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Research Article

Turbulence Characteristics of Cavitating Flows Downstream of Triangular Multiorifice Plates

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Cavitating flow fields downstream of triangular multiorifice plates with different geometrical parameters were measured by PIV technique, and effects of orifice size, orifice number, and orifice layout on turbulence intensity and Reynolds stress were analyzed. The experimental results showed that the turbulence intensity and Reynolds stress downstream of the different multiorifice plates exhibited sawtooth-like profiles. Decrease in orifice size, increase in orifice number, and taking staggered layout could contribute to intensification of turbulence mixing and shear effects of multiple cavitating jets downstream of the multiorifice plates and thus reaching the expected cavitation effects.

1. Introduction

Once flow velocity reaches a certain point where the pressure of flow lowers below the saturated vapor pressure at the corresponding temperature, a cavitation phenomenon will occur in liquids. The collapse of cavitation bubbles in the zone where pressure rises can generate super high pressure and temperature and forms microjets and shock waves in a micro second interval and thus will cause severe damage to ship propellers, hydraulic release structures, hydraulic components, and hydraulic machinery. Conversely, Pandit and Joshi [1] applied hydrodynamic cavitation into the hydrolysis of fatty oil. Since then, hydrodynamic cavitation has been studied for the potential application in water treatment. Many studies have found that the hydraulic condition of cavitation reactor was the major factor and played an important role in effective wastewater treatment [2–5]. Dong et al. [6] and Yao et al. [7] studied the cavitational characteristics due to circular and triangular multiorifice plates, and their results revealed that the multiorifice plates with larger and more orifices incurred stronger cavitation and hence improving the degradation rate. And Dong et al. [8] studied the degradation of hydrophilic and hydrophobic mixture due to the combination of the Venturi tube with the multiorifice plates. Wang et al. [9], Geng et al. [10], and Dong and Qin [11], respectively, used hydrodynamic cavitation due to the Venturi tube to kill Escherichia coli in raw water. They focused on the effects of variable diffusion angle, varying throat lengths, throat velocity, treatment time, cavitation number, and initial concentration of Escherichia coli on the killing rate. Also, killing rate of pathogenic microorganisms in raw water by hydrodynamic cavitation due to triangular and square multiorifice plates was, respectively, studied by the references [12–15]. As mentioned above, the characteristics of cavitating flow directly affect the degradation rates of refractory pollutants and the killing rates of pathogenic microorganisms. Dong et al. [16, 17] and Zhang et al. [18], respectively, reported time-averaged velocity and pressure distributions of the Venturi tube and triangular multiorifice plates and their combinations. In fact, characteristics of cavitating filed flow behind cavitation reactors such as multiorifice plates contribute further to understanding the mechanisms of degrading refractory pollutant and of killing pathogenic microorganism by hydrodynamic cavitation and to optimizing the design of cavitation reactor. However, less study of turbulence characteristics downstream of the multiorifice plates was reported. In this paper, cavitating flow fields downstream of 5 triangular multiorifice plates with different orifice sizes, numbers and layouts were measured by PIV technique, and the effects of the geometric parameters on turbulence intensity and Reynolds stress were analyzed.

2. Experimental Facility and Methodology

The experimental apparatus is shown in Figure 1. Five types of triangular multiorifice plates were designed in the experiment as shown in Figure 2. The size of each plate was 50 mm × 50 mm. The total orifice area of each plate remained the same. The orifice numbers of these multiorifice plates were $n = 9$, 16, 25, and 64, and the orifice sizes were $a = 2.6$, 4.0, 5.1, and 6.7 mm, respectively. The checkerboard-type and staggered layouts of orifices were arranged on the plates. The geometric parameters of the multiorifice plates are shown in Table 1. The size of cross-section of the working section was 50 mm × 50 mm, and the length of the working section was 200 mm. The top and two sides of the working section were installed by polymethyl methacrylate for observation window. The multiorifice plates and working section were made of stainless steel plate, which were fabricated by computer-controlled machine tool.

The basic principle of PIV technique is that the trace particles can be of good reflectivity and tracking features, whose relative density is equivalent to the fluid evenly spread in the measured flow field. Then, the moving images of these particles will be captured by a camera at certain interval before matching the particles in adjacent images. In this way, the parameters of movements can be worked out through calculating the velocity vector at each point in the flow filed. In this paper, lots of cavitation bubbles existed in the high-velocity flow, and since the tiny bubble and the moving fluid have better following characteristics, the speed of moving bubble was almost equal to that of fluid particle. So the motion of bubble can be used to reflect the motion of fluid particle. The Dantec 3D-PIV was used to measure the instantaneous velocity field downstream of the triangular multiorifice plates. The sampling frequency was 15 Hz, and the time interval of instantaneous flow field was 0.02 s. Considering that the number of instantaneous flow field should statistically meet the need of steady turbulent flow, 500 groups of instantaneous flow fields verified by the preexperiment were chosen to analyze the turbulence intensity and Reynolds stress of flow fields.

The measuring position was along the center line on the top surface in the working section, ranging within 50 mm × 200 mm. In order to analyze and compare turbulence characteristics in detail, the working section was divided into 8 cross-sections as shown in Figure 3 and the positions of cross-sections are listed in Table 2. For the sake of comparison, the position of cross-section was nondimensionalized by the length of working section ($L = 200$ mm).

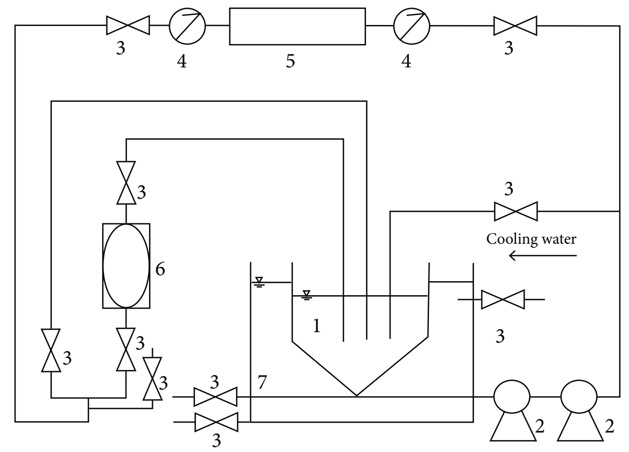


Figure 1: Sketch of experimental setup. 1: inner solution tank, 2: centrifugal pump, 3: control valves, 4: pressure gauge, 5: working section, 6: rotator flow meter, and 7: water cooling tank.

3. Results and Discussion

The relative longitudinal turbulence intensity can be expressed as

$$T_X = \frac{\sqrt{\acute{u}2}}{U}. \tag{1}$$

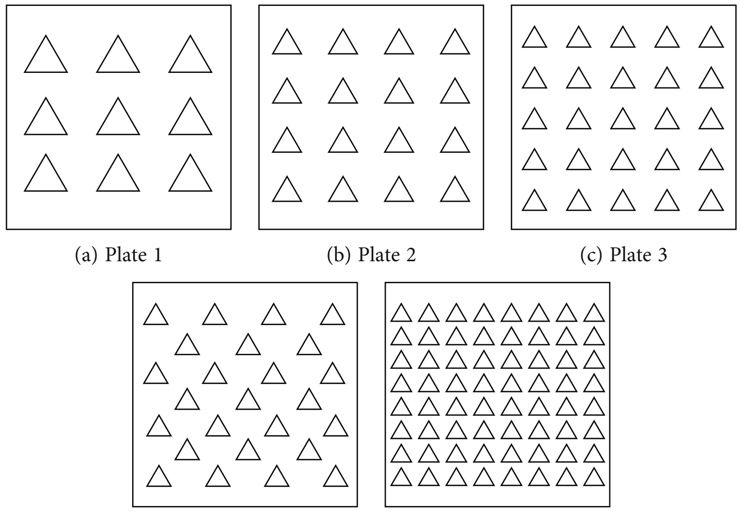
And the relative Reynolds stress can be defined as

$$\eta = \frac{\overline{\acute{u}\acute{v}}}{U^2}, \tag{2}$$

where $\acute{u}$ and $\acute{v}$ denote longitudinal and vertical fluctuating velocities and U means velocity of orifice.

3.1. Effect of Orifice Size on Turbulence Intensity and Reynolds Stress. The distribution of relative turbulence intensity at cross-section 1-1 was taken for an example, and variation in relative turbulence intensity for the 4 multiorifice plates, namely, side length of orifice $a = 2.6$, 4.0, 5.1, and 6.7 mm, is shown in Figure 4. It follows from the Figure that there exist different extents of turbulence as a result of shearing and mixing effects of multiple jets downstream of multiorifice plates. The turbulence intensity for $a = 4.0$ mm plate exhibits obvious sawtooth-like distribution. Intense turbulence means that the fluctuating velocity is larger, which can induce cavitation. Variation of turbulence intensity T_x with vertical height y/H is smaller, the turbulence intensity for $a = 6.7$ mm plate is the weakest among the 4 multiorifice plates, and the turbulence intensities for $a = 2.6$ mm and 5.1 mm plates are in between for $a = 4.0$ mm and $a = 6.7$ mm plates.

Distribution of Reynolds stress for the 4 multiorifice plates with different orifice sizes is shown in Figure 5. It follows that variation in Reynolds stress downstream of multiorifice plates also exhibits a sawtooth-like distribution, which means strong shearing effect took place among the



(a) Plate 1 (b) Plate 2 (c) Plate 3

(d) Plate 4 (e) Plate 5

Figure 2: Triangular multiorifice plates.

Table 1: Geometric parameters of triangular multiorifice plates.

Orifice number	Orifice arrangement	Side length of orifice, mm
9	Checkerboard-type	6.7
16	Checkerboard-type	5.1
25	Checkerboard-type	4.0
64	Checkerboard-type	2.6
25	Staggered	4.0

Table 2: Dimensionless cross-section positions behind multiorifice plates.

Cross-section	x/L	Cross-section	x/L
1-1	0.05	5-5	0.25
2-2	0.1	6-6	0.35
3-3	0.15	7-7	0.5
4-4	0.2	8-8	0.75

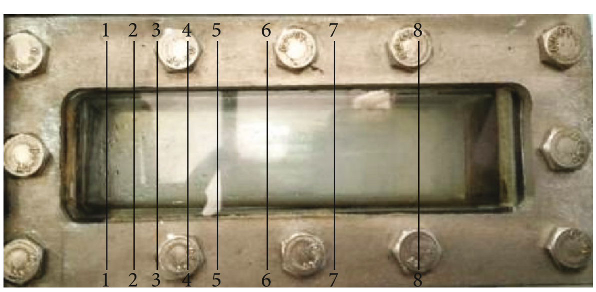


Figure 3: Cross-section positions downstream of multiorifice plate.

high-velocity multiple jets. The sawtooth-like distribution of Reynolds stress for $a = 5.1$ mm plate is denser than that for $a = 6.7$ mm plate and exhibits alternative fluctuations between positive and negative directions. Reynolds stress due to $a = 4.0$ mm plate is larger than that due to $a = 5.1$ mm plate along the vertical line, implying that the shearing effect among multiple jets downstream of the plate with smaller orifice is stronger. The reason is that velocity gradient between multijet and ambient fluid became larger due to the smaller orifice, so more intense entrainment and mixing occur, thus producing more eddies and increasing internal disturbance and turbulence energy in cavitating flow field.

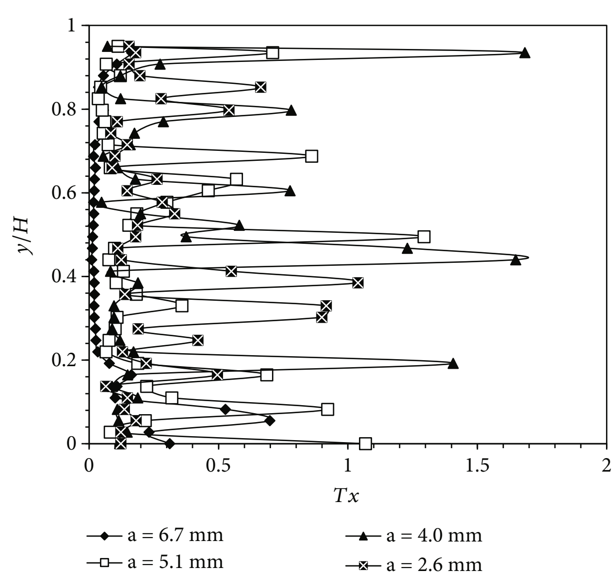


Figure 4: Effect of orifice size on turbulence intensity.

It was found through further comparison between $a = 4.0$ mm and 2.6 mm plates that the sawtooth-like distribution of Reynolds stress due to the latter was denser, but variation in the values was within a smaller range. Also,

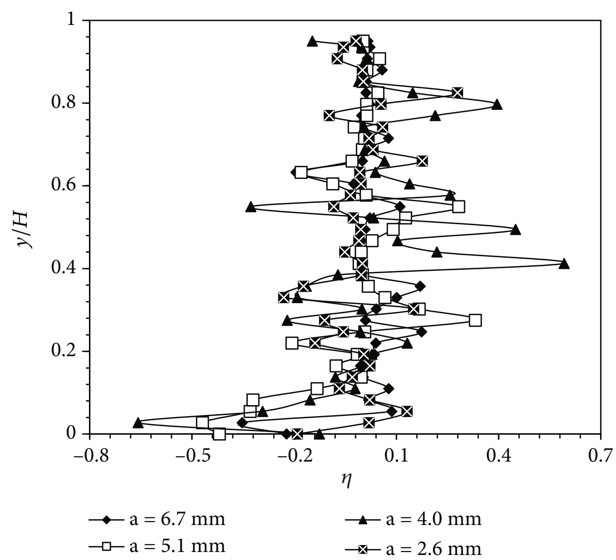


Figure 5: Effect of orifice size on Reynolds stress.

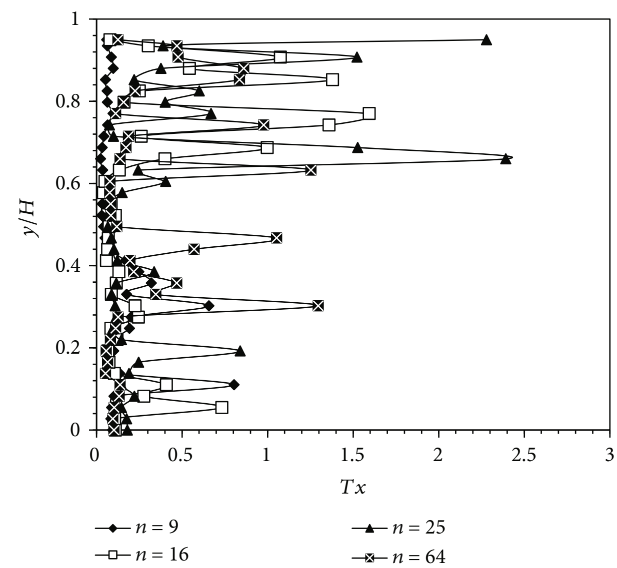


Figure 6: Effect of orifice number on turbulence intensity.

Reynolds stress for the latter was basically smaller than that for the former. It means the intense shearing effect could not occur for the minimum orifice in this experiment.

3.2. Effect of Orifice Number on Turbulence Intensity and Reynolds Stress. The variation of relative turbulence intensity for 4 multiorifice plates with different orifice numbers is shown in Figure 6. It can be seen from Figure 6 that the turbulence intensity for 9-orifice plate approximates a straight-line, and for 16-orifice and 64-orifice plates, the intensities exhibit sawtooth-like distributions. However, there are some larger values of turbulence intensity for 25-orifice plate, it means that a more intense turbulent shearing field occurred, and that numerous high-frequency and small-size eddies were generated in the field, which contributed to transfer of turbulence energy and increased pressure fluctuation. Therefore, an appropriate increase in orifice number could contribute to intensifying interjet mixing and to prompting formation, growth, and collapse of cavitation bubble, leading to intense cavitation effect.

Distribution of Reynolds stress due to multiorifice plates with different orifice numbers is shown in Figure 7. As can been seen in Figure 7, Reynolds stress downstream of 16-orifice plate changes between positive and negative range, which is more intense than that downstream of 9-orifice plate. In addition, the value of Reynolds stress due to 25-orifice plate is larger than that due to 16-orifice plate. All of these implied that the more the orifice number, the stronger the turbulence exchange and shearing effect, which could prompt the formation, growth, and collapse of cavitation bubbles. It was found based on the further comparison between 25-orifice and 64-orifice plates that the sawtooth-like distribution of Reynolds stress due to the latter was denser. However, the value of Reynolds stress due to 64-orifice plate only fluctuated within a smaller range, which was probably the weakening effect of combined jets due to more orifice numbers.

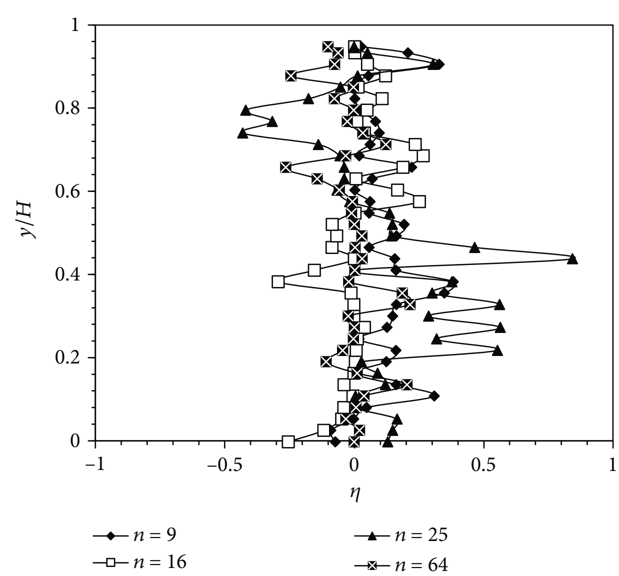


Figure 7: Effect of orifice number of Reynolds stress.

3.3. Effect of Orifice Layout on Turbulence Intensity and Reynolds Stress. Two multiorifice plates with the same size and number of orifice but different layouts of checkerboard-type and staggered orifices were taken for the effect on layout. The distribution of turbulence intensity is shown in Figure 8. It follows from the figure that variation in turbulence intensity for the checkerboard-type layout is relatively mild; however, the variation for the staggered layout is steeper. The reason is that the flow field due to the staggered layout was of more intense entraining and mixing effects of multiorifice plates.

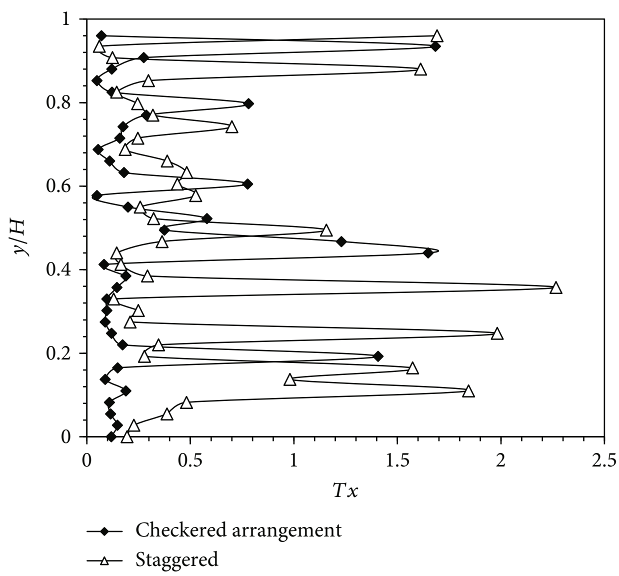


Figure 8: Effect of orifice layout on turbulence intensity.

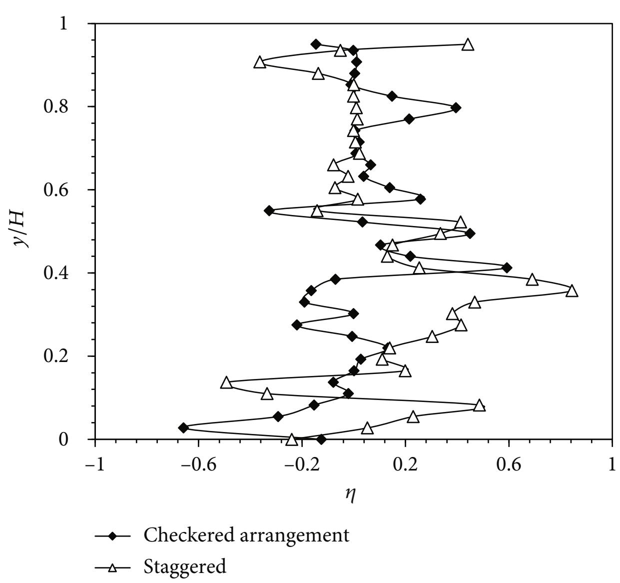


Figure 9: Effect of orifice layout on Reynolds stress.

The distribution of Reynolds stress due to two plates with the same size and number of orifice but different layouts of the checkerboard-type and staggered orifices is shown in Figure 9. We can easily see the variation in Reynolds stress due to the two plates is similar.

4. Conclusion

There existed different turbulence due to shearing and mixing effects of multiple jets downstream of different multiorifice plates. The turbulence intensity for $a = 4.0$ mm and 25-orifice plates exhibited apparent sawtooth-like distribution, which contributed to transfer of turbulence energy and increase in pressure fluctuation. Also, the variation in turbulence intensity for the staggered layout plate was steeper than that for the checkerboard-type one; Reynolds stress downstream of different multiorifice plates also exhibited sawtooth-like profiles. Appropriately decreasing the orifice size ($a = 4.0$ mm), increasing the orifice number ($n = 25$), and taking staggered layout could contribute to intensifying turbulence mixing and shearing effects of multiple jets downstream of multiorifice plates, thus resulting in an expected cavitation effect. Improving the velocity of orifice and designing the various shapes of orifice will be considered in the following study.

Data Availability

The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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