Numerical Analysis of Nozzles' Energy Loss Based on Fluent

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Abstract: Energy loss during the formation of high pressure water jet was investigated theoretically. Computational fluid dynamics software was used to simulate the high pressure water jet flow field produced by three kinds of nozzles, including cylindrical, conic and cosine nozzles. And the influence of the nozzle's conic angle, inlet diameter, outlet diameter and inlet pressure on energy loss coefficient was investigated. The results show that the energy loss of the high pressure nozzle is independent on the inlet pressure but related to the angle of the nozzle, inlet diameter and the outlet diameter. With the increasing of angle and inlet diameter and the decreasing of the diameter, the energy loss coefficient will be increasing. The energy loss coefficient of the cylindrical nozzle is the largest, and the energy loss coefficient of the conical nozzle is slightly larger than that of the cosine nozzle, if they are all with the same inlet outlet diameter. This work provides theoretical basis for optimal design and efficient improving of high pressure nozzles.

1 Introduction

Water jet technology is a new technology developed in recent 20 years. With high pressure water jet device, it can generate high pressure water. The water jet nozzle's role is to convert pressure energy into kinetic energy, thushigh speed water flow can complete the cleaning, cutting, crushing and other process technologies. The water jet nozzle is high pressure water jet device's execute component, and its role is through the contraction of the nozzle's cross-section, the high pressure energy of water can come together and be converted into kinetic energy, and finally ejected outward in the form of high-speed water jet, cleaning, breaking materialsand so on.

Research has shown that the geometric parameters of the nozzle determine the performance of high-pressure water jet flow field. Yang Guolai and his partners[1] analyze and compare the physical high-pressure water jet flow field of two different types of cone nozzle. They find cone-shaped nozzle has the fastest speed with aspect ratio of 2 to 3 and stability of water jet's boundary depends on the Weber number.Yang Yousheng and his partners[2] study the flow characteristics cylinder nozzles, cone nozzles, and cosine nozzles. They obtain the relations between cavitation energy loss, characteristic energy loss and nozzles' import and export conditions and characteristics parameters.Ma Fei and his partners[3]analyze the influence of the characteristics parameters of nozzles on field velocity distribution, pressure distribution and export speed of internal flow. Yang Guolai and his partners[4]study the influence of the characteristics parameters of nozzles on jet bunding and transverse velocity of the jet outlet boundary, coming to the conclusion thatwhen α = 13 °, l / d = 2 has the best jet bunding and when α = 22 ° -34 °, the outlet boundary have higher lateral speed. Liu Ping and his partners[5]analyze the influence of the characteristics parameters of nozzles such as cone nozzles' converging angle, aspect ratio of nozzle outlet'scylindrical section and nozzle outlet diameter on the attenuation characteristics of the jet axis velocity by numerical Simulation. Yi Can and his partners[6]study the relations between nozzle structure and high pressure jets, coming to the conclusion that nozzle structure have influence on jet flow characteristics, erosion performance, cavitation and so on.

This article will use the Fluent, a kind of computational fluid dynamics simulation software to simulate internal high-pressure water jet flow field in cylindrical, conical and cosine nozzle in order to study the effect of the nozzle geometry and the import conditions on the performance of high-pressure water jet.

2 Mathematical Model of the Jet Nozzle

Nozzle model is shown in Figure 1. Apply Bernoulli's equation between the I-I-section and O-O-section.

$$\frac{p_i}{\rho g}+\frac{\alpha_1 u_i^2}{2g}=\frac{p_o}{\rho g}+\frac{\alpha_2 u_o^2}{2g}+\Delta E_n \quad (1)$$

$$q=A_i u_i=A_o u_o \quad (2)$$

In equation (1) and (2), p_i、p_o are nozzle’s import and outlet pressure, u_i、u_o are nozzle’s import and outlet average flow rate, α_1、α_2 are kinetic energy correction factors, approximately equal to 1, A_i、A_o are nozzle import and export area, $A_i=\pi R^2$, $A_o=\pi r^2$, ρ is working medium density,g is acceleration of gravity, ΔE_n is energy loss of per unit mass, SI.

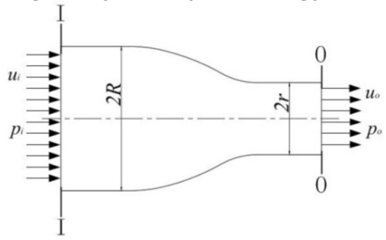


Fig.1 Model of Nozzles

Ignoring import flow rate u_i and energy loss, working medium is water($\rho=998kg/m^3$), in theory, nozzle outlet average flow rate and flow are as equation (3) and (4).

$$q_t=\frac{\Delta p}{R_{th}} \quad (3)$$

$$R_n=\frac{1}{A_o}\sqrt{\frac{\rho}{2}\Delta p} \quad (4)$$

Obviously, without energy loss, theoretical flow is proportional to the area of the nozzle outlet and 1/2 times of differential pressure.

In the actual case, energy loss cannot be ignored. According to the knowledge of fluid mechanics, energy loss in nozzle can be classified into local energy loss and route energy loss. By definition, the total energy loss is as equation (5).

$$\Delta E_n=\xi_n\frac{\Delta p}{\rho g} \quad (5)$$

Nozzle’s actual flow is as equation (6).

$$q=C_q q_t \quad (6)$$

In equation, ξ_n is energy loss coefficient, C_q is flow coefficient.

According to equation (1) to (6)

$$q_t=0.141r^2\sqrt{\Delta p} \quad (7)$$

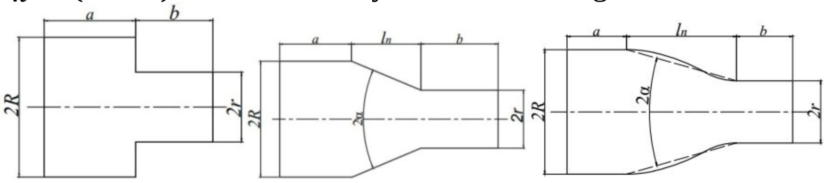
$$\xi_n=C_q^{-2}-1 \quad (8)$$

So, energy loss coefficient is related to flow coefficient. The actual flow rate q can be obtained by the simulation. The theoretical flow $q_t$can be obtained by equation (7). Flow coefficient $C_q$can be obtained by q/q_t. Energy loss coefficient ξ_n then can be obtained by equation (8). According to equation (7), the larger flow equation is, the smaller energy loss coefficient is, the more sufficient energy transformation is; and the smaller flow equation is, the larger energy loss coefficient is, the less sufficient energy transformation is.

3 Nozzle water jet simulation

3.1 Geometric parameters of the nozzles

Geometric parameters of cylindrical, conical and cosine nozzles are shown in Fig. 2. Geometric parameters of the nozzles include inlet diameter *2R*, outlet diameter *2r*, inlet length *a*, outlet length *b*, cone angle *2α* andcontraction length l_n.Cone angle *2α* and contraction length l_n are geometric parameters of contraction part.The inner contour curve of contraction part of conical nozzle is segment. The inner contour curve of contraction part of cosine nozzle is cosine curve. Cone angle of cosine nozzle is the angle between the line, formed by start point and end point of cosine curve, and the axis. The contraction length of cone nozzle l_n is a function of the contraction angle α, $\boldsymbol{l_n = (R - r)\cot\alpha}$. Similarly, contraction length l_n and contraction angle α of cosine nozzle.



(a) Cylindrical Nozzles (b) Conical Nozzles (c) Cosine Nozzles

Fig. 2 Geometric Parameters of Nozzles

These three kinds of nozzles have the same inlet length$a$ and outlet length b, but different inlet diameter 2R, outlet diameter 2r, contraction angle α and contraction length l_n.

Tab.1 Geometric Features of Nozzles

Nozzle type	inlet diameter *2R*/mm	outlet diameter *2r*/mm	inlet length *a*/mm	outlet length *b*/mm	cone angle *2α*/(°)
cylindrical nozzle	1.6+0.4n(n =1~9)	0.6+0.3n(n =1~9)	2	2	-
conical nozzle					20n(n=1~ 8)
Cosine nozzle					

3.2 Geometric Modeling and Fluid Simulation Based on CFD

The simulation of fluid in nozzle is performed in Fluent. Fluent is the world's popular commercial CFD software package, with a lot of physical models, advanced numerical methods and powerful processing capabilities around.Firstly, use SolidWorks to create computational fluid domain. Secondly, import domain into ICEM CFD to generate mesh. Thirdly, import mesh into Fluent to simulate. Set solver based on pressure, steady-state problem in time type. Activate energy equation. Set standard k-εmodel in turbulence model, default setting. Set inlet as pressure-inlet, outlet as pressure-outlet. Set SIMPLC algorithm for pressure-speed association algorithm, default setting.Choose iterative solver and mixed initialization.

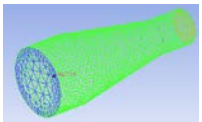


Fig.3 Meshing of Fluid Computational Domain

4 Fluid simulation results

In this paper, the three kinds of nozzles have the same parameters such as inlet length and outlet length and some different parameters such as inlet diameter *2R*, outlet diameter *2r* and some contraction parameters, thus we can analyze the influence of inlet diameter *2R*, outlet diameter *2r* and contraction parameters on energy loss coefficient.

The contraction surface of cylindrical nozzle is vertical to the nozzle axis. The inner diameter of the nozzle has a mutation. The contraction part of conical nozzle is circular conical surface. With the decrease of the contraction angle, the inner diameter of the nozzle becomes gradually smaller. The connection part has sharp corners.The inner contour curve of contraction part of cosine nozzle is cosine curve, without sharp corners. Set *2r* 1.8mm, $\boldsymbol{p_i}$ 20MPa.Change the cone angle to analyze the relation between energy loss coefficient $\boldsymbol{\xi_n}$ and cone angle α, shown as Fig. 4.

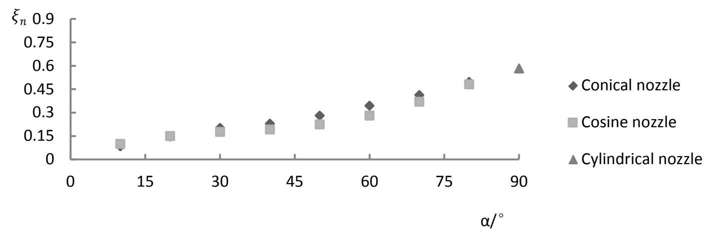


Fig. 4 Relations between Energy Loss Coefficient and Cone Angle

(1) Cylindrical nozzles have the most energy loss coefficient with the value 0.58. When high-pressure water enter nozzle, it will shrink rapidly because of the contraction of inner diameter, causing much energy loss. Differently high-pressure in conical and cosine nozzles shrink slowly, so they have less energy loss.

(2) The energy loss coefficients of conical nozzles range from 0.08 to 0.50. As cone angle becomes bigger, energy loss coefficient grows. According to the trend, when αapproach to 90°, $\boldsymbol{\xi_n}$ is almost equal to 0.58, that is the value of cylindrical nozzles' energy loss coefficient.

(3) The energy loss coefficients of cosine nozzles range from 0.09 to 0.49. As cone angle becomes bigger, energy loss coefficient grows. In the same condition, because the connection part between the contraction part and inlet, outlet part of cosine nozzles is smooth, but that of conical nozzles is not, so the local energy loss of cosine nozzles is less, so the energy loss coefficient of cosine nozzles is slightly less than that of conical nozzles.

Set $\boldsymbol{p_i}$ 20MPa, *2R* 3.6mm, 2α40°. Change the outlet diameter 2r to analyze the relation between energy loss coefficient $\boldsymbol{\xi_n}$ and outlet diameter 2*r*, shown as Fig. 5.

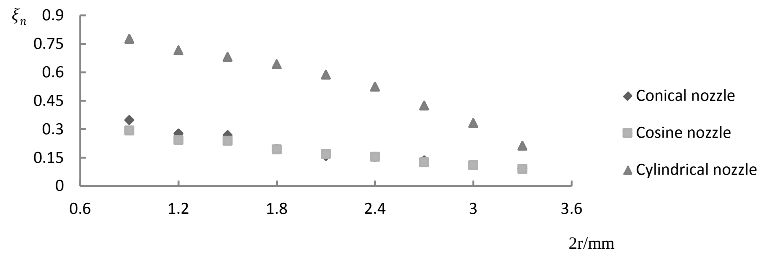


Fig. 5 Relations between Energy Loss Coefficient and Outlet Diameter

(1) The energy loss coefficients of cylindrical nozzles range from 0.21 to 0.78. In the condition of the same outlet diameter, cylindrical nozzles have the most energy loss.

(2) The energy loss coefficients of these three kinds of nozzles first grow and then reduce and then remain essentially unchanged as outlet diameter approach to inlet diameter. The gentler the contraction of high-pressure water is, the less the local energy loss is.

Set $\boldsymbol{p_i}$ 20MPa, *2r*1.8mm, 2α 40°. Change the inlet diameter *2R* to analyze the relation between energy loss coefficient $\boldsymbol{\xi_n}$ and inlet diameter 2*R*, shown as Fig. 6.

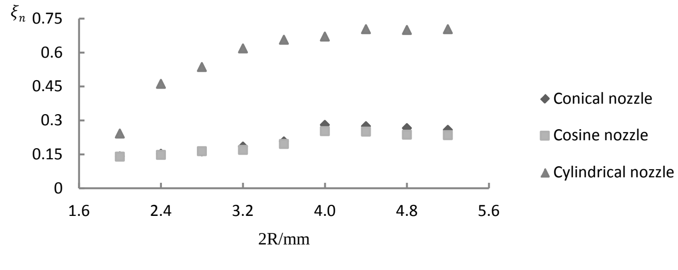


Fig. 6 Relations between Energy Loss Coefficient and Inlet Diameter

(1) The energy loss coefficients of cylindrical nozzles range from 0.24 to 0.71. In the condition of the same inlet diameter, cylindrical nozzles have the most energy loss.

(2) The energy loss coefficients of these three kinds of nozzles first grow and then reduce and then remain essentially unchanged as inlet diameter grows.

(3) Connect Fig. 5 and Fig. 6, we can find when $R/r \approx 1$, the energy loss coefficient is the least.

Set $2R$3.6mm, $2r$ 1.8mm, 2α 40°. Change the inlet pressure$\boldsymbol{p_i}$ to analyze the relation between energy loss coefficient $\boldsymbol{\xi_n}$ and inlet pressure, shown as Fig. 7.

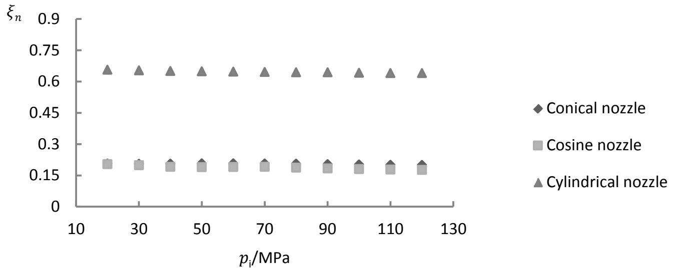


Fig. 7 Relations between Energy Loss Coefficient and Inlet Pressure

(1) Cylindrical nozzles have the most energy loss coefficient with the value 0.65. The energy loss coefficient of cosine nozzles is slightly less than that of conical nozzles.

(2) As inlet pressure grows, the energy of high-pressure water jet increases, but the energy loss coefficients of three kinds of nozzles remain almost unchanged. So the energy loss coefficient has no relation to inlet pressure. It's defined by the geometric parameters of the nozzles.

5 Conclusion

The reasons of energy loss in water jet are different. Study the energy loss of cylindrical, conical and cosine nozzles by simulation to analyze the relation between the energy loss coefficient and the geometric parameters of nozzles. The conclusions are as follow:

(1) In the condition that the inlet pressures are the same, the energy loss coefficient of cylindrical nozzles is the most, this is because there is the most local energy loss in the contraction part.

(2) The energy loss coefficient of conical nozzles and cosine nozzles are mainly influenced by cone angle and the ratio of inlet diameter and outlet diameter. The smaller the cone angle is, the less the energy loss coefficient is; the closer to 1 the ratio of inlet diameter and outlet diameter is, the less the energy loss coefficient is.

(3) In the condition that nozzles have the same inlet diameter, outlet diameter and cone angle, the energy loss coefficient of cosine nozzles is slightly less than that of conical nozzles, this is because the local energy loss of cosine nozzles is less than that of conical nozzles.

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