Experimental and numerical study of cavitation inside sharp-edged multi-hole orifice plate

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Abstract

Cavitation can be useful in many occasions, for example, it can be adopted to improve the mass and heat transfer of the solution and it can also be used during the wastewater treatment. Among the ways to generate cavitation in hydrodynamic devices, the sharp-edged orifice is often used because it has a simple structure and the tube that has multi-holes orifice plate is more likely to generate cavitation. In this paper, experiment and computational fluid dynamic (CFD) method are carried out, the flux of the test tube is recorded during the experimental process, and the cavitation model used in the numerical study is validated by comparing the simulated results with the experimental results, then triangular, rectangular, and circular shape of holes and different kinds of distributions of holes such as circular and rectangular distributions are numerically studied. The vapor volume fraction is visualized to find out the effects of holes shape and arrangement on cavitation intensity. Besides, study focusing on the inlet pressure is achieved using CFD simulations, and the cavitation number is calculated under different cases to find out their effects on cavitation intensity. It can be concluded from the obtained results that cavitation number decreases with the increase of pressure drop, and under a certain value of pressure drop, the orifice plates with circular holes have the minimal cavitation number and maximal cavitation intensity. When the holes are circular arrangement, the orifice plates with circular and triangular holes has higher cavitation intensity, and when inlet pressure is large enough, different arrangement and shape of holes barely affect the cavitation intensity.

Keywords: hydrodynamic cavitation; multi-hole orifice; cavitation number; pressure drop

Introduction

The implosion of cavitation bubbles formed when fluid flows through a restriction induces micro-jets and shock waves, which can release high intense energy and is conducive to the formation of strong oxidation conditions and the heat transfer enhancement. Many works have been done about the utilization of hydrodynamic cavitation. Sivakumar and Pandit [1] found that multi-hole orifice used in hydrodynamic cavitation reactor could enhance the degradation of a cationic dye rhodamine B solution. Schneider et al. [2] found that the heat transfer enhancement reached 67% compared with noncavitating flow conditions. Orifice plates are often treated as hydrodynamic cavitation reactor and has been investigated a lot. Ebrahimi et al. [3] studied the cavitating flow of a thick orifice plate under high-pressure conditions. Dong et al. [4] investigated the effect of the number, the arrangement and the ratio of triangular holes on the hydraulic characteristic of the orifice plates. Rudolf et al. [5] focused on the loss coefficient and cavitation number of single and multi-hole orifices using experimental methods, and they found that there was large loss coefficient drop in multi-hole orifices. Liu et al. [6] experimentally investigated the flow and cavitation characteristics of damping orifices with different ratio of the thickness and diameter of the orifice. He et al. [7] numerically investigated the flow characteristic of a nozzle with multi-hole. He et al. [8] also experimentally and numerically investigated the cavitation inception and cloud cavitation shedding in a rectangular nozzle orifice. Ji et al. [9] studied the effect of the upstream pressure and cavitation number of multi-holes orifice using experimentally and numerically methods. Rudolf et al. [10] studied the static and dynamic characteristic of multi-hole orifices carrying out experiments. By now, the circular holes, rectangular holes, and triangular holes of orifice plates have been discussed relatively by researchers, but a comparison of different shape of holes and different arrangement of these holes have barely been done. Therefore a comprehensive study of cavitation inside different multi-hole orifice plates under different pressure drop is presented in this study, and useful information for engineering application is provided.

Experiments

The schematic of the experimental facility is shown in Fig. 1, it mainly consists of a water reservoir tank, a centrifugal pump, a gate valve, and a test section including the investigated orifice plate. The test rig is mostly made from stainless steel with a nominal diameter of 50mm. The volumetric flow rate through the pipelines before the

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orifice is measured by a flow meter. The upstream and downstream pressure are obtained with two pressure transducers and recorded by adjusting the inlet flux. The surrounding temperature is a constant and is room temperature. All data are taken when the flow meter and pressure transducers readings are steady, and the accuracy of the flow meter and the pressure transducers is ± 0.5%.

Numerical method

Computational fluid dynamics (CFD) method is used to investigate different shape of orifice holes and different arrangements of these holes. Commercial software FLUENT is adopted and steady-state analysis is carried out. The Realizable k-ε turbulence model and Zwart-Gerber-Belamri cavitation model are used. As for the boundary conditions, a pressure inlet boundary is applied at the inlet and a pressure outlet boundary is applied at the outlet. Besides, no-slip wall boundary is applied for all walls, and standard wall function is adopted.

The working fluid is water and water vapor at 20°C, and their density and viscosity are listed in Table 1. The saturated pressure is 2,339 Pa at this temperature.

Three kinds of holes including circular, rectangular, and triangular holes and two kinds of arrangements that are circular distribution and rectangular distribution are investigated as shown in Fig. 2. The diameter of the orifice plate is 50mm, and the orifice plate thickness is 20mm. The circular, rectangular, and triangular holes have the same area, which means that the six kinds of orifice plates have the same opening ratio, and the diameter of the circular hole is 4mm.

Symmetrical model and hexahedral mesh are adopted in this study. Mesh around holes is fined and grid independence has been achieved and the number of cells is around 738,568. The orifice plate with one central circular hole is adopted in the experiment and the diameter of the circular hole is 10mm. The measured flow rate vs. pressure drop data are adopted to compare with the numerical results and the results are shown in Table 2. It can be found that the error between the experiments and the simulation is within 9.6%, so it can be inferred that the adopted numerical method is acceptable.

Results

The parameters are investigated synthetically, and the values are changed to 0.4, 0.6, 0.8, and 1MPa for the inlet pressure with different arrangements and shape of holes, as for the outlet pressure, the atmosphere that is 0.1 MPa is adopted. The water vapor volume fraction on the symmetry plane of the circular holes orifice plate with different arrangements and different inlet pressure is shown in Fig. 3. It can be found from Fig. 3 that the area of water vapor on the symmetry plane is larger under circular arrangement of holes when inlet pressure is small (0.4 MPa), while the inlet pressure in large (larger than 0.6 MPa), the water vapor distribution on the symmetry plane of the orifice plate is almost the same. Besides, it can also be seen that the water vapor distribution inside the circular holes is symmetrical about the middle plane. More water vapor appears at the outer circular holes compared with the central circular hole, and the wall of the circular holes away from the center of the orifice plate has more water vapor. In addition, the maximal water vapor volume fraction in the orifice plate with circular arrangement of circular holes is higher than the rectangular arrangement, so it can be inferred that cavitation intensity is higher when the holes of the orifice plates are circular arrangement.

The pressure distribution inside orifice plate is related to the cavitation, the static pressure along the centerline of the circular arrangement multi-hole orifice plates with different shape of holes and different inlet pressure is shown in Fig. 4. It can be seen from Fig. 4(a) that when inlet pressure is small (0.4 MPa), there is an apparent difference of the static pressure within the orifice under different shape of holes. The minimum pressure under three kinds of holes is close to each other, but after the pressure recovers within the orifice, the static pressure has the maximum when the shape of holes is triangular and has the minimum when the shape of holes is circular. At the outer of the orifice plate, the static pressure under three kinds of holes is almost the same. From Fig. 4(b), it can be found that under large inlet pressure, although there is a small fluctuation of the pressure difference between different kinds of holes, the static pressure is nearly the same.

When the water vapor volume fraction in each computational cell is higher than 0.5, the cavitation intensity is higher. Figure 5 depicts the 3D isosurfaces when the water vapor volume fraction is above 0.5 for inlet pressure 0.6 MPa. From Fig. 5, it can be found that cavitation mainly occurs near the wall of the hole but away from the center of the orifice plate, which is consistent with above analysis. When the shape of the hole is rectangular or triangular, the vapor mainly congregates around the edges, and the water vapor volume fraction on the symmetry plane is very small and can be neglected. From the water vapor distributions, it can be found that there is no apparent difference of the water vapor volume when the shape of the holes is rectangular and triangular. Besides, it can also be found that although the area of water vapor on the symmetry plane has the maximum in the central hole as shown in Fig. 3, the water vapor volume when water vapor volume fraction is above 0.5 is minimal in the central hole.

The cavitation number σ is always used to evaluate the cavitation intensity of different orifice plates and it is expressed as follows

$$\sigma = \frac{p_d - p_v}{0.5\rho v^2} \tag{1}$$

here p_d is the downstream pressure of the orifice plate, p_v is the saturated vapor pressure of water, ρ is the density of water, and v is the average velocity within the holes of an orifice plate.

Figure 5 shows the cavitation number of the six kinds of orifice plates under different inlet pressure. It can be found from Fig. 5 that the cavitation number decreases with the increase of inlet pressure for a given orifice plate, which means cavitation intensity increases with the rising of inlet pressure. Under the same inlet pressure, the orifice plate with circular holes has the minimal cavitation number and the orifice plate with triangular holes has the maximal cavitation number. For the orifice plates with circular and triangular holes, the cavitation number is larger when the holes are circular arrangement, but for the orifice plates with rectangular holes, the cavitation number is smaller when the holes are circular arrangement. Compare the six kinds of orifice plates, the orifice plate with circular arrangement circular holes has the minimal cavitation number for a given inlet pressure, and the largest cavitation number difference is 29.6% between the circular holes and the triangular holes when inlet pressure is 0.4 MPa. As the increase of inlet pressure, the cavitation number difference decreases and the cavitation number for the investigated orifice plates is almost the same when inlet pressure is 1 MPa.

Figures & Tables:

	Density (kg/m^3)	Viscosity (kg/m-s)
Water	998.16	0.0010016
Water vapor	0.0173	9.727E-06

Table 1 Water and water vapor properties used in this study

Pressure drop (Pa)	14,000	21,000	30,000	88,000
Measured flow rate (m3/h)	1.57	1.86	2.28	3.66
Simulated flow rate (m3/h)	1.42	1.74	2.13	3.46
Error	9.6%	6.5%	6.6%	5.5%

Table 2 Comparison between the simulated and the measured flow rate

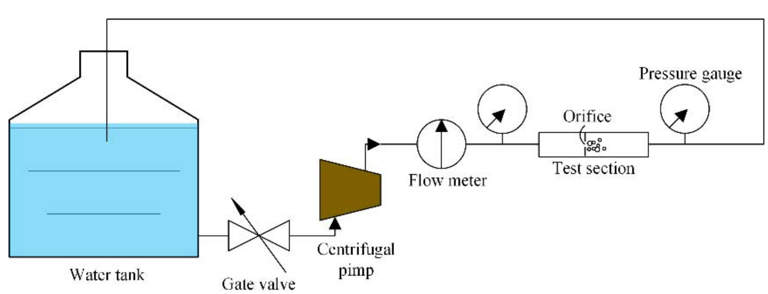

Figure 1 Schematic of the experimental facility

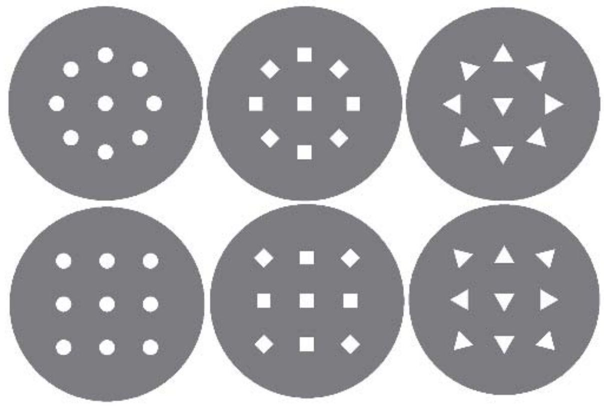

Figure 2 The shape and arrangement of the multi-holes

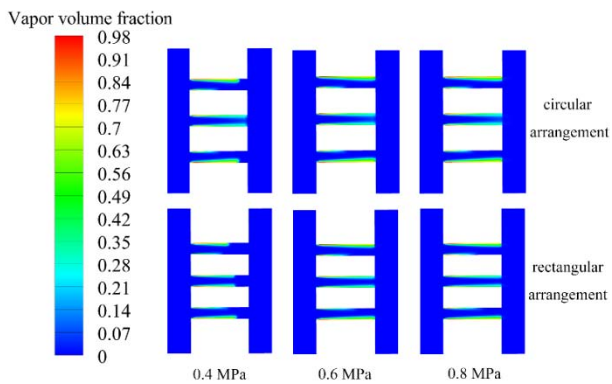

Figure 3 Vapor volume fraction on the symmetry plane with circular holes under different inlet pressure

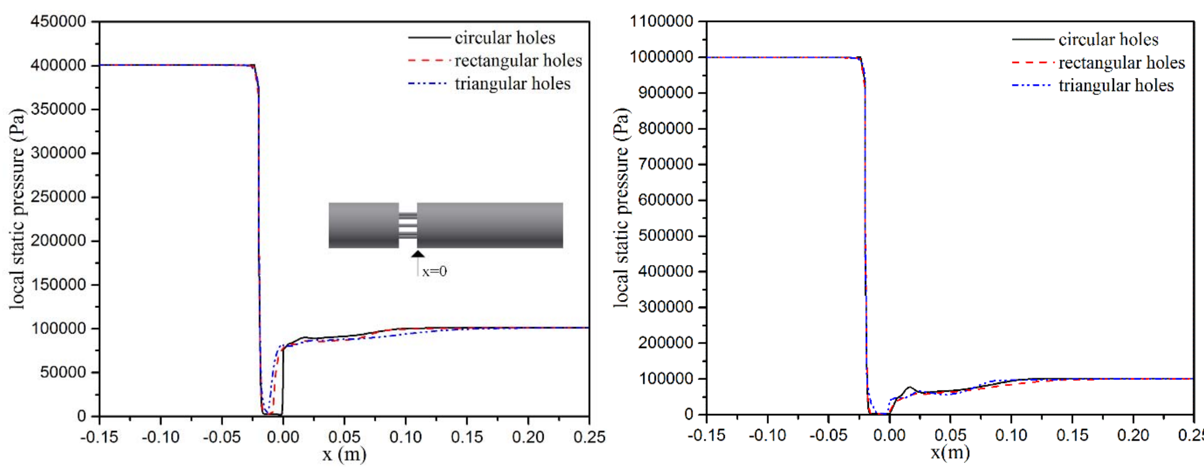

Figure 4(a) Inlet pressure is 0.4 MPa

Figure 4(b) Inlet pressure is 1 MPa

Figure 4 Static pressure along the centerline of the circular arrangement multi-hole orifice plates under different inlet pressure

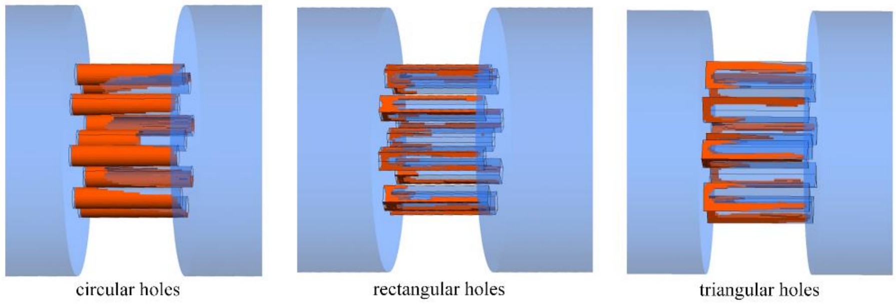

Figure 5 cavitation in circular arrangement multi-hole orifice plates

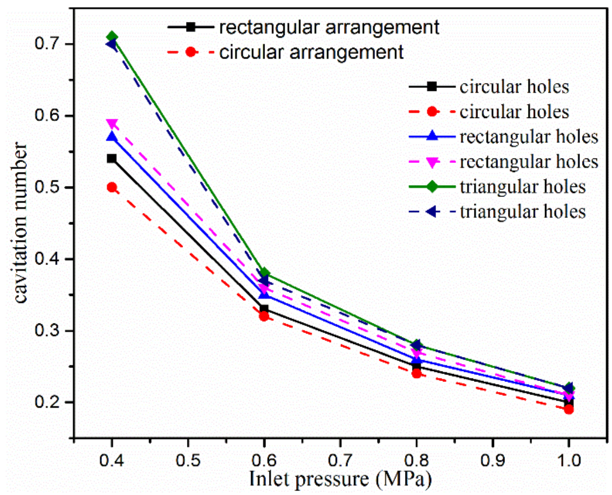

Figure 6 Cavitation number under different arrangement and shape of holes and different inlet pressure

Conclusion

A systematical numerical study is carried out with six kinds of orifice plates, and the numerical method is validated by experiment. The pressure drop, the arrangement and the shape of the holes are synthetically investigated to find out their effects on cavitation intensity. The cavitation intensity increases with the increase of pressure drop for all the studied orifice plates, and the circular arrangement orifice plate with circular holes has the maximal cavitation intensity compared with other orifice plates. For orifice plates with circular and triangular holes, the circular arrangement orifice plates have better cavitation intensity, but for orifice plates with rectangular holes, the rectangular arrangement orifice plates have better cavitation intensity. Besides, when pressure drop is small, large difference of cavitation intensity exists between different kinds of orifice plates, but under large pressure drop, the cavitation intensity of all the studied orifice plates is almost the same.

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