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An experimental investigation on the pressure characteristics of high speed self-resonating pulsed waterjets influenced by feeding pipe diameter †

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Abstract

The destructive power of a continuous waterjet issuing from a nozzle can be greatly enhanced by generating self-resonance in the nozzle assembly to produce a Self-resonating pulsed waterjet (SRPW). To further improve the performance of SRPW, effects of feeding pipe diameter on the pressure characteristics were experimentally investigated by measuring and analyzing the axial pressure oscillation peaks and amplitudes. Four organ-pipe nozzles of different chamber lengths and three feeding pipes of different diameters were employed. Results show that feeding pipe diameter cannot change the feature of SRPW of having an optimum standoff distance, but it slightly changes the oscillating frequency of the jet. It is also found that feeding pipe diameter significantly affects the magnitudes of pressure oscillation peak and amplitude, largely depending on the pump pressure and standoff distance. The enhancement or attenuation of the pressure oscillation peak and amplitude can be differently affected by the same feeding pipe diameter.

Keywords: Self-resonance; Pulsed waterjet; Axial pressure oscillation; Feeding pipe diameter; Organ-pipe nozzle

1. Introduction

Waterjet technology has achieved significant progress during the last few decades and is still experiencing tremendous development [1-3]. It is environmentally friendly and being applied in a wide range of industries from automotive and aerospace to medical, as well as mining and construction engineering [4]. More specifically, waterjet technology can be used in almost every field of modern construction engineering, including ground engineering, building rehabilitation, rock fragmentation, and pavement decontamination [5]. It is one of the most recent non-traditional methods and can be used to cut almost any material [6]. Moreover, waterjet is, hitherto, the only recognized non-thermal processing technology and especially useful for machining thermo-sensitive materials [7].

The rapid development of waterjet has led to the emergence of high pressure systems able to generate pressures up to 700 MPa. However, there is still a need for further increase of the pressure for higher performance and economical advantageousness as well as its adaptation to constantly more and more demanding environmental requirements [8]. As the design, manufacture, and maintenance of ultra-high pressure systems will dramatically increase the cost, an alternate approach is to pulse the jet without using such high pressures. This is because a pulsed waterjet can cause significantly greater target damage than a continuous waterjet does, mainly due to the water hammer effect [9]. Even several mechanical devices for producing pulsed waterjets have already been invented and could drive large scale oscillations of water flow and improve the erosion effect, but they require high levels of mechanical maintenance and have very limited durability in harsh industrial environments such as well drilling, tank cleaning, and rock breaking [10].

Under these conditions, SRPW, which takes full advantage of the natural tendency of an axisymmetric jet to organize into large structures, was proposed and developed by Johnson et al. [11, 12]. They came up with the concept based on the pioneering investigations conducted by Powell et al. [13, 14], who gave a detailed explanation of the phenomenon of self-sustained oscillation by taking account of disturbance feedback, variation of frequency and amplitude, onset of oscillation, and resonance effects. In the following years, these researchers conducted a series of investigations on the mechanism and applications of SRPW, driven by the demand of maximally improving the penetration rate of deep-hole drilling and at the same time reducing the cost of high pressure

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equipment. In more specific terms, Johnson et al. [15] performed a feasibility study of self-resonating waterjets with the purpose of evaluating means for exciting resonant pulsations in high speed waterjet so as to produce ring vortex structures in the flow. Several self-resonating nozzles were also designed like, "Pulser", "Laid-back Pulser", "Pulser-Fed CAVIJET", and "Organ-pipe". And, the organ-pipe nozzle, which has been experimentally shown to have a strong ability of successfully augmenting the cutting action of mechanical bits, was claimed to be the most promising nozzle for generating SRPWs because of its compact and simple structure [16]. Moreover, to have a basic understanding of the mechanism contributing to the self-resonance yielded by organ-pipe nozzles, Chahine and Johnson [17] further studied the operation principles and concluded that the volume fluctuations of the moving vortex bubble rings formed in the center of the large structure and the shear layer-nozzle lip interaction are the two predominant sources accounting for the generation of pulsation and cavitation. Additionally, Chahine and Courbiere [18] investigated the correlations of noise and erosion of self-resonating pulsed jets and suggested that the shifts in the relative importance of the various frequencies have followed the advancement of erosion, which could be of great advantage in determining the operation process in the applications of the jet. Yoshikawa et al. [19] experimentally examined vortex-sound generation in an organ pipe and demonstrated that the vortex layers formed along both sides of the jet act as the source of an accelerating force with periodically alternating direction to oscillate the jet flow, which contributes much to the understanding of the mechanism of SRPW.

In China, SRPW has been attracting the attention of related researchers for a few decades. Early in 1991, Shen et al. [20] conducted an experimental study to test the pressure pulsations and rock erosion ability of SRPW and concluded that the jets have a great ability of improving the drilling action and at the same time reducing the drilling cost. Similarly, Sun and Yan [21] designed a new self-resonating pulsed nozzle that could cause less energy loss and had a stronger erosion capability in comparison with a conventional organ-pipe nozzle. Li et al. [22] successfully applied SRPW in petroleum drilling engineering in China, based on the previous related research and their great efforts in studying the principles and characteristics of the jet. They claimed that by using SRPWs, the average rate of penetration and the maximum impact pressure were increased by 31.2 % and 37 %, respectively. Even today, SRPW is still a remarkably important topic focused on by many researchers in areas of fluid mechanics, mechanical engineering, and mining engineering [23]. Fang et al. [24] numerically studied the flow field of submerged self-resonating cavitating waterjets at different driving pressures and confirmed that the chamber length and diameter of organ-pipe nozzle were rather important parameters. Wang and Ma [25] designed different units of organ-pipe nozzles and studied the vibration and frequency characteristics of self-resonating cavitating waterjets, aiming at increasing the design efficiency of the nozzle and improving the scouring and cleaning efficiency of the jets. Li et al. [26, 27] extensively investigated the effect of nozzle inner surface roughness on the axial pressure oscillations and cavitation erosion characteristics, which provides useful information for improving the performance of self-resonating cavitating waterjets.

Regardless of the large number of investigations on self-resonating pulsed jets with respect to structure optimization, mechanism exploration, and application extending, the effect of feeding pipe diameter on the pressure oscillation characteristics of the jets has been so far seldom mentioned in the literature. Unfortunately, it is known to all that the workers usually connect the nozzle with the feeding pipe by using a suitable fitting without caring about the feeding pipe diameter in the utilizations of self-resonating waterjets. However, if the role of acoustics in the generation of self-resonance is considered based on the previous related results, it could be inferred that the feeding pipe diameter may influence the performance of SRPW to some extent. Kaji and Azzopardi [28] have experimentally demonstrated that pipe diameter has significantly important effects on the frictional pressure gradient and velocity of disturbance waves in the gas/liquid flow. Al-Wahaibi et al. [29] studied the performance of drag reducing polymers through two pipe diameters, and concluded that pipe diameter has a remarkable influence on the polymer efficiency in modifying flow patterns. Morel [30] has long pointed out that feeding pipe could dramatically affect the resonance and pressure oscillation of self-excited pulsed air jet. To be honest, the present study actually was driven by an accidental observation that feeding pipe diameter dramatically affects the impingement pressure of SRPW in one of our previous related experiments.

Therefore, it should be obvious that a clarification of the effects of feeding pipe diameter on the pressure characteristics of self-resonating waterjets would definitely contribute to better utilizations of the jets. And the present study is an attempt to understand these effects and servers as a complement to the previous research mainly focusing on illuminating the mechanism and structure optimization.

2. The generation and working mechanism of self-resonating pulsed waterjets

In Ref. [12] several nozzles which can passively achieve SRPWs were shown to be feasible, but the most frequently used in practical applications and research is organ-pipe nozzle because of its simplicity and high efficiency. Therefore, the concept of SRPW was explained here with the use of an organ-pipe nozzle. Then, several organ-pipe nozzles were used in the following experiment to investigate the pressure characteristics of SRPW influenced by feeding pipe diameter.

Fig. 1 is a schematic diagram showing the operation principles of an organ-pipe nozzle as well as the working mechanism of a pulsed waterjet.

In general, the concept of SRPW is based on transient flow,

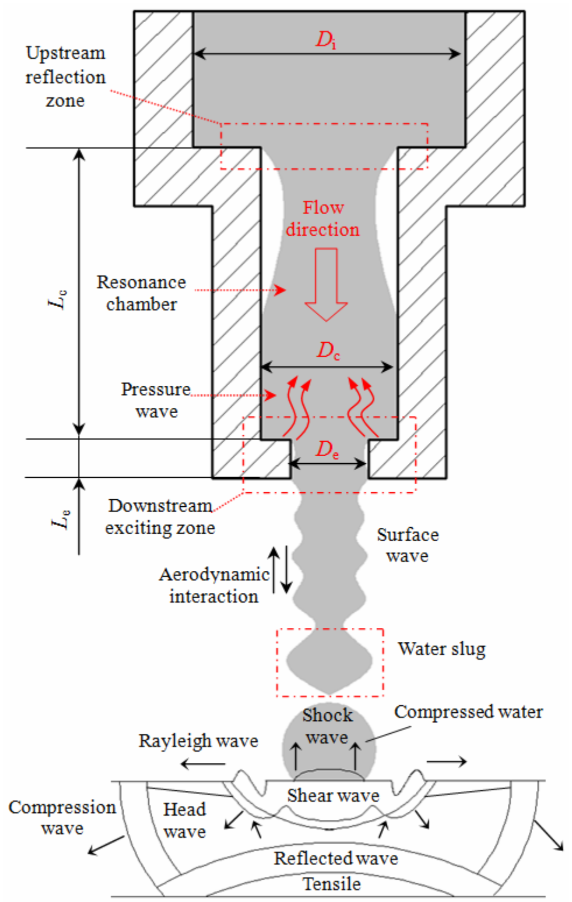

Fig. 1. Generation and operation principles of a SRPW.

elastic hydrodynamic, and passive acoustic oscillating theory. In more specific terms, an organ-pipe nozzle has two abrupt area contractions, called upstream contraction, D_i/D_c, and downstream contraction, D_c/D_e, respectively, as shown in Fig. 1. The two contractions form a pipe called a resonance chamber, whose diameter and length are D_c and L_c, respectively. When a high speed flow is passing though the nozzle, disturbances are formed at the downstream contraction because of the sudden and pronounced changes of the flow pressure and velocity. These disturbances propagate upward in the form of pressure waves and then are reflected at the upstream contraction because of the change of impedance. If the nozzle is shaped to generate an effective feedback of the incident pressure wave, a standing wave is formed in the nozzle chamber under the condition of a proper phase difference of the two waves. It should be obvious that a peak resonance can be achieved in the nozzle assembly when the fundamental frequency of the organ-pipe, f_0, is near the preferred jet structuring frequency, f_v, [12]. On the other hand, the peak resonance has a strong ability of structuring the shear layer into large vortex rings at a discrete frequency, which will make the oscillation of the jet grow in amplitude. Under these conditions, the jet will induce large shedding vortices and as SRPW is subsequently produced [21].

Additionally, the sudden area contractions not only trigger and feedback excitations, but also improve the cavitation and pulsation intensities of SRPWs. Specifically, when a high speed flow is passing the sharp corners, flow separation is formed, resulting in two low pressure zones inside the nozzle, as shown in Fig. 1. It is obvious that bubbles are easy to generate at these low pressure zones, which could increase the number of initial cavities in the flow. On the other hand, the motions and collapses of these bubbles also lead to perturbations that can disturb the jets, resulting in stronger pulsations of the jets.

Therefore, the organ-pipe nozzle is a pure fluid device because it is entirely passive and requires no outside energy supply. The energy for the pressure pulsation comes from the hydrodynamic and acoustic interactions.

As is known, the chamber length determines the resonance frequency of the nozzle assembly while the jet velocity and diameter together determine the structuring frequency. Thus, based on the formation conditions of a standing wave and frequencies match, an empirical analysis for designing the nozzle can be achieved:

$$S_t = \frac{f_v D_e}{u}, \tag{1}$$

$$L_c = K_n \frac{c}{f_0}, \tag{2}$$

where S_t is Strouhal number, u is the jet velocity, c is local sound speed, K_n is model number and can be expressed as:

$$K_n = func\left(n, \frac{D_c}{D_e}, M_a\right) = \begin{cases} \dfrac{2n-1}{4}; \ for \ \dfrac{D_c}{D_e} \gg \dfrac{1}{\sqrt{M_a}} \\ \dfrac{n}{2} \quad ; \ for \ \dfrac{D_c}{D_e} \ll \dfrac{1}{\sqrt{M_a}} \end{cases}$$

where n is a natural number, Ma is mach number defined as $Ma = u/c$.

Then, by combining Eqs. (1) and (2) and adding an end correction, β, proposed by Chahine and Johnson [17], an equation for determining the parameters of organ-pipe nozzle can be achieved.

$$f_0 = f_v \Rightarrow \frac{L_c}{D_e} = \frac{K_n}{M_a S_d (1+\beta)}. \tag{3}$$

As soon as a self-resonating waterjet is formed, it has strong pressure oscillations, which can take advantage of the water hammer effect and, therefore, be much more destructive than a continuous waterjet. As shown in Fig. 1, when a pulsed water slug impacts the surface of a target, the liquid adjacent to the contact zone becomes highly compressed and a shock wave is formed and proceeds upwards inside the pulse. Then, the rest of the pulse continues to move towards the surface due to the impact velocity, and the rate of increase in the contact area

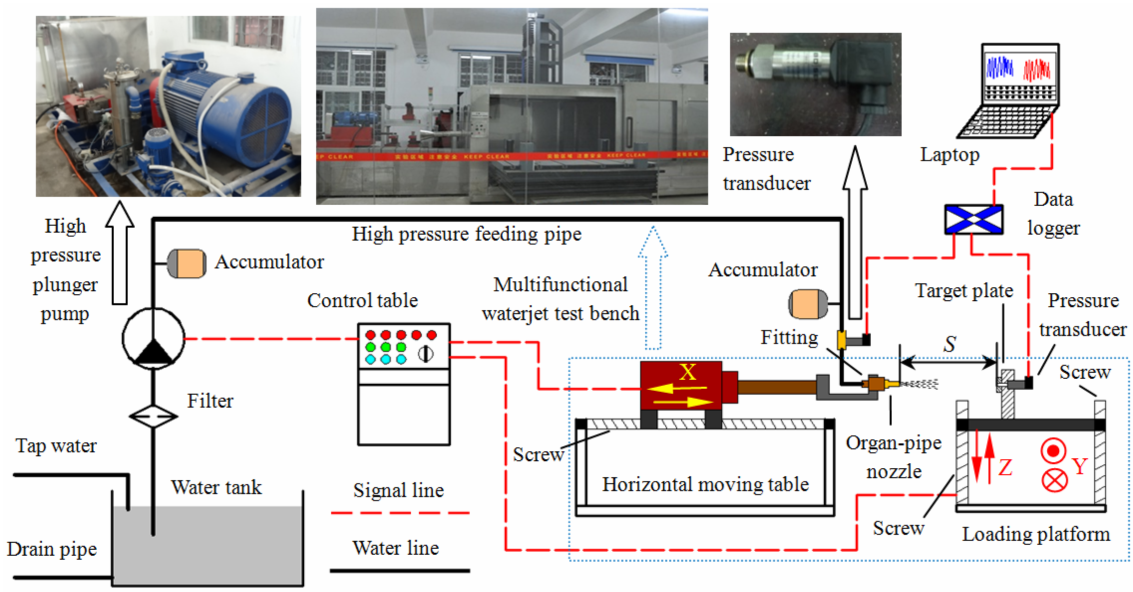

Fig. 2. Experimental setup for axial pressure measurement.

decreases below the shock velocity [31]. Specifically, the edge of the contact area between the liquid and the solid surface initially moves outwards at a supersonic velocity with respect to both the shock speed in the liquid and to the speeds of the dilatational and shear waves in the solid surface [9].

More detailed information on the generation of SRPWs as well as the working mechanism of a pulsed waterjet can be found in Refs. [8-12, 15-18, 20-22]. However, the formation of an actual pulsed waterjet composed by discrete water slugs by using the self-excitation method is still in its infancy. Currently, investigations on self-excited pulsed waterjet mainly focus on improving the oscillation pressure to make it as large as possible.

3. Experimental setup and procedures

3.1 Facilities and setup

A schematic diagram of the experimental setup for investigating the effects of feeding pipe diameter on the pressure characteristics of SRPWs is shown in Fig. 2. The experiment was conducted on a multifunctional test bench for waterjet research, which was independently developed by our research team.

Pressurized tap water was supplied from a plunger pump that has a maximum operating pressure of 600 bar and a maximum flow rate of 120 L/min. In the experiment, the pump pressure, P_u, could be continuously regulated through the control table by changing the working frequency of the motor powering the pump. The flow rate of the pump in each test could be directly read out on the control table. Four pump pressures, which were 100, 150, 200 and 250 bar, were used in the experiment.

As axial pressure oscillations of the jets were the focus of our study, and to make the results more reliable, two bladder accumulators were installed in the flow path to minimize the influence of flow rate and pressure fluctuations of the pump. In more specific terms, one accumulator was located close to the pump and the other was posited immediately near the nozzle, as shown in the figure.

As illustrated in Fig. 2, the nozzle could be given X motion and the target plate installed on the loading platform could be given Y and Z motions. All the motions had a precision of 0.1 mm. The target plate had a pressure tap of 1 mm diameter at the center and was communicating with a dynamic pressure transducer (Model: BD Sensors DMP333) that had been calibrated by the manufacturer with an accuracy of ±0.5 %FS in advance. Before each test, the axis of the nozzle was made collinear with that of the pressure tap by adjusting the location of the target plate. Then, by fixing the target plate, standoff distance, *S*, which was defined as the distance from the exit of the nozzle to the surface of the target plate, could be continuously regulated though horizontally moving the nozzle. During each test, the standoff distance was varied from 10 to 100 mm with an interval of 10 mm.

3.2 Organ-pipe nozzles and feeding pipes

As for the testing organ-pipe nozzles, the relations between chamber length and exit diameter were determined by using Eq. (3). The preferred Strouhal number, S_t, was 0.3, which was experimentally achieved by Johnson et al. [12]. Taking the experiment reliability into account, the first mode of resonance was applied in designing the nozzles because at the fundamental mode number the resonance will be the strongest. For each nozzle, the inlet, chamber, and exit diameters were 13, 7 and 2 mm, respectively, which were determined based on the “Organ-pipe nozzle design manual” established by Shen and Li [32].

Table 1. Parameters of the four testing organ-pipe nozzles.

Nozzle number	Pump pressure *Pu*/bar	Chamber length *Lc*/mm	Chamber diameter *Dc*/mm	Inlet diameter *Di*/mm	Exit diameter *De*/mm	Exit length *Le*/mm
I	100	20	7	13	2	5
II	150	17	7	13	2	5
III	200	15	7	13	2	5
IV	250	14	7	13	2	5

Table 2. Specifications of the feeding pipes.

Pipe size/mm	Inside diameter/mm	Outside diameter/mm	Working pressure/bar	Burst pressure/bar	Ratio of nozzle inlet diameter vs. pipe diameter
6	6±0.5	18±0.8	600	1800	0.46
13	13±0.5	24±0.8	420	1600	1
25	25±0.5	42±1	380	1520	1.92

Fig. 3. Photograph of the testing organ-pipe nozzles.

To ensure the integrity of the nozzles under the high testing pump pressures, the exit length of each nozzle was 5 mm, determined by the material strength of the nozzle. Detailed parameters of the nozzles corresponding to each pump pressure are shown in Table 1 and pictures of the testing nozzles are shown in Fig. 3. Note that pressure losses were neglected for simplicity during the calculation of chamber length, which should be reasonable according to a related study on SRPW [26].

According to the diameters of feeding pipe used in practical applications and allowing for the inlet diameters of organ-pipe nozzles used in the experiment, three inner diameters were employed: 6, 13 and 25 mm. This made three ratios of feeding pipe diameter to nozzle inlet diameter: D_f/D_i = 0.46, 1 and 1.92. The length for all the three pipes was 10 m. To increase the reliability of the experiment, all the three feeding pipes came from the same manufacturer, and detailed information of the pipes is shown in Table 2.

3.3 Disturbance elimination

From the generation mechanism of SRPW illuminated in Sec. 2, it can be inferred that any pressure or velocity disturbances in the high speed flow could have some effects on the resonance and then on the pressure oscillations. Since the diameter difference between feeding pipe and nozzle inlet can form area discontinuity able to cause disturbances, three fittings with special geometries were machined and applied to make the flow smoothly transit from the feeding pipe to the nozzle. In this way, feeding pipe diameter was made the only variable in each test, which would largely increase the reliability of the experimental results. In terms of the feeding pipes with diameters of 6 and 25 mm, the corresponding fittings Figs. 4(a) and (c) had inner contours linearly varying from one end to the other with an angle of 14°. The profiles and photographs of the three fittings are shown in Fig. 4.

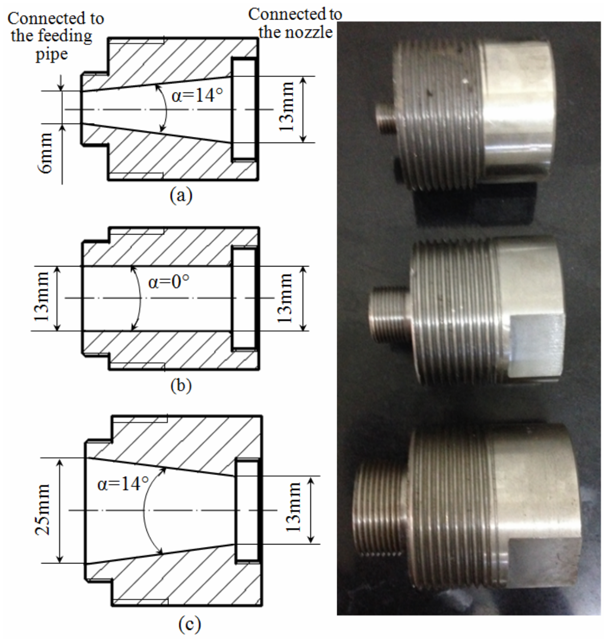

Fig. 4. Schematic diagram of the profiles and photos of the three fittings.

3.4 Pressure measurement

As is depicted in Fig. 2, another pressure transducer (Model: BD Sensors DMP333) was installed at the position just before

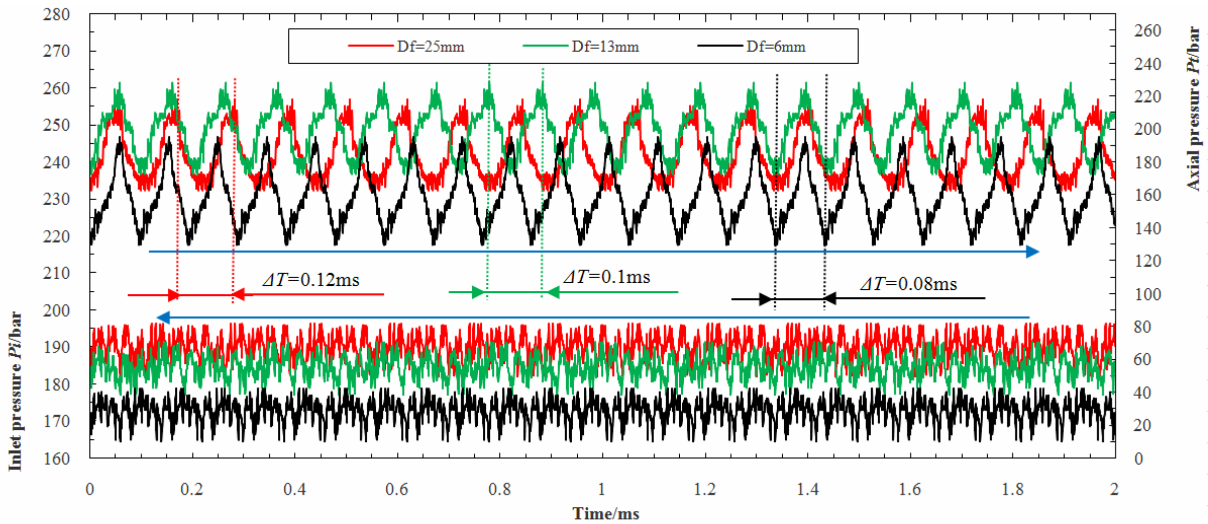

Fig. 5. Inlet pressure and axial pressure against time at standoff distance of 50 mm and pump pressure of 200 bar.

the flow enters into the nozzle. This pressure transducer had also been calibrated by the manufacturer and accuracy certificate was issued for a maximum error of ±0.2 %FS. Inlet pressure, P_i, which was defined as the pressure of the flow at the nozzle inlet, was obtained by this pressure transducer in each test in order to make a comparison with the axial pressure oscillations for a better analysis of the effects of feeding pipe diameter. Axial pressure oscillation peak, P_{max}, and amplitude, P_a, were used to evaluate the pressure characteristics influenced by feeding pipe diameter, for strong pressure oscillation mainly accounts for the destructive power and most represents the performance of SRPW. The pressure oscillation was defined as the following equation:

$$P_a = P_{max} - P_{min} \, , \tag{4}$$

where P_{min} is the pressure oscillation minimum. Both pressure oscillation maximum and minimum could be directly read out on the laptop connected with the data logger (Model: HBM QuantumX MX840B-8). The sampling frequency of the axial pressure measurement was 19200 Hz in each test.

3.5 Uncertainty of the experiment

As the experiment was performed at four pump pressures and axial pressure oscillations were used to evaluate the effects of feeding pipe diameter, experimental uncertainty mainly came from the accuracy of the pressure transducers measuring the pump pressure and jet pressure, and they were 0.5 %FS and 0.2 %FS, respectively. Another uncertainty was the linearity error of the data acquisition system, which was < 0.02 %FS. Even the real feeding pipe diameter was not exactly the same with the nominal one, which had an error of ±0.5; but this would have nearly no effect on the reliability of the results.

4. Results and discussion

As strong pressure oscillation is the most pronounced advantage of SRPW, the axial pressure oscillation peaks and amplitudes under each condition were plotted against standoff distance in order to characterize the pressure features of the jets affected by the different feeding pipe diameters.

4.1 Time-resolved axial pressure oscillations of the jets

The time-resolved axial pressures were obtained by the data acquisition system for each case. Then, it was found that they had almost the same trend with respect to the waveforms. The most significant difference was the range of pressure oscillation under different feeding pipe diameters, which will be discussed separately in the following subsections (Secs. 4.1 and 4.2). Therefore, only one figure (Fig. 5) illustrating the time resolved axial pressure at pump pressure of 200 bar and standoff distance of 50 mm was provided here, with the purpose of giving a visual understanding of how the axial pressures varied with time under different feeding pipe diameters. The variations of inlet pressure obtained by the pressure transducer installed near the nozzle are also plotted in Fig. 5 so as to make a comparison and help to give a general analysis of the effects of feeding pipe diameter.

As is shown in Fig. 5, the time-resolved axial pressure oscillations of the jets had almost the same feature with sequences of similar and regular cone-shaped waveforms, indicating that feeding pipe diameter had little effect on the oscillation form of SRPW. In terms of the oscillating frequencies, they could be obtained by calculating the reciprocals of the time intervals, which were 1.25×10^4, 1×10^4 and 8.3×10^3 Hz corresponding to feeding pipe diameters of 6, 13 and 25 mm, respectively. However, if values of the preferred Strouhal number, nozzle exit diameter, and jet velocity are substituted into Eq. (1), the oscillating frequency should be around

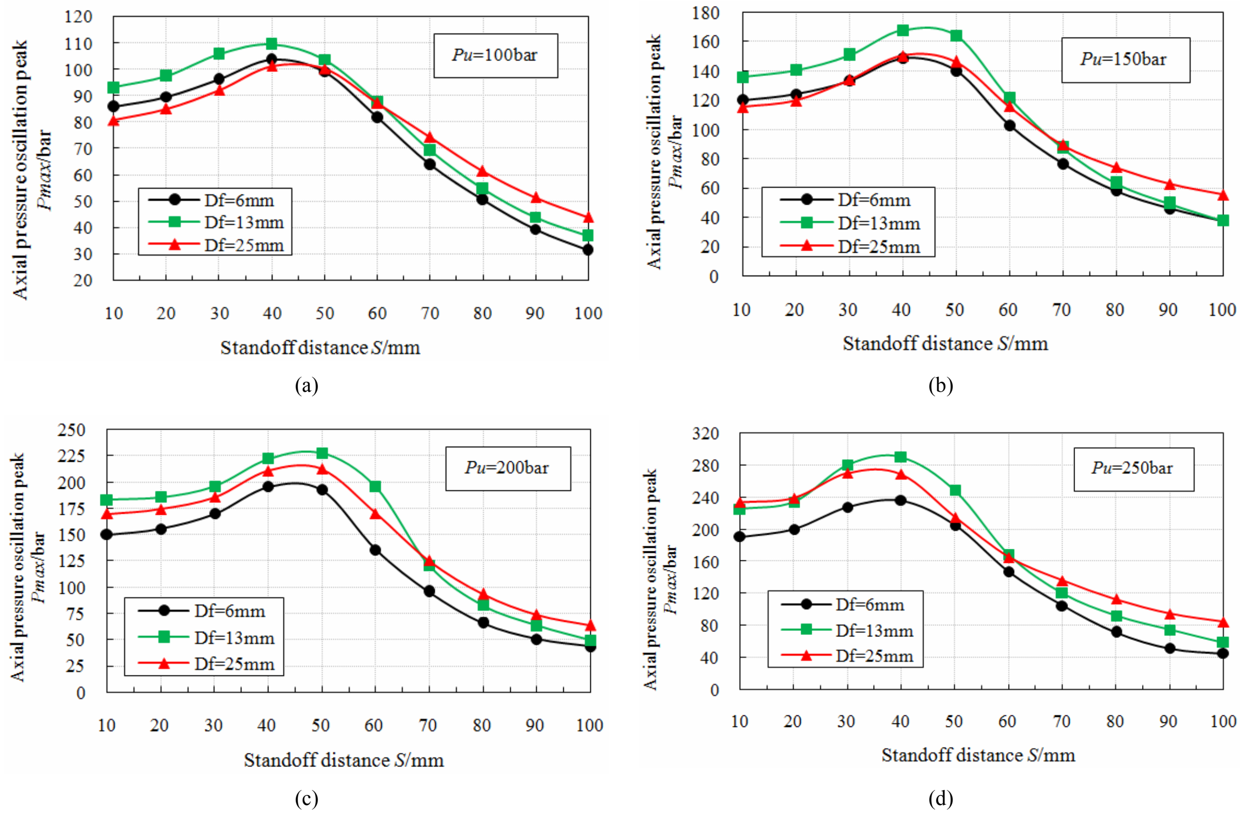

Fig. 6. Axial pressure oscillation peak as a function of standoff distance at different pump pressures.

2×10^4 Hz, which is about twice the experimental value. This inconsistency is mainly because the detailed design of an optimum system is quite complex and the current one is only a general approach [33]. On the other hand, the experimental frequency was actually in good agreement with that of a SRPW under similar conditions, which was 9.6×10^3 Hz, in the experiment performed by Chahine et al. [34].

According to the inlet pressures shown in the figure, it is obvious that the pressure loss increases with the decrease of feeding pipe diameter, due to the dramatically increased friction at higher flow speeds. However, more energy loss in the feeding pipe does not mean a lower pressure oscillation peak or amplitude of the jet. More specifically, the feeding pipe with a diameter of 25 mm caused less energy loss in the pipe than that caused by the feeding pipe with a diameter of 13 mm, but the latter led to a larger pressure oscillation peak. Furthermore, even the feeding pipe with a diameter of 6 mm resulted in the largest energy loss in the pipe; it at the same time brought about the greatest pressure oscillation amplitude. Since the axial pressure oscillation is mainly caused by self-resonance in the nozzle assembly, it can be deduced that feeding pipe diameter has great impacts on the resonance, like pipe-acoustic interactions.

4.2 Pressure oscillation peaks of the jets

Fig. 6 shows the axial pressure oscillation peaks of SRPW against standoff distance at four pump pressures. In general, it is found that all the pressure oscillation peaks first go up and then go down with the increase of standoff distance, regardless of the feeding pipe diameter. More specifically, each curve has a crest where the pressure oscillation peak reaches a maximum value, and the position where the maximum peak appears is called optimum standoff distance. Thus, it should be obvious that the existence of an optimum standoff distance is somehow an inherent feature of SRPW, which cannot be affected by the variations of feeding pipe diameter. This could seek an explanation from the generation mechanism of SRPW. On one hand, the initial disturbances caused by the self-resonance in the nozzle needs a certain time to grow into ones strong enough that could pulse the jet. On the other hand, the aerodynamic interaction between the jet and environment fluid (air), which greatly contributes to the formation of surface wave and subsequently the pulsation, is strongest at a certain distance from the nozzle exit [35].

Another interesting phenomenon that can be observed in the figure is that the optimum standoff distance generally increases with the increase of pump pressure, which is also independent of feeding pipe diameter. The optimum standoff distances were around 40, 45 and 50 mm, corresponding to pump pressures of 100, 150 and 200 bar, respectively. But at pump pressure of 250 bar, the optimum standoff distance was around 40 mm, which means the optimum standoff distance

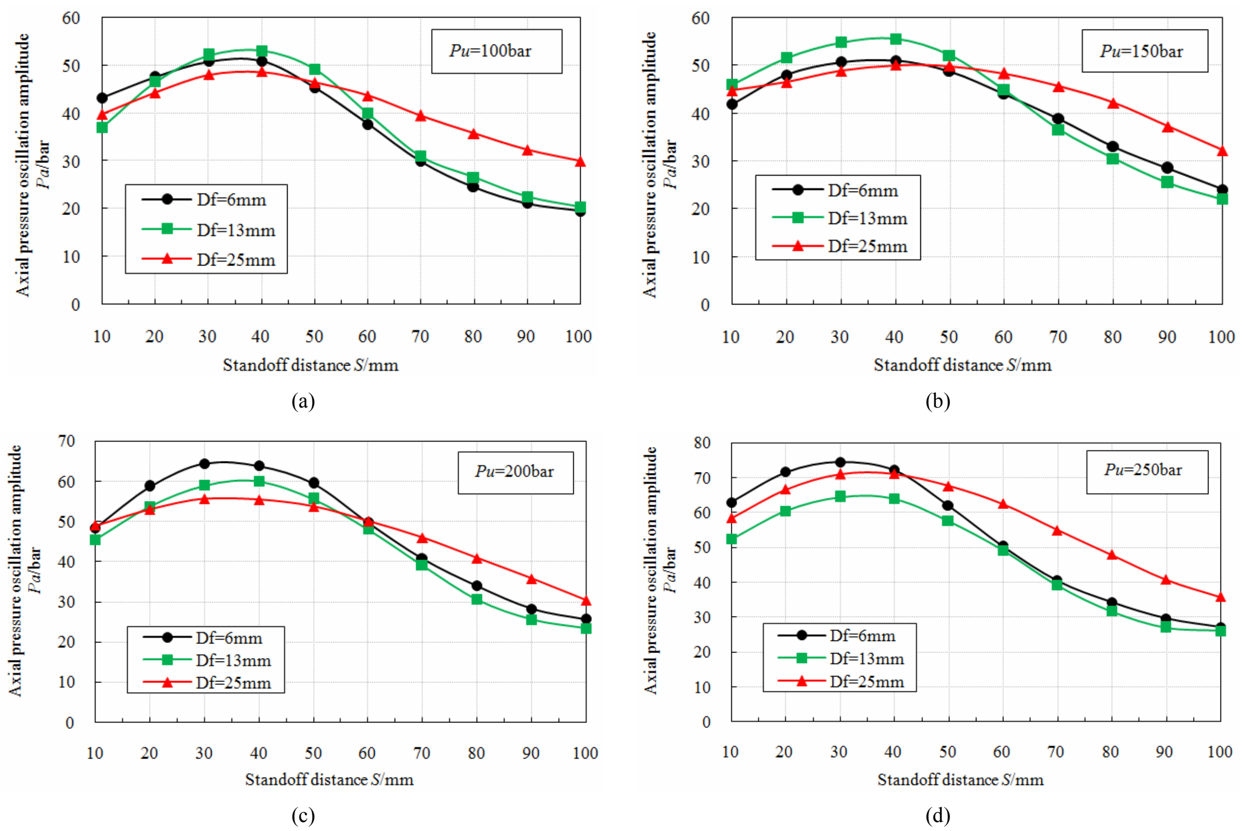

Fig. 7. Axial pressure oscillation amplitude as a function of standoff distance at different pump pressures.

would stop increasing at relatively higher pump pressures. The reason is most likely due to the dramatically increased Weber number at higher pump pressures, which could make the jet much divergent and result in a great amount of energy loss caused by the violent interactions between the jet and the environment fluid [36].

Even feeding pipe diameter has little effect on the existence and value of the optimum standoff distance under each pump pressure; it has significant effects on the magnitudes of the pressure oscillation peak. And these effects largely depend on standoff distance. To be more specific, the SRPW from the feeding pipe of diameter of 13 mm always has the largest pressure oscillation peaks at standoff distances below 60 mm; while the feeding pipe with a diameter of 25 mm turns to be the one leading to the greatest peak values at standoff distances exceeding 70 mm. It is known that the feeding pipe of diameter of 25 mm has the least energy loss in the pipeline (Fig. 5), but it still leads to the lowest pressure oscillation peaks at standoff distances below 40 mm and at pump pressures of 100 and 150 bar, shown in Figs. 6(a) and (b). This suggests that both smaller and larger feeding pipe diameters could cause some attenuation of the oscillation intensity. On the other hand, it should be clear from the figure that the magnitudes of the axial pressure oscillation peak for the three feeding pipe diameters at standoff distances above 70 mm are in accordance with the mentioned energy loss in Fig. 5. Thus, it can be inferred that at relatively smaller standoff distances, the effects of feeding pipe diameter on the pressure oscillation peaks are mainly through its impact on the self-resonance happening in the nozzle chamber; while at relatively larger standoff distances, the effects are strongly related to the energy loss in the feeding pipe.

It can also be observed in the figure that the effect of feeding pipe diameter of 25 mm for reducing the intensity of resonance and pressure oscillation intensity is weakening with increasing pump pressure, as the red curve is more close to the green curve. Conversely, the same effect of feeding pipe with a diameter of 6 mm is enhancing. And at pump pressure of 250 bar, the axial pressure peak under feeding pipe diameter of 6 mm is only 80 % of that caused by the feeding pipe of diameter of 25 mm, shown in Fig. 6(d). Moreover, the feeding pipe of diameter of 13 mm has the strongest ability of making the pressure oscillation peak greater than the corresponding pump pressure around the optimum standoff distance.

4.3 Pressure oscillation amplitudes of the jets

As the axial pressure oscillation amplitude is another important feature to evaluate the performance of SRPW, it is plotted against standoff distance at various pump pressures and shown in Fig. 7.

Similarly, the pressure oscillation amplitude also first increases and then decreases with increasing standoff distance with a maximum value at a certain standoff distance, which is also independent of feeding pipe diameter. However, the standoff distance for achieving the maximum pressure oscillation amplitude is a little different from that for the maximum pressure oscillation peak under the same pump pressure. At pump pressures of 100 150 and 200 bar, the standoff distances for the maximum pressure oscillation amplitudes are all around 40 mm; while at pump pressure of 250 bar, it is about 35 mm. Thus, there is no such a standoff distance where the maximum pressure oscillation peak and amplitude appear at the same time, and feeding pipe diameter has little ability to change this.

It is also observed in the figure that the change of pressure oscillation amplitude along standoff distance for the 25 mm case is slower that of the other two cases, meaning the range of pressure oscillation of SRPW can be narrowed by a larger feeding pipe diameter. This is most likely attributed to the relatively smaller turbulence intensity of the flow in the feeding pipe and the nozzle. Specifically, from the generation mechanism of SRPW, the jet is produced by taking advantage of the flow instabilities of organizing into structured vortex rings in the shear layer. Self-resonance is used to amplify a special frequency of instability and subsequently leads to the formation of pulsed waterjet. So, for a larger feeding pipe diameter, the flow velocity in the pipe will be lowered and the turbulence intensity of the flow and instability in the shear layer will be reduced. As a result, the pulse of the jet will be less obvious and the pressure oscillation will be weaker. Moreover, feeding pipe of diameter of 25 mm also makes the pressure oscillation amplitude the greatest at standoff distances larger than 60 mm.

As shown in Fig. 7, feeding pipe diameter has dramatic effects on the pressure oscillation amplitude, but the effects greatly depend on the pump pressure. In more specific terms, at pump pressures of 100 and 150 bar, a feeding pipe of diameter of 13 mm generates the greatest pressure oscillation amplitudes at the optimum standoff distance. However, when the pump pressure is increased to 200 and 250 bar, a feeding pipe diameter of 6 mm turns to be the preferred one for a wider pressure oscillation range.

Interestingly, even a feeding pipe diameter of 6 mm could cause the minimum pressure oscillation peaks at pump pressures of 200 and 250 bar; it leads to the maximum pressure oscillation amplitude at the same time. Similarly, under the pump pressure of 250 bar, a feeding pipe diameter of 13 mm causes both a maximum pressure oscillation peak and a minimum pressure oscillation amplitude at corresponding optimum standoff distances. These inconsistencies indicate that feeding pipe diameter has dramatically different effects on the pressure oscillation peak and amplitude of SRPW. Thus, a feeding pipe of proper diameter has the ability to enhance the pressure oscillation peak does not mean it can improve the pressure oscillation amplitude at the same time, and vice versa.

5. Conclusions

We have demonstrated an experimental approach for examining the effect of feeding pipe diameter on the pressure characteristics of SRPWs with respect to the axial pressure oscillation peaks and amplitudes. Unfortunately, there is currently very limited literature on the effects of feeding pipe diameter, especially in the field of self-excited pulsed waterjet. So, the present paper is a preliminary study and provides a qualitative analysis. Further investigations should be performed related to the interactions between feeding pipe and the self-resonance in the nozzle chamber and the propagations of pressure wave affected by feeding pipe diameter. However, the study still provides some useful information, which is concluded as follows:

(1) Feeding pipe diameter can affect the self-resonance in the nozzle chamber and the effects are much stronger and more obvious than those on the energy loss in the pipe line.

(2) Feeding pipe diameter cannot disorder the pressure oscillation form of the jet, but it has a little ability of changing the oscillating frequency. A smaller feeding pipe diameter can slightly increase the oscillating frequency, while a larger diameter can reduce the frequency by a little amount.

(3) Feeding pipe diameter nearly has no effects on the optimum standoff distance where the maximum pressure oscillation peak and amplitude appears. However, it has great effects on the magnitudes of pressure oscillation peak and amplitude, which significantly depends on the pump pressure and standoff distance.

(4) The effects of feeding pipe diameter on the pressure oscillation peak and amplitude are different. For example, a feeding pipe of diameter of 25 mm always maximally enhances the oscillation peak at standoff distances below 60 mm at all the testing pump pressures, but it is not as effective as the feeding pipe with a diameter of 6 mm for improving the oscillation amplitude at pump pressures of 200 and 250 bar.

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