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To cite this article: Gaofeng Song *et al* 2019 *IOP Conf. Ser.: Earth Environ. Sci.* **267** 042053

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Finite element analysis of nozzle selection based on high pressure water jet technology

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Abstract. High-pressure water jet technology is an emerging type of welding joint strengthening process in recent years, which has unique advantages such as non-polluting, high efficiency, and can strengthen some complicated welds that in dead end position such as fillet welds. However, there is no supporting water jet strengthening nozzle domestically, so this paper uses the computational fluid dynamics method to simulate the internal and external flow fields of the nozzle, which is the most commonly used four conical convergence nozzles with different structure of the current water jet technology, making the flow field velocity distribution of the four nozzles and the impact pressure on the target surface compared and analysed. The results show that the impact pressure and axial speed of the conical short-line nozzle are slightly smaller than that of the conical (13°) nozzle, but conical short-line nozzle's jet collection property and stability are superior to the other types of nozzles. Therefore, the conical short-line nozzle should be selected when the high-pressure water jet technology is utilized for welding joint reinforcement.

1. Introduction

In recent years, high pressure water jet technology has been widely used in various industrial fields. The working principle of the high-pressure water jet is to pressurize the water through the specific device and then through the high-pressure pump deliver it to the nozzle where the water is converged to convert the pressure energy into kinetic energy. After that, the water flow is accelerated by the nozzle and is sprayed in the form of a high-speed water stream, which impacts the surface of the weld to reduce the residual stress of the weld [1-3]. As a new surface strengthening technology for welding joints, high-pressure water jet has the advantages of low cost, high efficiency, no pollution, no damage to surface materials, easy automation, and is not affected by the shape and position of welds, making welds of some complicated structures such as the dead corners strengthened to avoid the failure of the broken corners such as the roots, which has broad application prospects [4-6]. At present, the conical convergence nozzle is mainly used in industrial applications, and is applied to cleaning, cutting, crushing, etc. There is no strengthening nozzle matched with high-pressure water jet device in China.

During the jet process, water and air will undergo intense momentum exchange. Therefore, the water jet usually involves a gas-liquid two-phase mixed medium, and the mechanism is complicated.



Efficient and convenient analysis and calculation of the high pressure water jet process can be realized by using the CFD technology. Aimed at four kinds of conical convergence nozzles with different structures that are used in the current water jet technology and based on Fluent software, this paper simulates the internal and external flow fields of the nozzle, and compares the flow velocity distribution of the four nozzles and the impact pressure on the target surface, hoping it can play a guiding role in nozzle selection and design.

2. Governing equations and mathematical models

According to the literature [7-10], this analysis uses the N-S equations as the governing equation and the standard - model as the computational model.

Continuity equation:

$$\frac{\partial u_i}{\partial x_i} = 0 \quad (1)$$

In the formula (1): u_i represents the velocity tensor and x_i represents the displacement tensor.

N-S equations:

$$\rho \frac{\partial u_i}{\partial t} + \mu \left(\frac{\partial^2 u_i}{\partial x_i^2} \right) = \rho \frac{du_i}{dt} \quad (2)$$

In the formula (2): $i=x, y, z$, when the subscript is used, it represents the X, Y, Z axis, otherwise it represents the displacement tensor. u_i indicates the speed tensor, μ indicates the dynamic viscosity.

k - ε equation:

k equation:

$$\frac{\partial(\rho k)}{\partial t} + \frac{\partial(\rho k u_i)}{\partial x_i} = \frac{\partial}{\partial x_j} \left[\left(\mu + \frac{\mu_t}{\sigma_k} \right) \frac{\partial k}{\partial x_j} \right] + G_k + G_b - \rho \varepsilon - Y_M + S_k \quad (3)$$

ε equation:

$$\frac{\partial(\rho \varepsilon)}{\partial t} + \frac{\partial(\rho \varepsilon u_i)}{\partial x_i} = \frac{\partial}{\partial x_j} \left[\left(\mu + \frac{\mu_t}{\sigma_\varepsilon} \right) \frac{\partial \varepsilon}{\partial x_j} \right] - C_{2\varepsilon} \rho \frac{\varepsilon^2}{k} + C_{1\varepsilon} \frac{\varepsilon}{k} (G_k + C_{3\varepsilon} G_b) + S_\varepsilon \quad (4)$$

In the formula (3) and (4): G_b represents the turbulent kinetic energy caused by buoyancy force; G_k represents the turbulent kinetic energy caused by the average velocity gradient; $C_{1\varepsilon}$, $C_{2\varepsilon}$, $C_{3\varepsilon}$ are empirical constants; Y_M represents the effect of compressive turbulent pulsation expansion on the total dissipation rate; σ_k and σ_ε are the Prandtl number respectively corresponding to the turbulent kinetic energy k and dissipation rate ε ; S_k and S_ε are user-defined source terms; turbulent viscosity coefficient: $\mu_t = \rho C_\mu \frac{k^2}{\varepsilon}$.

In Fluent, as default constants, $C_{1\varepsilon}=1.44$, $C_{2\varepsilon}=1.92$, $C_{3\varepsilon}=0.09$, the Prandtl number corresponding to the turbulent kinetic energy k and dissipation rate ε are $\sigma_k = 1.0$, $\sigma_\varepsilon = 1.3$ [11].

3. Geometric modelling and meshing

Most of the practical applications in projects are conical convergence nozzles. In this analysis, four conical convergence nozzles are used as an example for the analysis of the contraction angle α , the cylinder length to diameter ratio l/d , the inlet diameter d_1 , and the outlet diameter d_2 , four parameters are predetermined, and four kinds of nozzle main structural parameters shown in Table 1:

Table1. A slightly more complex table with a narrow caption.

Numbering	α (°)	l/d	d1(mm)	d2(mm)
Conical short straight type	13	2.5	4.5	1
Conical long straight type	118	10	4.5	1
Conical (6°) type	6	0	4.5	1
Conical (13°) type	13	0	4.5	1

Since the water jet involves a gas-liquid two-phase mixed medium, an air flow field needs to be set outside the nozzle outlet. The air flow field size is defined as the length 200 mm, width of 15 mm according to the literature [12]. Four kinds of nozzle models Figure 1 Shown as follows:

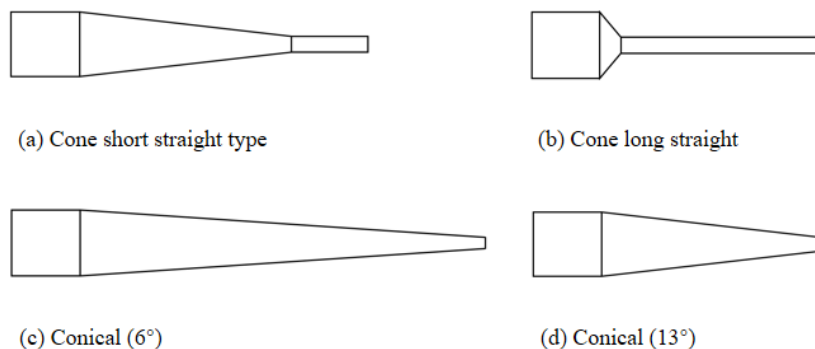


Figure 1. Structure diagram of the three nozzles.

According to the symmetrical characteristics of the non-submerged environment high-pressure water jet structure, the two-dimensional axisymmetric model is used in the modeling, which can improve the efficiency and reduce the calculation amount. This analysis uses the dotted line method to model. The grid is divided into quadrilateral structured grids, and the certain refinement is done inside the nozzle and near the nozzle exit because the model is regular. Each side is divided to ensure that the total number of nodes on the opposite side is same, and then the mesh of the faces is divided.

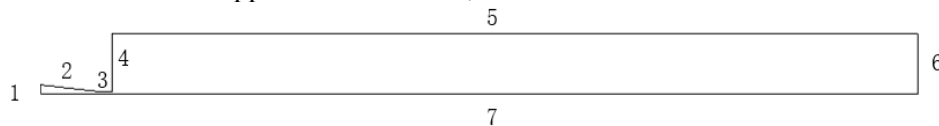


Figure 2. Flow field model of conical short straight nozzle.

After the geometric modeling and meshing are completed, the boundary conditions need to be set in the Gambit software to indicate the type of each boundary of the model. As shown in Figure 2, the short straight conical nozzle, for example, the inlet pressure is set to 10 MPa and the outlet pressure is set to 0 MPa. Each side of the boundary conditions defined in Table 2:

Table2. A slightly more complex table with a narrow caption.

Numbering	Boundary conditions
Nozzle inlet 1	PRESSURE_INTEL
Nozzle wall 2,3	WALL
Nozzle outlets 4,5	PRESSURE_OUTLET
Impacted object surface 6	WALL
Symmetry axis 7	AXIS

After the definition of the boundary conditions, the fluid model needs to be exported to a mesh file in .msh format and then post-processed by simulation software Fluent.

4. Analysis of flow field simulation results

4.1. Comparison of velocity distribution

As shown in Figure 3, after comparing the axial velocity distributions of the nozzle of the four different structures, it can be seen that initially the jet velocity increases rapidly in the axial direction, reaches the maximum in the throat, and then gradually decreases. This is because the pressure energy is converted into the kinetic energy of the jet after the jet being converged and accelerated by the nozzle condensation, and then the velocity is rapidly attenuated due to the resistance of the flow field outside the nozzle. The conical long linear nozzle has the most severe velocity attenuation in the external flow field and the other three nozzles have slower velocity attenuation and better jet concentration. Among them, the conical short-line nozzle has the most concentrated velocity distribution, and the jet clustering property is Stability is superior to other types of nozzles.

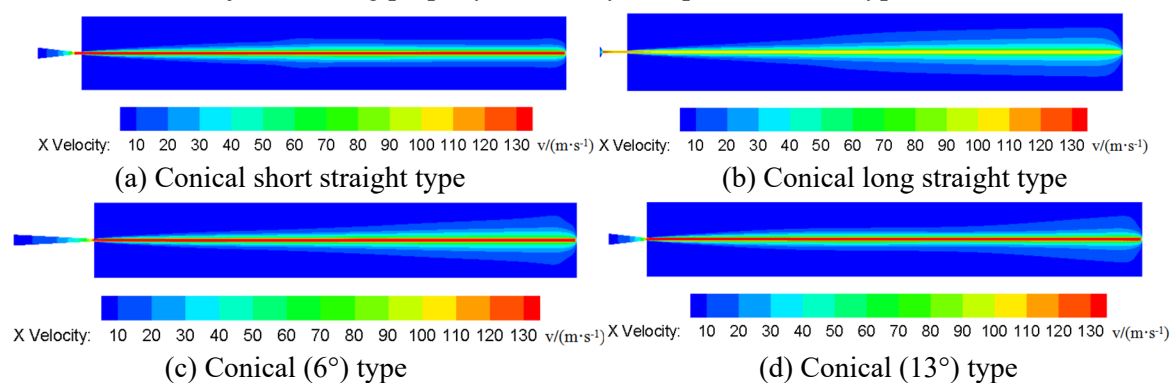


Figure 3. Jet velocity distribution cloud map of different structure nozzles.

Comparing the conical short linear nozzle and the conical (13°) nozzle, we find that the difference between the two is whether there is a cylindrical section. As can be seen from Figure 3, the axial velocity distribution of the conical short linear nozzle is more stable. The reason is that when the fluid suddenly turns, the jet will shrink due to the water flow line not immediately turning into the direction parallel to the axis of the pipeline, but the jet will be affected by the resistance. If there is a cylindrical section of suitable length, the jet will fill the entire section before the ejection, that is, the shrinkage section exists in the tube, so that the section shrinkage coefficient=1, so that there is vacuum at the contraction section, dynamic pressure drive and vacuum suction simultaneously drive the jet, that is why the flow rate is larger than that of the conical nozzle without the cylindrical section and a jet with a more stable velocity distribution can be obtained. However, it should be noted that the absolute pressure of the shrinkage section should be avoided below the local saturated steam pressure, otherwise gasification of the water flow at the cross section will occur.

In order to more intuitively show the velocity distribution of the water jet, we establish three sections perpendicular to the axis of symmetry in three places 50 mm, 100 mm, and 150 mm from the nozzle outlet respectively, and compare the distribution of high-pressure water jet velocity on the three sections. Figure 4 shows that the jet velocity reaches its maximum at the axial center and decays rapidly as the radial distance increases. Therefore, when the welding joint is strengthened, the nozzle axis should be aligned with the part to be welded so that the axis of the high-pressure water jet is perpendicular to the weld surface of the weldment, making impact treated successful. In addition, as can be seen from Figure 4, the axial speeds of the conical nozzles with two different contraction angles are basically the same, about 141 m/s, and the axial speed of the conical short linear nozzle is slightly lower than the former two, and the conical long linear nozzle is the smallest, and on the sections with different axial distances, the conical long-line nozzle has the most serious divergence. In 50 mm and 100 mm cross section, the aggregation of the conical (13°) nozzle is optimal. In cross-section of 150 mm, the aggregation of the conical (6°) nozzle is the best. The initial section of the jet is an effective area for the welding joint reinforcement operation, so the conical (13°) nozzle is superior to the conical (6°) nozzle when the welding joint is strengthened by high-pressure water jet technology.

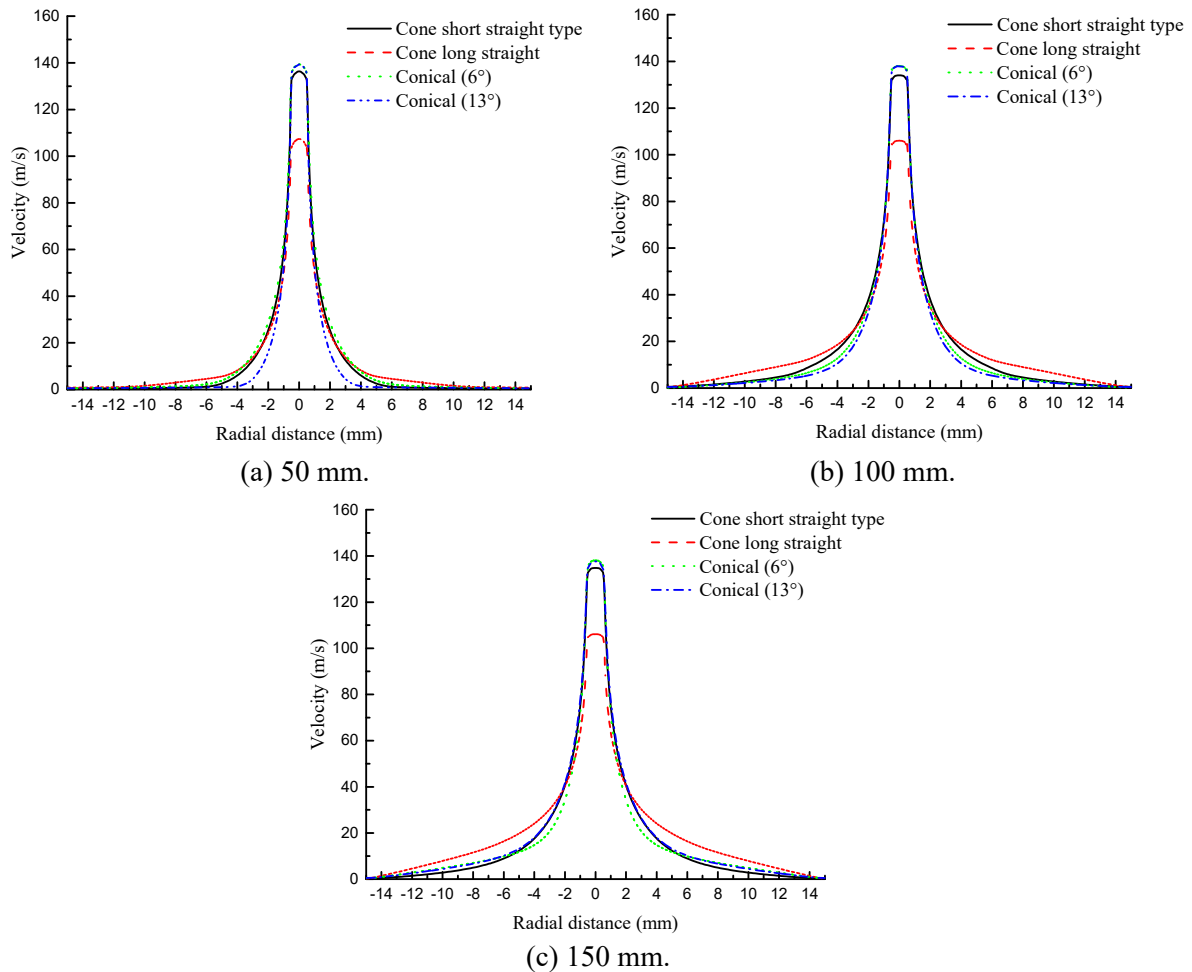


Figure 4. Velocity Comparison of Four Nozzles at Different Sections from the Exit.

4.2. Impact pressure comparison

It can be seen from Figure 5 that the impact pressure of the nozzle of the four different structures is similar in the radial direction, that is, the impact pressure reaches the maximum at the axial center, and is rapidly attenuated from the axial center to both sides. Among them, the impact pressure of the conical short straight nozzle and the conical (13°) nozzle on the target is basically the same, the former is 9.43 MPa, the latter is 9.54 MPa, indicating that the energy loss is small, the jet is not easy to diverge, and the convergence is better. The impact pressure of the conical (6°) nozzle is 9.11 MPa, indicating that as the shrinkage angle is reduced, the resistance formed in the contraction section becomes larger, resulting in an increase in energy loss and a smaller impact pressure on the surface of the target.

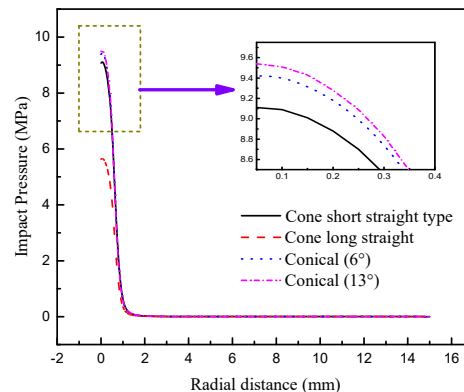


Figure 5. Radial impact pressure distribution.

5. In conclusion

In this paper, geometric modelling and meshing of nozzles with four different structures were carried out, and the velocity distribution and impact pressure of the four nozzle water jets were analyzed by Fluent software. The simulation results were basically consistent with the theoretical calculations. Although the impact pressure and axial speed of the conical short-line nozzle were slightly smaller than that of the conical (13°) nozzle, but the jet's collection property and stability were superior to the other types of nozzles. Therefore, when the high-pressure water jet technology is utilized for welding joint reinforcement, the conical short-line nozzles should be selected.

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