Numerical simulation of adjustable nozzles

S B Zhang and J M Zhu

School of Power and Mechanical Engineering, Wuhan University
Key Laboratory of Hubei Province for Water Jet Theory and New Technology
8 East Lake Southern Road, Wuhan, 430072, P R China

E-mail: zhangsongbo@whu.edu.cn

Abstract. This paper presents the optimal combination of the nozzle and needle valve in adjustable nozzles. With numerical simulation tool of FLUENT, water jet out of different nozzles with contraction angle 30°, 40°, 50°, 60°, 70°, 80° are simulated, and within nozzles there are different needle valves with contraction angle 20°, 30°, 40°, 50°, 60°, the simulation results are compared and analyzed. The needle valves locate at the same position in the nozzles in different combinations. After water jet flows out of the nozzle, along the direction of flow there are three flow stages: initial stage, transitional stage and basic stage. The sectional area of bundle of jet shrinks near the exit of the nozzle when fluid flows out of the nozzle. Ignoring the transitional stage, the shrinkage of the bundle of jet occurs in the initial stage. The severer the contraction of jet is, the bigger the maximum velocity of the jet is, the faster the axial velocity decays. When the contraction of the jet is slight, jet flow is stable, the attenuation of the axial velocity is slower. The flow field is investigated by two-dimensional numerical analysis. Different combinations are analyzed to find the performance variation in order to select the best combination. The study offers references for the selection of the nozzle shape and needle valve shape for adjustable nozzle. It has important significance in the design and manufacture of adjustable jet pump.

1. Introduction
The adjustable nozzle is mainly applied to Pelton turbine and the adjustable jet pump[1,2], in the past, investigation achievements of the performance of the adjustable nozzle are much less than that of the performance of the traditional nozzle[3,4,5]. A lot of numerical simulation and experimental study have been done on the selection of the best contraction angle in traditional nozzles. But the performance of the adjustable nozzle is quite different from the traditional nozzle. In practical application of adjustable nozzles, how to select the combination of the nozzle and the needle valve to achieve the best performance is still the main problem. So it is necessary to study profoundly on the performance of the adjustable nozzle, which makes the flow structure within adjustable nozzles be well understood and make the theory of jet pump be enriched. The research findings of adjustable nozzles can instruct its optimization design and operation, and there is very significant in theory or practice.

In the adjustable nozzle, due to existing of spindle, the flow out of the nozzle sometime is dense jet, and sometime is hollow core annular jet. The flow structure within adjustable nozzle is very complicated. With numerical simulation tool of FLUENT, different combinations of the nozzle and needle valve in adjustable nozzles are simulated, the simulation results are compared and analyzed.
Through studying on the distribution of the main physical quantities in flow field of adjustable nozzles, a reference for the practical application is provided.

2. The mathematical model and boundary conditions

2.1. Mathematical model

The flow field is incompressible, steady, isothermal turbulent flow. In a Cartesian coordinate system continuity equation in tensor form is as follows:

\[
\frac{\partial \rho u_i}{\partial x_i} = 0
\]  

Momentum equation of incompressible viscous fluid motion is as follows:

\[
\frac{\partial u_i}{\partial t} + \frac{\partial }{\partial x_j} (u_i u_j) = -\frac{1}{\rho} \frac{\partial p}{\partial x_i} + \frac{\partial }{\partial x_j} (\nu \frac{\partial u_i}{\partial x_j} - u_i u_j)
\]  

Standard \( \kappa-\varepsilon \) equation turbulence model in jet simulation:

\[
\begin{align*}
\frac{\partial (\rho k)}{\partial t} + \frac{\partial (\rho k u_i)}{\partial x_j} &= \frac{\partial }{\partial x_j} [(\mu + \frac{\mu_t}{\sigma_k}) \frac{\partial k}{\partial x_j}] + G_k - \rho \varepsilon \\
\frac{\partial (\rho \varepsilon)}{\partial t} + \frac{\partial (\rho \varepsilon u_i)}{\partial x_j} &= \frac{\partial }{\partial x_j} [(\mu + \frac{\mu_t}{\sigma_k}) \frac{\partial \varepsilon}{\partial x_j}] + \frac{C_1 \varepsilon}{k} G_k - C_2 \varepsilon \frac{\varepsilon^2}{k}
\end{align*}
\]

\[\mu_t = \rho C_{\mu} \frac{k^2}{\varepsilon}, C_{1\varepsilon} = 1.44, C_{2\varepsilon} = 1.92, C_{\mu} = 0.09, \sigma_k = 1.0, \sigma_{\varepsilon} = 1.3\]

2.2. Meshing and boundary conditions

The nozzles are axisymmetric structure, there is a straight pipe section at the exit of the nozzle, physical model samples are shown in Figure 2.1 and Figure 2.2. The grid division for the axisymmetric flow field of the traditional nozzle is shown in Figure 2.3, The grid division of the adjustable nozzle is shown in Figure 2.4. The inlet diameter of nozzle is 50mm, outlet diameter is 20mm, contraction angles of adjustable nozzles are 30°,40°,50°,60°,70°,80°, the diameter of needle valves are 16mm, contraction angles of needle valves are 20°,30°,40°,50°,60°. Computational domain is 25d*8d, the straight pipe section at the exit of the nozzles is 1/4d, d is the outlet diameter of the nozzle. In order to show the mesh details, length of calculations zone is not fully displayed. ICEM software is used to draw the shapes and calculating area of nozzles, jet is submerged jet and accompanying jet.

Entrance boundary condition is Velocity inlet, velocity of jet in the nozzle entrance is 20m/s, velocity of the accompanying jet is 10m/s. The outlet boundary condition is Outflow, the boundary condition on the axis is Axisymmetric. The wall surface satisfies the no-slip condition, the standard wall function method is used near wall region.

![Figure 2.1 Traditional nozzle](image1)

![Figure 2.2 Adjustable nozzle](image2)
3. Numerical simulation and analysis

3.1. The analysis of the optimal contraction angle of traditional nozzles with a straight pipe

Traditional nozzles with contraction angle $5^\circ, 10^\circ, 13.5^\circ, 20^\circ, 30^\circ, 40^\circ, 50^\circ, 60^\circ$ are simulated, physical model sample is shown in Figure 2.1. For the analysis and comparison of velocity characteristics of different nozzles, according to numerical results of the nozzles, the axial velocity values of the axis are collected and placed in the same coordinate system as shown in Figure 3.1.

![Figure 3.1 The distribution of the axial velocity values on the axis](image)

The zero position locates at the exit of the nozzle, these curves show the results of numerical simulation of nozzles with contraction angle $5^\circ, 10^\circ, 13.5^\circ, 20^\circ, 30^\circ, 40^\circ, 50^\circ, 60^\circ$.

The smaller the contraction angle of the nozzle is, the longer the length of the nozzle is, it is not economical and practical in applications. According to the calculation results, the velocity of jet increases in the contraction section of the nozzle, the velocity continues to increase when water jet inflows the straight pipe, the sectional area of bundle of jet shrinks near the exit of the nozzle when fluid flows out of the nozzle until the maximum axial velocity. As the contraction angle of the nozzle increases, the bundle of jet shrinks severer nearer the exit of the nozzle, the maximum velocity at the exit of the nozzle is greater, and the axial velocity decays faster, the jet flow is unstable. Through these above comparisons, when the contraction angle of the nozzle is $10^\circ$, the performance of the nozzle is optimal.

3.2. Comparison of the nozzle without a straight pipe and the nozzle with a straight pipe

When contraction angle of the nozzle is $13.5^\circ$, physical mode of the nozzle without a straight pipe is shown in Figure 3.2. For the analysis and comparison of velocity characteristics of different nozzles,
according to numerical results of the nozzles, the axial velocity values of the axis are collected and placed in the same coordinate system as shown in Figure 3.3. According to the calculation results, the jet out of the nozzle without a straight pipe shrinks severer, the maximum velocity near the exit of the nozzle is greater and the axial velocity decreases rapidly. The performance of the nozzle with a straight pipe is better and more stable. In practical application and design, the nozzle with a straight pipe is a better selection.

**Figure 3.2.** Traditional nozzle: without a straight pipe section at the exit of the nozzle

The zero position locates at the exit of the nozzle.

**Figure 3.3.** Comparison of two kinds of nozzles

### 3.3. Numerical Simulation and Analysis of Adjustable nozzles

Select the nozzles with contraction angle $30^\circ, 40^\circ, 50^\circ, 60^\circ, 70^\circ, 80^\circ$, and the needle valve with contraction angle $20^\circ, 30^\circ, 40^\circ, 50^\circ, 60^\circ$, 24 kinds of combinations of different adjustable nozzles are
simulated. The needle valves locate at the same position in the nozzles in different combinations as shown in Figure 2.2. For the analysis and comparison of velocity characteristics of different nozzles, according to numerical results of the nozzle, the axial velocity values of the axis are collected and placed in the same coordinate system as shown in Figure 3.4.

("3020" means in this combination, the contraction angle of the nozzle is 30° and the contraction angle of the needle valve is 20°).

According to the above numerical results, for different combinations of adjustable nozzles, the main influence factor on its performance is the contraction angle of the nozzle, as the contraction angle of the nozzle increases, the influence of the contraction angle of the needle valve is gradually larger. The sectional area of bundle of jet shrinks near the exit of the adjustable nozzle when fluid flows out of the nozzle. According to the maximum axial velocity near the exit of the nozzle and the rate of decay of the axial velocity on the axis, when the contraction angle of the nozzle is 30°, the maximum velocity at the exit of the adjustable nozzle is minimum and the axial velocity decays least, the jet flow is most stable, the performance of adjustable nozzle is optimal.

3.4. Numerical Simulation and Analysis of Adjustable nozzles when adjusting the needle valve

When the waterway cross section area of nozzle is changed by adjusting the opening degree of needle valve, the performance of the adjustable nozzle is altered. Select the nozzle with contraction angle 60° and the needle valves with contraction angle 30°, 40°, 50°, 60°, the waterway cross section area at the entrance of the straight pipe section is adjusted to 1/2 to the area of the exit of the nozzle (physical model is shown in Figure 3.5), through the numerical simulation, the axial velocity values of the axis are collected and placed in the same coordinate system as shown in Figure 3.6.

When the contraction angle of the needle valve is 60°, the maximum velocity near the exit of the nozzle is minimum, and the axial velocity decays least, the jet flow is most stable. So if the contraction angle of the nozzle is fixed at 60°, when the contraction angle of the needle valve is 60°, the performance of the adjustable nozzle reaches optimal.
4. Conclusion
The numerical simulation shows that: (1) As to the tradition nozzle, when the contraction angle of the nozzle is 10°, the sectional area of bundle of jet shrinks least near the exit of the nozzles, the axial velocity decays least, the performance of the nozzle is optimal. (2) The performance of the nozzle with a straight pipe is better than that of the nozzle without a straight pipe. (3) For different combinations of adjustable nozzles, when the contraction angle of the nozzle is 30°, the maximum velocity near the exit of the nozzle is minimum and the axial velocity decays least, the jet flow is most stable. (4) When the contraction angle of the nozzle is fixed at 60° in adjustable nozzles, the needle valve with contraction angle 60° is the best combination, the performance of the adjustable nozzle reaches optimal.

References
[1] Wang D M 1993 Transactions of the Chinese Society for Agricultural Machinery 24 No.4
[2] Zhu J M and Zhang S N 2013 China Rural Water and Hydropower 160-162
[3] Zhang K, Shen S Q and Yang Y 2010 International Journal of Low-Carbon Technologies 5(2) 51-56
[4] Zhou W H 2008 Simulation of flow field of high-pressure water-jet from nozzle with FLUENT (Lanzhou: Lanzhou Univ. of Tech)
[5] Khan M E H and Geskin E S 1993 A Numerical Investigation of Turbulent Behaviors of Water Flow Inside Nozzle Proc. 7th US Water Jet Conf. (Seattle, Washington, USA, 28-31 August 1993)
[6] Peng Z J, Su K, Zhang P et al 2010 Numerical simulation of an electrolytic spray process with volume-of-fluid model 18th annual Conf. of the CFD society of Canada (London, Ontario, Canada, 17-19 May 2010)