Numerical investigation on flow field characteristics of Helmholtz oscillator

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Abstract. Self-excited oscillation pulsed(SOP) jet, is capable of great destruction. As a typical kind of SOP nozzle, Helmholtz oscillator has its special application. Previous researches mainly focus on optimization of the structure parameters, erosion ability of jets and so on. In this paper, the flow field of Helmholtz oscillator was numerically simulated. 20 nozzles with different structures were manufactured according to simulation results; their performances were tested on different driving pressure and confining pressure under the condition of submerging. Conclusions can be drawn as follows: Compared with traditional conical nozzle, the flow characteristics of Helmholtz nozzle are obviously different. Change of structural parameters has obvious influence on the amplitude of pressure fluctuation. If the structure parameters are reasonably adjusted, energy dissipation will be reduced and working ability will be optimized. A large scale vortex structure is formed by the flow turbulence of SOP jet. In some cases that require suction and mixture, SOP nozzle has unique advantages. Since the theory of the SOP nozzle is still evolving, it is necessary to further study the pulse mechanism to realize artificial modulation.

1. Introduction

The phenomenon of self-sustained oscillation, partially caused by Kelvin-Helmholtz instability, was discovered through a large number of experimental observations of the shear layer impact device. The Helmholtz cavity consists of an upper nozzle, an upstream collision wall, an oscillation chamber, a downstream collision wall, a lower nozzle and the like. It is generally believed that the high-energy fluid enters the oscillating cavity from the upstream nozzle and exerts a strong shearing action on the fluid in the cavity, entrains the fluid and transfers energy to it, and forms a strong vortex in the periphery of the cavity. The jet flow centerline is of high velocity, which causes local pressure to drop below the saturated vapor pressure at the corresponding temperature. Then liquid phase converts to gas
phase and cavitation occurs to form a cavitation cloud. When the high-speed water reaches the vicinity of the downstream collision wall, the spilt effect of the collision wall on the fluid and the cavitation cloud, due to the development and diffusion of the jet, causes the fact that part of the cavitation cloud enters into the downstream nozzle and exits at a high speed, but another part of the fluid impacts the downstream collision wall and moves along the surface to form a large reflow vortex with the pressure wave feedback to the upstream. The schematic diagram is shown in figure 1.

![Schematic diagram of SOP jet](image)

1-upper nozzle; 2-lower nozzle; 3-upper collision wall; 4-lower collision wall; 5-oscillation cavity

Fig 1. Schematic diagram of SOP jet.

Organ pipe and Helmholtz nozzle are two commonly used types that conduct SOP(see figure 2.). Helmholtz oscillator is composed by upper nozzle, lower nozzle, upper collision wall, lower collision wall and oscillation cavity. Water enters into the cavity via upstream pipeline, and sprays out as pulsed jet from downstream nozzle. Previous relevant studies mainly focus on impact effect and structure optimization. Rockwell and Naudascher studied the self-sustained oscillation phenomena produced by fluid flowing past the different cavity, and confirmed this conclusion through a lot of experiments. Their further research indicated that structure of cavity led to a large number of vortexes near the boundary layer, part of which appeared orderly feature. What is more, the ordered structure exactly induced self-sustained oscillation(Rockwell and Naudascher 1979, Rockwell 1978). Chahine and Conn did some pioneering work, oscillation mechanism was deeply discussed under low pressure and system transmission model was built based on the theory of pressure wave feedback. To improve the effect of jet oscillation, a more efficient new nozzle was developed which obtained several times erosion effect of continuous jet. Dehkhoda and Lio’s studies showed that water hammer pressure caused by low frequency oscillation was much higher. Compared with high frequency jet, crack propagation range of specimen surface, depth and strength was significantly increased and could eliminated the bottom hole pressure effect(Lio et al. 2008, Dehkhoda and Hood 2013). Nederveen and Dalmont realized low frequency modulation of water jet based on resonance theory. However, resonance would cause the decrease of nozzle reliability, so it was not usually applied in actual engineering(Nederveen and Dalmont 2004). Kolsek and Jelic achieved better self-sustained characteristic under low frequency by changing nozzle structure parameters, but it only applied to low Reynold number condition and flow losses was quit high(Kolsek et al. 2007). Li J Y, Tang C L, Li X H, et al. attempted to change the structure (cavity length, cavity diameter, downstream exit diameter) to realize low frequency modulation. When the working pressure was within a certain range, self-sustained oscillation phenomenon would take place. Aiming at the flow characteristics, this paper illustrated the flow behavior and vortices pattern of Helmholtz chamber.
2. Experiment setup and procedures

In order to better understand the jet characteristics of SOP jet, a test system of pressure pulsation was established, as shown in figure 3. Water stored in the tank was pressurized through a series of pipes, ejected from the nozzle at the end of the connecting rod and finally impacted on the target plate. A surge tank was used to keep the pressure steady. The target plate was fixed on the tank, and the impact pressure was tested by a hole through the target plate outside the water tank to test the impact pressure of the water jet. The test data was transmitted to the computer through the acquisition card.
structure parameters consist of upper nozzle diameter $d_1$, lower nozzle diameter $d_2$, collision wall angle $\alpha$, oscillation cavity length $L_c$, oscillation cavity $D_c$.

When parameter was $L_c/d_1=2$, inlet pressure $P_i=2$ MPa, the pressure fluctuation was shown in figure 5., and the impact pressure was pulsed from 1.0 to 2.5 MPa.

![Pressure pulsation plot](image1.png)

**Fig 5.** Pressure pulsation plot.

Figure 6. shows the relationship between cavity length and peak pressure under different working pressure($D_c/d_1=8, \ \alpha=120^\circ$). As can be seen from the figure, the higher pressure of nozzle inlet is, the higher pulsation peak is. The water flowed from upstream nozzle into the chamber, through modulation of the chamber, the continuous flow turned into the periodic jet with the pressure oscillation. The higher inlet pressure is, the higher peak of pulsation is, and the better the impact performance of nozzle exit is. The peak pressure decreased as the nozzle cavity grew, for the reason that the upper nozzle converted the pressure energy of the water into kinetic energy, which had already begun to attenuate in the cavity. The jet flowed in the cavity and entrainment of the surrounding fluid, a small vortex was constantly formed near boundary layer and there was intense energy exchange between jet stream and ambient fluid. With the increase of cavity length, the degree of turbulence and energy dissipation increased. At the same time, the vortex feeding back from downstream to upstream collision wall also aggravated the decay of axial velocity.

![Relationship between cavity length and peak pressure](image2.png)

**Fig 6.** Relationship between cavity length and peak pressure.
Figure 7. shows the relationship between cavity diameter and peak pressure under different working pressure($L_c/d_1=2$, $\alpha=120^\circ$). It can be seen from the figure that the variation range of peak pressure and working pressure ratio is around 1.2~1.5. The higher the working pressure is, the higher the peak of pulsation is. It proves that the oscillating chamber is always amplifying the jet. As the cavity length increases, the peak pressure decreases first and then increases, reaching the maximum at $D_c/d_1=10$. In the case that cavity length is constant, the cavity diameter mainly affects the vortex of the downstream impact wall. When the cavity diameter is too small, the jet flows in cavity and drives surrounding fluid, forming a backflow vortex, which cannot be effectively developed in the chamber, and the backflow is restricted by the chamber wall, so that the energy dissipation increases. When the cavity diameter is too large, although the vortex has developed completely, due to the sufficiently large radial space, far away from the jet axis, the feedback from the collision wall cannot give rise to effective modulation and interference. Therefore, under certain conditions, peak pressure can reach the maximum.

![Figure 7. Relationship between cavity diameter and peak pressure.](image)

3. Numerical simulation

In order to obtain the flow details of the jet field, a large eddy simulation is used to calculate the nozzle flow. The pressure on the target plate was captured with the FFT transformation, and the amplitude frequency characteristic curve was obtained which filtered out the high frequency phase. The main frequency(724 Hz) was close to numerical results(743 Hz), whose error was only 2.6%, so the accuracy of numerical simulation was verified(see figure 8.).
Fig 8. Pressure amplitude frequency characteristic plot by experiment.

Figure 9 shows the velocity contour of flow field in the nozzle at a certain time. The velocity field inside the chamber was a periodic separation of velocity mass which was quite different from uniform flow field of ordinary jet. The maximum velocity reached as high as 1.3 times of inlet velocity. The pulsation of the internal flow field caused the periodic velocity pulse of the outflow field, which formed fluctuation of the whole velocity field.

Fig 9. Velocity contour of nozzle flow field.

In the calculation, the conical taper nozzle with the same outlet diameter was selected for comparison under the same solution strategy. The coherent structure is a key mechanism for the generation and maintenance of turbulence. Among many criteria, $Q$ criterion is one of the eddy criteria of Euler system, which is defined as

$$Q = \frac{1}{2} |\Omega|^2 - |\mathbf{S}|^2$$

$\Omega$-vorticity tensor; $S$-Strain rate tensor

The iso-surface ($Q=1\times10^7$) was obtained as a basis evaluation for vortex structure of transient flow field between conical taper nozzle ($P_i=2$ MPa) and Helmholtz nozzle ($L/d_i=4$, $D_c/d_i=8$, $P_i=1, 2, 3$ MPa), see figure 10.

The high speed fluid of the upstream pipeline of conical nozzle passed through tapered pipe, which turned pressure energy to kinetic energy. The only difference of SOP nozzle was that in the pipeline
there was a cavity which could modulate jet pulse by adjusting the chamber structure, so the jet characteristics would be affected.

![steady vortex ring](image)

(a) Conical taper nozzle

(b) $P_i=1.0$ MPa

(c) $P_i=2.0$ MPa

(d) $P_i=3.0$ MPa

Fig 10. Coherent structure under different pressure, $Q=1\times10^7$.

As can be seen from figure 10, periodic steady vortex ring was shed from edge of the nozzle due to uniform flow of the ordinary conical nozzle. The vortex ring spayed into the flow field in the fluid around the entrainment, the surrounding fluid in process of the flow field became disorder, and then large-scale braided vortex was formed. The vortex continuously mixed and broke, the whole flow field in vortex structure is like a horn with a symmetric distribution. While SOP nozzle turned the uniform flow into turbulence, the energy exchange was more fierce than that of conical nozzle. Vortex of the nozzle exit was no more steady and the scale was larger. The flow field was asymmetric and jet energy was more concentrated. As the Reynolds number increased, the flow field of the nozzle outlet became turbulent, and the energy exchange between the jet and the external fluid was more intense. As time went on, the ‘crescent’ vortex on the jet boundary gradually evolved into a larger ‘horseshoe’ vortex.

4. Conclusion
Some conclusions can be drawn as follows:

(1) Compared with traditional conical nozzle, the flow characteristics of Helmholtz nozzle are obviously different. Change of structural parameters has obvious influence on the amplitude of pressure fluctuation. If the structure parameters are reasonably adjusted, energy dissipation will be reduced and working ability will be optimized.

(2) A large scale vortex structure is formed by the flow turbulence of SOP jet. In some cases that require suction and mixture, SOP nozzle has unique advantages.

(3) Since the theory of the SOP nozzle is not perfect, it is necessary to further study the pulse
mechanism to realize artificial modulation.

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