INTERNATIONAL JOURNAL OF FLUID POWER
2018, VOL. 19, NO. 3, 165–172
https://doi.org/10.1080/14399776.2018.1514931

ARTICLE

Flow measurement for the pre-stage of jet pipe servo valve using 2D -PIV technique

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ABSTRACT
In order to investigate the internal flow field characteristic for the pre-stage of jet pipe servo valve, a large-scale low-speed flow field visualisation experimental platform was developed. The internal flow field for the pre-stage of jet pipe servo valve was measured directly by particle image velocimetry (PIV), and its internal flow characteristics were obtained. The experimental results show that four vortices exist in the upper area and the lower area of the lower chamber of pre-stage. The upper chamber has two wide range of vortex in the pre-stage of jet pipe servo valve, and the vortex scale increases with the increase of flow rate. With the flow rate increases, the vortex in the upper area will disappear. The scale of the vortex in the lower area gradually increases with the increase of the flow rate, and the position gradually moves upwards. Under different deflection angles of jet pipe, the main characteristics of the vortex pre-stage are roughly the same, but the size and core of the vortex are different. The results provide a reference for the structural optimisation of the jet pipe servo valve.

ARTICLE HISTORY
Received 9 January 2018
Accepted 28 June 2018

KEYWORDS
Jet pipe servo valve; particle image velocimetry(PIV); flow field; vortex

1 Introduction

Electro-hydraulic servo valve is the key component in electro-hydraulic servo control system, and its performance directly determines and restricts the control accuracy, response characteristics, reliability and life expectancy of electro-hydraulic servo. It is a kind of hydraulic control valve which receives the analogy electric signal and outputs the modulated flow and pressure. At present, the most common use of electro-hydraulic servo valve are the jet pipe servo valve and nozzle flapper servo valve. Compared with the nozzle flapper servo valve, the jet pipe servo valve is widely used in aviation, aerospace, military and other fields because of its high resistance to contamination, high reliability and other advantages (Wang 1999, Fang and Huang 2007, Huang and Hou 2007, Chen *et al.* 2014, Zhou *et al.* 2014).

The pre-stage of the jet pipe servo valve is a jet pipe amplifier, and its structural parameters have an important influence on the performance of the servo valve. The hydrodynamic characteristics of the jet pipe amplifier are very complex, currently, the optimisation and analysis for pre-stage of the jet pipe servo valve are mainly accomplished by experimentation and computer simulation. (Yin and Wang 2015) established the mathematical model of the pre-stage jet pipe servo valve, and analysed the impact of the jet pipe deflection displacement, the radius of jet pipe nozzle and the radius of receiving hole on its internal fluid pressure, nozzle exiting velocity and recovery pressure receiver. (Ji *et al.* 2008, Wang *et al.* 2012, Zhao *et al.* 2016, Zhao K.Y. et al. 2016) used CFD software to model and simulate the internal flow in the amplifier, and analysed the recovery flow rate and recovery pressure characteristics of the jet amplifier under different deflection angles of the jet. (Li 2013) analysed the cavitation phenomenon of the flapper nozzle servo valve with different working conditions by using mathematical models and experimental methods. (Li *et al.* 2011) used CFD technology to analyse the internal flow of the amplifier in different medium, and studied the effect of the main geometry parameters on the flow characteristics. (Somashekhar *et al.* 2007) established mathematical model of jet valve, and analysed the effect of the feedback spring components on the recovery pressure. (EI-Araby *et al.* 2011) established the non-linear mathematical model of two-stage servo valve and analysed dynamic characteristics in the different structural parameters of the servo valve. (Li 2016) developed a mathematical model based on the energy transfer processes and the physical mechanism of the jet pipe valve, and verified by the numerical simulation and experimental method.

Direct experimental investigation on the flow field of the pre-stage of jet pipe servo valve is still rare. Based on this, particle imaging velocimetry (PIV) is

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used to measure the internal flow field of the pre-stage, the intuitive image and the vortex distribution characteristic of the servo valve pre-stage are obtained, which provides a reference for the structural optimisation for the pre-stage of jet pipe servo valve.

2 Experimental setup

2.1 *Experimental system for measuring flow field*

In order to obtain the internal flow field characteristics for the pre-stage of jet pipe servo valve, flow measurement experiment platform for the pre-stage is built, as shown in Figure 1. The system mainly consists of submersible pump, inlet pipe, outlet pipe, throttle valve, test valve block, electromagnetic flow meter, frequency converter, NI signal acquisition system, PIV measurement system, etc.

Because the size of the pre-stage flow channel of jet pipe servo valve is very small, and the curvature of the flow channel is large, the refraction and scattering effect at the wall of the pre-stage flow channel is strong. It is almost impossible to directly measure the pre-stage flow field of the prototype jet pipe servo valve. To obtain the flow field of the pre-stage based on 2D-PIV technique, the size of the pre-stage is amplified properly. In order to ensure the flow field characteristics of the test valve block and the prototype valve are same, the geometric and operating parameters of the test valve block are determined according to similarity criterion. The viscous force of the fluid plays a dominant role in the pre-stage of jet pipe servo valve, and other forces can be ignored, so Reynolds similarity criterion is adopted. If the hydraulic oil is used as flow medium, tracer particles are too difficult to spread, therefore, water is used as the flow medium in the experiment.

Reynolds similarity criterion:

$$\frac{\rho_p l_p v_p}{\mu_p} = \frac{\rho_m l_m v_m}{\mu_m} = \mathrm{Re} \tag{1}$$

Where ρ is the density, l is the characteristic length, in this paper refers to the nozzle diameter, v is the fluid velocity, in this paper refers to the velocity of the nozzle, μ is the fluid dynamic viscosity, the subscript p and m are prototype valve block and experimental valve block respectively.

Definition:

$$k_\rho = \frac{\rho_p}{\rho_m}\ k_v = \frac{v_p}{v_m}\ k_l = \frac{l_p}{l_m}\ k_\mu = \frac{\mu_p}{\mu_m}$$

Where k_ρ is the density ratio coefficient, k_v is the speed ratio coefficient, k_l is the length ratio coefficient and k_μ is the viscosity ratio coefficient.

Substituting the above definition parameters into Equation (1):

$$\frac{k_\rho k_v k_l}{k_\mu} = 1 \tag{2}$$

According to Equation (2), the test valve block parameters are calculated. The parameters of prototype valve block and test valve block are shown in Table 1. The flow rate at the nozzle of jet pipe servo valve is 0.45 L/min, and the average flow rate at the inlet of the test valve is 0.62 L/min. Before the experiment, a certain concentration of Polyamid Seeding Particles

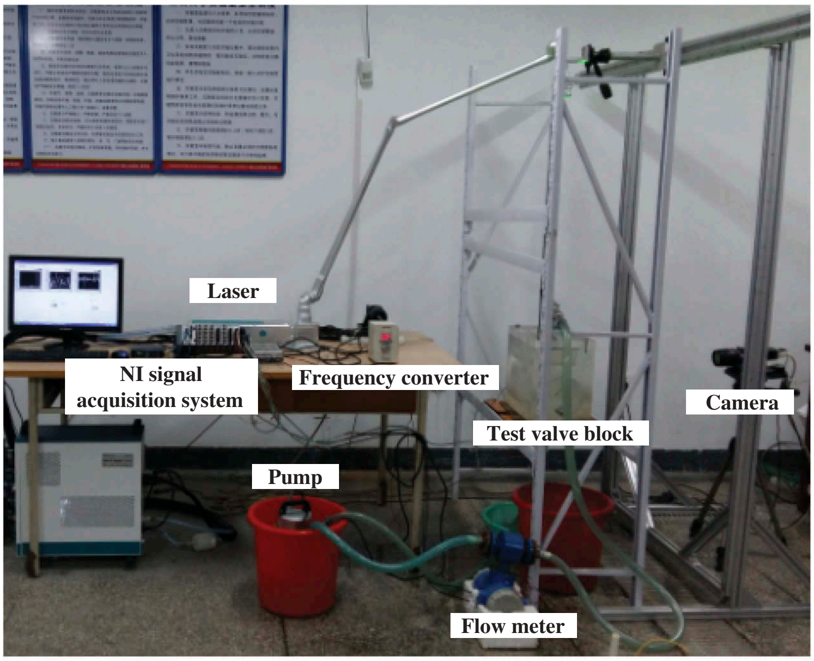


Figure 1. Flow measurement experiment platform for the pre-stage of jet pipe servo valve.

Table 1. Parameters of prototype valve block and test valve block.

	Length	Medium density	Dynamic viscosity	Velocity	Flow rate
	l	ρ	μ	v	q
Prototype block	0.22	855	0.0125	197.4	0.45
Test block	4.4	1000	0.001005	0.68	0.62

(PSP) with a mean diameter of 20 μm was spread in water as tracer particles. PSP are suitable tracers for flow investigations in water, which are a round but not exactly spherical shape with a high intensity of reflection, and are very close to the density of water. In order to explore the changes of the pre-stage flow field under different flow rates, the pre-stage flow conditions of 0.62 L/min, 4.5 L/min and 6.5 L/min were measured respectively.

2.2 *Test valve block*

The test valve block is made of transparent plexiglass, this kind of material with high transparency, is conducive to laser light transmission which can light up tracer particles. The back of the test valve block is treated with blackening to create a sharp contrast between the white particles and the black background to increase the accuracy of the interpretation of the software.

The test valve block is an enlarged valve block based on the structural parameters of the key sections of the prototype servo valve pre-stage. However, internal flow field characteristics of the pre-stage is changed. The purpose of enlarging the prototype valve is to enable it to meet the PIV high definition imaging requirements. The test valve block is shown in Figure 2.

In the actual work of the jet pipe servo valve, deflection angle of jet pipe is small, about 0–0.5°. Direct measurement of the flow field characteristics under this operating condition makes it difficult to compare the experimental results. In the experiment, three different deflection angles of the jet pipe are designed with angles α of 0°, 1.5°and 3° respectively. Jet pipe structure is shown in Figure 3.

2.3 *2D-PIV system*

The 2D-PIV system used in this paper is developed by Dantec and has a CCD camera (Dantec Flow Sense Infinity X-32, 1600 × 1200pixels), an Nd: YAG laser system (200 mJ/pulse and λ = 532 nm) with a maximum frequency of 15 Hz, a signal synchronizer and Dynamic Studio V2.3 software. A Nikon objective lens (Nikon Nikkor r60/2.8) with a focal length of 60 mm and a lens was used in the camera. Laser sheet is generated by solid-state laser produced by Beamtec, and the pulse light is obtained by Q-switch trigger

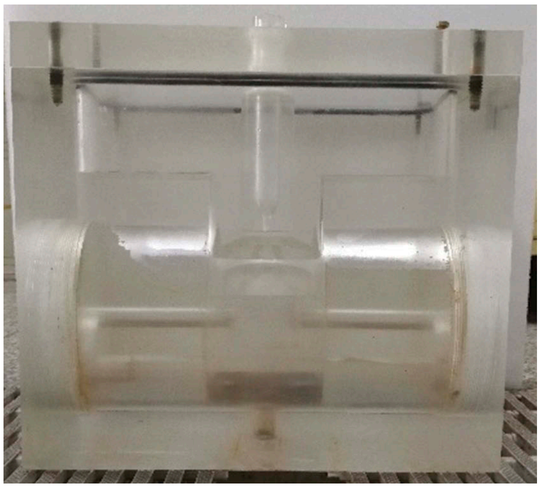


Figure 2. Test valve block.

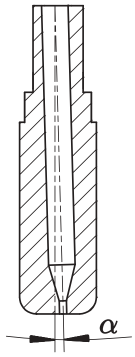


Figure 3. Jet pipe structure.

mode. The pulse width of the laser is 6–8 ns, time between pulses up to the level of micro-seconds, and specific values is adjusted according to the experimental conditions. The narrowest light thickness of laser sheet is about 1 mm, and the maximum field view of 2D-PIV system up to 200 mm × 200 mm. The CCD camera and the laser were controlled with a signal synchronizer. The Dynamic Studio V2.3 software system is used to control, monitor the whole process of data acquisition and set the acquisition parameters. The measurement accuracy of the 2D-PIV system is about 1%.

2.4 *2D-PIV system debugging*

Before the PIV measurement, it is necessary to consider carefully the arrangement of the PIV optical path system and the selection of time between pulses.

According to the position requirements of the 2D-PIV measurement system on the model, the camera and the laser head, the central plane of the amplifier is selected as the flow field measurement area and the upper surface of the valve block is the laser incidence plane. By adjusting the laser head, CCD camera experimental valve block position, the valve block centre plane flow field was measured. After determining the measurement area, PIV system calibration is needed. Because this experiment is a 2D-PIV system, the dividing ruler is used for calibration.

Time between pulses (also known as double exposure time) settings not only related to the flow velocity, but also to the query area size. Generally, the displacement of the tracer particles should be 1/3 ~ 1/2 of the side length of interrogation region (32 pixels× 32 pixels) in the twice exposure images. According to the literature (Qin *et al.* 2009) of the time between pulses Δt determination method ($\Delta t v_{max}$ = 250, where v_{max} is the maximum velocity in the measurement area).

By calculated and repeated experiments, the flow field measurement effect is better, when the flow rate is 0.62 L/min, 4 L/min and 6 L/min and the corresponding time between pulses are 30000 μs, 3000 μs and 2600 μs, respectively.

In this paper, adaptive-correlation developed by DANTEC is used to process the data of the original double exposure particle image. In the course of data analysis, the interrogation window size is set to 32 pixels× 32 pixel, the overlap rate is 25%, and the trigger frequency is 15 Hz which means 15 pairs of images can be obtained in one second. In the following, the measurement results are statistical averaged results of 80 pairs original image after processing, which the time-averaged flow field is obtained.

3 Results and discussion

3.1 *The characteristics of the flow field under different flow rates*

In the experiment, the flow field in the pre-stage symmetry plane of the jet pipe valve was measured. When the deflection angle of the jet tube is 0°, the pre-stage of jet pipe servo valve is symmetrical structure, so the PIV system measured one side (left half region) flow field. To obtain high-quality images, taking into account the size of the model and the camera's pixel aspect ratio, the flow field of the pre-stage is divided into two major regions for

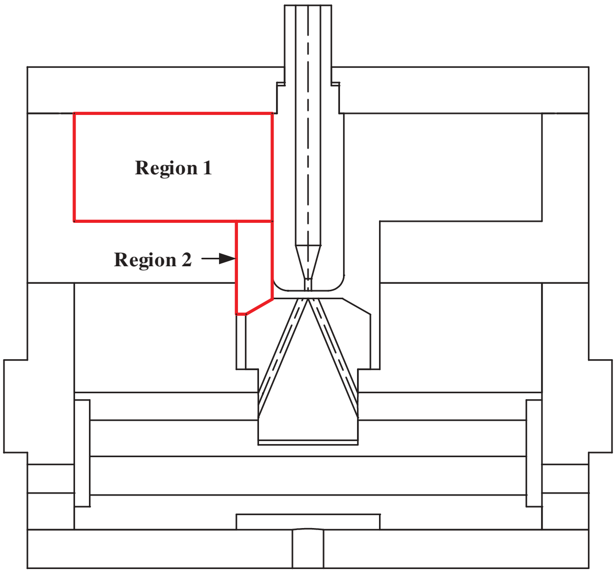
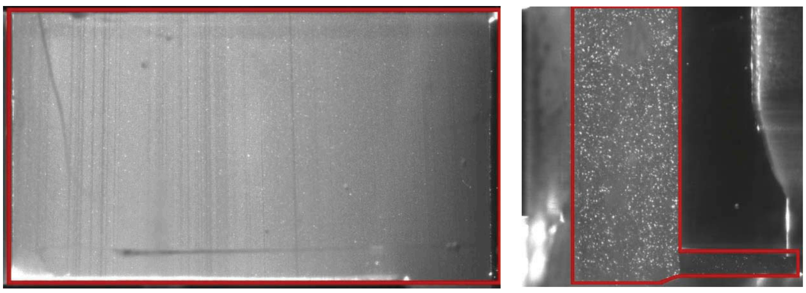


Figure 4. Experimental measurement regions.

experiment analysis by PIV, the experimental measurement regions are shown in Figure 4. The original images of PIV are shown in Figure 5.

The experimental results of region 1 under different flow rates are shown in Figure 6. The figure of the velocity vectors, contours and streamlines are obtained by processing the original PIV measurement data with Tecplot software.

The experimental results show that there is a large range of vortex in region 1, and the vortex is generated by the fluid induced which is emitted by the jet pipe and reflected by lower chamber. Meanwhile, it is also an important factor of energy dissipation and flow instability. At the flow rate of 0.6 L/min, the distribution characteristics of vortex system in region 1 are different. Instead of forming a main vortex, it is multiple and forms a number of small vortices. At the same time, the distribution of flow field is more uncertain. Under different flow rates, the flow field form is not exactly the same. However, the main characteristics, structure and trend of flow field are the same. With the increase of the inlet flow rate, the velocity in the region 1 increases gradually, and the vortex position gradually moves away from the jet pipe.



(a) (b)

Figure 5. The original PIV particle image of the measurement plane. (a) Original particle image of region 1. (b) Original particle image of region 2.

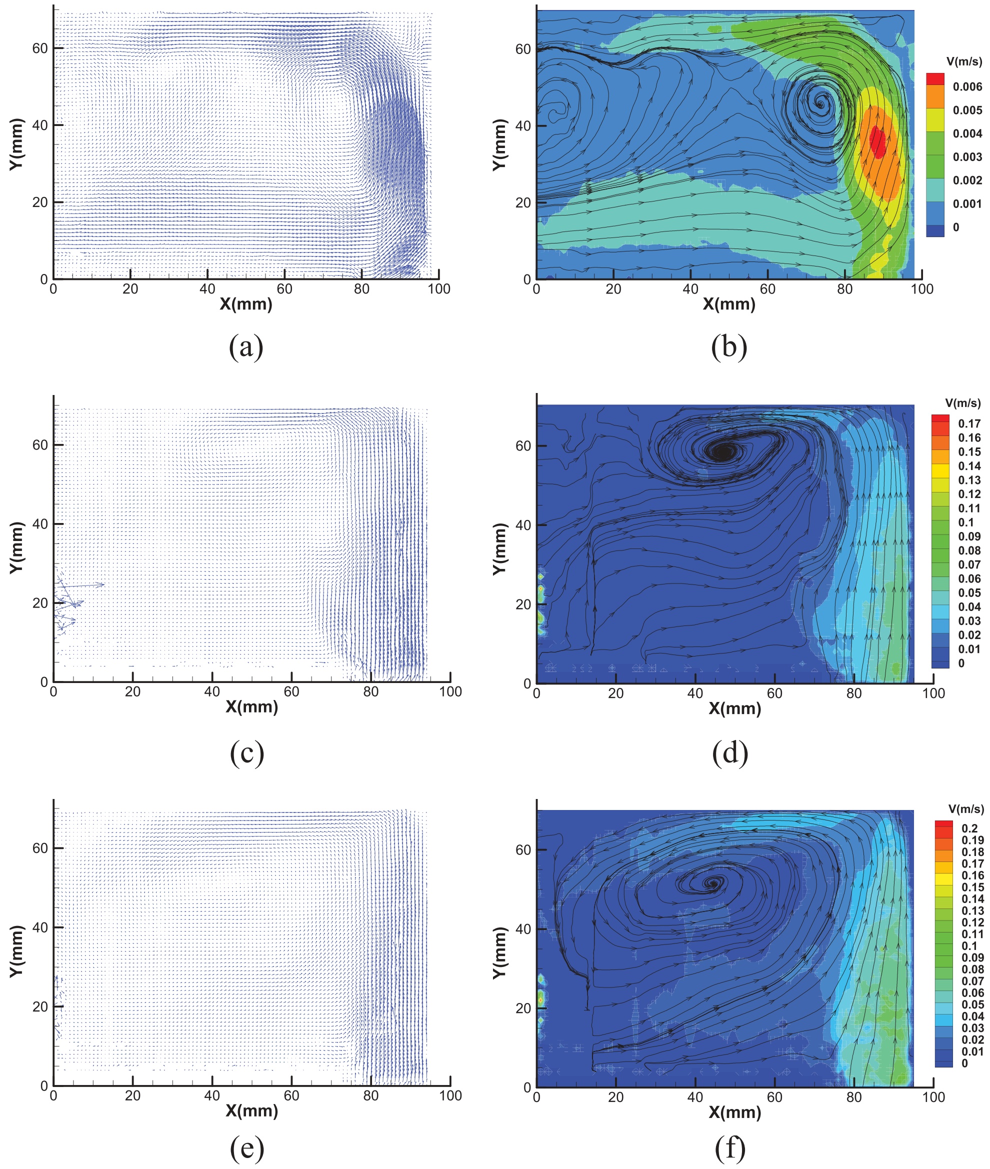


Figure 6. PIV flow field measurement results for region 1 at different flow rates. (a), (c), (e)are 0.6L/min, 4.5L/min, 6L/min velocity vector respectively. (b), (d), (f) are 0.6L/min, 4.5L/min, 6L/min velocity contour and streamlines respectively.

The experimental results of region 2 under different flow rates are shown in Figure 7. The experimental results are handled in the same way as above.

The results show that there are two vortices in the upper and lower parts of the region 2 at the flow rate of 0.6 L/min. Among them, the intensity of vortex in lower part is larger, which is the most important characteristics in the region 2 internal field. The vortex is produced by the ejecting action of the fluid ejected from the jet pipe and the receiver slit. At low flow rates, the ejector action is limited to the vicinity of the slit. The vortex in upper parts of the region 2 is an unstable vortex formed by the combined action of the reflection flow in the lower area and the flow in the upper area, it appears when the fluid in the upper part flow into the lower chamber. As the flow rate increases, the vortex in the upper part of region 2 will disappear, meanwhile, the intensity of the lower vortex gradually increases, and the position of vortex gradually moves up. However, the situation which the upper fluid intrudes into the lower chamber no longer occurs, and the effect of the slit jet is spread to the entire lower chamber. The characteristics of the flow field in region 2 are quite different under different flow rates, but the flow characteristics are relatively consistent under larger flow rates.

3.2 The characteristics of the flow field under different deflection angles of the jet pipe

In the experiment, the flow field in the pre-stage symmetry plane of the jet pipe valve was measured at the flow rate of 4.5 L/min. The flow field of the pre-stage is divided into four major regions for experiment analysis by PIV, the experimental measurement regions are shown in Figure 8.

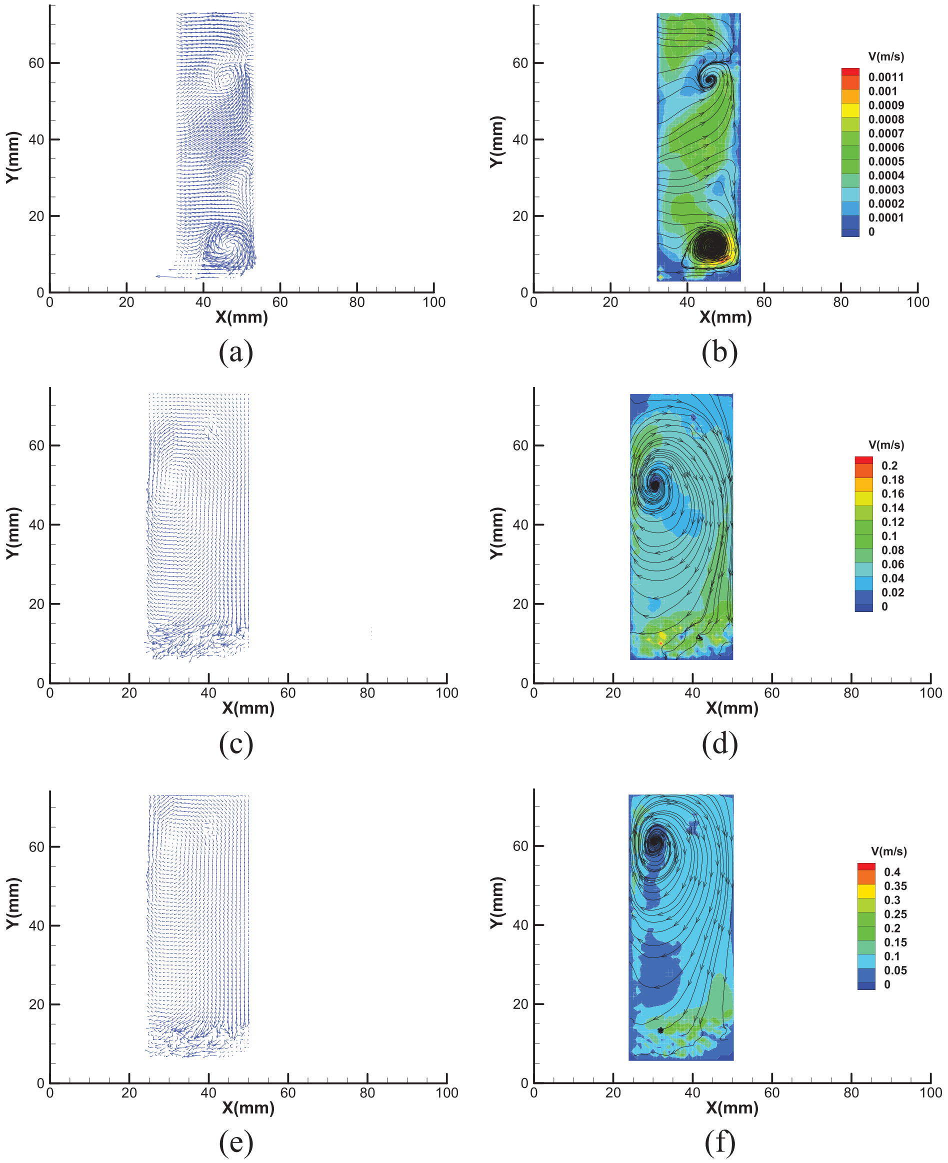


Figure 7. PIV flow field measurement results for region 2 at different flow rates. (a), (c), (e)are 0.6L/min, 4.5L/min, 6L/min velocity vector respectively. (b), (d), (f) are 0.6L/min, 4.5L/min, 6L/min velocity contour and streamlines respectively.

Figures 9 and 10 are the flow fields of the pre-stage of the jet pipe servo valve when the deflection angle of the jet pipe is 1.5° and 2°, respectively. There are mainly four vortices in the flow field of the jet valve, which are located in four different regions. Two significant vortices exist in region 1 and region 3, and the scale of vortices is larger. The range of vortices in region 1 and region 3 is smaller, which exists near the gap formed by the nozzle and the receiver. Under different deflection angles of jet pipe, the main characteristics of the vortex in the pre-stage are roughly the same, but the size and core of the vortex are different, and the core position of the vortex is quite different. When the jet pipe deflects to the left, the velocity in the left region is larger and the flow is relatively stable; the velocity in the right region is small and the flow is complex and unstable.

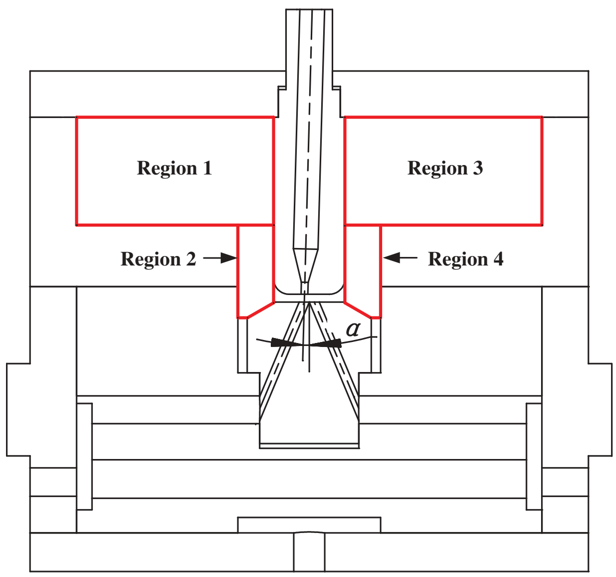


Figure 8. Experimental measurement regions.

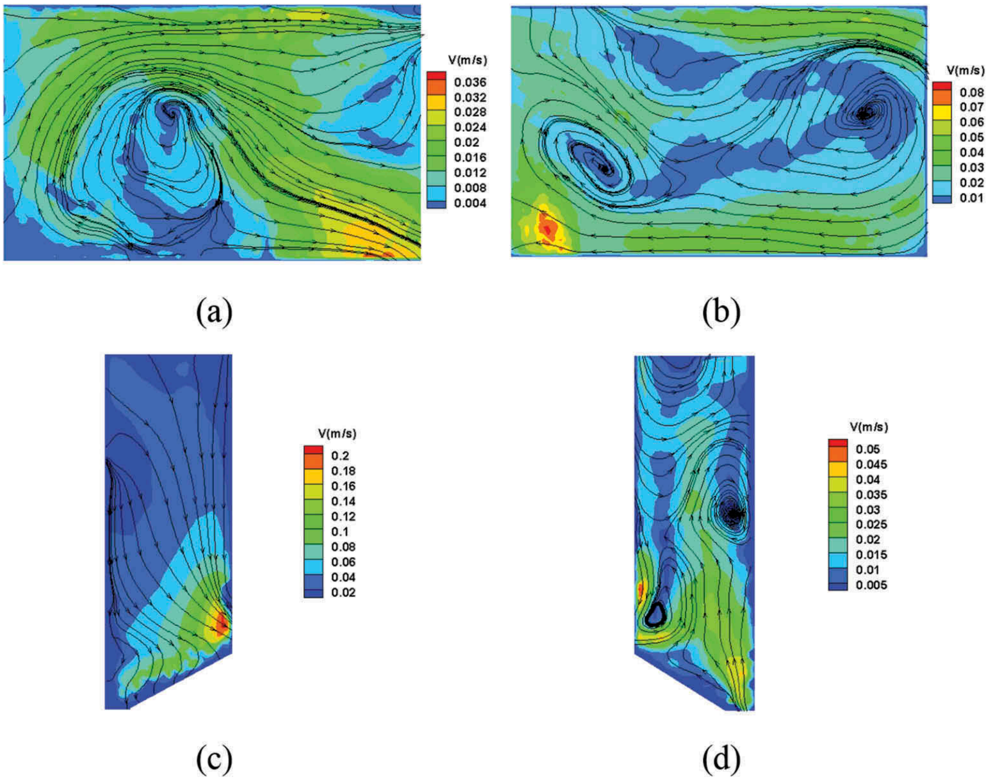


Figure 9. Flow field at jet pipe deflection angles of 1.5°. (a) Region 1. (b) Region3. (c) Region2. (d) Region4.

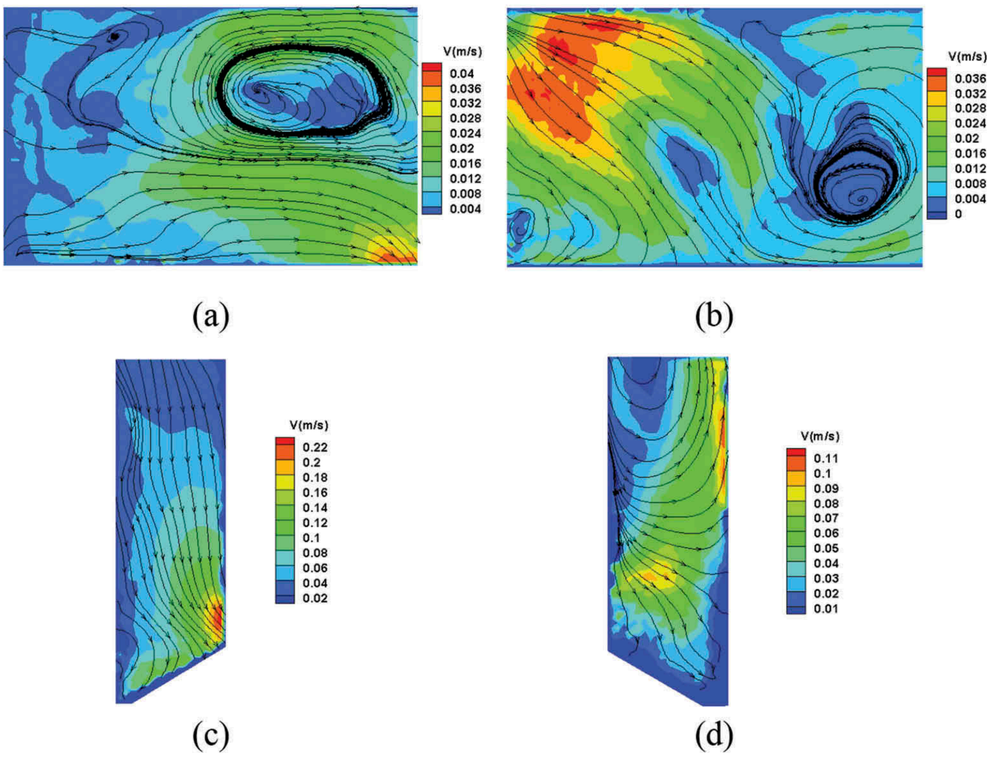


Figure 10. Flow field at jet pipe deflection angles of 3°. (a) Region 1. (b) Region3. (c) Region2. (d) Region4.

4 Conclusion

(1) There are mainly four notable vortices in the pre-stage flow channel of the jet pipe valve, which are located in the upper chamber (region 1and region 3) and the lower chamber (region 2 and region 4) of the pre-stage respectively.

(2) Flow field of region 1 has a large range of vortex, which is an important factor of energy dissipation and flow instability. The scale of the vortex

gradually expands and the core of vortex gradually moves away from the jet pipe with the jet pipe flow rates gradually increase. Under different flow rates, the main characteristics, structure and trend of flow field are the same.

(3) The characteristics of the flow field in region 2 are different under different flow rates, however the structures of the main vortices are almost the same. As the flow rate increases, the intensity of the main vortices gradually increases and the centre position gradually moves up.

(4) Under different deflection angles of jet pipe, the main characteristics of the vortex pre-stage are roughly the same, but the size and core of the vortex are different. When the jet pipe deflects to the left, the flow in the left region is relatively stable; however, the flow in the right region is complex and unstable.

Nomenclature

μ	Dynamic viscosity [Pa•s]
L	Length [mm]
Re	Reynolds number
Δt	Time between pulses[μs]
v	Velocity [m/s]
q	Flow rate [L/min]
ρ	Fluid density [kg/m^3]

Acknowledgements

The authors would like to give their acknowledgement to the National Natural Science Foundation of China (No. 51705446) and Open Foundation of the State Key Laboratory of Fluid Power and Mechatronic Systems (No. GZKF-201716) for financial support.

Disclosure statement

No potential conflict of interest was reported by the authors.

Funding

This work was supported by the National Natural Science Foundation of China (CN) [No. 51705446] and Open Foundation of the State Key Laboratory of Fluid Power and Mechatronic Systems [No. GZKF-201716].

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