FLOW FIELD CHARACTERISTICS OF ULTRA-HIGH PRESSURE POST-MIXED ABRASIVE WATER JET APPLIED FOR NON-EXPLOSIVE TUNNEL EXCAVATION

by

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Ultra-high pressure abrasive water jet (AWJ), as a non-explosive tunnel excavation method, is proposed to reduce the impact on surface resident and other environmentally sensitive areas. In this paper, we carried out multi-phase simulation analysis of AWJ flow field based on Euler model to optimize the operation parameters of the post-mixing AWJ under the dual constraints of jet velocity and abrasive consumption. The characteristics of sand mixing in the nozzle, the evolution of the flow field and abrasive consumption under ultra-high pressure were obtained and analyzed. Considering the joint constraints of jet velocity and abrasive consumption, the operation parameters were optimized and recommended for tunnel contour cutting. This study is expected to provide theoretical and engineering guidance for future application of high pressure AWJ non-explosive tunnel excavation.

Key words: *flow field, multi-phase flow, AWJ, non-explosive excavation, contour cutting*

Introduction

Drilling and blasting excavation is the common method of tunnel excavation with low construction cost and less initial investment. However, it faces some challenges such as large disturbance of surrounding rock, over and under excavation and poor working environment, which restricts tunnel construction efficiency. To address the aforementioned issues, ultra-high pressure AWJ is proposed to apply in the tunnel excavation as a new idea of non-explosive method [1]. In this method, the robot arm drives the ultra-high pressure water jet to cut the tunnel contour accurately, and then the hydraulic splitting is used to realize the rock breaking and tunnel excavation avoid surrounding rock disturbance, over-excavation and under-excavation and poor working environment caused by explosion [2]. The AWJ is a high energy beam jet formed by mixing abrasive particles with high speed flowing water through the nozzle [3]. Since the abrasive water jet is a cold single point kinetic energy, it has a strong erosion effect on

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the material, and does not change the mechanical, physical and chemical properties of the material during the erosion process [4]. In the process of tunnel excavation, to ensure the efficiency of excavation, the cutting depth of a single contour line is required to be no less than 1 m, that is, AWJ is required to have high velocity and good rock-breaking ability at long jet distance [5, 6]. Nevertheless, from an economic point of view, the consumption amount of abrasive should not be too high, usually < 4 kg per minute, which requires us to reduce the jet velocity oppositely. Therefore, the operation parameters and the nozzle structure of the post-mixing AWJ needs to be optimized under the dual constraints of jet velocity and abrasive consumption.

In this paper, we carried out multi-phase simulation analysis of AWJ flow field based on Euler model. The characteristics of sand mixing in the nozzle, the evolution of the flow field and abrasive consumption under ultra-high pressure were obtained and analyzed to optimize the nozzle structure and parameters for contour cutting. This study is expected to provide theoretical guidance for application of AWJ non-explosive tunnel excavation.

Model and computation set-up

Problem description and geometry model. In the post-mixed abrasive jet, the water jet is imposed into mixing cavity of nozzle with high velocity around 750-800 m/s by high pressure pump. According to Bernoulli energy equation, the high velocity will cause low pressure which is even lower ambient pressure. Accompany with gravity, this pressure difference between ambient and mixing cavity will make the abrasive sand absorbed into the mixing cavity. The abrasive and water are mixed in the cavity and then sprayed from the mixing nozzle. Figure 1(a) shows the structure of post-mixing jet nozzle, including water nozzle, abrasive inlet, mixing cavity and tube. For simplification, we set the abrasive nozzle angle, θ, fixed at 60° and the contraction angle, α, at 20°.We adopted the axis-symmetry assumption considering the nozzle structure axis-symmetric to construct the 2-D model as shown in fig. 1(b).

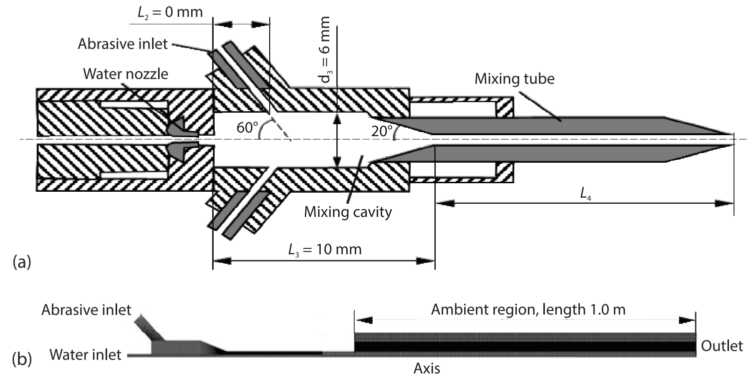

Figure 1. Structure of post-mixing nozzle;
(a) structure of post-mixing jet nozzle and (b) geometry model

Model formulation and parameter set-up. According to some research, the realizable k-ε turbulence model is suitable for jet flow simulation. The model equation of k and ε [4]:

$$\frac{\partial}{\partial t}(\rho k)+\frac{\partial}{\partial x_i}(\rho k u_i)=\frac{\partial}{\partial x_j}\left[\left(\mu+\frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right]+G_k-\rho\varepsilon-Y_M+S_k \tag{1}$$

$$\frac{\partial}{\partial t}(\rho\varepsilon)+\frac{\partial}{\partial x_i}(\rho\varepsilon u_i)=\frac{\partial}{\partial x_j}\left[\left(\mu+\frac{\mu_t}{\sigma_\varepsilon}\right)\right]+\rho C_1 S\varepsilon-C_{2\rho}\frac{\varepsilon^2}{k+\sqrt{v\varepsilon}}+C_{1\varepsilon}C_{3\varepsilon}G_b+S_\varepsilon \tag{2}$$

where ρ is the fluid density, k – the turbulent kinetic energy, t – the time, u_i – the mean velocity components, μ_t – the turbulent viscosity, G_k – the generation of turbulent kinetic energy due to mean velocity gradients, G_b – is the Generation of turbulent kinetic energy due to buoyancy, ε – the dissipation rate of turbulent kinetic energy, Y_M – the contribution of the fluctuating dilatation in compressible turbulence to the overall dissipation, and S_k – the user-defined source term for k:

$$\frac{\partial}{\partial t}(\alpha_i\rho_i)+\nabla(\alpha_i\rho_i\vec{v}_i)=\sum_{i=1}^{n}(m_{ij}-m_{ji}) \tag{3}$$

with

$$C_1=\max\left[0.43,\frac{\eta}{\eta+5}\right],\ \eta=S\frac{\varepsilon}{k},\ S=\sqrt{2S_{ij}S_{ij}}$$

where α_i is the volume fraction of phase, ρ_i – the density of phase, and m_{ij} – the mass transfer. Equation (3) is the transport equation of each phase. The boundary conditions and the physical property of AWJ jet is show in tab. 1.

Table 1. Boundary conditions and the physical property of AWJ jet

Parameter	Value	Parameter	Value
Water inlet pressure/ [MPa]	350	Abrasive diameter [mm]	0.2
Outlet pressure [MPa]	0	Abrasive shape	Sphere
Density of abrasive [kgm^{-3}]	3000	Fluid density [kgm^{-3}]	998
Abrasive concentration [%]	100	Fluid viscosity [Pa·s]	0.001

Results and analysis

In the nozzle shown in fig. 2, the abrasive can be absorbed into mixing cavity smoothly. The abrasive mainly distributes around the water jet and there is almost no abrasive in the center of water jet. The abrasive enters in the mixing tube and abrasive distribution develops and becomes steady occupying the axis zone of the tube. In the mixing cavity, there are two low fraction belts of water, where the abrasive is absorbed. In the ambient region, the abrasive jet keeps desirable shape after 1 m long trip. The water and abrasive region are restricted into a small zone and there is little dispersion of water and abrasive. This shows that the abrasive jet can keep good convergence even at 1 m jet distance.

We investigate the velocity development of jet in the ambient zone, as shown in fig. 3. The maximum velocity magnitude is around 70 m/s which is about 800 m/s in nozzle. This is the difference due to the diameters. As the diameter of water nozzle is only

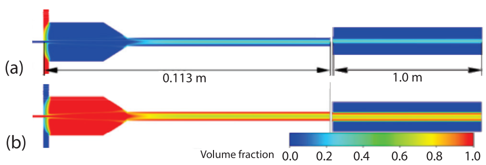

Figure 2. Distribution of fluid concentration; (a) water and (b) abrasive

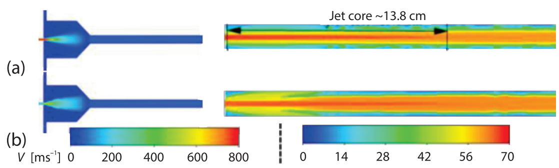

Figure 3. Velocity filed in AWJ simulation; (a) water and (b) abrasive

0.8 mm but the nozzle of mixing tube is 3 mm in this case. The same as velocity in nozzle, the jet in ambient zone has full structure, too. As the abrasive jet is spray into air, the jet core is long with length around 13.8 cm. The velocity of abrasive has the same structure of water.

Figure 4 shows the velocity along axis in nozzle and ambient zone. In nozzle, the water jet keeps almost stable along the axis and then decreases. After entering mixing tube, the velocity keeps stable again at around 67 m/s. In ambient zone, the velocity is not stable. After the jet core, velocity of water and abrasive both decrease quickly at first and then reduce gradually, with velocity at 61 m/s after 1 m long travel. Figure 4(b) shows the impact pressure of abrasive jet. It is obvious that the curves have similar trend with velocity curves. But the impact pressure of abrasive is about three times higher than that of water. The velocity of abrasive exceeding threshold value is a key factor for breaking the rock.

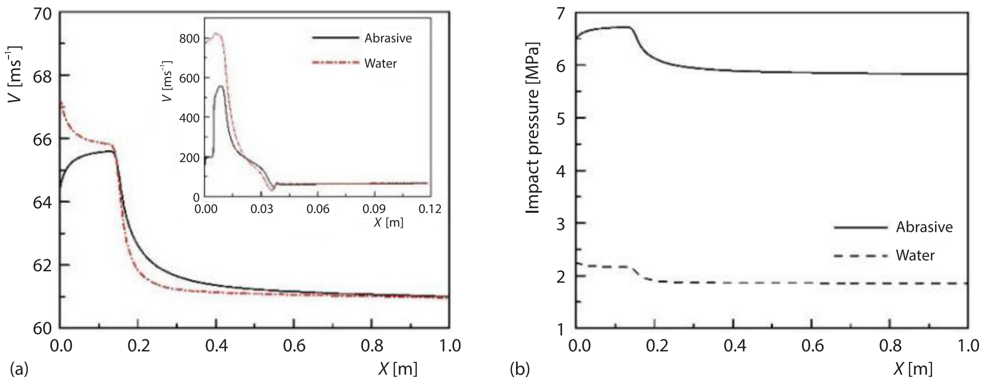

Figure 4. Velocity and impact pressure profile along jet axis; (a) velocity and (b) impact pressure

Figure 5 contrasted the AWJ flow field under submerged and non-submerged conditions. Under non-submerged conditions, the jet velocity remains about 61 m/s after the jet distance reaches 1 m, which has a certain impact capability. In contrast, the jet dissipates and attenuates rapidly in the case of submerged condition. When the jet distance exceeds 15 cm, the jet velocity basically decreases to 0. To ensure rock-breaking capacity, it is necessary to keep the slurry in the cutting groove discharged to avoid water cushion in the non-submerged jet condition. The jet velocity and equivalent impact pressure of AWJ with sand tube diameter of 2 mm and 3 mm were contrasted in figs. 6(a) and 6(b).

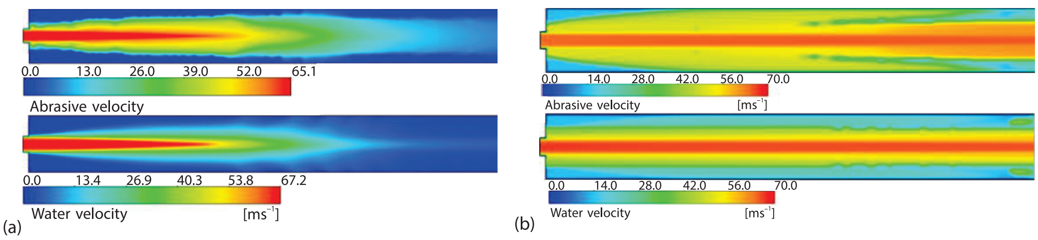

Figure 5. Flow field of submerged (a) and non-submerged (b) AWJ

At the length of 160 mm, the jet acceleration performance is best, with the maximum jet velocity at the outlet. Figure 7(b) shows the effect of pump displacement on jet velocity and abrasive concentration at the outlet. The jet velocity and impact capacity improve significantly with the increasing pump displacement, but accompanied by the growing abrasive consumption simultaneously. For the sand tube with the diameter of 3 mm, the maximum operating displacement is recommended to be <17 Lpm, with the jet velocity of 38~40 m/s at the jet distance of 1 m, fig. 7(c), considering the abrasive consumption limitation of <4 kg per minute and corresponding costs in the engineering. Regarding to pump pressure, as the pump pressure increases, the jet velocity and impact pressure improve greatly, but resulting in larger abrasive consumption, as shown in fig. 8. With the abrasive consumption limitation of 4 kg per minute, the recommended pump pressure is ≤160 MPa in the actual tunnel excavation process.

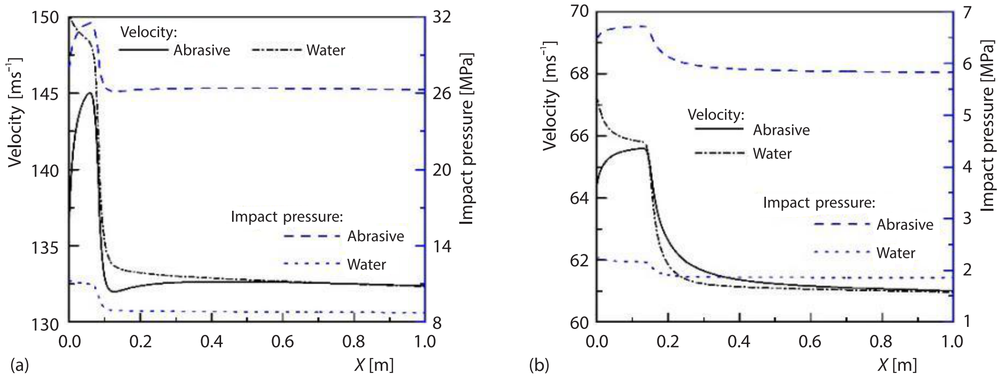

Figure 6. Jet velocity and equivalent impact pressure along jet axis; (a) 2 mm and (b) 3 mm

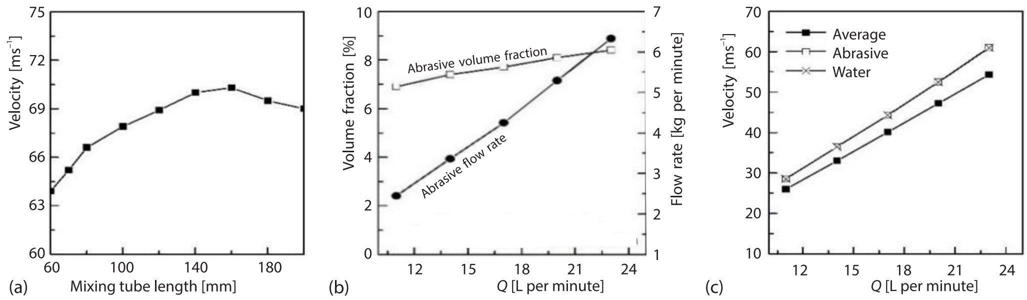

Figure 7. The effect of mixing tube length and pump rate on AWJ flow field

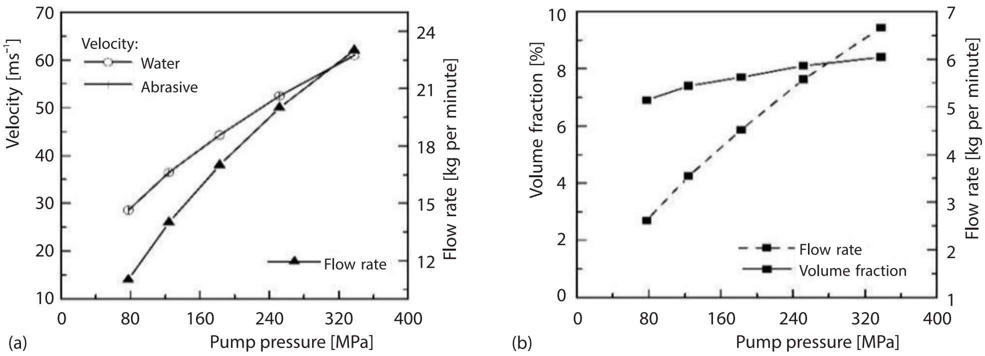

Figure 8. Influence of pressure on velocity (a) and abrasive usage (b)

Conclusion

The velocity field of AWJ is characterized by three typical zones: potential core, diffusion zone and decay zone. As AWJ jet transits from the potential core to the decay region, the velocity drops sharply, and then basically remains stable. The velocity of jet axis at 1 m spray distance reaches 61 m/s, with a small attenuation amplitude of only 10%. Unlike the non-submerged state, the submerged jet dissipates and attenuates faster, and the effective spray distance is less than 15 cm. To ensure sufficient rock-breaking capacity, it is necessary to ensure that the slurry in the cutting groove is discharged in time, avoiding the influence of water cushion and maintaining the non-submerged jet state. Abrasive particle size mainly affects the self-imbibition ability of abrasive, small particle size leads to higher self-imbibition flow rate of abrasive and increased abrasive consumption. With increasing pump rate and pressure, the jet velocity and impact force increase, but leads to larger abrasive consumption. To keep the abrasive consumption <4 kg per minute, the maximum pump rate and pump pressure is recommended to be <17 Lpm and <160 MPa.

Nomenclature

m_{ji} – mass transfer, [molm^{-2}s^{-1}]
$\vec{v}$ – velocity, [ms^{-1}]

Greek symbols

α_i – volume fraction of phase, [–]
ρ_i – density of phase, [Kgm^{-3}]

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