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AN INVESTIGATION OF PRESSURE PULSATION AT SOLID SURFACE UNDER IMPACT OF HIGH SPEED WATER-AIR JET

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ABSTRACT

It was published that the water-air two-phase jet could show better impact erosion ability than the common water jet. However, its mechanism remains unproved. This paper tried to investigate the mechanism. Simulation of an air bubble in the water jet impacting on solid surface was carried out. It showed that the bubble burst near the solid surface resulted in pressure pulsation on the solid surface. A test platform was established to compare the pressure pulsations resulted by the water-air jet and water jet impacting on solid surface, respectively. Results validated that impacting pressure pulsation of the water-air jet was higher than that of the water jet, and air bubbles could strengthen the pressure pulsation of water jet impacting on solid surface. An experimental formula of the enhancement factor for the pressure pulsation is obtained.

KEYWORDS: Impact erosion, Impact pressure, Water-air jet, Spectrum analysis, Pressure pulsation.

1. INTRODUCTION

The high speed water jet is applied to remove concrete blocks on steels, the rust on boiler pipes, even cut metal or other hard materials, such as rock (Li et al.,2006; Cui et al., 2007;Reinsch Tet al.,2018). Performances of cleaning and cutting are influenced by the working pressure of the jet. For cutting rock and metal materials, its working pressure is above 300 MPa (Wang and Fang, 2009). To improve the performance, abrasive grains are introduced into the water jet, which is called as abrasive water jet. The abrasive water jet has been used in machining, and now in spatial objects shaping (Borkowski and Borkowski, 2010). However, skin friction effect results in abrasion of its nozzle (Dong and Fricke,2012).

Cavitation jet flow has been successfully applied to metal cutting (Z and Josef, 2012; Aoyagi et al., 2001). Large numbers of cavitation bubbles filled with vapor are distributed in the jet. When the cavitation jet impacts on objects, vapor in the bubbles condenses into water in a very short time about 10-8 seconds. It resulted in collapse of cavitation bubbles. Researches have shown that the cavitation bubble collapse could result in a shock wave with very huge pressure impulse about 103-105 atm (SHAW and SPELT, 2010). This is the reason why cavitation jet flow could cut materials efficiently (Mori et al., 2008; Hattori et al., 2009). Such an erosion effect of the cavitation bubble is called as cavitation (Brennen, 1995).

Collapse process of the cavitation bubble is a focus of researches in this domain (Leighton et al., 2000; Brujan et al., 2005; Johnsen and Colonius, 2009; Okada et al., 1996). It is nearly impossible to observe the cavitation bubble collapse process under the high speed jet flow (Robert et al., 2007). Many scientists have carried out theoretical studies and experiments research on the collapse process of quiescent cavitation bubbles (Xu et al., 2010; Jayaprakash et al., 2012; Zhang and Zhang, 2004; Zhang and Zhang, 2005). A small jet is formed during the collapse of the bubble, as shown in Fig.1 (Brennen, 1995). When the jet penetrates through the bubble, a shock wave is emitted (Popinet and Zaleski, 2007), and a huge pressure impulse is generated (Coralic and Colonius, 2013). With the development of the high-speed camera technology, this mechanism of the jet formation and shock wave emission has been further confirmed.

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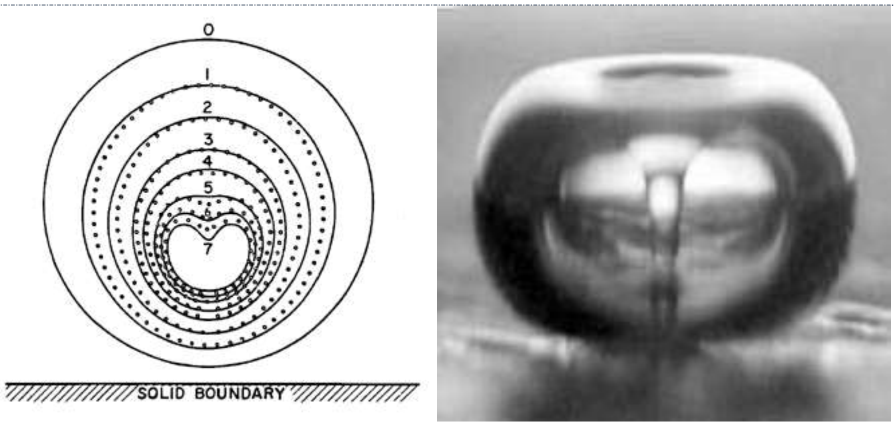

(a) ***(b)***

Figure 1: Collapse process of the cavitation bubble (Brennen, 1995)
(a) Depression of the cavitation bubble; (b) Small jet during the collapse of the cavitation bubble.

Many researchers also carried out research of air bubbles. Research results show that collapse process of an air bubble is similar to that of the cavitation bubble (Wang at al., 2010; Wang et al., 2010; Wang et al., 2008). During the collapse of the air bubble, small liquid jet is formed and penetrates the bubble. The spherical bubble is deformed into toroid bubble (Robert et al, 2007; Wang et al., 2010; Zhu et al, 2008; Heymann, 1969; Engel, 1955;Cheng F,2018). Burst of rising bubble in quiet water presents the same mechanism, as shown in Fig. 2 (Wang et al., 2010). Obviously, such a small liquid jet impacting might bring pressure pulsation too.

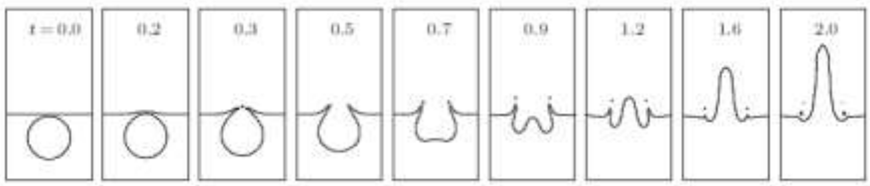

Figure 2: Generation of liquid jet during the burst of a rising bubble near a free surface (Wang et al, 2010)

Paper (Zhu et al, 2008) published experiments results of water-air jet for cleaning. The water-air two-phase jet showed similar erosion ability with the cavitation jet. In this paper we tried to valid that air bubbles burst could strengthen pressure pulsation of water jet impacting on solid surface.

2. MECHANISM OF THE WATER-AIR JET IMPACTING ON SOLID SURFACE

The max impacting pressure of a liquid drop on solid surface can be estimated by water hammer principle (Heymann, 1969). Paper (Engel, 1955) gives that the impacting pressure of spherical shape water drop on solid surface.

$$\Delta p = \alpha \rho c u \qquad (1)$$

Where, the value of coefficient α is recommended to be about 0.45; c is the sound velocity in water; and u is the velocity of the generated small water jet.

The collapse process of the bubble in water-air jet during impacting on the solid surface was obtained by the simulation in this paper, as shown in Fig.3.

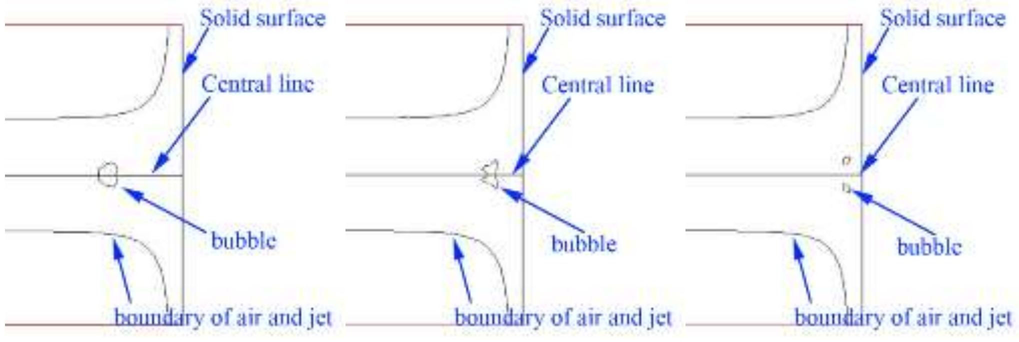

Figure 3: Burst process of a bubble in two phase jet impacting on solid surface with the velocity of 400m/s.

It showed that the two sides of the bubble (along its moving direction) deformed firstly. Then, the two surfaces impacted together near the solid surface. This was a water-to-water impact. Such an impact generated a pressure wave similar to water hammer. When the pressure wave propagated to the solid surface, a pressure pulsation at the solid surface was generated. Such a pressure pulsation resulted by water-to-water impact was much smaller than the water hammer. On the other hand, the pressure deteriorated due to the distance from the position where the pressure pulsation was generated to the solid surface. Thus, the pressure pulsation decreased.

According to the above analysis, the pressure pulsation on the solid surface would be smaller and similar to the water hammer. Thus, the pressure pulsation generated by the bubble burst could be described by substituting a new coefficientαin to Eq.(1). Obviously, the bubble size would influence this coefficient α. According to water-air flow mechanism, the size of the bubble is determined by the section size and the velocity of the water-air jet (Evans et al, 1992). Thus, the new coefficient α could be rewritten as:

$$\alpha(d_{\mathrm{n}}, v) \qquad (2)$$

Here, d_{n} is the section size of the two-phase jet, and v is the velocity of the two phase jet.

However, the real pressure pulsation generated by the bubble burst during water-air jet impacting on solid surface is almost unable to be recorded by experiments.

Firstly, there are too many air bubbles in the water-air jet as shown in Fig.4. It cannot make sure only one air bubble burst at the sensor at one time.

Figure 4: An ejecting situation of immersed two-phase jet

Secondly, the velocity of the water-air jet is very high and the size of the air bubble is too small. That means a pressure sensor with enough short response time is necessary. There is no such type of pressure sensors. For example, the diameter of the air bubble could be predicted by the u^2 Weber Number (Evans et al, 1992; Ryskin and Leal, 2016; Miksis et al, 1981; Hinze, 1955) and the burst time of the bubble could be estimated. If the pump pressure of the water jet is 1 MPa, the maximum diameter of the air bubble is predicted to below 68 □m.

A higher pressure will leads to a smaller diameter of the bubble. The burst time would be below 0.68 □s. The time is too short for a pressure sensor.

Thirdly, because the size of the air bubble is too small, it is very difficult to find a pressure sensor with enough small size to record the pressure pulsation. In our experiments, a high-speed camera was used to test diameters of the air bubbles. Results showed that the diameters of the air bubbles were below 0.15 mm. It is still too small for a sensor.

Although we couldn't record the pressure pulsation introduced by the burst of one air bubble, an average pressure pulsation of the water-air jet could be tested. That means the enhancement on the pressure pulsation of the air bubbles could be found by experiments.

3. THE EXPERIMENTS

The pressure test method

To record the pressure pulsation, the bubble must burst at the sensor membrane surface to let the small liquid jet directly impact onto the sensor surface. Piezoelectric pressure sensor was selected.

The jet impacted on the pressure sensor directly. The sensor pressure, p_{sp}, is the average pressure, expressed by

$$p_{sp} = \int_{A_s} p \mathrm{d}A \tag{3}$$

Where, A_s is the area of the sensor, and p is the pressure at the sensor surface. Because a random number of air bubbles burst at the sensor surface, the pressure, p_{sp}, is not a fixed value. When a large number of air bubbles burst at the same time, the pressure, p_{sp}, might be very high. On the contrary, the pressure, p_{sp}, might be very low. Thus, the pressure, p_{sp}, will fluctuate in a wild range. By the analysis of the sensor pressure p_{sp}, the pressure pulsation range could be obtained. The difference of the values of the lowest and the highest impacting pressures is defined as the average impacting pressure pulsation, p_{ap}. Obviously, the bigger the average impacting pressure pulsation is, the stronger the erosion ability will be. The enhancement effect of the air bubbles on the average impacting pressure pulsation is defined as an enhancement factor, γ.

$$\gamma = \frac{\Delta p_{ap\_wa}}{\Delta p_{ap\_w}} \tag{4}$$

Where, subscript ap_wa denotes the water-air jet, and the subscript ap_w denotes the water jet.

The experiment method and platform

Comparative test between the water-air jet and water jet was carried out. The experiment platform is shown in Fig. 5. It was composed of a water-air ejector, pressure sensor and ejector base, water tank and a water pump. The water pump provided water to the ejector. The ejector introduced air into the jet to form water-air jet. And then the jet impacted on the pressure sensor fixed on the base. After impacting on the sensor, the water flowed to the water tank and then to the water pump. A NI Data Acquisition System was used to record the pressure signal. The water pump could provide water with the flow rate of 23 L/min and the pressure below 35 MPa. An ICP piezoelectric pressure sensor with integrated error below 0.07 MPa was used to record the impacting pressure per 1/1000 second.

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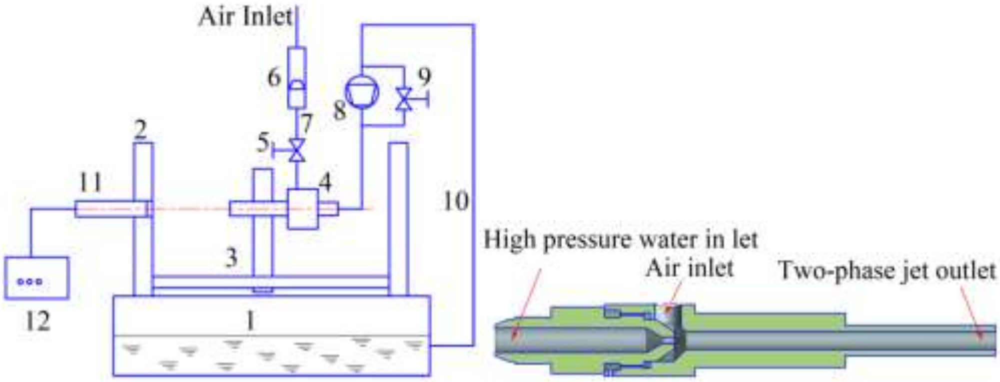

(a) *(b)*

Figure 5:The experiment platform. (a) Diagram of the experiment set (1 water tank, 2 pressure sensor base, 3 guide and base of water-air ejector, 4 water-air ejector, 5 air valve, 6 rotameter, 7 air pipe, 8 high pressure pump, 9 regulating valve, 10 water pipe, 11 pressure sensor, 12 NI Data Acquisition System); (b) Structure of the water-air ejector.

Water-air ejectors were designed to introduce air into the water jet. When air was introduced into the ejector, it was mixed with the water in the throat. Strong turbulence between the water and the air could separate the air into small air bubbles.

A rotameter was used to measure air the flow rate introduced into the ejector. During the test, the air flow rate was controlled below 0.4 m^3/min, to make sure all air introduced into the ejector could be mixed with the water adequately. Then, the distance between the outlet of the ejector and the sensor base was changed, to test the pressure pulsation at difference impacting distance. By closing the air valve of the ejector, pressure pulsation of pure water jet can be tested. Then, the water pressure was changed, and the above operations were repeated. The test was carried out under four working conditions, with its liquid Reynolds Number, Re_L at the outlet of the ejector from 76000 to 150000.

4. EXPERIMENT RESULTS AND ANALYSIS

The impacting pressure and the impacting pressure pulsation

The results of the experiments show that both water jet and water-air jet impacting on the solid surface result in impacting pressure pulsations. When the water liquid Reynolds Number, Re_L, is 10^5(inlet velocity of the water jet was 38 m/s), the impacting pressure is shown in Fig. 6. It is obvious that the impacting pressure fluctuates and the pressure pulsation of the water-air jet is larger than that of the water jet.

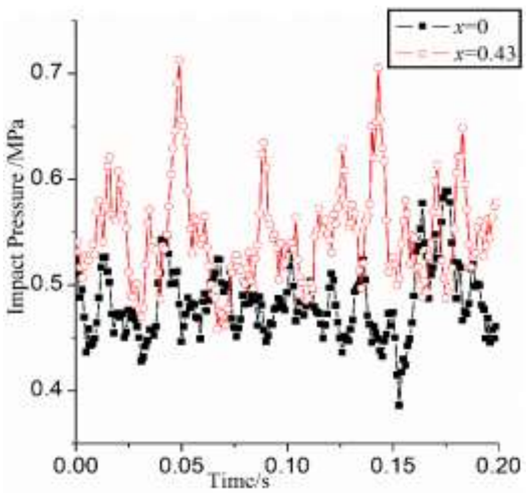

Figure6: Impacting pressure of water-air jet (water velocity 38 m/s)

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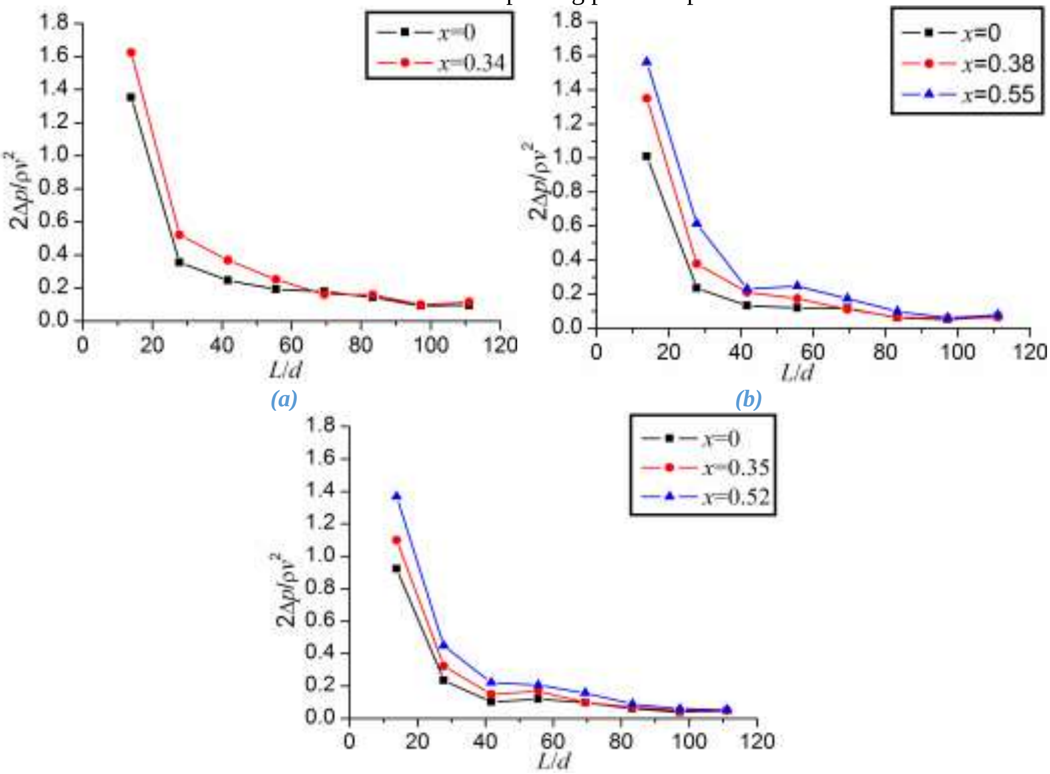
Non-parametric tests show that the obtained pressure pulsation does not obey the Normal distribution and the Poisson distribution. However, a significant influence of the void rate, *x*, on the impacting pressure is shown in Fig.6. It can be found that the average value of the impacting pressure of water jet is 0.48 MPa, and the average value of the water-air jet is 0.57 MPa. That means that the air bubble burst increases the impacting pressure. In Fig.6, the pressure pulsation of the water jet is 0.21 MPa, and the pressure pulsation of the water-air jet is 0.25 MPa. It is obvious that the pressure pulsation of the water-air jet is larger. For this case, the enhancement factor, γ, of the impacting pressure pulsation is 1.19. Statistics of the average impacting pressure and the impacting pressure pulsation of the experiments were carried out to verify the enhancement effect of air bubbles on the pressure pulsations.

Experiment results and analysis

Impacting pressure pulsations of water jet and water-air jet under different liquid Reynolds Number, Re_L, are shown in Fig. 7. Here,□*p* is the pressure pulsation; *ρ* is density of water; *v* is the velocity of the jet; *L* is the distance from the out let of the ejector to the sensor; *d* is diameter of the ejector exit;$\rho v^2/2$ is the kinetic energy of the water jet. The dimensionless pressure, 2□p/v^2, means the ratio of the kinetic energy converting into pressure pulsation energy. It is shown that the ratio increases with the increase of void rate, *x*. This phenomenon supports the conclusion that the air bubble could enhance the pressure pulsation of the water-air jet, and much more air bubbles in the jet would result in higher impacting pressure pulsation.

Another interesting point is that the ration of the kinetic energy converting into the pressure pulsation, 2□p/v^2, declines slowly along the increase of the liquid Reynolds Number, Re_L. However, the absolute values of the impacting pressure pulsations, □*p*, increase with the liquid Reynolds number. This can be explained using the air bubble diameter. According to the Web Number, the diameter of the bubble decreases with the increase of the turbulence and the liquid Reynolds Number, Re_L. According to the numerical simulation results, a smaller diameter of the bubble could reduce its effect on the impacting pressure pulsation.



(c)

Figure 7: Impacting pressure pulsation of the two-phase jet. (a) Re_L=7.6×10⁴; (b) Re_L=1.3×10⁵; (c) Re_L=1.5×10⁵. (Here, Δp was the pressure pulsation, ρwas density of water, x was the void rate, v was the velocity of the jet, L was distance from the out let of the ejector to the sensor, and d was diameter of the ejector exist)

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It could be concluded that the impact pressure pulsation is related with the Reynolds number, the impacting distance and the void rate, *x*. According to Eq.(4), the enhancement factor, , varies with the impacting distance, as shown in Fig.8.

As shown in Fig.8, the enhancement factor, , varies with the impacting distance, the Reynolds number, and the void rate. It could be found that the relation between Re and is complex. The effect of void rate, *x*, to the enhancement is also complex. When Re = 128000, the enhancement factor increases with the void rate. However, when Re = 150000, the enhancement factor decreases when the void rate increases from 0.35 to 0.52. The enhancement factor could be written as：

$$\gamma = \left[6.96\times10^{-3}\left(L/d\right)^3 - 1.48\left(L/d\right)^2 + 81.58\left(L/d\right) + 1227.39\right] \left[9.1\times10^{-4}\left(\mathrm{Re}/10^5\right) + 0.028\right]\left(3.99\times10^{-2}x + 5.4\times10^{-3}\right) \quad (5)$$

This experimental formula is available when the void rate is between 0.34 and 0.55, Re is between 76000 and 150000, and the impacting distance is between 5 cm and 40 cm.

It is clear that, there is a max enhancement factor along the impacting distance. The relation between the impacting distance and the enhancement factor can be described by a cubic function. But, more researches and work are still necessary to find an experiment formula for the enhancement factor.

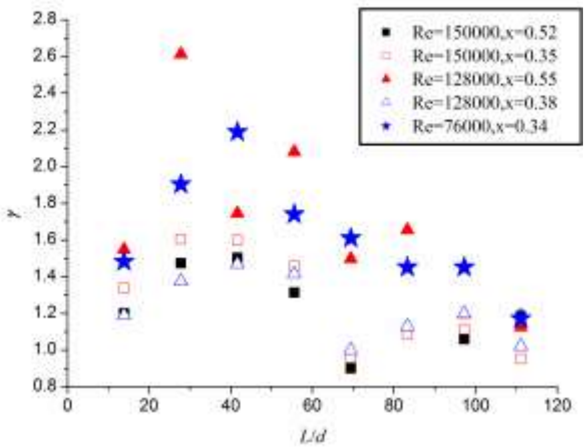

Figure 8: Enhancement factor with different factors. (Here, x was the void rate, L was distance from the out let of the ejector to the sensor, and d was diameter of the ejector exist)

To investigate the pressure pulsations further, spectrum analysis of the impacting pressure is carried out. The primary swing of the spectrogram of the impacting pressure in Fig.6 is at 0 Hz with the value of 0.48 MPa when *x* = 0.4. And when *x* = 0.4, it is 0.56 MPa. It is much bigger than the swing at other frequencies. This result means that the average impacting pressure is strengthened by the air bubble. The spectrogram for frequency higher than 0 Hz is shown in Fig.9.

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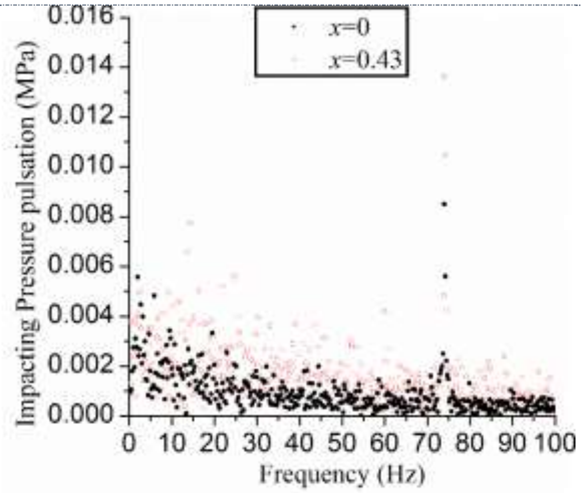

Figure 9: The spectrogram of impacting pressure when Re_L=7.6×10^4

It is obviously shown that almost all the impacting pressure between 0 Hz and 100 Hz are strengthened. Especially, when at the frequency of 74 Hz, the impacting pressure is the second primary swing. It is because that the water is supplied by a piston pump with three cylinders.

5. CONCLUSIONS

This paper verifies that the water-air jet has better enhanced impact erosion ability than that of the water jet.

- It proposes that the higher pressure pulsation generated by the air bubbles in the water-air jet enhances the impact erosion ability of the jet. And the physical model of the pressure pulsation generated by the bubble is analyzed. Numerical simulation results show that the burst of the air bubble could introduce water-to-water impact, which results in strengthened impacting pressure pulsation.
- A test platform is designed to investigate the pressure pulsations generated by water jet and water-air jet on solid surface, respectively. The results validate that a higher void rate leads to higher impacting pressure pulsation. The range of the void rate in the experiment is 0 to 0.56. An experimental formula of the enhancement factor for the pressure pulsation is obtained.

Next step of the work would be finding the enhancement mechanism of the impacting pressure pulsation.

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