{r}\frac{\partial}{\partial r}(r\,\rho_g v q)=\frac{\partial}{\partial x}\left[\left(\mu_L+\frac{\mu_T}{\sigma_h}\right)\frac{\partial q}{\partial x}\right]+\frac{1}{r}\frac{\partial}{\partial r}\left[\left(\mu_L+\frac{\mu_T}{\sigma_h}\right)r\frac{\partial q}{\partial r}\right]+M_h \qquad (5)$$

where q is the enthalpy of gas, M_h is the rate of heat transfer between droplets and gas, μ_L is the laminar viscosity of fluid and μ_T is the turbulent viscosity.

2.2 Disperse phase (droplet)

Continuity equation:

$$\frac{\partial u_{pi}}{\partial x}=C_D\frac{18\mu}{\rho_p d_p^2}\frac{\mathrm{Re}}{24}(u_i+u_{pi})+g_i\frac{\rho_g-\rho}{\rho_g}+F_{xi} \qquad (6)$$

where u_{pi} is the particle velocity and ρ_p and ρ_g are the densities of particles and gas.

Energy conservation:

$$m_p c_p=\frac{dT_p}{dt}=hA_p\left(T_g-T_p\right)+\frac{dm_p}{dt}h_{fg} \qquad (7)$$

where h_{fg} is the latent heat, dm_p/dt is the evaporation rate, T_g is the local hot medium temperature and T_p is the particle temperature.

The model equations of the spray dryer mentioned above are solved using Fluent software. The model validation is performed by comparing the prediction result with published data (Kieviet, 1997) under the same operating conditions. Figure 2 shows the gas velocity profile at different levels in the drying chamber; the predicted velocities agree quite well with the measured results. There is a non-uniform velocity distribution in the core region of the chamber and the maximum deviation of the model prediction is found in this area.

3. Result and discussion

Simulation of a spray dryer is performed based on parameters and condition summarized in Table 1. Air with relative humidity of 75 % is introduced to a drying chamber at temperature of 468 K. It is assumed that droplets (particles) are trapped at wall of the chamber; the volatile material present in the trapped droplet is to be released to the gas phase. An injection condition is defined here to specify the spray with a given droplet size distribution. The droplet diameter distribution is modelled using a Rosin-Rammler curve. Because there is no swirling flow in the drying chamber, the standard k-ε turbulence model is used.

Figure 3 shows the gas temperature, glass transition temperature (Tg) and sticky-point temperature (Ts) within a spray dryer at conical and cylindrical walls when the anthocyanin solution without a drying agent material is fed to a spray dryer. The results show that particles hit the wall in the sticky state and attach on the dryer wall because the gas temperature is higher than the stickiness temperature and glass transition temperature.

Table 1: Design parameters and operating conditions for simulation of the spray dryer

Inlet Air	
- Temperature (K)	468
- Mass flow rate (kg/s)	0.336
- Velocity (m/s)	9.15
Outlet Condition	
- Pressure (Pa)	-100
Turbulence Inlet Conditions	
- Turbulence k-value (m^2/m^2)	0.027
- Turbulence ε-value (m^2/m^3)	0.37
Liquid Spray From Nozzle	
- Liquid feed rate or spray rate (kg/s)	0.0139
- Feed temperature (K)	300
- Spray angle (◦)	76
- Minimum droplet diameter (µm)	10
- Maximum droplet diameter (µm)	138
- Average minimum droplet diameter (µm)	70.5
- Particle velocity at nozzle (m/s)	59
- Rosin-Rammier parameter	2.05
Chamber Wall Condition	
- Chamber wall thickness (mm)	0.002
- Wall material	Steel
- Overall wall heat transfer coefficient ($W/(m^2.K)$)	3.5
- Air temperature outside wall (K)	300

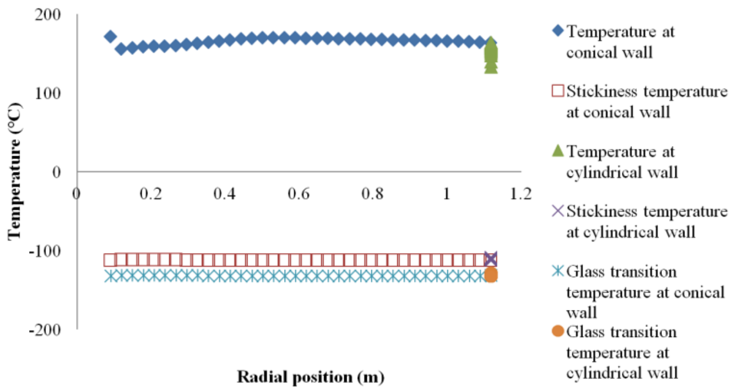

Figure 3: Temperature profiles within the spray drying of the anthocyanin solution

In general, additive agent materials are used to change the physical properties of products, reducing the stickiness and wall deposition in spray drying. Effect of the addition of maltodextrins with a dextrose equivalent (DE) of 36 (DE 36, MW = 550), as a drying agent additive to the anthocyanin solution, is shown in Figure 4. Although the glass transition temperatures and the stickiness temperatures increase, they are lower than the gas temperature and thus particles still adhere to the wall. Use of maltodextrins with low DE values (high molecular weight) will reduce the gas transition temperatures (not shown in the figure). It is found that when the anthocyanin solution is added with maltodextrins (DE = 5), the gas temperature profile is lower than the stickiness temperature and the glass transition temperature. This implies that particles in the dryer are in a non-sticky region; the possibility of particle deposition on the wall can be avoided.

Next, the position and temperature of particles at walls are investigated as the obtained data can be used for design and operation of the spray dryer. Particle stickiness is related to wall deposition, depending on the fluid flow patterns within the dryer. It is assumed that hot dried air and water mixed with maltrodextrin (DE 10) are in the continuous and disperse phases and heat transfer coefficient of the dryer wall is 3.5 $W/(m^2•K)$. Table 2 shows the temperature range and percentage of particles at the wall chamber. Most

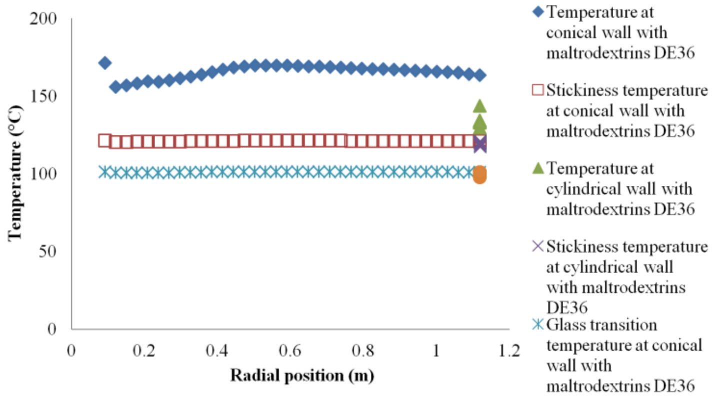

Figure 4: Temperature profiles within the spray drying of the anthocyanin solution with DE 36

Table 2: Temperature and percentage of particles at the chamber walls

Temperature	Percentage of particles (%) at the walls		
	Conical wall	Cylindrical wall	Total
37.5 - 72.5	0	0	0
72.5 - 90.0	0	0	0
90.0 - 107.5	0	0	0
107.5 - 125.0	0	0	0
125.0 - 142.5	0	2.86	1.44
142.5 - 160.0	17.14	42.86	30.00
160.0 - 177.5	82.86	54.28	68.57
177.5 - 468.0	0	0	0
468.0 - 500.0	0	0	0

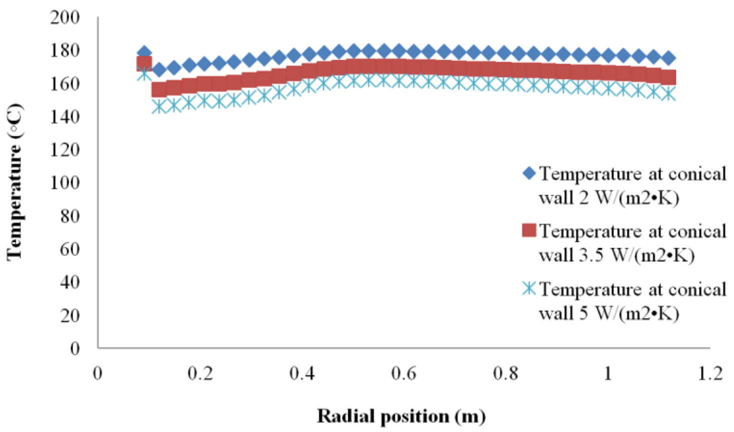

Figure 5: Temperature profiles at the wall with different heat transfer coefficients.

particles (68.57 %) impact the wall at the temperature range of 160.0 - 177.5 °C, which is higher than the glass transition temperature. Therefore, these particles are in a sticky state and attach on the walls. The result also shows that particles are attached on the conical wall more than the cylindrical wall.

Effect of using the chamber wall with different heat transfer coefficient on the particle deposition is studied. It is found that when the wall with a lower heat transfer coefficient is employed, the gas temperature at the wall will be higher (Figure 5). In case of the wall with heat transfer coefficient of 2 W/(m^2•K), all particles hit the wall at the temperature range of 172.62 - 175.91 ^{o}C and thus attach on the wall. These particles are in the sticky state due to the particle temperatures higher than the glass transition temperature. It is noted that the design of dryers using material with suitable heat transfer coefficients is alternative choice to avoid the wall deposition problem.

4. Conclusions

A two-dimensional computational fluid dynamic model of a spray dryer was developed to study effects of the addition of drying agent material to feed solution on the fluid flow pattern within the spray dryer and the percentage and position of particle deposition. The developed spray dryer model was validated with published data and a good agreement of the model prediction and experimental data was observed. The glass transition temperature was used as a reference parameter to predict the particle stickiness on the dryer wall. The results showed that adding a maltodextrin as a drying agent material can change the glass transition temperature and thereby affecting the deposition of particles. The use of wall material with different heat transfer coefficients is an alternative option to overcome the particle deposition problem. It was found that when the dryer wall with high transfer coefficient was used, the gas temperature at the wall will decrease and lower than the gas transition temperatures. Most particles is not in a sticky state and not be attached on the wall.

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