CFD Simulating to Compare Tangential-inlet Swirl Nozzle with Coaxial Nozzle on Internal Flow for Preparing Nano-drug in SEDS Process

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Abstract: The comparison on the performance between tangential-inlet swirl nozzle and coaxial nozzle was conducted by Computational Fluid Dynamics (CFD) simulation. The two nozzles were special for the preparation of nano-drug in Solution enhanced dispersion by supercritical fluid (SEDS) process. Turbulent intensity, velocity magnitude and volume fraction of ethanol were selected to act as the parameters to be compared. The results of CFD simulation indicate that, on the one hand, both coaxial nozzle and tangential-inlet swirl nozzle can meet the requirement of preparing nano-drug in SEDS process and have their advantages. Coaxial nozzle can prepare particles with more even size distribution than tangential-inlet swirl nozzle. And tangential-inlet swirl nozzle, with more merits, can produce higher turbulence intensity on the boundary layer which prevents the crystal nuclei precipitated from adhering on the inner wall. In additional, tangential-inlet swirl nozzle can produce higher velocity at outlet which can decrease the growth time of crystal nuclei so as to prepare superfine particles. On the other hand, both of the nozzles have their relative defects which should be improved in future study.

Keywords: CFD simulation, SEDS, tangential-inlet swirl nozzle, coaxial nozzle, nano-drug

INTRODUCTION

The pharmaceutical industry aims at producing nano-drug for use in drugs administered by various routes including the inhalation and oral modes. For instance, application of aerosol powders enables fast, controlled delivery of drugs into the human lungs and then into the blood. To achieve optimal efficiency of therapy the drug has to be formulated into uniform microparticles of the appropriate size and shape (Henczka et al., 2005). The method of preparing nano-drug include High-gravity Anti-solvent Precipitation (HGAP) (Chen et al., 2006), Medium Milling (MM) (Aim-Ai and Gupta, 2008), Emulsification Method (EM) (Trotta et al., 2001), Crystallization by Supercritical Fluid Technology (CSFT) (Chen et al., 2012; Sheth et al., 2012) and so forth. The particles prepared by classical precipitation methods are non-uniform in size and particle size distribution is very wide. Use of supercritical fluids enables easier production of ultrafine (micro- or nanosized) powders with desired properties and precise control of particle size and morphology. Supercritical Fluids are easily separated from crystalline products providing clean and recyclable technologies (Henczka et al., 2005).

According to the different roles of supercritical fluid in crystallization process, CSFT is categorized into three types, including Supercritical Anti-solvent (SAS) (Lesoin et al., 2011), Rapid Expansion of Supercritical Solutions (RESS) (Chen et al., 2011) and Particles from Gas Saturated Solutions (PGSS) (Rodrigues et al., 2004). In all of these processes, oversaturation of drug solution generated in SCF is utilized to achieve drug recrystallization in order to prepare nano-drug crystal. However, their mechanisms are different. In the process of RESS, drug need to be dissolved in supercritical CO\textsubscript{2} firstly and then sprays, crystallizes. Whereas, the solubility of many drugs in supercritical CO\textsubscript{2} (SC-CO\textsubscript{2}) is very low or even near zero, which limit the use of RESS. PGSS process was useful mainly for impregnating active ingredients into polymer matrices. While in the process of SAS, drug need to be dissolved in certain kind of organic solvent and then the solution mixes with SC-CO\textsubscript{2} in nozzle. The solubility of solute in the solution decreases dramatically; consequently, the uniform particles of solute precipitate because of supersaturation and then spray out promptly forming nano-drug. Based on the principle of SAS, solution enhanced dispersion by supercritical fluid
(SEDS) has been developed. This process needs a nozzle with two passages to introduce SCF and a solution of active substance(s) in order to make these two fluids mix completely and to spray fiercely.

Nozzle is the key component of equipment for SEDS process. The reports about nozzle design frequently appear in literatures, such as capillary injection tubes (Reverechon et al., 2000), coaxial nozzles (Baldyga et al., 2010a), internal twin-fluid mixing nozzles (Ghaderi et al., 1999), jet-swirl nozzle (Jasser et al., 2003), Tangential-inlet Swirl Nozzle (Xiao and Ma, 2007). All of above-mentioned mixing configurations are merely verified meeting the requirement of SEDS process. However, there are seldom comparisons among them on the important parameters of internal flow in the goal of distinguishing their relative advantages and disadvantages. In this study, CFD Simulation was utilized to compare on the important parameters of internal flow between tangential-inlet swirl nozzle and coaxial nozzle for preparing nano-drug in the same conditions so as to find the advantages of one nozzle compared to the other.

CFD SIMULATION

Nozzle structures and computational domain modeling:

Baldyga et al. (2010b) designed coaxial nozzle for preparing nano-drug in SEDS process. The structure and dimensions of this nozzle were shown in Fig. 1. There were three values for L, in the literature. In this study, the value of L was 4 mm, one of that three. Supercritical CO₂ is introduced from an annular orifice and ethanol is introduced from a circular orifice. The flow directions of supercritical CO₂ and ethanol are the same and axial. The 3D geometrical computational domain of coaxial nozzle under consideration for CFD simulation is shown in Fig. 2a.

Xiao and Ma (2007) designed tangential-inlet swirl nozzle for preparing nano-drug in SEDS process. The structure and dimensions of the nozzle were shown in Fig. 3. The main feature of this nozzle is that solution and anti-solvent are injected, respectively from two tangential inlets and mixing of the jets occurs within the swirl chamber of the nozzle. The application of swirl flow plays the role of enhancing mixing because swirl flow produce strong shear stress, high turbulence and rapid mixing rates. The centrifugal force is imparted to the bulk liquid by a free vortex in the swirl chamber. The swirling liquid in the swirl chamber produce a swirling hollow-cone annular jet by passing through the outlet passage. Moreover, the strong shear stress can prevent particles precipitated from adhering in the inner wall of the nozzle. The 3D geometrical computational domain of this nozzle was shown in Fig. 2b.

The dimensions of these two kinds of nozzles are similar and both of the nozzles are designed for preparing nano-drug in SEDS process. In this study, the performance of these two nozzles was compared by comparing the important parameters of their internal flow by CFD simulation.

Governing equations: The continuity equation is defined as Eq. 1:

\[
\frac{\partial (\rho u)}{\partial x} + \frac{\partial (\rho v)}{\partial y} + \frac{\partial (\rho w)}{\partial z} = 0
\]  

(1)

where u, v, w are, respectively the component of velocity vector in x, y and z direction. \( \rho \) is the density of the mixture. The momentum conservation equations are defined as Eq. 2-4:

\[
\frac{\partial (\rho u)}{\partial t} + \nabla \cdot (\rho u u) = \nabla \cdot (\mu \nabla u) - \frac{\partial p}{\partial x} + S_u
\]  

(2)

\[
\frac{\partial (\rho v)}{\partial t} + \nabla \cdot (\rho u v) = \nabla \cdot (\mu \nabla v) - \frac{\partial p}{\partial y} + S_v
\]  

(3)

\[
\frac{\partial (\rho w)}{\partial t} + \nabla \cdot (\rho u w) = \nabla \cdot (\mu \nabla w) - \frac{\partial p}{\partial z} + S_w
\]  

(4)

where, \( S_u, S_v \) and \( S_w \) are the generalized source term of the momentum conservation equations.

![Fig. 1: Schematic diagram of structure and dimensions of coaxial nozzle (Baldyga et al., 2010a)](image-url)
Standard model was employed to simulate the turbulence of the flow in tangential-inlet swirl nozzle. The governing equation groups are shown as Eq. 6 and 7:

$$\frac{\partial (\rho u_i)}{\partial t} + \frac{\partial (\rho u_i u_j)}{\partial x_j} = \frac{\partial}{\partial x_j} \left[ \left( \mu + \mu_t \right) \frac{\partial u_i}{\partial x_j} \right] + G_i - \rho \varepsilon$$  

$$\frac{\partial (\rho \varepsilon)}{\partial t} + \frac{\partial (\rho \varepsilon u_i)}{\partial x_j} = \frac{\partial}{\partial x_j} \left[ \left( \mu + \mu_t \right) \frac{\partial \varepsilon}{\partial x_j} \right] + \frac{144 \varepsilon}{k} G_i - 1.92 \frac{\varepsilon^2}{k}$$  

Turbulent kinetic energy $k$ can be calculated by Eq. 4:

$$k = \frac{3}{2} \left[ \langle u' \rangle^2 \right]$$  

where, $\langle u' \rangle$ is the mean velocity at inlet, which can be calculated by mass flow rate. $I$ is the turbulent intensity of inlet, which can be calculated by Eq. 5:

$$I = 0.16 \left( \frac{Re_{in}}{D} \right)^{1/2}$$

Turbulent dissipation rate $\varepsilon$ was estimated by Eq. 6 and 7:

$$\varepsilon = 0.093^{3/4} \frac{k^{3/2}}{I}$$

$$I = 0.07 L$$

where, $k$ is turbulent kinetic energy, $L$ is characteristic length, which can be calculated according to the equivalent diameter.

**Numerical scheme:** The CFD approach uses a numerical technique for solving the governing equations for a given flow geometry and boundary conditions. In this study, a commercial CFD code, Fluent 6.3, was selected to simulate the flow pattern through the two nozzles. In order to simulate the precipitation in a two-phase system, Eulerian model was chosen to act as MultiPhase Model. Both SCF and solution were assumed as continuum phases. For turbulent flow calculations, the realizable $k-\varepsilon$ turbulence model was selected with standard wall functions. The phase coupled SIMPLE algorithm was utilized to achieve Pressure-velocity coupling. The first order upwind discretization schemes were employed to solve the volume fraction, the turbulence, the momentum equations and the energy equations. The solution was convergent when the scaled residuals were less than $1 \times 10^{-3}$.

**Materials and operating parameters:** Ethanol and SC-CO$_2$ were selected as solvent and anti-solvent, respectively.
Boundary conditions: For coaxial nozzle, as shown in Fig. 1, the inlet of CO$_2$ was inlet 1 and the inlet of ethanol was inlet 2. For tangential-inlet swirl nozzle, as shown in Fig. 3, inlet 1 was the inlet of SC-CO$_2$, and inlet 2 was the inlet of ethanol. For both of the nozzles, in terms of the inlet boundary condition of inlet 1, a simple mass flow inlet was selected and allowed to specify mass flow and temperature of SC-CO$_2$, turbulent kinetic energy, turbulent dissipation rate and initial volume fraction of ethanol. The mass flow and temperature of SC-CO$_2$ were 5.46 x 10$^{-5}$ kg sec$^{-1}$ and 363 K, respectively. The volume fraction of ethanol was zero.

For inlet 2, the inlet boundary condition was designated to be velocity-inlet. The velocity magnitude was 0.5 m sec$^{-1}$. Turbulent intensity is 1% and hydraulic diameter is 0.35 mm. The temperature of inlet 2 was 313 K. The pressure-outlet boundary condition was selected as the boundary condition of outlet. The pressure of outlet was set to be 8 Mpa. The conditions of pressure, temperature, mass flow rate and velocity magnitude used in this work were selected because they presented the best results regarding the morphology and the particle size distribution of the obtained particles (Baldyga et al., 2010a, b).

RESULTS AND DISCUSSION

Comparison of turbulent intensity at outlet: The contours of turbulent intensity at the outlet of these two nozzles were shown in Fig. 4. Turbulent intensity distribution on the diameter of the outlet of these two nozzles were shown in Fig. 5. As can be seen from Fig. 4a and 5a, the turbulent intensity on the outlet center of coaxial nozzle is 15% higher than that on the outlet edge. That because the flow in the nozzle is just like the flow in a tube and the resistance of boundary layer can not be ignored. On the contrary, for tangential-inlet swirl nozzle, the turbulent intensity on edge is higher than that on center as shown in Fig. 4b and 5b. That mainly because the fluids were introduced in the nozzle from tangential direction which counterweight the resistance of boundary layer. Moreover, the turbulent intensity in tangential-inlet swirl nozzle is far higher than that in coaxial nozzle. In SEDS process, high turbulent intensity is facilitated to mix SC-CO$_2$ fully with solution so as to form superfine particles. And particles are prone to adhere on the inner wall of nozzle so that the outlet is blocked. Therefore, high turbulent intensity on edge is more essential than that on center for nozzles. Consequently, from the aspect of turbulent

![Fig. 4(a-b): Contours of turbulent intensity at the outlet of nozzle, (a) Coaxial nozzle and (b) Tangential-inlet swirl nozzle](image-url)
intensity, the tangential-inlet swirl nozzle improved the distribution of turbulent intensity and outshined the coaxial nozzle.

**Comparison of velocity magnitudes at outlet:** The velocity magnitudes of the flow at outlet, influencing the growth time of crystal nuclei and particle size distribution, is an important parameter to indicate the performance of nozzle. The contours of velocity magnitudes at the outlet of the two nozzles were shown in Fig. 6. Velocity magnitudes distribution on the diameter of the outlet of the two nozzles was shown in Fig. 7. On the one hand, from the comparison of Fig. 6a and b, it can be concluded that the velocity magnitude distribution of coaxial nozzle is more even than that of tangential-inlet swirl nozzle. Even velocity magnitudes distribution is facilitated to control narrow particle size distribution. In this respect, the coaxial nozzle exceeds tangential-inlet swirl nozzle. On the other hand, from the comparison of Fig. 7a and b, it can be inferred that the velocity magnitudes on the diameter of tangential-inlet swirl nozzle are far higher than that of coaxial nozzle. High velocity can decrease the growth time of crystal nuclei, contributing to forming superfine particles. Consequently, the size of particle prepared by tangential-inlet swirl nozzle will be smaller than that of particle prepared by coaxial nozzle. From all above-mentioned CFD analysis, it can be conclude that tangential-inlet swirl nozzle can produce smaller particles, but the particle size distribution is not desired.

**Comparison of volume fraction of ethanol in the nozzles:** As shown in Fig. 8a and b, SC-CO₂ and ethanol began to mix in the upper part of these two nozzles and became entirely mixed in the lower part of these two nozzles. SC-CO₂ and ethanol was mixed by axial force in coaxial nozzle and by tangential force in tangential-inlet swirl nozzle. When the mixture reached outlet, SC-CO₂ had

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Fig. 5(a-b): Turbulent intensity distribution on the diameter of the outlet of the two nozzles, (a) Coaxial nozzle and (b) Tangential-inlet swirl nozzle

Fig. 6(a-b): Contours of velocity magnitudes at the outlet of the two nozzles, (a) Coaxial nozzle and (b) Tangential-inlet swirl nozzle
Fig. 7(a-b): Velocity magnitudes distribution on the diameter of the outlet of the two nozzles. (a) Coaxial nozzle and (b) Tangential-inlet swirl nozzle

Fig. 8(a-b): Contours of volume fraction of ethanol on the longitudinal section of the two nozzles. (a) Coaxial nozzle and (b) Tangential-inlet swirl nozzle

given full play to the function of anti-solvent and the solute was precipitated. Therefore, from the aspect of mixing, both of the nozzles can meet the requirements of preparing nano-drug in SDES process. Although the structures are different, the results are similar.

CONCLUSION

In this study, the comparison on the performance between tangential-inlet swirl nozzle and coaxial nozzle was conducted by CFD simulating. Turbulent intensity, velocity magnitude and volume fraction of ethanol were selected to act as the parameters compared. From all above CFD simulations, on the one hand, it can be deduced that both coaxial nozzle and tangential-inlet swirl nozzle can meet the requirement of preparing nano-drug in SDES process and have their advantages. Coaxial nozzle can prepare particles with more even size distribution than tangential-inlet swirl nozzle. And tangential-inlet swirl nozzle, with more merits, can produce higher turbulence intensity on the boundary layer which prevents the crystal nuclei precipitated from adhering on the inner wall. In additional, tangential-inlet swirl nozzle can produce higher velocity at outlet which can decrease the growth time of crystal nuclei so as to prepare superfine particles. On the other hand, both of the nozzles have their relative defects which should be improved in future study.
ACKNOWLEDGMENT

This work was financially supported by the National Key Technology R and D Program for the 12th Five-Year Plan (No. 2011BAD44B01).

REFERENCES


