International Journal of Fluid Machinery and Systems
Vol. 6, No. 4, October-December 2013

DOI: http://dx.doi.org/10.5293/IJFMS.2013.6.4.206
ISSN (Online): 1882-9554

Original Paper (Invited)

Study on the frequency of self-excited pulse jet

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Abstract

Self-excited pulse jet is a specific nozzle with a closed chamber which can change a continuous jet into a pulse one. Energy of the pulse jet can be output not only unevenly but also with multifrequency. With the peak pressure of pulse jet, the hitting power would be 2~2.5 times higher than that of continuous jet. In order to reveal the correlation between the self-excited pulse frequency and nozzle diameter ratio, nozzle spacing and operating pressure, the model of 3D unsteady cavitation model has been used. We found that with the same nozzle structure parameters and the different operating pressure, the self-excited frequency and the width of peak crest are different, but the wave profiles are similar. With FFT, we also found that the less bandwidth of amplitude in low frequency range will lead to the wider wave crest of outlet velocity in its time domain, and the larger force of the strike will be gained. By studying the St of self-excite nozzle, not only the frequency of a certain nozzle can be predicted, but also a nozzle structure with a certain frequency can be designed.

Keywords: Self-excited; Pulse Jet; Frequency; Numerical Simulation.

1. Introduction

Self-excited pulsed nozzle with fluidic self-excitation has been widly applied in many kinds of industry such as cleaning, cutting and rock breaking[1]. It can be not only improved the efficiency but also reduced the technical request of system power, the level of operating pressure and the difficulties of manufacture if the striking frequence can be used properly accordding to the objective material characteristic. Based on the need of the hydraulic cleaning industry, we are going to set the correlation between the vapor-liquid phase change and the self-excited frequencies by revealing the mechanism of the self-excited pulse jet generation and analyzing the effects of the phase change time to pulse jet. Then the frequency modulation method can be drawn. The study mainly includes the numerical simulation theory of 3D turbulent jet of limited space with periodic phase change in self-excited oscillation chamber, frequency domain analysis of phase change and the method of frequency modulation of self-excited jet.

Self-excited nozzle is a pulse jet design with a closed chamber which can change a continuous jet into a pulse one. The output energy is evenly distributed in a continuous jet, while is distributed in multifrequency in a pulse one. By using the transient peak of the periodic unsteady strike force, the strike power will be increased by times. So it can be widely used in many kinds of industry such as jet cleaning and deep well drilling[1]. Different shapes of jet flow bunch with different pressure are shown in fig.1 and fig.2. The characteristics of self-excited pressure wave profiles in the nozzles are studied in the article. The correlation between the structure and frequency is explored. It'll provide theoretical calculation for the industry nozzle design.

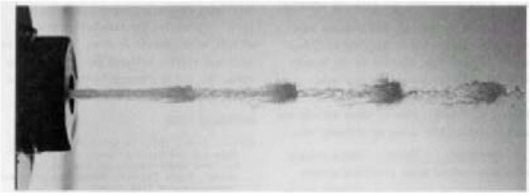

Fig. 1 Self-excitation phenomena in high pressure level

Fig. 2 Self-excitation phenomena in low pressure level

Received September 10 2012; revised January 21 2013; accepted for publication February 28 2013: Review conducted by Prof. Hyung-Hee Cho.
(Paper number O13013S)

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This paper was presented at 5th International Symposium on Fluid Machinery and Fluids Engineering, October 24-27, 2012, Jeju, Korea.

2. 3D Unsteady Flow Numerical Simulation with Cavitation Model

The structure of self-excited pulse nozzle is shown in figure 3. According to the explanation of pulse jet mechanism of self-excited nozzle in literature [2], when the continuous jet goes into the chamber of self-excited nozzle, the cavity pressure periodically fluctuates in a range of the vaporization. Meanwhile, the phase change appears in the jet boundary layer. So the 3D unsteady turbulent model and cavitation model must be used as the governing equations. We extend the inlet nozzle to a certain length in order to ensure that the inlet velocity is evenly distributed. Then the pressure boundary condition can be used in inlet and outlet of self-excited nozzle. The inlet pressure is set on an operating gauge pressure and the outlet pressure is atmospheric pressure. Physical field modeling and grid partition modeling are shown in figure 4.

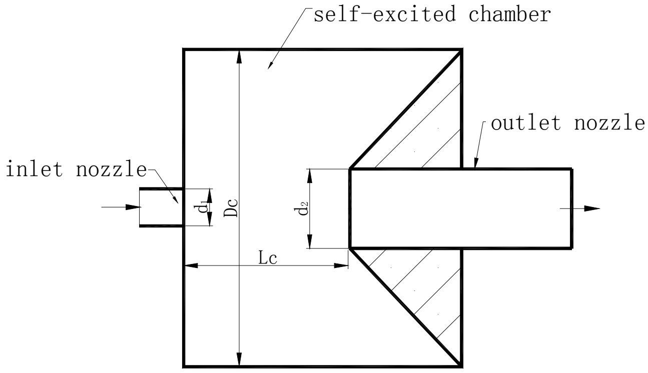


Fig. 3 Structure of self-excited nozzle

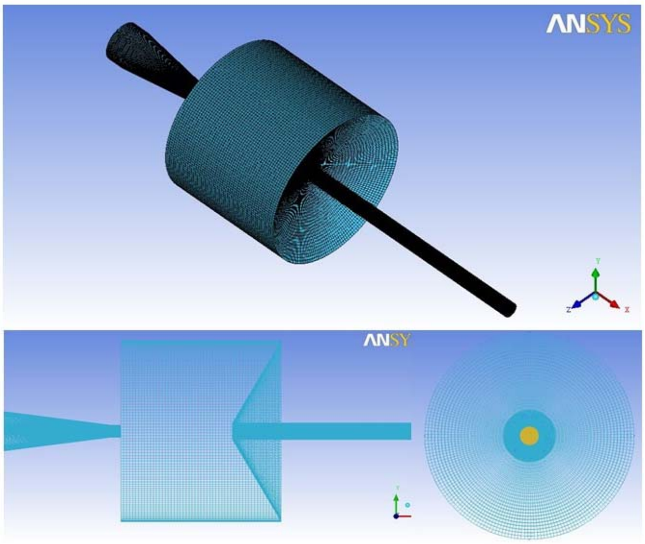


Fig. 4 Grid of the self-excited nozzle

2.1 Influence of diameter ratio (d_2/d_1) to self-excited frequency

According to the authors' earlier model test, the factor of nozzle diameter ratio d_2/d_1 plays an extremely important role that a self-excited phenomenon can be generated. In order to prove the influence of diameter ratio (d_2/d_1) to self-excited pulse frequency and amplitude, based on model test, the optimized test model has been chosen to do the numerical simulation with inlet diameter d_1=6mm, chamber diameter D_c=60mm, nozzle space L_c=36mm, operating pressure P=4MPa, and a series of diameter ratio (table 1) have been used.

Table 1 Simulation conditions of nozzle diameter ratio

d_1（mm）	d_2/d_1	d_2（mm）	D_c（mm）	L_c（mm）	P（MPa）
6	1.6	9.6	60	36	4
6	1.8	10.8	60	36	4
6	2.0	12	60	36	4

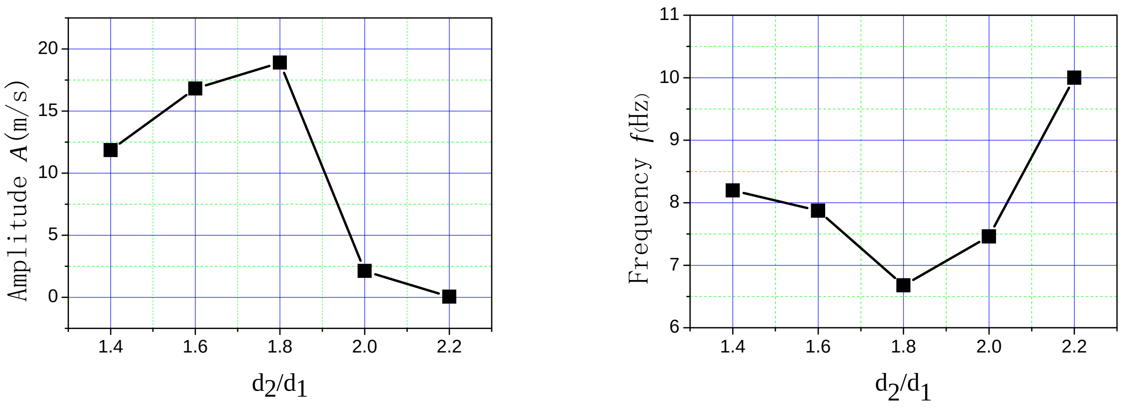


Fig. 5 The influence of diameter ratio (d_2/d_1) to frequency and amplitude of self-excited pulse

Obviously, it does have an optimum diameter ratio among the simulation condition. When the diameter ratio of self-excited nozzle is d_2/d_1=1.8, the frequency is lowest and the amplitude is maximized. Meanwhile the self-excited phenomenon is the most obvious. It is completely consistent with the model study.

2.2 Influence of the nozzle space to self-excited

Because the generation of the self-excited phenomenon depends on the feedback of downstream pressure wave to the upstream disturbance, the nozzle spacing is very important to the self-excited frequency. The optimized test model has been chosen to do the numerical simulation with inlet diameter d1=6mm, outlet diameter d2=10.8mm, nozzle space Lc=36mm, operating pressure P=4MPa, and a series of nozzle space Lc (table 2) have been used.

The figure 6 shows, among the different nozzle spaces, there is a best one which could make the outlet velocity wave reach to its maximum value. Analyzing the influence curve of nozzle space to different frequency and amplitude，it's found that the lowest frequency corresponds to the highest amplitude, and vice versa. The simulation result is consistent with the experiment. Self-excited phenomenon is relevant with the formation and breaking of cavitation in the chamber. The cavitation vapor pockets will move faster when the frequency is higher. It goes out of the nozzle before it fully developing to a certain large volume and so make smaller amplitude. Otherwise, if the cavitation vapor pockets gains a full development, it'll greatly affect the outlet velocity.

Table 2 Numerical simulation about nozzle space

d_1	d_2	D_c	L_c/D_c	L_c	P
6	10.8	60	0.5	30	4
6	10.8	60	0.6	36	4
6	10.8	60	0.7	42	4

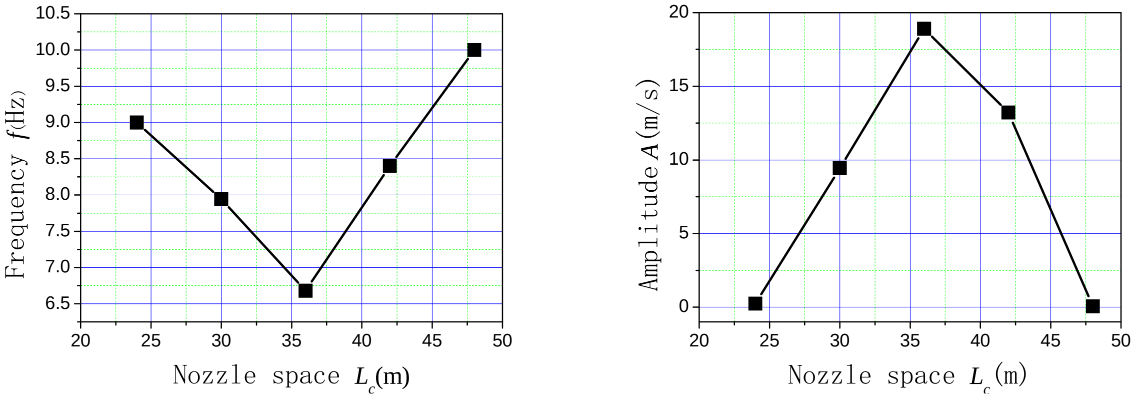


Fig. 6 The influence of nozzle space Lc to frequency and amplitude of self-excited pulse

2.3 Influence of operating pressure to self-excited frequency

Because the self-excited nozzle structure selectively amplifies some specific frequency components of the wave and vortex, different amplitude waves are gained [1]. So the operating pressure is important for self-excited nozzle. We take the range of 1～10 MPa as our operating pressure to do the simulation. The operating conditions are shown in table 3.

Table 3 Simulation of operating pressure

Inlet d1(mm)	Outlet d2(mm)	Chamber Dc(mm)	Nozzle Space Lc(mm)	Operating pressure P(MPa)
6	10.8	60	36	1～10

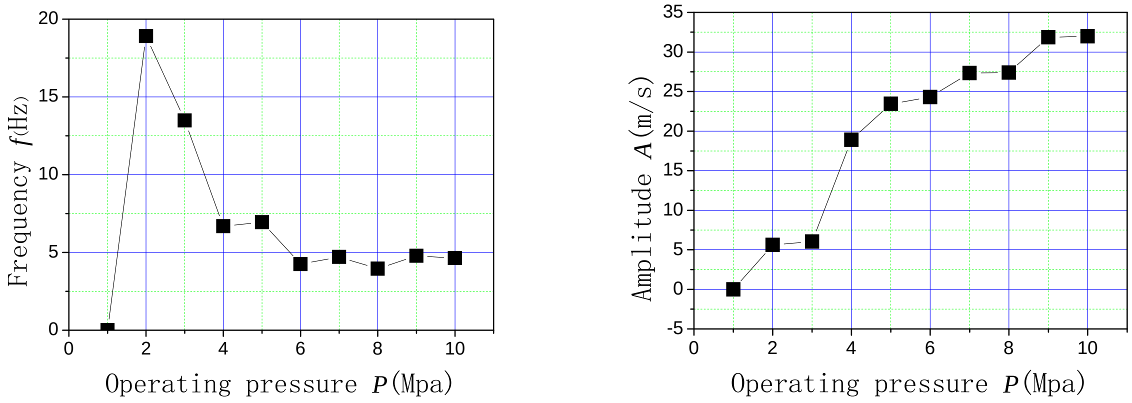
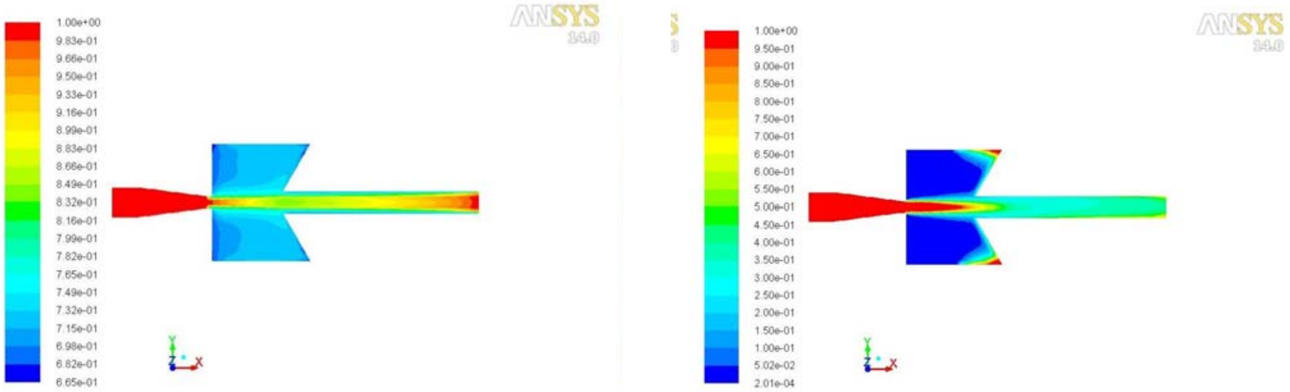


Fig. 7 The influence of operating pressure to frequency and amplitude of self-excited pulse

According to fig.7, there are no self-excited phenomena when the operating pressure is about 1MPa and the jet is continuous. The frequency of the pulse jet is largest but the amplitude is low when the pressure is 2MPa. With the rising of the pressure, the self-excited frequencies drop quickly and the decline trend becomes flattened when the pressure reaches 4MPa. In the jet cleaning industry, different cleaning object may need different cleaning frequency, at this time, the frequency modulation of self-excited nozzle can be operating under the pressure ranges of 1 ~ 4 MPa.

2.4 Comparison of the outlet velocity of pulse jet and continuous jet

Because of the effect of cavitation vapor pockets in the nozzle chamber, the self-excited nozzle could change constant energy to a pulse one. There are two phases, which are energy releasing phase and energy storage phase (fig.8). As a result, the instantaneous strike force can reach to several times of a continuous one. Fig.9 shows the difference of outlet velocity of the self-excited nozzle (d_1=8mm, d_2=10.8mm, D_c=60mm, L_c=36mm) and continuous nozzle which have the same d_1 under the pressure range of 1~10MPa. Obviously, the largest outlet velocity of the pulse jet can achieve about 2 ~ 2.5 times of that in continuous jet. So in the same level of power, the strike effect can be significantly improved and the loading demands of the equipment can be reduced.



(a) During releasing phase (b) During storage phase

Fig. 8 Volume fraction of liquid phase in Self-excited nozzle

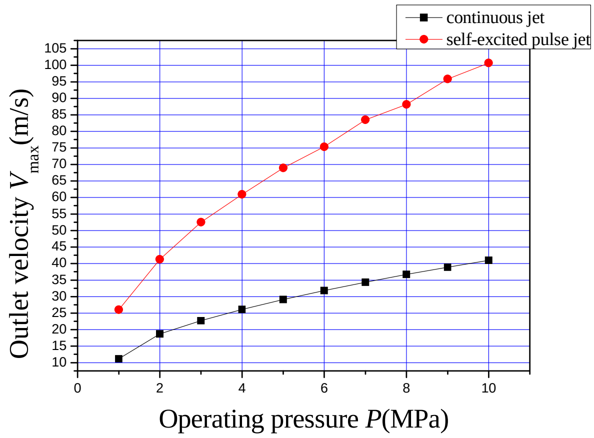


Fig. 9 Comparing the peak outlet velocity between continuous jet and pulse jet against operating pressure

3. The wave profile and frequency of self-excited oscillation

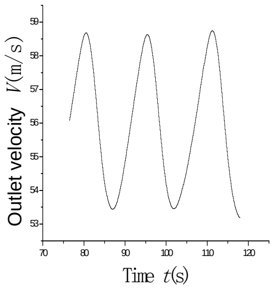
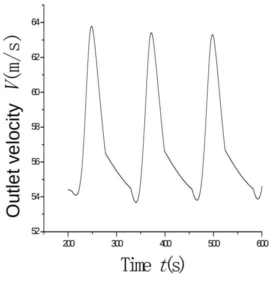
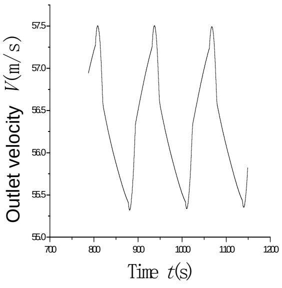
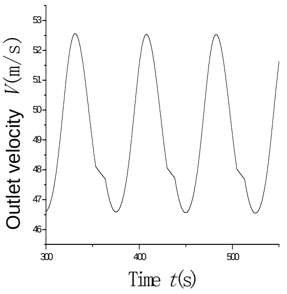
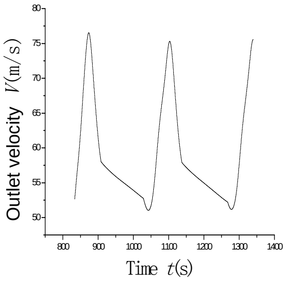
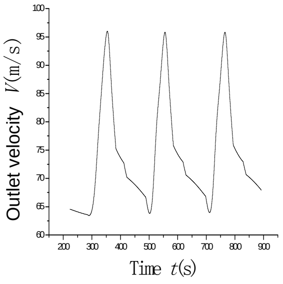
By observing the curve of self-excited pulse nozzle outlet velocity against time, some interesting rule can be found. The first row of table 4 shows the wave profile types with the different d_1 and the same operating pressure. While the second row shows the wave profile types with the same d_1 and the different operating pressure. Hence, with the same operating pressure, a different nozzle size will cause a different wave profile type. When the nozzle size is the same, operating pressure can only change the basic frequency, the wave profile will keep the same trend.

Studying the wave profile is important to assess its striking power. Only when the outlet velocity peak lasts long enough, can effective strike be obtained. Otherwise, even if the frequency is proper and the amplitude is high enough, the object material can't be broken. Therefore, with the requirement of frequency and peak strike force, the proper wave profile of the outlet velocity must be chosen so that the striking effects reach its best.

Because the periodic oscillation wave of the self-excited pulse is harmonic wave, it can be regarded as a superposition of sine waves and cosine waves. As for a self-excited nozzle with d_1=4mm, d_2=5.5mm, D_c=48mm, L_c=19mm, P=4MPa (as the condition of 4-5.5-48-19-4 shown in table 5), the amplitude is low and the frequency component is relatively simple.

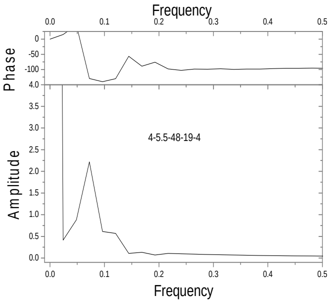
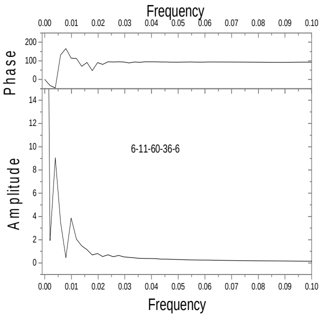
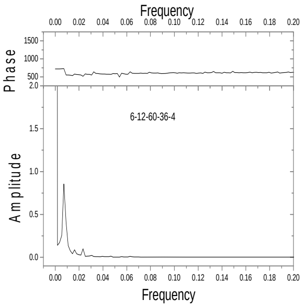
The outlet velocity variation is relatively stable. On the other hand, with d_1=6mm, d_2=11mm, D_c=60mm, L_c=30mm, P=6MPa (as the condition of 6-11-60-30-6 shown in table 5), except for the basic frequency, there are several other frequency components. When this happen, the self-excited become unsteady which affects not only the striking effect but also the stability of the pipe system. Therefore frequency analysis must be undertaken and the relatively single frequency should be chosen when choosing the wave profile type.

Table 4 the self-oscillation waveform of outlet velocity

		
4-5.5-48-19-4	6-11-60-30-4	6-12-60-36-4
		
6-11-60-36-3	6-11-60-36-6	6-11-60-36-9

Note: The numbers below each figure mean d1-d2-Dc-Lc-P (show in fig.3). The units of the first four numbers are mm and last one is MPa.

Table 5 Frequency domain analysis of self-excited oscillation harmonic

		
4-5.5-48-19-4	6-11-60-30-6	6-12-60-36-4

Note: The numbers below each figure mean d1-d2-Dc-Lc-P. The units of the first four numbers are mm and the last one is MPa.

4. Strouhal number

Strouhal number is an important parameter because it is defined by self-excited frequency, characteristic length and inlet velocity as formula (1). So it can be used to describe the frequency characteristics of self-excited jet.

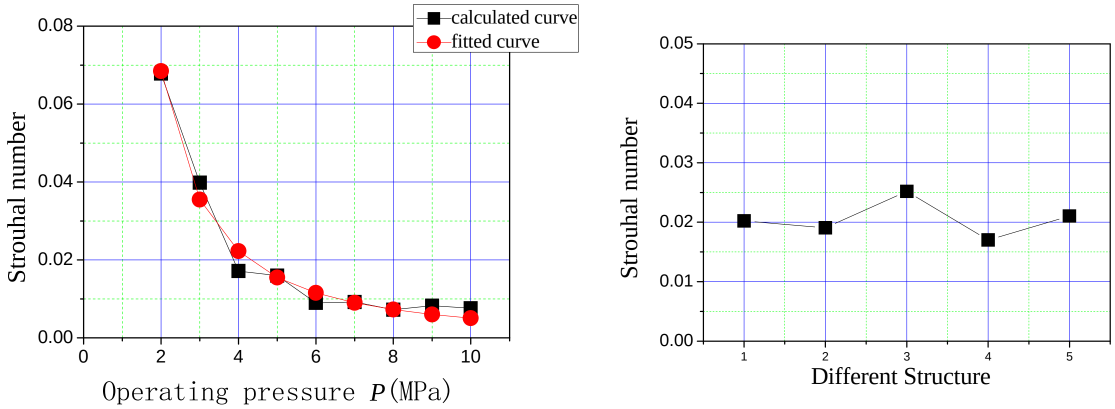
$$St = fL / v \qquad (1)$$

Where f is basic frequency of the jet, L is nozzle space and v is inlet velocity.

Power function can be used to fit the Strouhal number curve against operating pressure according to the calculating data shown in fig.7 which is the example of the nozzle sizes are d_1=6mm, d_2=10.8mm, D_c=60mm and L_c=36mm. (fig.10a).

The fitted empirical formula of power function is eq.(2). However the Strouhal number curve against the different nozzle structures (which sizes are shown in Table 6) is almost horizon (fig.10b).

$$St = 0.21P^{-1.62} \tag{2}$$



(a) (b)

Fig. 10 The dependence of Strouhal number on operating parameter and nozzle structure

Table 6 The nozzle structures of right figure in Fig.10

Sequence	**d_1(mm)**	**d_2(mm)**	**D_c(mm)**	**L_c(mm)**
1	6	9.6	60	36
2	6	12	60	36
3	6	11	60	42
4	6	11	60	30
5	6	8.4	60	36

With the eq.(1) and eq.(2), eq.(3) can be drawn.

$$f = \frac{13.5 g \mu^2}{vL} \tag{3}$$

Because the nozzle space is constant, C can defined as followed.

$$C = \frac{1136.64 \times (g\mu^2)^{1.62}}{L} \tag{4}$$

Then eq.(3) is eq.(5):

$$f = \frac{C}{v^{2.24}} \tag{5}$$

For this example, the value of C is 2977 which is defined by nozzle space Lc. We can use the eq.(5) to predict the frequency of a certain nozzle.

Figure 7(b) shows us that the Strouhal numbers of different outlet diameter d_2 are relatively stable. As an example, when the operating pressure is 4MPa, the Strouhal number in fig.10b is approximate 0.02. So we can design a nozzle structure with a certain frequency.

5. Concluding remarks

This paper has discussed how the construction of the self-excited nozzle affects the self-excited frequency and amplitude. Comparing to the continuous jet and pulse jet, the following conclusions could be drawn.

(1) The ratio of d_2/d_1 is the most important parameter for self-excited effect. When d_2/d_1=1.8, the self-excited frequency is lowest with the amplitude highest and the self-excited effect is the most obvious.

(2) When nozzle space L_c=36 mm, the self-excited effect is the best among the simulation conditions. Reducing or increasing the L_c, the outlet velocity amplitude is reduced and the obvious self-excited phenomenon is hard to show.

(3) Only when the pressure is above 2MPa, can the self-excited pulse phenomena be shown. With the pressure rising, the basic frequency becomes lower while its amplitude goes up. Both changing trends will reach to the horizon at last. The frequency modulation of self-excited nozzle can be operated under the pressure ranges of 1 ~ 4 MPa.

(4) With the same pressure, the largest outlet velocity of the pulse jet can achieve about 2 ~ 2.5 times of that in continuous jet and the strike effect is better.

(5) With the same operating pressure, a different nozzle size will cause a different wave profile type. While the nozzle size is the same, changing the operating pressure can only change the frequency of self-excited, the wave profile is similar.

(6) Under the same conditions, the narrower bandwidth of amplitude curve in frequency domain, the lower frequency and the wider crest of outlet velocity it is. In this case, the self-excited pulse nozzle will generate a better strike effect.

(7) By studying the St of self-excite nozzle, not only the frequency of a certain nozzle can be predicted, but also a nozzle structure with a certain frequency can be designed.

Acknowledgements

Supported by NSFC (the national natural science foundation of China), project No. 50979079

Nomenclature

A	Amplitude[m/s]	f	Frequency of the outlet velocity[Hz]
d_1	Diameter of the inlet[mm]	L_c	Length of the cavity or nozzle space[mm]
d_2	Diameter of the outlet[mm]	P	Operating pressure[MPa]
D_c	Diameter of the cavity[mm]	St	Strouhal number

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