Optimization of Abrasive Water Jet Nozzle Based on Numerical Simulation

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Abstract. In this paper, based on numerical simulation method, the rosin-rammler method was introduced to describe the non-uniqueness of particle diameter of abrasive water jet nozzle and the two-way coupling method was used to simulate the interaction between discrete phase and continuous phase. Through CFD simulation software, the influence of nozzle convergence angle, focus tube length on the outlet velocity of mixed-phase, and the relationship between abrasive flow rate and nozzle inner wall wear were obtained.

1. Introduction
As a new processing technology with rapid development in recent decades [1, 2], abrasive water jet technology has been applied in many industries, such as aerospace, petroleum exploitation, and other fields. Compared with the traditional machining method, abrasive water jet machining has the advantages of high machining flexibility, no tool wear, and high machining accuracy [3, 4, 5, 6]. Hence, abrasive water jet machining is often used in processing a variety of hard and brittle materials, such as ceramics, marble, aluminum alloy, etc.

As a key component of abrasive water jet, the nozzle has an important influence on the quality of the workpiece [7, 8, 9, 10]. In the process of abrasive water jet machining, the wear of the inner wall of the nozzle will affect the change of the diameter of the nozzle, leading to the decrease of the surface quality of the processed workpiece [11, 12]. Yu Feng & Wang et al [13]. studied the change of the velocity of abrasive and water jet in the nozzle along the focusing tube by SPH(Smoothed Particle Hydrodynamics) coupled FEM(Finite Element Method) numerical simulation method, and found that the velocity of abrasive particles at the nozzle outlet was the key factor affecting the cutting ability of jet. Gabriel Pozzetti & Xue Y et al [14, 15]. proposed a numerical erosion model for abrasive water jet nozzles based on the coupling of the recent dual-grid multimodal algorithm used in CFD-DEM (Computational Fluid Dynamics- Discrete Element Method) and experiments show that this method can predict erosion profile well. D. Deepak et al [16]. analyzed the influence of inlet pressure on the surface friction coefficient and the kinetic energy at the jet outlet and concluded that the surface friction coefficient would increase with the increase of inlet pressure.

It is concluded that most of the studies on water jet are based on liquid-solid two-phase simulation [17, 18], there are few studies on the three-phase simulation of solid-liquid-gas. In this paper, the difference between this paper and the previous work is that the rosin-rammler method is introduced to
describe the nonuniqueness of particle diameter, and two-way coupling between abrasive particles and high-pressure water is realized by DPM, which can simulate the practical application more accurately.

2. Mathematical model

To simulate the solid-liquid-gas multiphase flow of abrasive water jet, Fluent is used to achieve this simulation. Considering that the velocity of each phase is not consistent, the mixture model is used to simulate the continuous phase in this study.

2.1. Mathematical model of the continuous phase

In this simulation, liquid water is selected as the primary phase and the continuity equation (the mass conservation equation) of the mixture is as follows:

$$\frac{\partial}{\partial t}(\rho_m) + \nabla \cdot (\rho_m \bar{v}_m) = 0$$  \hspace{1cm} (1)

Where $\bar{v}_m$ is the mass-averaged velocity, $\rho_m$ is the density of the mixed-phase.

The momentum equation for a mixture can be obtained by adding the momentum equations for the water and gas phases, and it can be expressed by the following equation:

$$\frac{\partial}{\partial t}(\rho_m \bar{v}_m) + \nabla \cdot (\rho_m \bar{v}_m \bar{v}_m) = -\nabla P + \nabla \cdot \left[ \mu_m \left( \nabla \bar{v}_m + \nabla \bar{v}_m^T \right) \right] + \rho_m \ddot{g} + \bar{F} - \nabla \cdot \left( \sum_{k=1}^{n} a_k \rho_k \bar{v}_{dr,k} \bar{v}_{dr,k} \right)$$  \hspace{1cm} (2)

Where, $\bar{F}$ represents the volume force of the mixture phase, $\mu_m$ represents the viscosity of the mixture, and $\bar{v}_{dr,k}$ represents the drift velocity of the secondary phase.

According to the law of conservation of energy, the energy equation of the mixed-phase can be deduced as follows:

$$\frac{\partial}{\partial t} \sum_{k=1}^{n} (a_k \rho_k E_k) + \nabla \cdot \sum_{k=1}^{n} (a_k \bar{v}_k (\rho_k E_k + P)) = \nabla \cdot (k_{eff} \nabla T) + S_E$$  \hspace{1cm} (3)

Where $p$ is pressure, $k_{eff}$ is effective conductivity, $T$ is mass-average mixing temperature, and $E_k$ is average mass-average energy.

The Realizable k-ε model is selected as a turbulence model in this paper, the mathematical expression of the Realizable k-ε model is expressed by the following equation:

$$\frac{\partial}{\partial t} (\rho k) + \frac{\partial}{\partial x_j} (\rho u_j k) = \frac{\partial}{\partial x_j} \left[ \left( \frac{\mu + \mu_t}{\sigma_k} \right) \frac{\partial k}{\partial x_j} \right] + G_k + G_b - \rho \varepsilon$$  \hspace{1cm} (4)

$$\frac{\partial}{\partial t} (\rho \varepsilon) + \frac{\partial}{\partial x_j} (\rho u_j \varepsilon) = \frac{\partial}{\partial x_j} \left[ \left( \frac{\mu + \mu_t}{\sigma_\varepsilon} \right) \frac{\partial \varepsilon}{\partial x_j} \right] + \rho C_1 S_\varepsilon - \rho C_2 \frac{\varepsilon^2}{k + \sqrt{\varepsilon}} + \frac{\varepsilon}{k} C_{1e} \frac{\varepsilon}{k} C_{3e} G_b$$  \hspace{1cm} (5)

Where $G_k$ is the turbulent kinetic energy generated by the average velocity gradient, $G_b$ is the turbulent kinetic energy caused by buoyancy, $C_2$, $C_1$, $C_{1e}$, $\sigma_k$ and $\sigma_\varepsilon$ are constants, the model constants are as follows:

$$C_{1e} = 1.44, \ C_2 = 1.9, \ \sigma_k = 1.0, \ \sigma_\varepsilon = 1.2$$

2.2. Mathematical model of discrete phase

The volume fraction of particles in abrasive water jet is usually less than 10% [19], so the DPM is appropriate in this paper [20]. A two-way coupling method is used to simulate the interaction between the fluid phase and the discrete phase in this part, the dispersed phase, and the continuous phase, exchanging momentum, mass, and energy with each other. Considering that the abrasive diameter is not
a constant value, the equation rosin-rammler is introduced to describe the nonuniqueness of particle
diameter. This is also the difference between this study and previous studies. According to Newton's
second law, the motion equation of the particle can be obtained as:

$$m_p \frac{d\vec{u}_p}{dt} = m_p \vec{u} - \vec{u}_p + m_p \frac{\vec{g}(\rho_p - \rho)}{\rho_p} + \vec{F}$$

(6)

Where, the subscript $p$ represents the particle, $m_p$, $\vec{u}_p$ and $\rho_p$ represents the mass, velocity, and
density of the particle respectively, the last term on the right represents the additional force, $\tau_r$
represents the relaxation time of the particle.

3. Simulation setup

3.1. Geometric model and meshing

Considering that the model is symmetrical, the axial symmetric structure of the nozzle model is
established, and half of the symmetrical structure of the nozzle is selected as the calculation area to save
calculation resources. In view of the high-frequency interaction between water jet and abrasive particles
in the central axis area of the nozzle, a more precise mesh division is adopted, the size of the model is
shown in Table 1.

| Table 1. Model size of nozzle |
|--------------------------------|
| Description                     | Parameters |
| Mixing chamber diameter         | 5 mm       |
| Mixing chamber length           | 8 mm       |
| Focus tube diameter             | 0.8 mm     |
| Focus tube length               | 20-100 mm  |
| Waterjet orifice diameter       | 0.3 mm     |
| Convergence angle               | 20°-70°    |

3.2. Boundary conditions and solution Settings

In the simulation model, high-pressure water enters the mixing chamber at an initial speed of 700m/s
from the orifice and abrasive particles enter the mixing chamber at a speed of 10m/s from the abrasive
inlet pipe. The rosin-rammler method is introduced to describe the nonuniqueness of particle diameter,
and two-way coupling between abrasive particles and high-pressure water is realized by DPM. The
pressure equation is in PRESTO format, the volume fraction is in GEO-Reconstruct format and the other
formats are set as the second-order upwind format.

4. Results and discussions

4.1. Effect of length of focus tube and convergence angle on exit velocity of mixed-phase

As can be seen from Fig. 1, the velocity of the abrasive water jet in the nozzle changes greatly. As the
jet enters the mixing chamber, the speed on the axis of the mixing chamber decreases rapidly. At the
end of the contraction section, as it is close to the cylinder inlet of the abrasive nozzle, the fluid has a
relatively stable flow direction. Under the acceleration of the contraction section, the jet velocity begins
to rise. However, as the length of the focusing tube increases, there is little change in speed. When the
length of the focus tube is 40mm, the exit speed reaches the maximum.
Fig. 1 CFD simulation results: (a) cloud image of flow field distribution inside the nozzle, (b) velocity distribution of nozzle center axis.

As the abrasive is sucked into the mixing chamber due to the venturi effect, particles enter the focus tube for mixing and acceleration. As shown in Fig. 2, with the increase of the contraction angle, the exit velocity of the mixed-phase gradually decreases. The reason is that with the increase of the nozzle convergence angle, the expansion angle of the jet and the intensity of the vortex all increase, but the larger the contraction angle is, the lower the kinetic energy of the jet will be, leading to the continuous decrease of the outlet velocity of the mixed-phase. Hence, the convergence angle of the nozzle should not be too large.

Fig. 2 CFD simulation results: (a) When the contraction angle is 40°, the velocity streamlines in the nozzle velocity streamline in the nozzle, (b) the evolution of the outlet velocity of the mixed-phase with the convergence angle.

4.2. Influence of abrasive flow rate on nozzle wear

After the abrasive particles enter the mixing chamber, on account of the influence of the vortex of the flow field, the abrasive will collide with the inner wall of the nozzle and wear the inner wall of the nozzle, as shown in Fig. 3.

The maximum wear of the nozzle is positively correlated with the abrasive flow, when the abrasive flow increases, the wear of the inner wall of the nozzle increases. The reason is that when the abrasive
flow rate increases, the abrasive concentration per unit volume increases, the number of abrasive and nozzle internal collision increase, aggravate the nozzle internal wear.

![Image](Fig. 3 CFD simulation results: (a) when the abrasive flow rate is 20g/s, the wear cloud image of the inner wall of the nozzle, (b) the evolution of the maximum wear of nozzle inner wall with abrasive flow rate.)

5. Conclusions

Based on the current work, the following conclusions can be drawn.

1. The convergence angle is negatively correlated with the jet velocity, the smaller the convergence angle is, the higher the mixed-phase velocity at the outlet of the abrasive water jet nozzle is. From this point of view, the optimal contraction angle of the nozzle is 30°.

2. When the abrasive water jet enters the mixing chamber, the velocity of the mixing phase decreases before increases, and finally tends to be stable in the focusing tube.

3. The abrasive flow rate is positively correlated with the wear of the nozzle inner wall, when the abrasive particle flow rate increases, the wear of abrasive particles on the inner wall of the nozzle is greater.

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