Analysis and reconstruction of waterjet characteristics in double-side wall confinement

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Abstract. Water jet flow characteristics in double-side wall confined space is investigated, two-dimensional particle image velocimetry is performed on confined plane and unconfined plane, and using Proper orthogonal decomposition to perform dimensionality analysis, extract large-scale coherent structure and reconstruct flow field. Results illustrate that velocity and vorticity fluctuation distribution, mainly reflected in low-order modes, is seriously affected on account of a symmetrical double-wall existence; Reconstruction instantaneous velocity field by the first m modes saving 70% of turbulent kinetic energy, indicating that reconstructed velocity fluctuation fields can truly reflect original fields.

1. Introduction

Waterjet cutting is that fluid with high energy density focus on target material surface resulting in scale of target material dropped out by undergoing complex physical interaction process and forming strongly erosive [1-3]. In practical application, after cutting, a narrow slit, namely double-side wall confined space, is formed, cutting section surface exhibits irregular characteristics which could be caused by waterjet complex flowing characteristics in this double-side wall confinement. For confinement flow characteristics, a large number of scholars have performed extensive experiments and simulations on wall and free-surface-bounded jets. Shinneeb et al.[4] using particle image velocimetry (PIV) to analyse jet flow characteristics in shallow water confined by free surface and wall, average flow, turbulence characteristics and vortex structure in different vertical directions is discussed, results show that flow field structure generates great changes due to vertical restriction, total number of vortex ring decrease with vertical confinement gradually decrease, but size of vortex ring increases; Raiford and Khan [5] using same submergence ratio and offset ratio of 2, 3 and 4 in different confined height to investigate growth rate in vertical and horizontal planes along with decay of maximum velocity, find that horizontal velocity profile is self-similar, essentially agree with free jet profile and experimental results made by Shinneeb[4]; Chowdhury et al.[6] using RANS equations along with standard k-ε turbulent closure scheme to simulate circular turbulent jets in shallow water to investigate effect of different submergence
ratios and offset ratios, results indicate that riverbed influence is larger than free surface in flow field structure; Wang et al.[7] and Vinze et al.[8] respectively adopted large eddy simulation method and experimental method to investigate heat transfer in confined space.

On account of nozzle inlet with high-pressure and small size, waterjet in double-side wall confinement belongs to high Reynolds number flow. In order to describe flow fields with high spatial resolution obtained by PIV, proper orthogonal decomposition (POD) with powerful dimension reduction and analysis capabilities is gradually adopted [9-12]. Lumley[13] firstly used POD to analyse flow fields, and identified large-scale coherent structure, a large number of scholars then employ POD to analyse plane jet[10], free jet[14] and pulsed jet[15]; Oudesuden[16] employed POD to investigated different incident angle influence on flow field around cylinder, results show that large-scale coherent structure extracted could effectively illustrate vortex shedding process, and also be used for evaluating impact of incident angle on flow field; Chaab and Tachie[17] analysed flow characteristics of three-dimensional wall jets, primarily including average velocity, turbulent intensity and Reynold stress in different sections, results indicate that low-order modes contribute more to turbulence statistics in self-similar region than in developing region. The Reynolds shear stress is the biggest benefactors of the low-order modes contribution while the wall-normal turbulence intensities is the least; Shinneeb et al.[4, 18] carried POD to quantitatively extract large-scale coherent structures from flow fields in space confined by free surface and wall, vortex recognition algorithm was employed to quantitatively analyse size and number of vortexes, results show that a number of vortexes with different sizes and directions appear in waterjet field, and vortexes number in axial direction decreases as size increases, meantime, vortexes size in vertical plane is affected by water depth.

In present work, PIV velocity measurements is performed on different sections to investigate double-side wall confined waterjet flow, POD is employed to decompose PIV data to obtain coherent structures in different modes. A comparative analysis among different modes in different cross-sections is performed, Large-scale coherent structure in low-order modes is used to reconstruct flow field, and compares with original instantaneous flow field.

2. Experimental Rig

2.1. facilities setup
In order to accurately measure instantaneous flow fields in double-wall confined space, a complete measurement system is indispensable. As shown in Figure 1, the entire experimental measurement system is visibly divided into three major test systems, named by water circulation system, pressure-flow test system and automatic PIV test system.

![Figure 1. Schematic diagram of experimental measurement](image)

1. Water tank 2. Centrifugal pump 3. Electromagnetic flowmeter 4. Valve 5. Battery of lens 6. Nozzle 7. CCD camera 8. Light guide 9. Double YAG pulsed laser 10. Synchroscope 11. Graphoscope 12. Mainframe 13. Experimental bench
Water circulation system mainly consisted of a high-pressure centrifugal pump with flow rate of 46 m³/h and head of 240 m, frequency-modulated system, water tank with volume of 3 m³ and covered reservoir. The demand of water flow rate in experimental process is relatively small, therefore water tank capacity is sufficient to satisfy experimental operation requirement; HBM data acquisition system, KROHNE electromagnetic flowmeter and pressure transducer makes up pressure-flow test system. The electrical signal of flow rate and pressure collected by HBM data acquisition system (sampling frequency: 200 Hz) is directly transmitted to computer analyses; the automatic PIV test system produced by TSI corporation is named as Ultra-II (pulsed laser power: 120 mJ/pulse; pulsed frequency: 30 Hz; sweep scan: 3.75/s). The figure signal of experimental bench mainly comes from the high resolution image caught on CCD camera (pixel resolution: 1600×1200 pixels; frame rate: 32 fps; image size: 200×200 mm; measured speed range: 0~100 m/s).

2.2. Nozzle and test region
The shape and size of waterjet nozzle have significant influence on turbulent velocity distribution in double-wall confined space, therefore, for the purpose of obtaining a satisfactory jet fluid, the type and size of waterjet nozzle are selected according to research results of Jegaraj and Babu[19].

![Figure2. Profile of nozzle](image)

In order to eliminate velocity boundary layer influence on nozzle exit velocity, a calculated region in front of nozzle is added to reach a full development status for waterjet, and then flowing into the double-side wall confinement; For the sake of making the velocity field retaining a uniform distribution, well contraction and reducing the pipeline pressure loss, it is very necessary to increase a section of shrink tube between the tube outlet and the nozzle inlet, therefore, the contraction angle is $\beta = 14^\circ$ and nozzle diameter is $D=4$ mm.

Physical model is extracted from actually technological application and material processing, therefore, the size of restricted direction in double-side wall confinement is much smaller than that unrestricted direction. For purpose of reducing the influence of unconfined space, the horizontal plane of plexiglass water tank is designed as $1 \times 1$ m. The confined width 60mm is the distance between upside wall and downside wall. The definition of dimensionless width is the ratio of confined width to the nozzle outlet diameter. Then the dimensionless width is 15. Measuring regions of flow field are marked in three-dimensional coordinate, as showed in Figure 3:

![Figure3. Illustration of plexiglass water tank and measuring regions.](image)

a) The measuring region of horizontal plane; b) The measuring region of vertical plane
Table 1. The measuring regions of flow field are shown

| Plane   | 1y            | 2y            | The distance 1y and 2y | 1z            |
|---------|---------------|---------------|------------------------|---------------|
| Size    | 90×130 mm     | 90×130 mm     | 8 mm                   | 120×170 mm    |
| Spatial discretization | 98×132         | 98×132         |                        | 73×93         |

3. Results and discussion

3.1. modes analysis

The number of POD modes based on velocity and vorticity on confined plane and unconfined plane respectively is 160, energy contribution rate of each mode is evidently different. The lower-order modes with a larger energy contribution rate, represents a large-scale coherent structure. On the contrary, the physical meaning with the high-order mode is small-scale fluctuation in flow fields. The first hundred velocity and vorticity POD modes contribution to TKE is shown in Figure 4a and 4b, respectively. In order to intuitively show the change of contribution to TKE for each pod modes, horizontal axis is plotted with function log10 ().

![Figure 4](image-url)

**Figure 4.** Contribution of each mode to TKE. a) Instantaneous velocity fields in different plane. b) Instantaneous vorticity in different plane

The first pod mode with the largest contribution to TKE dominates turbulent fluctuation development. In the case of velocity fields in different planes (Figure 4a), the first pod mode contributes 53% and 44% of TKE respectively on 1y plane and 2y plane, which is much higher than corresponding the second and third pod mode. Subsequently TKE contribution decreases rapidly, reaches less than 2% from the seventh mode. The above-mentioned pattern on unconfined plane also is clearly reflected in vorticity on unconfined plane. Thacker et al.[20] explaining the large difference between the first mode and the others is that the first mode is exclusively associated with global velocity fluctuation, while the others are associated with a large-scale vortex emission and turbulent motion. However, the above-mentioned pattern completely disappears on confined plane. The first pod mode for velocity field and vorticity field on confined plane respectively contributes 2.7% and 3%, and is basically equal to the second and third pod model. Energy distribution pattern is not the same between confined plane and unconfined plane, that is mainly because that global turbulent fluctuation on unconfined plane has been fully development. On the contrary, waterjet flow space is limited by a symmetrical double-side wall, therefore the law of global turbulent fluctuation is obviously constrained on confined plane.
Figure 5. The axial time-average velocity and the first three modes of axial velocity on unconfined plane

According to POD physical meaning in flow fields, multi-scale structure could be characterized by different pod modes. Time-averaged velocity of waterjet flow field dominates overall flowing law considered as the zero order mode of flow field. Consequently, the first three modes of axial velocity on unconfined plane are presented in Figure 5. Obviously, the axial time-averaged velocity contour is symmetrically distributed in centreline of nozzle axis, and diffusion angle of waterjet is 290. The first pod mode of velocity fields with 53% of TKE is shown in Figure 5b. It can indicate that axial velocity contour is divided into negative zone and positive zone by nozzle axis, which is exclusively associated with global velocity fluctuation; Making a comparison between Figure 5c and Figure 5d, we can indicate that the negative zone and positive zone of axial velocity distribution are gradually mixed each other and the size of large-scale structure decreases as the number of modes increases, what’s more, at initial stage of waterjet, small-scale structures are generated and is gradually increasing in downstream direction.

The vorticity is defined as the curl of velocity, and used to measure vortex strength and direction, therefore, the high-intensity vorticity means high energy consumption. As shown in Figure 6, vorticity distribution is mainly concentrated near the nozzle axis on unconfined plane (1y) and is fully symmetrical, which means that turbulent energy consumption is mainly generated in that zone. Making a comparison among figure 6b, 6c and 6d, the negative zone and positive zone of vorticity contour are gradually mixed each other, and are basically completely mixed each other in figure 6d. In consideration of the analysis about axial velocity contour in Figure 5, the number of large-scale structure corresponding to low-order modes is less, therefore the interaction between vortices is small and uniform distributed. Nevertheless, the interaction between the vortices with more quantity and small size is intense in the high-order modes, hence the mix of negative and positive zone is complex in Figure 6d.

Figure 6. The time-average vorticity and the first three modes of vorticity on unconfined plane
The first pod mode of axial velocity and vorticity on confined plane are presented in Figure 7. Time-averaged velocity contour on confined plane is basically similar to that on unconfined plane, but diffusion angle of waterjet is significantly reduced comparing with that on unconfined plane. The mainly reason is that waterjet on confined plane is obviously restricted by double-side wall, as a consequence, the diffusion has a significant change; At the same time, making a comparison among Figure.7 b1, a2 and b2, the velocity and vorticity distribution in region X/D=0~33 show a certain regularity, but in region X/D=33~43 is completely mixed together. Hence waterjet diffusion on confined plane in region X/D=0~33 is not obvious effected by double-side wall confinement.

3.2. Analysis of reconstruction flow field on unconfined plane

Ignoring the high-order modes with low energy contributions, and then instantaneous velocity fields are accurately reconstructed by using the low-order modes with high energy contributions. Using the first m modes to reconstruct instantaneous velocity fields on confined plane and on unconfined plane, the truncation error is shown in Figure 8:

It is interesting to note that when the first m modes are used to reconstruct instantaneous velocity fields, the truncation error is greatly affected by the value of m in Figure 8. When truncation error is reduced to 3%, the number of modes required for reconstruction of velocity field is 24 on 1y plane and 21 on 2y plane; Therefore, the fewer pod modes can reconstruct the flow field with high-precision achieving simplifying model.

The number of modes used for POD reconstruction was selected based on a target of 70% energy content. The reconstructed velocity field and original velocity field is shown in Figure.9 and Figure.10:
The significant parameters of vortices such as size, number, location and direction, are basically the same in Figure 9 and Figure 10, indicating that reconstructed velocity field can truly reflect original field. The streamline of the reconstructed flow field is much smoother, that is because that small-scale coherent structure is filtered, while large-scale coherent structure is preserved; The vortices is generated in strong turbulence region formed at nozzle outlet, the size of vortices gradually increases as the vortices moving downstream, but the direction is not changed.

4. Conclusion
In present study, flow characteristics on unconfined plane and confined plane in double-side wall confinement is tested using PIV, POD is employed to decompose and reconstruct instantaneous velocity fields, the low-order modes of axial velocity and vorticity on unconfined plane and confined plane is analysed. The following conclusion is a summary of this investigation.

(1) On account of existence of a symmetrical double-wall, velocity and vorticity distribution mainly reflecting in low-order modes is seriously affected. Contributions to total energy for the first three modes is basically the same on confined plane, nevertheless, it is obviously different from the pattern, which is mainly due to the fact that waterjet on confined plane cannot be fully developed, expressed on unconfined plane.

(2) Turbulent energy consumption through analysing the low-order modes of vorticity is mainly symmetrically distributed near nozzle axis, waterjet diffusion on confined plane is limited by two side wall and couldn’t be fully developed, but this feature is not exhibited on unconfined plane.

(3) Using the first m-order modes contained 70% of TKE to reconstruct instantaneous velocity field on unconfined plane, results indicate that vortices are generated in strong turbulence region formed at nozzle outlet, vortices size gradually increases as vortices moving downstream.

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