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NUMERICAL SIMULATION ANALYSIS AND EXPERIMENTAL RESEARCH ON MULTISTAGE THROTTLE ORIFICE

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Abstract. *Multistage orifice is widely used in large pipe transmission systems. In order to find the key factors which affect the energy dissipation, the orifice characteristics with different geometrical parameters were analyzed by numerical simulation and experiment. At first, numerical model of orifice was built. Then simulation results were got with different orifice thickness, distribution diameter and chamfering of orifice hole by Fluent. Finally, experiment was performed to verify the simulation which proved that the simulation results were correct and practical.*

Keywords: Energy dissipation, Geometrical parameters, Pressure drop

1. **Introduction.** Throttle orifice is a kind of metal plate with open holes, using the throttling principle to measure the fluid flow or dissipate the fluid energy of pipeline. As a pressure adjusting device, the throttle orifice produces resistance when fluid flows through the orifice, making the pressure drops [1]. Because throttle orifices are cheap and easy to install, they are widely used in various kinds of large pressure drop transmission systems, such as water spillway system, the airplane oil system and nuclear power station pipeline system [2].

According to the theory of fluid mechanics, when the fluid flows through the throttle device, it will generate a pressure drop, and the pressure drop not only depends on the throttling effect, but also relates to thermodynamic condition of fluid flow through the orifice and the pressure of equipment after the throttle orifice [3]. Therefore, if the throttle orifice is designed or selected improperly, the fluid through it will produce a big pressure drop which could make lots of problems, such as cavitation, and even produce flash, causing the separation of vapor-liquid phase, big vibration and noise, damaging the pipeline structure, and harming health of workers [4]. So reasonable design and optimization of throttle orifice parameters will prolong use age, improve the safety and reduce noise which is of great significance for the green production and efficient production.

There are lots of literature dealing with the energy consumption of different types of throttle. Nahra and Kamotani researched on the influence of different diameters on fluid flow ratio and flow velocity by visual experiment [5]. Osman et al. did the simulation and experiment about the high speed flow of two-phase flow in small diameter pipe under the condition of different velocities and orifice diameters. It was concluded that there were three different areas for the pressure distribution along the orifice: negative pressure gradient extension area in the entrance, constant pressure area in the middle, and compression area in the outlet [6]. Liu et al. analyzed the influence of the hole diameter and diameter-length-ratio on the cavitation, and got the conclusion that the cavitation occurred firstly in the entrance of the hole and moved forward to the outlet with the increase of pressure drop, and the bigger diameter-length ratio is, the more easily cavitation would occur [7]. Numerical analysis of fluid through a pipe orifice was performed by Cheng et al., and they got that corresponding to the flow rate, change deceases with the increasing Re [8]. Moussou et al. studied on the cavitation and noise when fluid flew through the orifice and they got the method to reduce the noise and optimize the structure [9]. Zhao and Zhang studied influence characteristics on throttle orifice with the different structure parameters. They got the results that equivalent diameter ratio was the biggest factor on throttling characteristics according to the experiment [10]. Wang and Liu compared the cavitation with different shapes of cross section and analyzed the formation mechanism and influence factors of cavitation [11]. Aman et al. did simulation on two different kinds of orifice, they got mathematical model of laminar flow and turbulent flow, and improved the accuracy of the numerical simulation [12]. Liu et al. simulated the small aperture multistage by iteratively finding proper initial flow field, and showed that the number of the orifices is the major factor which influences the flow coefficients of the multistage orifice units [13]. The cavitation phenomenon was explored based on the analysis of gas-liquid two-phase flow by Liu and Zhao, and then experimental verification was performed. The simulation results showed that the fluid pressure clearly decreased while flowing through the poppet area [14]. Jin et al. studied on the high multi-stage pressure, and got the conclusion that with the increasing of openings, the maximum velocity, turbulent dissipation rate and pressure loss were all increasing gradually, while the temperature did not change significantly [15].

In the past, the researchers have achieved some results about the energy dissipation characteristic. However, the researches about the throttle orifice used in nuclear power are seldom reported. The high pressure pipeline has the characteristics of short distance and high pressure drop, so it is necessary to use multistage energy dissipation method to achieve decreasing pressure smoothly, especially considering the working security. In this paper, the influences of geometrical parameters such as orifice thickness, distribution diameter and chamfering on energy dissipation in nuclear power industry are analyzed. At first, the throttle orifice model is established. Then the influences of geometrical parameters are gotten by numerical simulation. At last, experiment results are compared with the simulation, and the influence regulations are concluded.

2. **Numerical Simulation Model.**

The multistage throttle orifice is shown in Figures 1(a) and 1(b). Different geometrical parameters such as distribution diameter of orifice, orifice thickness, front end chamfering and back end chamfering are shown in Figure 1(c).

The flow will increase with the increasing of the differential pressure ΔP between two sides of orifice. When differential pressure ΔP goes up to a certain value, the pressure will drop below the fluid saturation vapor pressure P_V, then fluid becomes to vaporize, and flow in the pipeline will no longer increase with the increasing of the differential pressure ΔP. At this time, differential pressure ΔP between two sides of the orifice is called blocking differential pressure ΔP_S. When the differential pressure ΔP is smaller than ΔP_S, cavitation phenomenon can be avoided.

$$\Delta P_S = 0.81(P_1 - F_f P_V) \tag{1}$$

$$F_f = 0.96 - 0.28\sqrt{\frac{P_V}{P_C}} \tag{2}$$

where, P_1 is inlet pressure of orifice, F_f is critical pressure ratio coefficient, P_V is saturated vapor pressure, and P_C is thermodynamic critical pressure of the water.

When the pressure drop is too big, single stage throttle orifice will not meet the requirements, so multistage throttle orifice should be used. The differential pressure ΔP of each stage should be smaller than the corresponding ΔP_S. And pressure drop of multistage orifice decreases according to geometry [15].

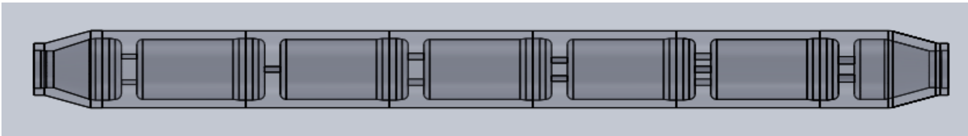
$$\Delta P = \Delta P_1 + \Delta P_2 + \Delta P_3 + \cdots + \Delta P_n \tag{3}$$

$$\Delta P_1 = 2\Delta P_2 = 4\Delta P_3 = \cdots = 2^{n-1}\Delta P_n \tag{4}$$

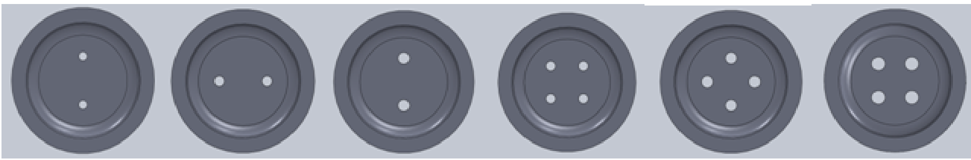
The hole diameter of orifice can be calculated as below:

$$d_k = \sqrt{\frac{421.6G}{\sqrt{\rho \Delta P}}} \tag{5}$$

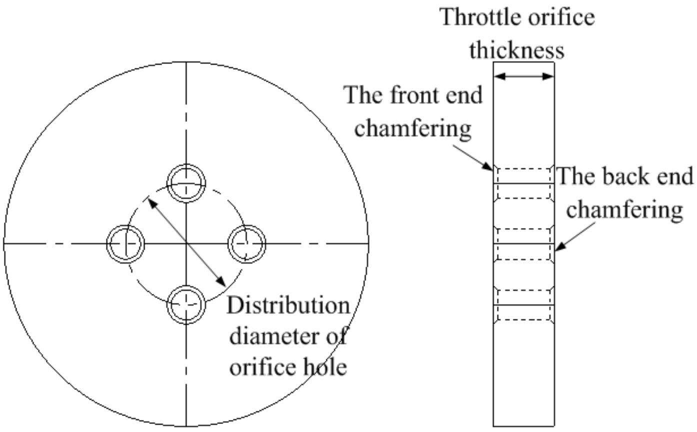
where, d_k is hole diameter of orifice, G is flow through the orifice, ρ is density of the water, and ΔP is differential pressure between two sides of orifice.



(a) Multistage throttle orifice pipe



(b) Throttle orifice of each stage



(c) The key parameters of throttle orifice

Figure 1. Multistage throttle orifice

In this study, the pipe inlet pressure is 18MPa, flow rate is 13.6m^3/h, working temperature is 46°C, and outlet pressure is 0.18MPa. Because the differential pressure ΔP is 17.82MPa, and ΔP_S is 14.572MPa gotten from Formula (1) which is smaller than ΔP, there will be cavitation if only signal stage throttle orifice is adopted. According to Formulas (3) and (4), if six stages orifice is used, the differential pressure ΔP of every stage will be less than ΔP_S for each stage, so the six-stage orifice is adopted. And the diameter of each stage can be calculated from Formula (5).

In the simulation model, the calculation is used in steady station, absolute velocity, N-S control functions and standard k-ε turbulence model. Other boundary conditions are as follows.

(1) The pressure is the inlet boundary condition which is 18MPa.

(2) The mass flow is the outlet boundary which is 3.7664kg/s by calculation.

(3) No slip wall boundary is adopted.

(4) The working medium is water which is 46°C.

3. The Analysis of Energy Dissipation with Different Geometrical Parameters.

3.1. Throttle orifice thickness. Only the orifice thickness is changed to 8mm, 13mm, 18mm, 23mm and 28mm respectively. The results of numerical simulation analysis are shown in Figure 2.

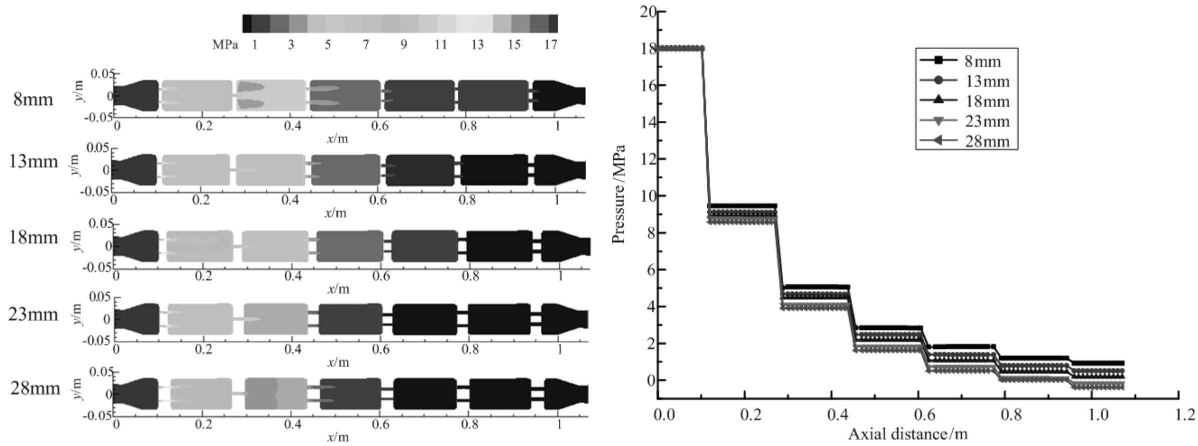


FIGURE 2. Pressure distribution with different thickness

TABLE 1. Pressure drop with different thickness

Thickness /mm	First pressure drop/MPa	Second pressure drop/MPa	Third pressure drop/MPa	Fourth pressure drop/MPa	Fifth pressure drop/MPa	Sixth pressure drop/MPa	Total pressure drop/MPa
8	8.523	4.366	2.179	1.087	0.541	0.278	16.976
13	8.897	4.517	2.237	1.129	0.564	0.283	17.639
18	9.036	4.522	2.262	1.142	0.566	0.287	17.817
23	9.275	4.599	2.284	1.157	0.567	0.294	18.159
28	9.399	4.732	2.425	1.096	0.625	0.297	18.578

Table 1 summarizes pressure drop of each stage and total pressure drop with different thickness.

Results indicate that pressure drop increases with increasing of the orifice thickness. And all the differential pressure at each stage is smaller than the blocking differential pressure, so cavitation will not occur.

3.2. Distribution diameter of orifice hole. The orifice thickness is 18mm, and the orifice hole distribution diameter is changed to 20mm, 25mm, 30mm, 35mm and 40mm respectively. The results of numerical simulation analysis are shown in Figure 3.

Table 2 summarizes pressure drop of each stage and total pressure drop with different distribution diameters.

Results indicate that pressure drop is almost the same with increase of the distribution diameter. And all the differential pressure at each stage is smaller than the blocking differential pressure, so cavitation will not occur.

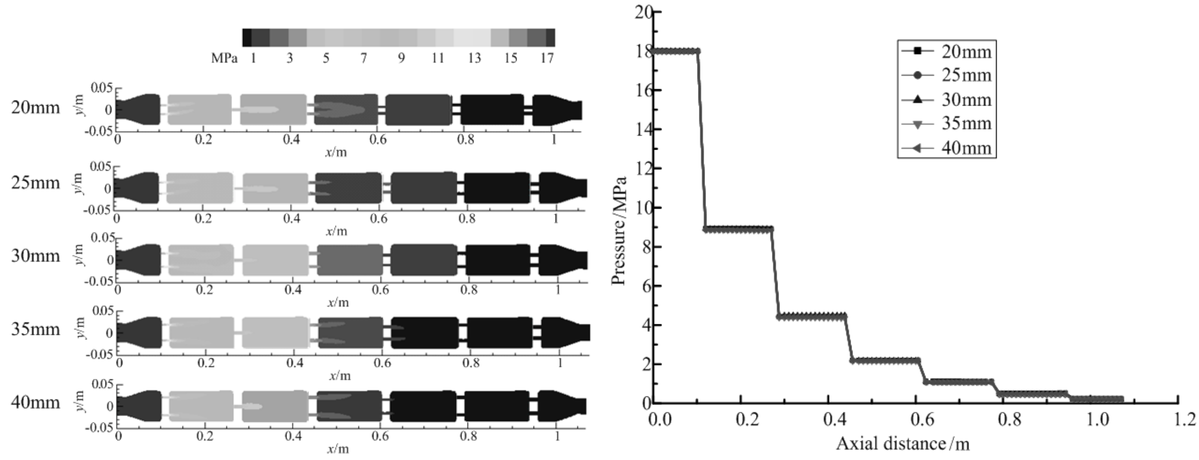


Figure 3. Pressure distribution with different distribution diameters

Table 2. Pressure drop with different distribution diameters

Diameter /mm	First pressure drop/MPa	Second pressure drop/MPa	Third pressure drop/MPa	Fourth pressure drop/MPa	Fifth pressure drop/MPa	Sixth pressure drop/MPa	Total pressure drop/MPa
20	9.048	4.488	2.257	1.092	0.565	0.271	17.722
25	9.023	4.521	2.254	1.139	0.552	0.286	17.777
30	9.036	4.522	2.262	1.142	0.566	0.287	17.817
35	9.109	4.474	2.346	1.194	0.615	0.280	17.812
40	9.002	4.469	2.223	1.098	0.541	0.249	17.751

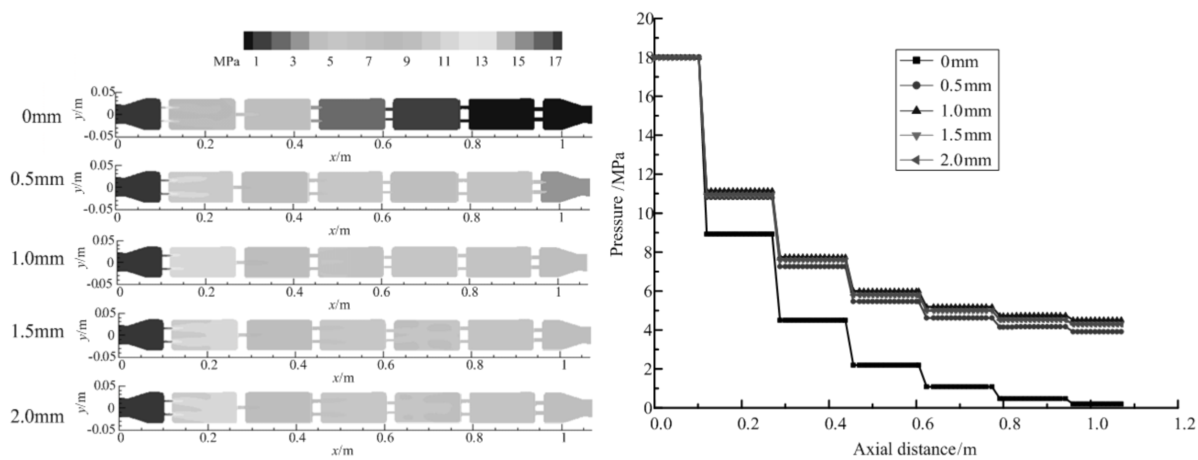


Figure 4. Pressure distribution with different front end chamfering

3.3. **Chamfering of orifice hole.**

3.3.1. *The front end chamfering of orifice hole.* The orifice thickness is 18mm, and orifice hole distribution diameter is 30mm. Only the front end chamfering of orifice hole is changed to 0mm, 0.5mm, 1.0mm, 1.5mm and 2.0mm respectively and the back end is not chamfered. The results of numerical simulation analysis are shown in Figure 4.

Table 3 summarizes pressure drop of each stage and total pressure drop with different front end chamferings.

Results indicate that pressure drop decreases with the front end chamfering. When the chamfering increases from 0.5mm to 1.0mm, pressure drop decreases. When the

Table 3. Pressure drop with different front end chamferings

Chamfering /mm	First pressure drop/MPa	Second pressure drop/MPa	Third pressure drop/MPa	Fourth pressure drop/MPa	Fifth pressure drop/MPa	Sixth pressure drop/MPa	Total pressure drop/MPa
0	9.036	4.522	2.262	1.142	0.566	0.287	17.817
0.5	7.117	3.574	1.816	0.877	0.454	0.255	14.093
1.0	6.755	3.457	1.753	0.845	0.444	0.226	13.480
1.5	6.986	3.464	1.767	0.853	0.449	0.234	13.753
2.0	6.962	3.466	1.769	0.854	0.451	0.229	13.720

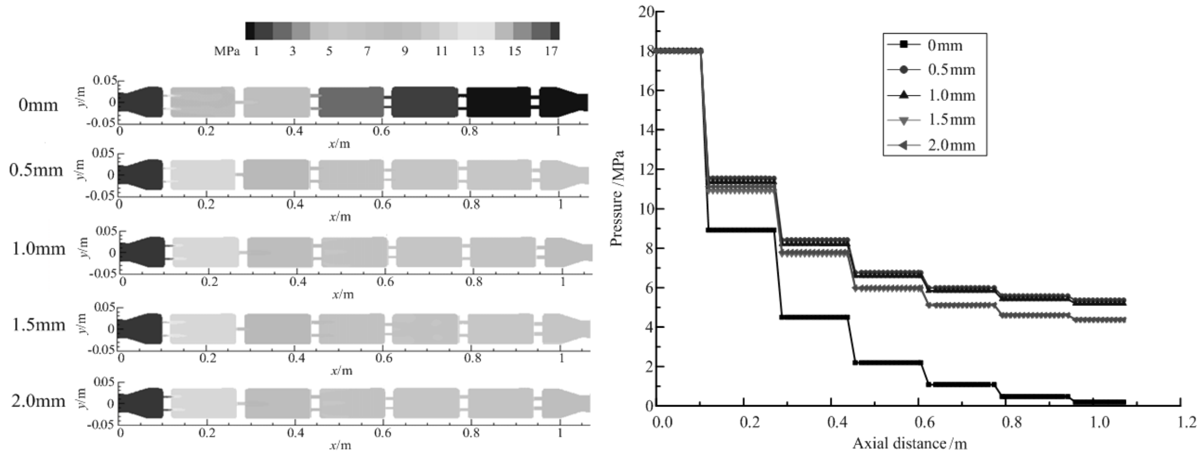


Figure 5. Pressure distribution with different back end chamferings

Table 4. Pressure drop with different back end chamferings

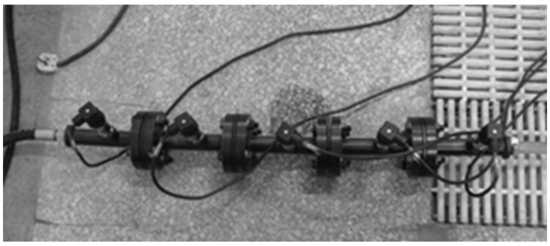
Chamfering /mm	First pressure drop/MPa	Second pressure drop/MPa	Third pressure drop/MPa	Fourth pressure drop/MPa	Fifth pressure drop/MPa	Sixth pressure drop/MPa	Total pressure drop/MPa
0	9.036	4.522	2.262	1.142	0.566	0.287	17.817
0.5	6.412	3.146	1.660	0.785	0.411	0.216	12.631
1.0	6.598	3.169	1.615	0.790	0.410	0.219	12.802
1.5	6.965	3.298	1.775	0.862	0.484	0.225	13.608
2.0	6.939	3.264	1.759	0.939	0.483	0.227	13.611

chamfering increases to 1.5mm, pressure drop increases. When the chamfering is 2.0mm, pressure drop is almost the same with 1.5mm one. All the differential pressure at each stage is smaller than the blocking differential pressure, so cavitation will not occur.

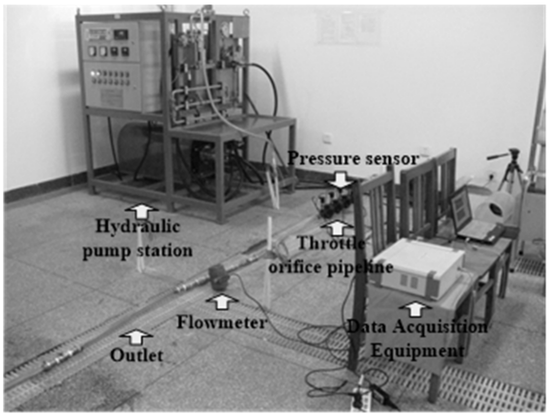
3.3.2. *The back end chamfering of orifice hole.* The orifice thickness is 18mm, and orifice hole distribution diameter is 30mm. Only the back end chamfering of orifice hole is changed to 0mm, 0.5mm, 1.0mm, 1.5mm and 2.0mm respectively, and the front end is not chamfered. The results of numerical simulation analysis are shown in Figure 5.

Table 4 summarizes pressure drop of each stage and total pressure drop with different back end chamfering.

Results indicate that pressure drop decreases with the back end chamfering. When the chamfering increases from 0.5mm to 1.5mm, pressure drop increases. When the chamfering increases to 2.0mm, pressure drop is almost the same with 1.5mm one. All the differential pressure at each stage is smaller than the blocking differential pressure, so cavitation will not occur.

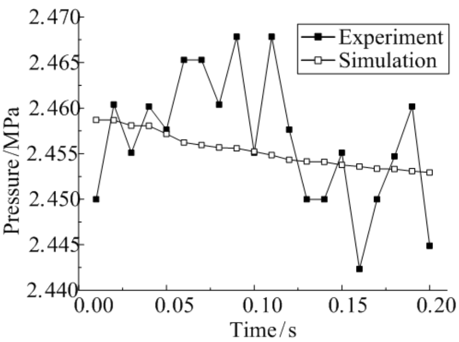


(a) Experimental model of orifice

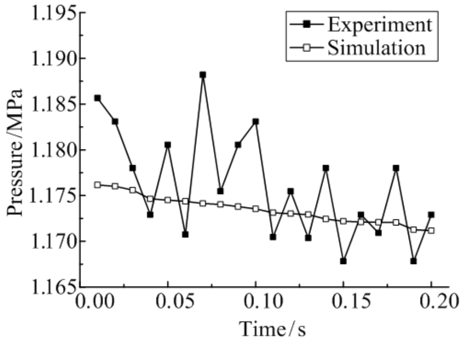


(b) Experimental equipment

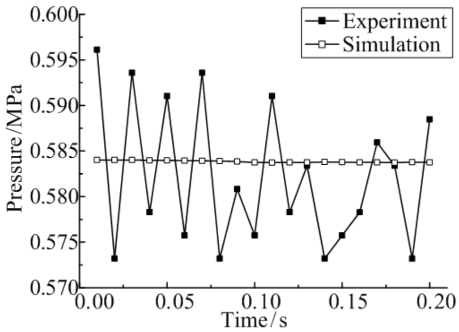
Figure 6. Experiment system



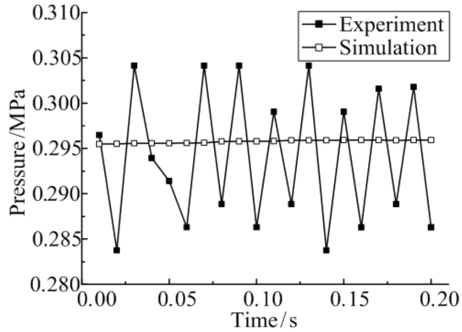
(a) Pressure after first stage of orifice



(b) Pressure after second stage of orifice



(c) Pressure after third stage of orifice



(d) Pressure after fourth stage of orifice

Figure 7. Pressure distribution at each stage of orifice

4. **Experiment Analysis.** In order to verify the correctness of the numerical simulation model, experiment results using the dynamic measurement method are compared with simulations. The experimental model of orifice is shown in Figure 6(a), and experimental equipment is shown in Figure 6(b). The working medium is water. The system pressure is 10MPa, and the motor speed is 1500r/min.

As the pressure of water system in lab is unable to reach 18MPa, experimental pressure is set as 5MPa considering security. There are five test points to get the pressure which are inlet, after first stage of orifice, after second stage of orifice, after third stage of orifice and after fourth stage of orifice separately. The frequency of NI data acquisition is set as 500Hz, and each test point collected 10000 data. Using the same simulation model with 5MPa as above in Fluent. Comparisons between the results of simulation and the experiment are shown in Figure 7.

Results indicate that the deviations between the experiment and simulation fluctuate up and down are in permitted value range, and the deviation range is less than 5%, which verifies that the simulation is reliable.

5. **Conclusion.** The following conclusions can be drawn through the above analysis.
(1) The pressure drop increases with increasing of the orifice thickness.
(2) The pressure drop is almost the same with different distribution diameters.
(3) When the front end chamfering increases from 0.5mm to 1.0mm, pressure drop decreases. When the front end chamfering increases to 1.5mm, pressure drop increases. When the chamfering is 2.0mm, pressure drop is almost the same with 1.5mm one.
(4) When the back end chamfering increases from 0.5mm to 1.5mm, pressure drop increases. When the chamfering is 2.0mm, pressure drop is almost the same with 1.5mm one.

The results of the study can lay the foundation of multistage throttle orifice design and optimization. The main work in the future will concentrate on the reason of different pressure drop with different geometrical parameters and how to control pressure drop dynamically.

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