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The Formation Principle and Characteristics of Self-supercharging Pulsed Water Jet

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Abstract: High-pressure pulsed water jet technology has high development potential in the field of rock fragmentation. Technical bottlenecks such as difficulty in pressurization and inconvenient frequency adjustment for existing types of pulsed jets, a self-supercharging pulsed water jet generation method is proposed based on the theory of pulsed water jet and principle of hydraulic boosting, which changes the flow direction of fluid medium through the valve core to make the piston reciprocate in the cylinder, and relies on the effective area difference between the front and rear chambers in the stroke stage of the piston to realize the organic combination of

“pulse” and “supercharging” of the jet, so as to self-supercharging pulsed water jet. Based on revealing the formation principle of self-supercharging pulsed jet, the self-supercharging pulsed jet generation system was designed, and the self-supercharging pulsed jet testing platform was built, many groups of pressure collection and jet shape observation experiments were carried out for different operating parameters. The research results show that both the jet pressure and the jet shape show periodic change, and higher pulse pressure can be obtained at lower inlet pressure. The error of the pressure ratio calculated according to the experimental results is less than 3% compared with the theoretical design value, thus verifying the feasibility of the method. Pulse pressure and pulse frequency are controllable, that is, as the inlet flow rate increases in the stroke phase of the piston, the pulse pressure and pulse frequency increase, and the pulse duration decreases, as the inlet flow rate increase in the backward stroke phase of the piston, the pulse frequency increases, and the pulse pressure and pulse duration remain unchanged. The research results lay the foundation for enriching the theory of pulsed jet generation and expanding its application range.

Keywords: High-pressure water jet; Pulsed water jet; Self-supercharging; Pulse pressure; Pulse frequency; Pulse duration

1. Introduction

The technology of water jet for rock-breaking has the advantages of dust-free, non-pollution and high efficiency [1-2], and is widely used in mining, tunneling and oil drilling [3-6]. Pulsed water jet is a kind of water jet acting on the target in the form

of pulse, which can make the rock produce tensile, shear and fatigue damage under low jet pressure, and form macro cracks that lead to volume fracture by effectively applying the water-hammer effect of the jet to the target, the stress wave under the impact and the pulsed cyclic shock [7-9]. Research results show that the erosion ability of pulsed jet is significantly higher than that of continuous water jet under the same pressure, and the specific energy consumption is lower [10-11].

The existing types of pulsed jet are mainly divided into four types: percussion pulsed jet, disc-slotted pulsed jet, ultrasonic modulation pulsed jet and self-excited oscillation pulsed jet. The percussion pulsed jet is generated by using explosives, flywheels or free-falling heavy hammers as the power source to transfer energy to the compression piston, the water in the cavity is quickly extruded after compression piston obtains energy, as shown in Fig. 1(a). Sdekhoda et al [12-15] established the dynamic model of cavity pressure, and obtained the relationship between the liquid height of cavity, piston mass, nozzle diameter and pulse pressure. The advantage is that it can form large-diameter and high-speed pulsed jet, but the formation process is complicated, and water injection and resetting are required before each operation, and the continuous emission cannot be performed. The disc-slotted pulsed jet periodically cuts the jet with a slotted disc, and cuts the continuous jet into a series of discrete jet segments, as shown in Fig. 1(b). Sevda Dehkhoda et al. [16-17] found through rock breaking experiments that the formation, crack propagation, and internal damage of rock craters are related to pulse length and pulse frequency. Pulse length and pulse frequency can be controlled by slot width, number of slots and rotational speed disc,

reasonable rock-breaking can be selected according to the research results parameters, however, the jet pressure depends on the pump pressure and jet deflection causes energy loss during the cutting off process. The ultrasonic modulated pulsed jet concentrates the ultrasonic energy through the ultrasonic generator, and a high-density sound field is applied to the fluid inside the nozzle to cause a periodic change of pressure before the ejection, as shown in Fig. 1(c). Piush Raj et al. [18-20] used 20kHz or 40kHz pulse frequency to perform cutting experiments on sandstone and bone cement, and obtained the nozzle exit velocity field and flow pattern changes. The fluctuation speed of the jet velocity gradually decreased with the increase of the jet distance. For rock-cutting experiments, it is necessary to strictly control the target distance, it is difficult to eliminate the impact of the "water-cushion effect" on the target body due to the high pulse frequency. The basic principle of self-excited oscillation pulsed jet is that the fluid passes through the resonant chamber, commonly referred to as the Hemholtz oscillating chamber, so that the fluid produces steady-state oscillation of a certain frequency, and jet pressure exhibits a macroscopic change, as shown in Fig. 1(d). Dong Hu et al. [21-24] revealed the effects of pump pressure and oscillating cavity structure on pressure fluctuations through experimental research. Although high-frequency pulsed jet can be formed, the pressure fluctuation amplitude is not significant when the pump pressure is high, and the nozzle structure is very harsh.

The main hydraulic parameters affecting the rock breaking efficiency of pulse jet include pulse pressure, pulse frequency and pulse duration [16-17, 25-27]. These four

types of pulsed jets have their own advantages, such as the higher pulse pressure that can be formed by percussion pulsed jet, and the pulsed pressure and pulse frequency of disc-slotted pulsed jet can be controlled, generation methods of ultrasonic modulation and self-excited pulse jet are simple. However, there are also unfavorable factors for rock breaking. The percussion pulsed jet generation method is complicated and its emission frequency is too low. The disc-slotted pulsed jet cannot produce supercharging effect. The ultrasonic modulation and self-excited pulsed jet have limited pressure fluctuations and the frequency adjustment is inconvenient. The existence of these unfavorable factors will lead to the reduction of rock breaking efficiency, which is difficult to meet the needs of the site.

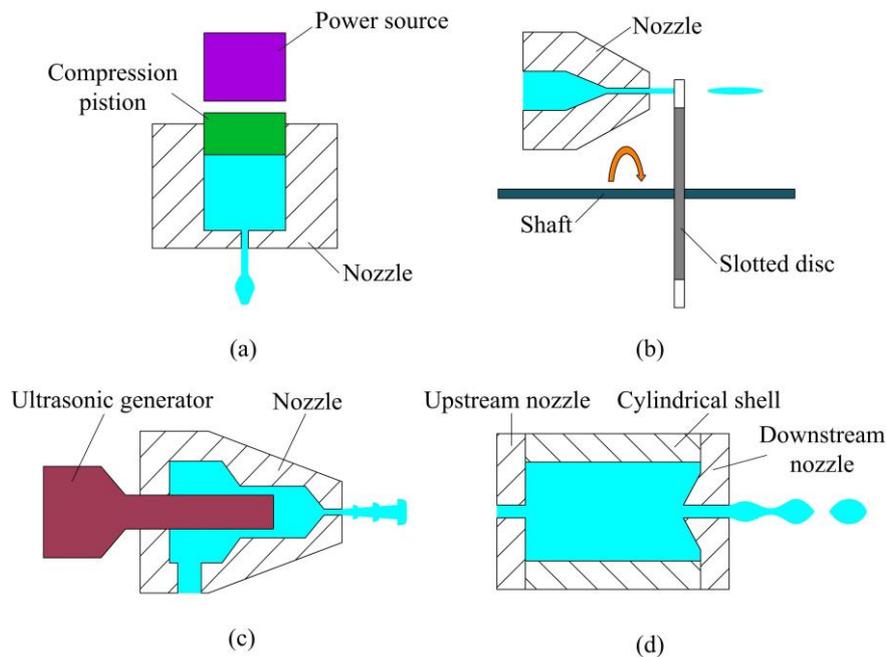


Fig. 1. Types of pulsed jet

In this paper, a self-supercharging pulsed jet generation method is proposed based on the theory of pulsed water jet and principle of hydraulic boosting. Higher pulse pressure can be obtained at smaller inlet pressure through reasonable structural

design and piping connection without requiring an additional power source, both pulse pressure and pulse frequency can be adjusted, not only can meet the needs of efficient rock-breaking, but also reduce the use cost and be safe and reliable. In order to explore the feasibility of this method, self-supercharging pulsed jet generating system is designed, self-supercharging pulsed jet generating device is developed, and the working process of the system is introduced. The self-supercharging pulsed jet test platform was built, and multiple experiments were carried out for different working parameters to obtain the evolution characteristics of pulse pressure and jet shape, the self-supercharging effect was analyzed and the influence law of inlet flow rate in the stroke stage and return stroke stage of the piston on pulse pressure, pulse frequency and pulse duration was explored.

2. Generation method and formation principle of self-supercharging pulsed jet

2.1 Generation method of self-supercharging pulsed jet

The self-supercharging pulsed jet is generated by using fluid medium as power source to drive the piston to reciprocate and squeeze the water in the chamber, the pressurized water is converted into kinetic energy through nozzle and ejected at high speed. The piston reciprocates once and the high-pressure water is ejected once, the jet pressure changes periodically because of the intermittent ejected. The action area of the big end and the small end of the piston is not equal, according to the principle of hydraulic boosting, higher jet pressure can be obtained under lower inlet pressure, the specific method is shown in Fig. 2. The piston movement includes two stages of

backward stroke and stroke: when the reversing valve is in the right position, the 4 chamber is connected with the oil inlet, the chamber 7 is connected with the oil outlet, the high-pressure fluid enters the chamber 4 to push the piston to the right, and the chamber 1 is used for water supplement. When the end face A1 of the piston moves to the chamber 5, the chamber 4 and the chamber 5 are connected, and the piston return stroke ends. The reversing valve switches to the left position, and the chamber 4 and the chamber 7 are connected with the oil inlet to form differential connection. Due to the difference of the effective action area, the high-pressure oil enters the chamber 7 to push the piston to the left, and the water in chamber 1 is extruded, the pressure rises rapidly and ejects from the nozzle to form jet. When the end face A2 of the piston moves to the chamber 5, the chamber 5 and the chamber 6 are connected, the piston stroke ends, the pressure of chamber 1 drops rapidly, the reversing valve switches to the right position, and the next return stroke stage of the piston will soon start.

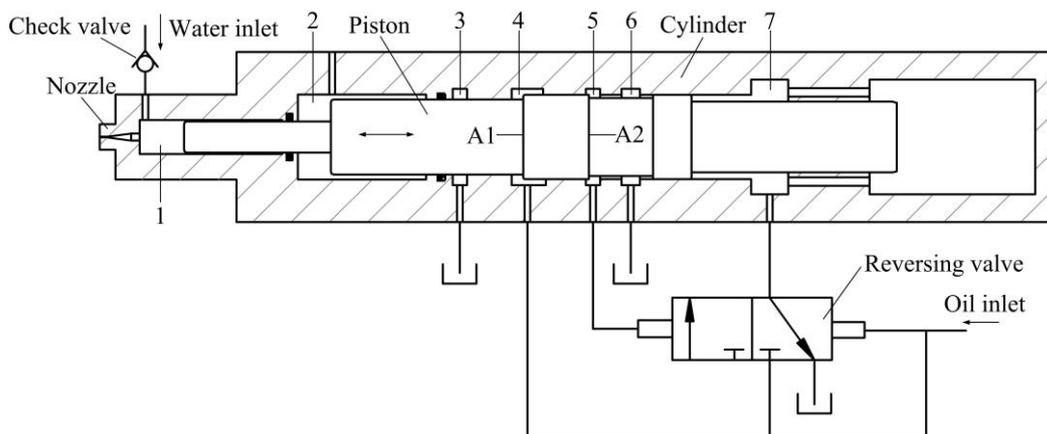


Fig. 2. Self-supercharging pulsed water jet generation diagram

The characteristics of the self-supercharging pulsed jet generation method is that under the continuous injection of fluid, the state of the reversing valve is switched to change flow direction of fluid that push the piston reciprocating motion to

intermittently extrude the water in chamber 1, and the pressure of chamber 1 will change periodically. When the piston stroke, the jet pressure is higher than the inlet pressure, which can generate a certain pressure ratio, the theoretical pressure ratio is equal to the ratio of the action area difference of piston in chamber 7 and chamber 4 and the action area of piston in chamber 1. Therefore, this method can generate consecutive high-pressure pulse jet without high-pressure components (high-pressure pump, high-pressure hose, high-pressure valve, etc.) under the continuous injection of low-pressure fluid, which not only has low cost, but also the security can be guaranteed.

2.2 Formation principle of self-supercharging pulsed jet

The self-supercharging pulsed jet generation system is a valve-controlled piston motion system with fluid as the energy transfer medium, the establishment of system dynamic model can theoretically reveal the principle of self-supercharging pulsed jet generation.

2.2.1 Dynamic analysis of system

The piston is the main moving body of the system, it return stroke and stroke under the action of oil pressure. The motion equations corresponding to different motion states of the piston are different, and the motion states are as shown in Fig. 3. To facilitate the derivation and calculation, the following assumptions are made when establishing the equation of motion of the piston: 1. Fluid is not compressible; 2. The temperature, viscosity, bulk modulus of fluid is constant; 3. Pistons and other components are absolutely rigid; 4. Regardless of mechanical friction loss and oil

pressure loss; 5. Grooves are circumferentially applied to the piston surfaces, which can ignore the influence of hydraulic lock force [28].

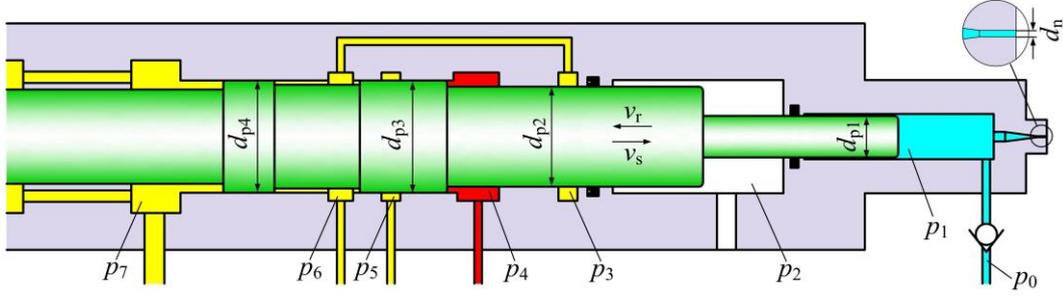


Fig. 3. Piston movement diagram

When the piston returns stroke, the dynamic equation is expressed as:

$$ma_r = \frac{\pi}{4} [d_{p1}^2 p_1 + (d_{p2}^2 - d_{p1}^2) p_2 + (d_{p3}^2 - d_{p2}^2) p_4 - d_{p4}^2 p_7] \quad (1)$$

Where:

$$p_4 = p_{in}$$

$$p_7 = p_6 = p_3 = p_{out}$$

$$p_1 = p_0$$

When the piston strokes, the dynamic equation is expressed as:

$$ma_s = \frac{\pi}{4} [d_{p4}^2 p_7 - (d_{p3}^2 - d_{p2}^2) p_4 - (d_{p2}^2 - d_{p1}^2) p_2 - d_{p1}^2 p_1] \quad (2)$$

Where:

$$p_4 = p_7 = p_{in}$$

$$p_6 = p_3 = p_{out} = 0$$

Where m is the mass of piston, kg; a_r is the return stroke acceleration of piston, m/s^2 ; a_s is the stroke acceleration of piston, m/s^2 ; p_{in} is the inlet pressure, MPa; p_{out} is the outlet pressure, MPa; p_0 and p_2 is the tap water pressure and atmospheric pressure, respectively, which can be negligible, MPa; when chamber 4 and chamber 5 are connected, $p_5 = p_{in}$, when chamber 4 and chamber 5 are disconnected, $p_5 = p_{out}$; d_{p1} is the diameter of the piston in chamber 1, m; d_{pi} is the diameter of the relative

movement of the piston and the cylinder ($i = 2, 3, 4$), $m, d_{p3} = d_{p4}$.

2.2.2 Analysis of pulse pressure, pulse frequency and pulse duration

Pulse pressure, pulse frequency and pulse duration are important factors affecting the rock-breaking ability of pulse jet. The expressions of pulse pressure, pulse frequency and pulse duration of the self-supercharging pulsed jet can be derived from the pulsed water jet theory and the dynamics equation of piston.

When the piston backward stroke, the inlet pressure, outlet pressure, inlet flow rate, and outlet flow rate are expressed as:

$$\left\{ \begin{array}{l} p_{\text{in}} = \frac{d_{p4}^2 p_{\text{out}} + \frac{4}{\pi} m a_r}{d_{p3}^2 - d_{p2}^2} \\ p_{\text{out}} = k_x q_{\text{out}}^2 + k_y \frac{q_{\text{out}}^2}{A_y^2} \\ q_{\text{rin}} = \frac{\pi}{4} (d_{p3}^2 - d_{p2}^2) v_r \\ q_{\text{out}} = \frac{\pi}{4} d_{p4}^2 v_r \end{array} \right. \quad (3)$$

Where q_{out} is the outlet flow rate, m^3/s ; k_x is the coefficient related to the pipeline resistance and fluid properties, $\text{Pa}\cdot\text{s}^2/\text{m}^6$; k_y is the coefficient related to the resistance caused by throttle valve and fluid properties, $\text{Pa}\cdot\text{s}^2/\text{m}^6$; A_y is the overflow area of throttle valve, m^2 ; q_{rin} is the inlet flow rate in return stroke stage of piston, m^3/s ; v_r is the return stroke velocity of piston, m/s .

According to the Bernoulli equation, the relationship between chamber 1 pressure and jet velocity can be obtained:

$$v_{\text{jet}} = \mu \sqrt{\frac{2p_1}{\rho}} \quad (4)$$

Where v_{jet} is the jet velocity, m/s ; μ is the flow coefficient; ρ is the fluid density,

kg/m³.

Flow rate of nozzle:

$$q_n = \frac{\pi}{4} d_n^2 v_{\text{jet}} \quad (5)$$

Where q_n is the flow rate of nozzle, m³/s.

When the piston stroke, the inlet pressure, outlet pressure, inlet flow rate, and outlet flow rate are expressed as:

$$\left\{ \begin{array}{l} p_{\text{in}} = \frac{d_{p1}^2 p_1 + \frac{4}{\pi} m a_s}{d_{p2}^2} \\ p_1 = \frac{8\rho q_n^2}{\pi \mu^2 d_n^4} \\ q_{\text{sin}} = \frac{\pi}{4} d_{p2}^2 v_s \\ q_n = \frac{\pi}{4} d_{p1}^2 v_s \end{array} \right. \quad (6)$$

Where q_{sin} is the inlet flow rate in stroke stage of piston, m/s; v_s is the stroke velocity of piston, m/s.

According to the equation (6), chamber 1 pressure can be expressed as:

$$p_1 = \frac{8\rho d_{p1}^4 q_{\text{sin}}^2}{\pi \mu^2 d_n^4 d_{p2}^4} \quad (7)$$

Chamber 1 pressure is finally converted into jet dynamic pressure, which is expressed as:

$$p_{\text{jet}} = \frac{1}{2} \rho v_{\text{jet}}^2 = \mu^2 p_1 \quad (8)$$

Where p_{jet} is the jet dynamic pressure, MPa.

Theoretical pressure ratio:

$$i = \frac{d_{p2}^2}{d_{p1}^2} \quad (9)$$

Where i is the pressure ratio.

Travel distance of piston:

$$h = \int_0^{t_r} v_r dt = \int_0^{t_s} v_s dt \quad (10)$$

Where h is the travel distance of piston, m; t_r is return stroke time of piston, s; t_s is stroke time of piston, which is also the pulse duration.

According to equation (3), (6) and (10), the travel distance of piston can be expressed as:

$$h = \int_0^{t_r} \frac{4q_{rin}}{\pi(d_{p3}^2 - d_{p2}^2)} dt = \int_0^{t_s} \frac{4q_{sin}}{\pi d_{p2}^2} dt \quad (11)$$

Pulse frequency is expressed as:

$$f = \frac{1}{t_r + t_s} \quad (12)$$

Where f is the pulse frequency, Hz.

From equation (7), (8), (11) and (12), the jet pressure p_{jet} depends on the operating parameter q_{sin} and the structural parameter (d_{p1} , d_{p2} , d_n), the pulse frequency f depends on the operating parameter (q_{rin} , q_{sin}) and the structural parameter (h , d_{p2} , d_{p3}), the pulse duration t_s depends on the operating parameter q_{sin} and the structural parameter (h , d_{p1} , d_{p2} , d_n).

3. Self-supercharging pulsed jet generation system design

3.1 Generation device design

The self-supercharging pulsed jet generation device is the power mechanism of the system, which is mainly composed of piston, valve core and cylinder, as shown in Fig. 4. The piston is used to pressurize the low-pressure water in the chamber 1, the valve core is used to realize the movement reversal of the piston, and the continuous

generation of the pulsed jet is realized by the coupling of their movements. It is necessary to reasonably design the structure of the piston and the valve core and the connection relationship between the inner chamber of the device.

Both the piston and the spool are stepped shafts, the diameter of the relative moving part between them and cylinder satisfies the relationship: $d_{v3} > d_{v4} > d_{v2} = d_{v1}$, $d_{v3} > d_{v4} > d_{v2} = d_{v1}$, the side wall of the valve core is provided with a throttle groove and a throttle hole. Five oil chambers are formed between the piston and the cylinder, which correspond to chamber 3 ~ chamber 7, respectively, and 5 oil chambers are formed between the valve core and the cylinder, which correspond to chamber 3 ~ chamber 7, respectively, and the chambers are connected by internal channels. The chamber 4 and 8 are connected to the P port; the chamber 3, 6, 10 and 12 are connected to the T port; the chamber 7 and 9 are connected, and the chamber 5 and 11 are connected.

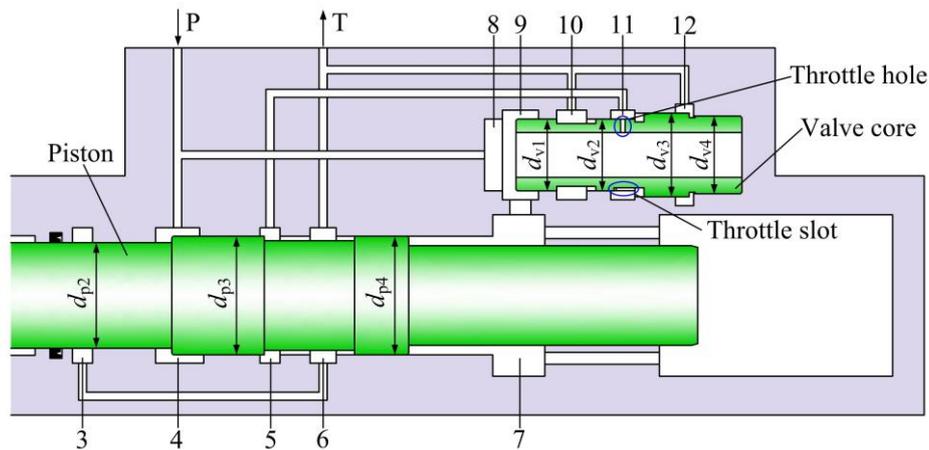


Fig. 4. Structure of self-supercharging pulsed jet pressure device

3.2 Generation system design

On the basis of the generation device, self-supercharging pulsed jet generation system was designed, as shown in figure 5. In addition to the generation device, the

system also includes the power source, the pressure acquisition system and the image collection system.

The power source mainly consists of oil pump, relief valve and throttle valve. The oil pump provides power for the generation of the self-supercharging pulsed jet, the relief valve regulates the inlet pressure, and the throttle valve adjusts the pulse frequency. The principle of frequency regulation of the throttle valve as follows: The structural parameters of the device are fixed, according to equation (3), (11) and (12), if the inlet flow area A_y is reduced without changing the inlet pressure, the outlet flow rate q_{out} decreases, the backward stroke velocity v_r of the piston decreases and the backward stroke time t_r becomes longer, but the stroke time t_s is constant, the pulse frequency f will decrease and vice versa. The oil-return line is added with throttle valve to adjust the pulse frequency without changing the pulse pressure.

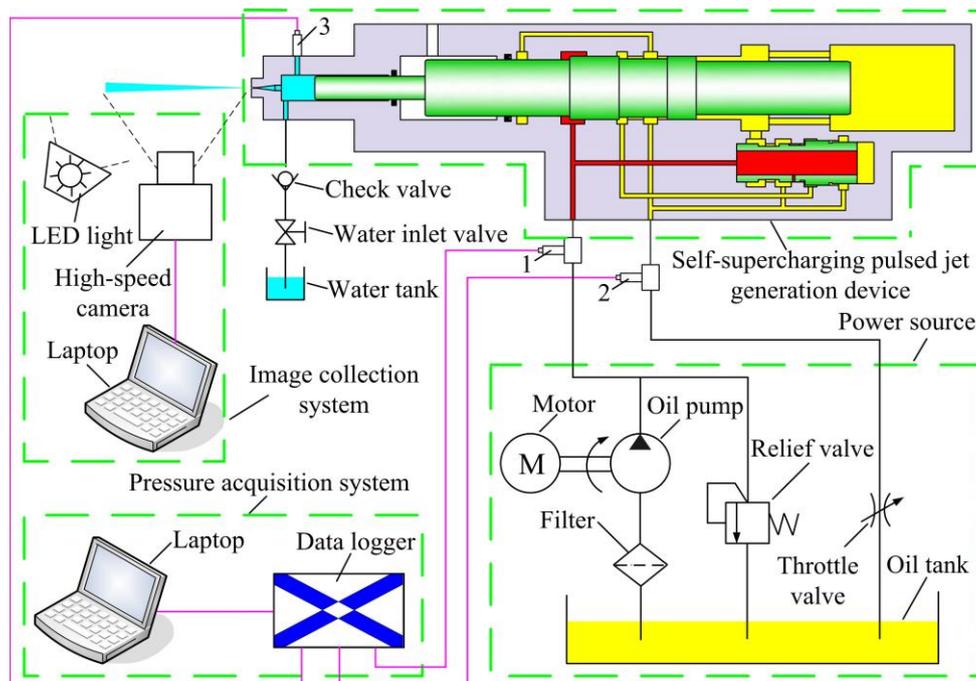


Fig. 5. Schematic of self-supercharging pulsed jet pressure test system

The pressure acquisition system consists of pressure sensor, data collector, and

laptop. Three pressure sensors are required to measure the inlet pressure, pulse pressure and outlet pressure. The pressure sensor is connected to the data collector and the pressure can be monitored and recorded in real time through the acquisition software on the laptop.

The image collection system consists of high-speed camera, LED light and a laptop. The generation of self-supercharging pulsed jets is visualized by capturing shape changes of the jet.

3.3 Working process of system

The formation process of the self-supercharging pulsed jet corresponds to the six movement states of the piston, as shown in Fig. 6. Among them, yellow area represents low-pressure oil, red area represents high-pressure oil, light blue area represents low-pressure water, and dark blue area represents high-pressure water.

State one: Backward stroke accelerated movement of the piston, as shown in Figure 6(a). The high-pressure oil is divided into two ways, and the first way enters the chamber 8, since the upper end surface area of the spool is larger than the lower end surface, the spool is pushed to the bottom dead center by the high-pressure oil, and the chamber 9 and chamber 10 are connected at this time. The second way enters the chamber 4, and pushes the piston backward stroke acceleration, the low-pressure oil in the chamber 7 passes through the chamber 9 and the chamber 10 in turn, then reaches the oil outlet. The volume of the chamber 1 increases, the low-pressure water passes through the check valve to supply water for chamber 1.

the piston will be balanced after a certain distance and enter uniform movement state. The chamber 5 and chamber 6 is disconnected, the chamber 11 and chamber 10 are connected through the throttle slot of spool, and the oil leaking from the chamber 4 to the chamber 5 passes through the chamber 11, the throttle slot of spool and the chamber 10 in turn, finally to reach oil outlet to ensure that the chamber 11 is in low pressure state and the spool is located at the top dead center before the end of the backward stroke movement of piston.

State three: Backward stroke deceleration movement of the piston, as shown in Figure 6(c). When the front end surface of the piston moves to the chamber 5, the chamber 4 and the chamber 5 are connected, the high-pressure oil enters the chamber 11 through the chamber 5, the chamber 8 and the chamber 11 are filled with the isobaric high-pressure oil, since the sum of the action area of the bottom end surface of the spool and action area of spool in the chamber 11 is larger than the top end face, the high-pressure oil pushes the spool to the top dead center. The 7 chamber is changed from low-pressure chamber to high-pressure chamber, and the return stroke velocity of piston is reduced to zero.

State four: Stroke decelerated movement of the piston, as shown in Figure 6(d). The spool is located at the top, chamber 8 are connected with the chamber 7, the high-pressure oil enters the chamber 7 through the chamber 8, the chamber 4 and the chamber 7 are filled with the isobaric high-pressure oil, the action area of piston in chamber 7 is greater than chamber 4, and the high-pressure oil pushes the piston move down, while the chamber 1 pressure is rapidly increased, the check valve is closed,

and a jet pulse is formed at the nozzle outlet. The high-pressure oil in chamber 3 enters the chamber 6 through the chamber 7 to form differential connection.

State five: Stroke uniform movement of the piston, as shown in Figure 6(e). Since the pressure of chamber 1 increases with the increase of the stroke speed of the piston, the piston is balanced by a certain distance and enters uniform movement state. The difference the action area of the piston in chamber 7 and chamber 6 is larger than in chamber 1. According to the supercharging principle of hydraulic, the pressure of chamber 1 is higher than the inlet pressure, and the formed jet has supercharging effect. After the piston moves for a distance, the chamber 4 and chamber 5 is disconnected, and the chamber 11 and chamber 8 are connected through the throttle hole of spool to ensure that the 11 chambers are in a high pressure state and the spool is located at bottom dead center before the end of stroke movement of the piston.

State six: Stroke decelerated movement of the piston, as shown in Fig. 6(f), when the front end surface of the piston moves to the chamber 4, the chamber 5 and chamber 6 are connected, and the chamber 11 becomes the low-pressure chamber due to the top end surface area of the spool is larger than the bottom end surface. High-pressure oil pushes the spool to the bottom dead center. The 7 chamber is changed from the high-pressure chamber to the low-pressure chamber, and the stroke velocity of piston is reduced to zero, and a working cycle is completed. Subsequently, the high-pressure oil pushes the piston return strike and enter the next working cycle.

4. Experimental research on self-supercharging pulsed jet

4.1 Experimental platform construction

According to the designed experimental system, the performance test platform of the self-supercharging pulsed jet generation device was built on the basis of four-dimensional water jet test experimental platform independently developed by our team, the physical diagram connection of the experimental device is shown in Fig. 7.

The power source is the hydraulic pump station of ZYG01B model. It is mainly composed of explosion-proof motor, duplex gear pump (A pump and B pump), oil tank, filter, cooler and relief valve. B pump was used in the experiment with rated pressure of 25MPa and rated flow rate of 60L/min, the pressure regulating range of the relief valve is 0~31.5MPa, the inlet valve is a solenoid valve and is controlled by PLC. The XBS100 model digital pressure sensor was used in the pressure acquisition system with maximum sampling frequency of 100 Hz and accuracy of 0.1%, the ranges are 0 ~ 40MPa, 0 ~ 20MPa and 0 ~ 120MPa, which are connected to the P port, T port and chamber 1, respectively. The support frame is fixed on the test platform, the generation device was fixed on the support frame by U-shaped iron after assembled, and the rubber was padded to achieve the purpose of shock absorption. A gem-embedded nozzle with good processing quality was used, the flow coefficient is approximately 1, and it can be considered that the experimentally measured chamber 1 pressure is equal to the jet dynamic pressure. The center of the draft tube is directly opposite the nozzle, which is used to collect the jet ejected from the nozzle. The image acquisition system selected Phantom v2012 high-speed camera.

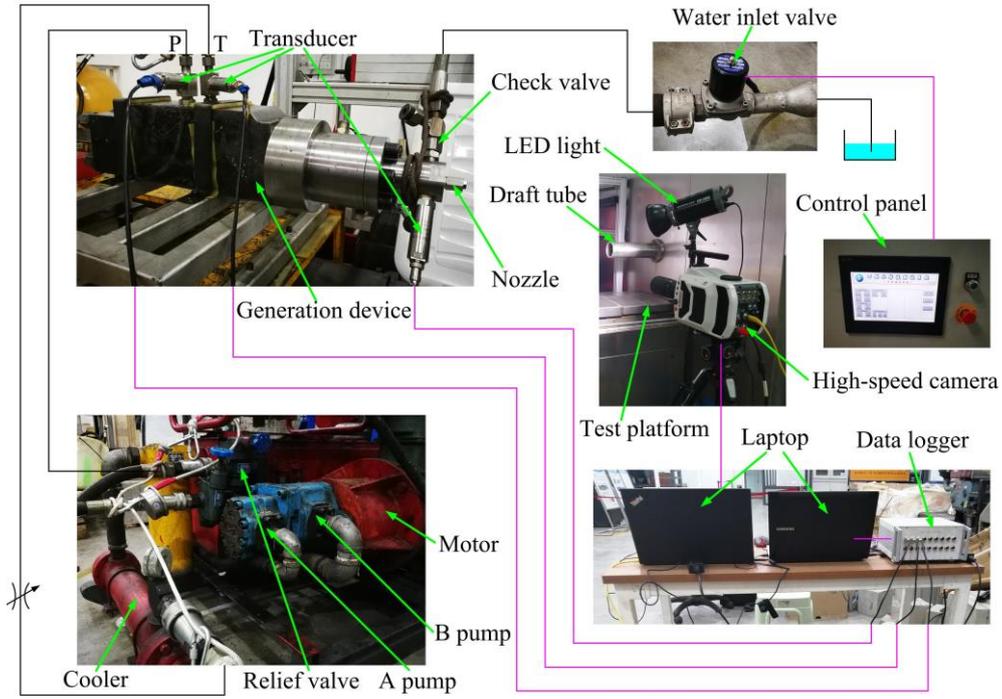


Fig. 7. Physical connection diagram of experimental device

According to the experimental requirements, the main structural parameters of the device are designed, as shown in Table 1.

Table 1 Structural parameters

$d_{p1}(\text{mm})$	$d_{p2}(\text{mm})$	$d_{p3}(\text{mm})$	$d_{p4}(\text{mm})$	$d_n(\text{mm})$	$h(\text{mm})$	i
22	53	60	60	0.45	35	5.8

4.2 Experimental parameters

The experiment was divided into 9 groups, as shown in Table 2. The first five sets of experiments maintain the maximum opening of the throttle valve, which corresponding to opening value is 1, only the inlet pressure was changed, the inlet pressures are set to 2MPa, 4MPa, 6MPa, 8MPa, and 10MPa, respectively. The last four sets of experiments maintain inlet pressure at 8MPa, only the inlet flow rate in return stroke stage of the piston was changed, and the throttle valve is set to 4 different opening. Because there is no suitable flow meter and pressure sensor for

synchronous acquisition, the inlet flow rate in return stroke and stroke stage of piston can only be obtained based on the experimental results and the relationship derived in section 1.2.2. The opening of the throttle valve satisfies the following relationship: $0 < k_4 < k_3 < k_2 < k_1 < 1$.

Table 2 Experimental parameters

Group number	p_{in} (MPa)	q_{rin} (L/min)	q_{sin} (L/min)	Throttle opening
1	2	2.4	14.8	1
2	4	3.3	18	1
3	6	6.2	22.8	1
4	8	8.7	29.7	1
5	10	9.3	33	1
6	8	5	29.7	k_1
7	8	2.7	29.7	k_2
8	8	1.6	29.7	k_3
9	8	1.1	29.7	k_4

4.3 Experimental procedure

Firstly, connect the pipe line and transmission line of the system. Secondly, open the water inlet valve, the water enters the chamber 1 under the action of gravity and generates low-pressure jet. Thirdly, Align the high-speed camera lens with the jet axis and the midpoint of the shooting area, and set the shooting frame rate to 24722fps, that is, the time interval between two consecutive photos is $40.5\mu s$. After focusing, use a steel ruler to calibrate the shooting area, the jet length of each image is 180mm. Fourthly, adjust the opening degree of the relief valve to the maximum, turn on the hydraulic pump while starting collecting data. At this time, the inlet pressure was the lowest, the opening of the relief valve was slowly adjusted according to the inlet pressure displayed on the laptop until the inlet pressure reaches the set value, locked the relief valve, and then adjust the opening of the throttle valve. The inlet pressure,

jet pressure and outlet pressure were collected for a period of time, collect the jet shape of the nozzle exit while collecting pressure. Finally, close the oil pump and inlet valve after the acquisition is complete, and save the data. This process was repeated for each group of experiment until the end of all experiments.

5. Result and discussion

5.1 Analysis of jet pressure and jet morphology

The opening of throttle valve is maximum, for different inlet pressures, part of experimental results are shown in Fig. 8 (a) and (b). The inlet pressure, jet pressure and return pressure are periodical changed. The supercharging of the jet is generated during the stroke phase of the piston, and the rise, stability and fall of the jet pressure correspond to the three states of stroke acceleration, uniform speed and deceleration, respectively. Pulse pressure increase with the increase of inlet pressure, due to the influence of the diameter and length of the oil return pipeline, certain outlet pressure will occur in the backward stroke phase of piston, and in the stroke phase of piston, the outlet pressure is almost zero, which is consistent with the theoretical analysis.

The inlet pressure is unchanged, for different opening of throttle valve, as shown in Fig. 8 (c) and (d), the inlet pressure, pulse pressure, and outlet pressure show periodic changes and the trends are consistent. With the increase of inlet flow rate in the return stroke stage of the piston, the pulse pressure remains unchanged, and the interval between pulses becomes longer, that is, the backward stroke time of the piston becomes longer. The frequency modulation method using meter-out can realize the adjustment of the pulse frequency without changing the pulse pressure.

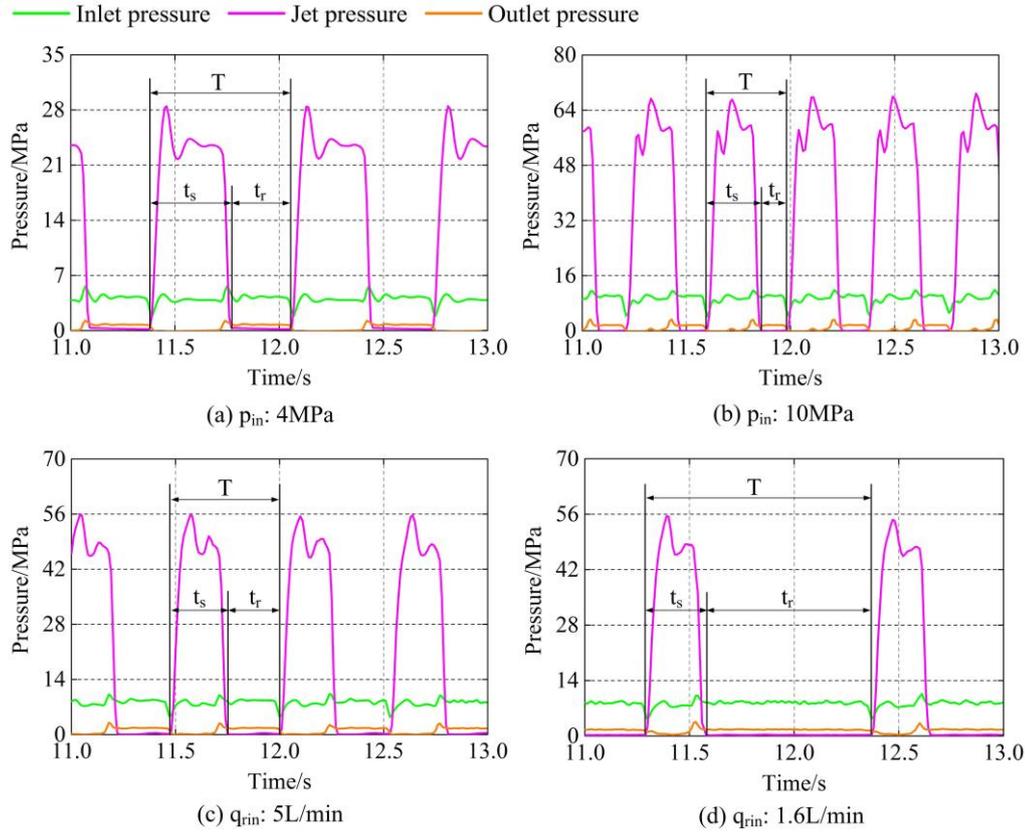


Fig. 8. Inlet pressure, jet pressure and outlet pressure versus time curves

It can be seen from figure 8 that the inlet pressure fluctuates with time, especially in the rising and falling stages of pulse pressure, which are also the two phases of the beginning and end of piston stroke, the pressure fluctuation is more obvious. Movement reversal of piston changed the system load, and the opening of relief valve produced rapid dynamic changes, resulting in drastic fluctuations in flow rate and pressure. It takes a period of time for the opening of relief valve to transition from dynamic to steady state, the corresponding inlet pressure to be stable for a while. In the initial stage of the piston stroke, the jet pressure fluctuates with the fluctuation of the inlet pressure due to the constant pressure ratio, as the inlet pressure increases, the jet pressure stabilization time becomes shorter and the fluctuation is more obvious.

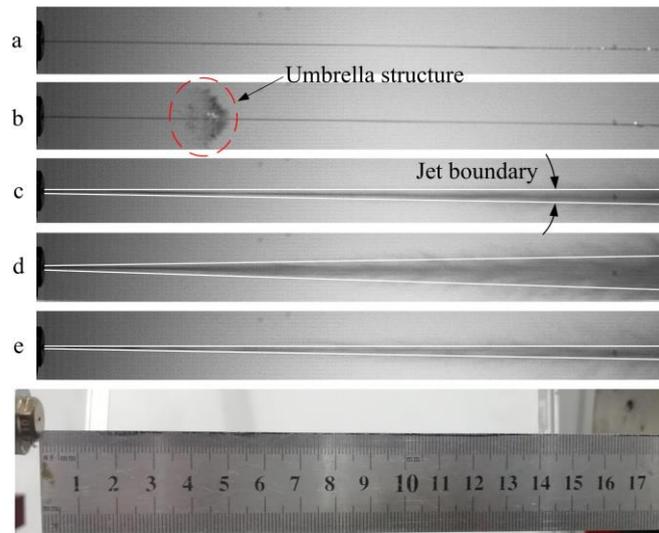


Fig. 9. Picture of jet shape at different times of a single pulse

The shape of the jet changes with the change of the pressure of the jet, the law of the change of the shape of the jet under different parameters is basically the same. The shape of a single pulsed jet at inlet pressure of 10MPa is analyzed, as shown in Fig. 9. The jet in frame a corresponds to the backward stroke of the piston and belongs to continuous jet. The jet pressure is determined by the water inlet pressure, due to the low water inlet pressure, the nozzle diameter is small and the jet is thin. The jet shape in frame b corresponds to the initial stage of the piston stroke. When the piston starts stroke, it immediately squeezes the water to form high-speed jet, which forms umbrella structure under the action of air friction resistance. As the piston continues to squeeze, it can be observed in frame c that the shape of the jet changes from thin line to horn. The increase of the jet velocity increases the entrained air and the jet boundary gradually expands to the surroundings. The frame d corresponds to the stage of uniform stroke of the piston. During this period, the pulsed jet keeps the horn shape, and the jet shape is basically stable. The frame e corresponds to the stroke deceleration stage of the piston. At this stage, the pulse pressure gradually decreases,

the diffusion degree of jet decreases, and finally returns to the shape of thin line.

5.2 Analysis of supercharging effect

The supercharging effect can be reflected by the supercharging ratio, the supercharging ratio is the average value of the ratio of the pulse pressure and the inlet pressure, as shown in Fig. 10. The supercharging ratio under different working parameters is between 5.67 and 5.75, which is very close to the theoretical design value, but smaller than design value. There are two reasons for this result: on the one hand, the pressure measured in the experiment is the inlet pressure, during the supercharging process, high-pressure oil from the inlet to the chamber 7 will cause pressure loss, the actual pressure of chamber 7 is lower than the inlet pressure. On the other hand, during the movement of the piston, it is affected by the frictional resistance of the seal. In fact, the theoretical design ignores pressure loss and frictional resistance.

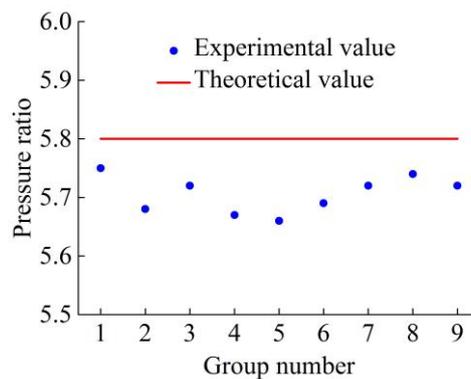


Fig. 10. System pressure versus time curve under different outlet flow rate

The experimental results verify the feasibility of the self-supercharging pulsed jet generation method. Considering the pressure bearing capacity of the device, the maximum inlet pressure is set to 10MPa in the experiment. Pulse pressure is

determine by the inlet pressure and pressure ratio, increasing the pressure bearing capacity of the device or the design value of pressure ratio under the condition that the flow rate of oil pump is sufficient, higher pulse pressure can be obtained. Increasing the inlet pressure means increasing the pressure bearing capacity of the device, but the inlet pressure is limited by the rated pressure of the pump. Increasing the pressure ratio means that more inlet flow rate is required to achieve the desired pulse pressure, but the inlet flow rate is limited by the rated flow rate of the pump. Therefore, both the rated pressure and the rated flow of the pump needs to be considered in the design of the rated pressure and pressure ratio of the generation device.

5.3 Analysis of pulse frequency and pulse duration

According to the experimental results and the equations in section 1.2.2, the relationship between the inlet flow rate and the pulse frequency or pulse duration can be calculated when the opening of throttle valve is the maximum, as shown in Fig. 11 (a). When the inlet flow rate in the backward stroke and stroke phase of the piston are increased from 2.4L/min to 9.3L/min, from 14.8L/min to 33L/min, respectively, the pulse frequency is increased from 0.9Hz to 2.56Hz, and the pulse duration is reduced from 0.54s to 0.25s. Increasing the inlet flow rate in the backward stroke phase of the piston will increase the backward stroke speed of the piston. Similarly, increasing the inlet flow rate in the stroke phase of the piston will increase the stroke speed of the piston. The travel distance of piston is determined by the structure of the device and remains unchanged, so that the reciprocation period of piston is shorten and the pulse frequency is increased. The pulse duration corresponds to the stroke time of the piston,

the acceleration of the stroke speed of piston makes the pulse duration shorter.

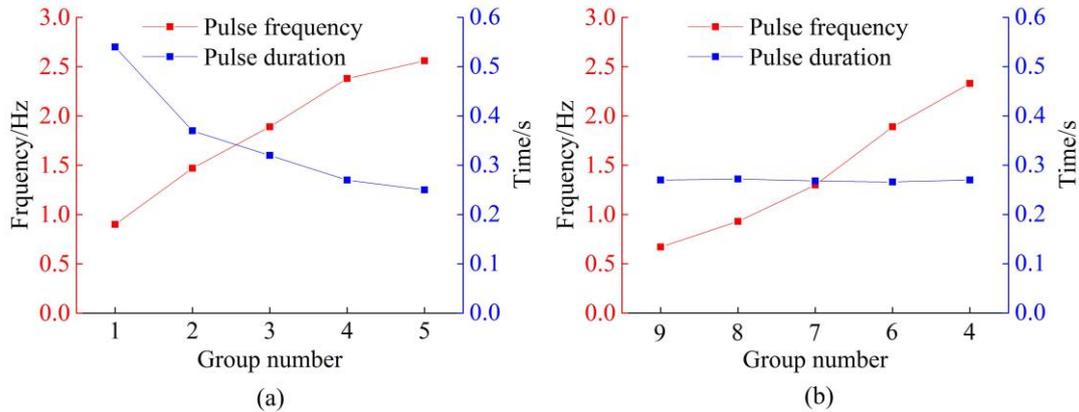


Fig. 11. Pulse frequency and pulse duration versus inlet flow rate curve

When the inlet pressure is 8MPa, the relationship between the inlet flow rate and the pulse frequency or pulse duration is shown in Fig. 11(b). The inlet flow rate in the stroke phase of the piston remained unchanged at 29.7L/min, when the inlet flow rate in the return stroke phase of the piston increased from 1.1L/min to 8.7L/min, the pulse frequency increased from 0.67Hz to 2.33Hz, and the pulse duration was maintained at about 0.27s. The pulse frequency depends on the stroke velocity and the backward stroke velocity of piston, the pulse duration depends only on the stroke velocity of piston. The inlet flow rate in the stroke phase of the piston remained unchanged, so the stroke velocity of piston does not change. As inlet flow rate in the backward stroke phase of the piston increases, the backward stroke velocity increases. The travel distance of piston remains unchanged, thus, the reciprocation period of piston is shorten, the pulse frequency is increased, and the pulse duration is constant. Due to the influence of the diameter and length of the oil return pipeline, the oil return resistance will always be generated. If the diameter of the oil return pipeline is increased and the length is shortened, the oil return resistance can be reduced, and the

return velocity of piston can be increased, and the pulse frequency can be further increased under the condition that the inlet pressure is constant.

The pulse pressure, pulse frequency and pulse duration of the self-supercharging pulsed jet can be adjusted, which provides guidance for the parameter selection of subsequent rock-breaking experiments. The inlet flow rate in the stroke phase of the piston determines the pulse frequency and pulse duration, while the change in inlet flow rate in the backward stroke phase of the piston only plays a role of frequency modulation. In addition, other structural parameters of the device, such as piston diameter, nozzle diameter, and travel distance of piston, will also affect the pulse frequency and pulse duration. The influence law needs to be further studied, which provides a basis for the optimal design of the generating device structure.

6. Conclusion

1. A method for self-supercharging pulsed generation is proposed. Through the structural design of the device and the connection of the pipeline, the self-supercharging pulsed water jet with adjustable pulse pressure, pulse frequency and pulse duration can be formed by the mutual feedback of travel distance of spool and piston under the continuous injection of the hydraulic oil and low-pressure water.

2. The regularity of the jet pressure and the shape of jet was obtained. The rise, stability, and decline of jet pressure correspond to three states of piston stroke acceleration, uniform speed, and deceleration, respectively. The measured pressure ratio is basically consistent with the theoretical design value, thus verifying the feasibility of the method

3. As the inlet flow rate in the stroke phase of the piston increases, the pulse pressure and pulse frequency increase, and the pulse duration decreases. As inlet flow rate in the backward stroke phase of the piston increases, the pulse frequency increases, and the pulse pressure and pulse duration remain unchanged. The influence of structure parameters of device on pulse frequency and pulse duration needs to be further studied.

7. Declaration

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Availability of data and materials

The datasets used or analyzed during the current study are available from the corresponding author on reasonable request.

Authors' contributions

Yuanfei Ling and Yiyu Lu conceived and designed the study. Yangkai Zhang, Lei Wang and Qi Yao performed the experiments. Yiyu Lu provided the experimental instruments. Yuanfei Ling wrote the paper. Zhaolong Ge and Jiren Tang reviewed and

edited the manuscript.

Competing interests

The authors declare no competing financial interests.

Consent for publication

Not applicable.

Ethics approval and consent to participate

Not applicable.

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Figures

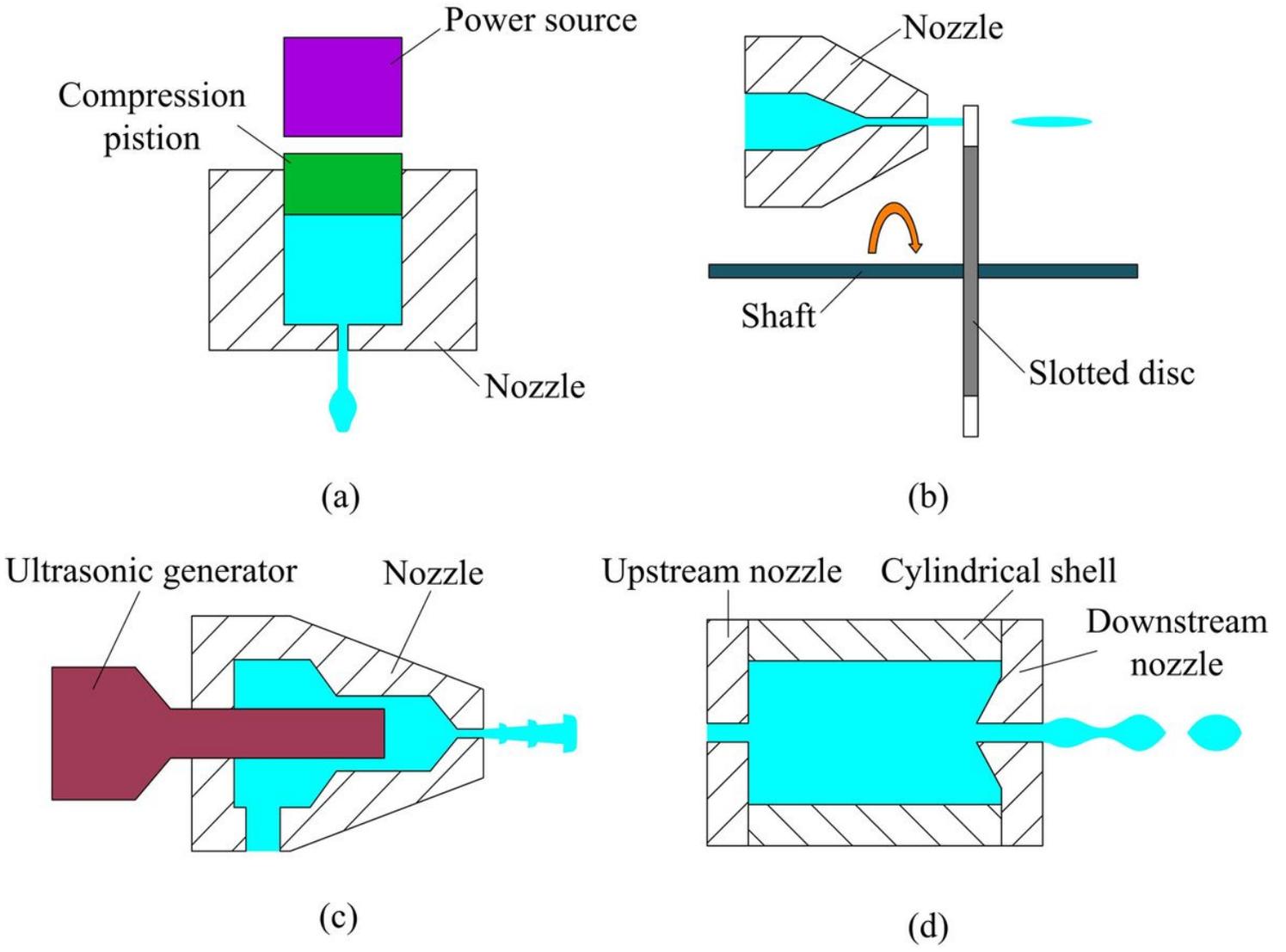


Figure 1

Types of pulsed jet

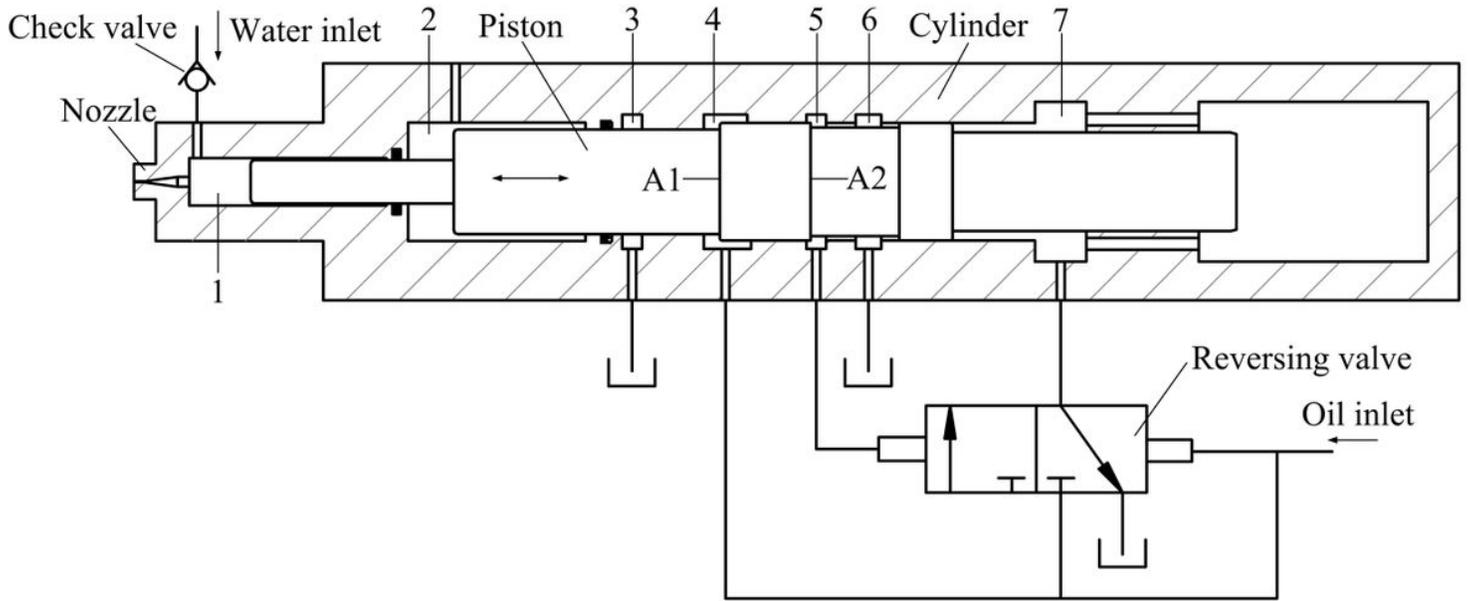


Figure 2

Self-supercharging pulsed water jet generation diagram

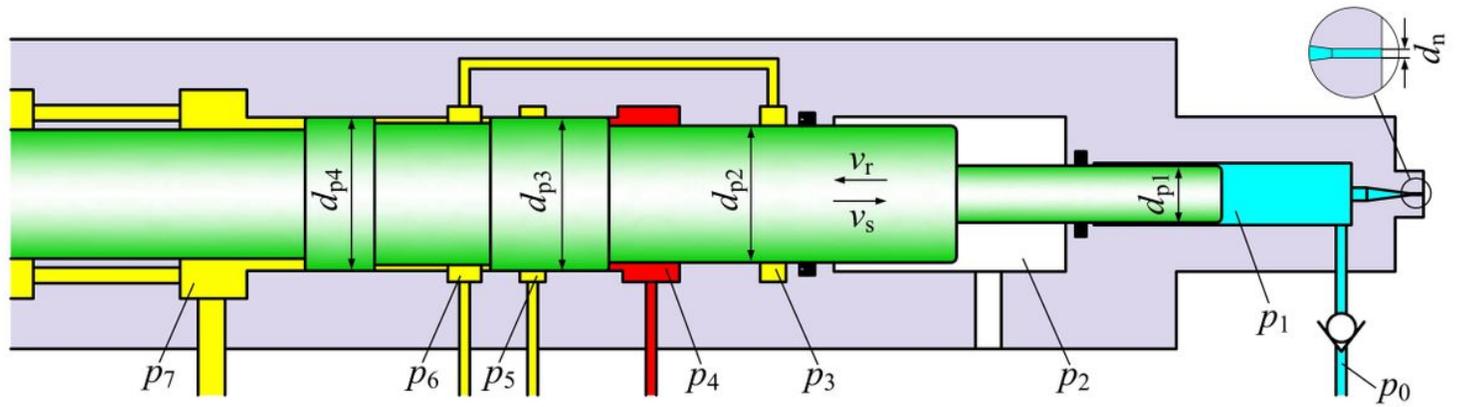


Figure 3

Piston movement diagram

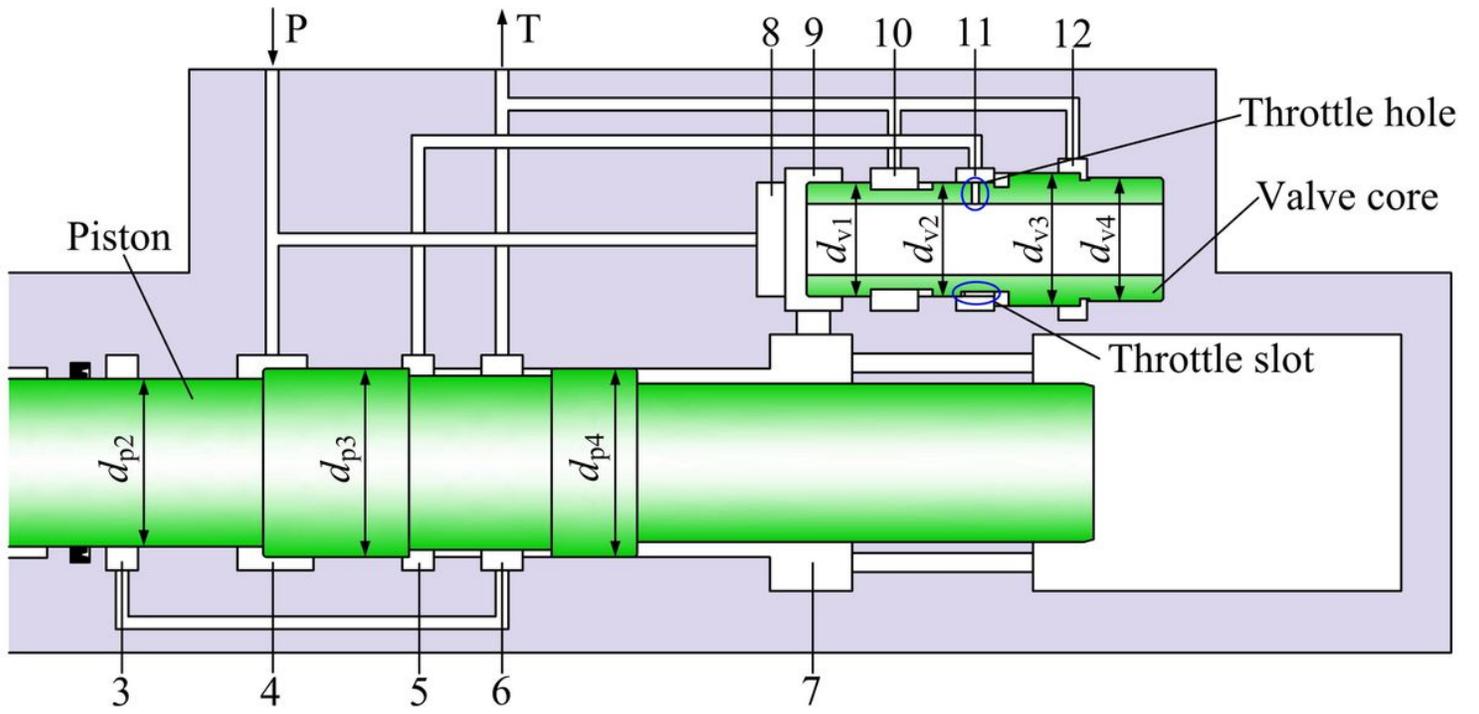


Figure 4

Structure of self-supercharging pulsed jet pressure device

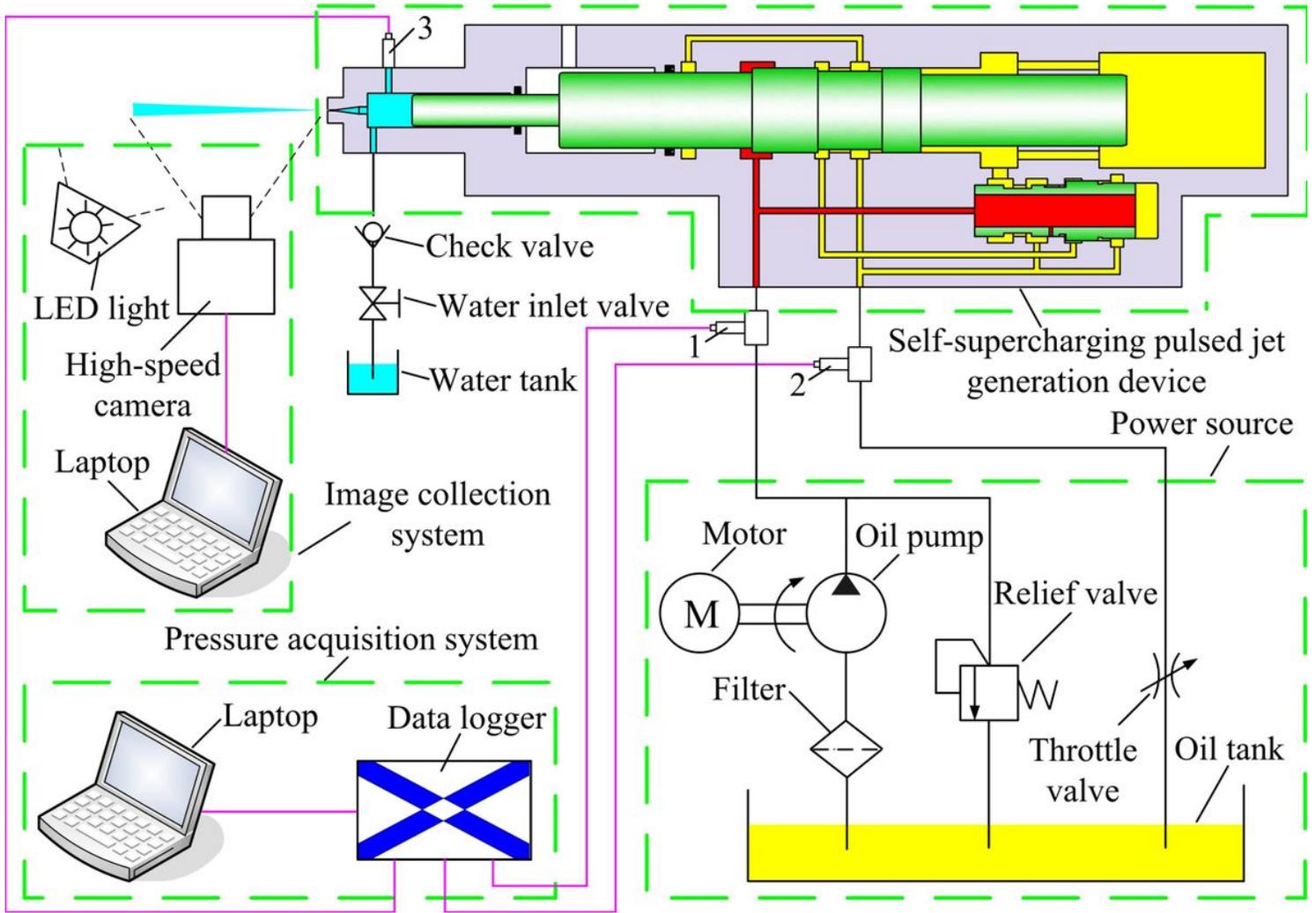


Figure 5

Schematic of self-supercharging pulsed jet pressure test system

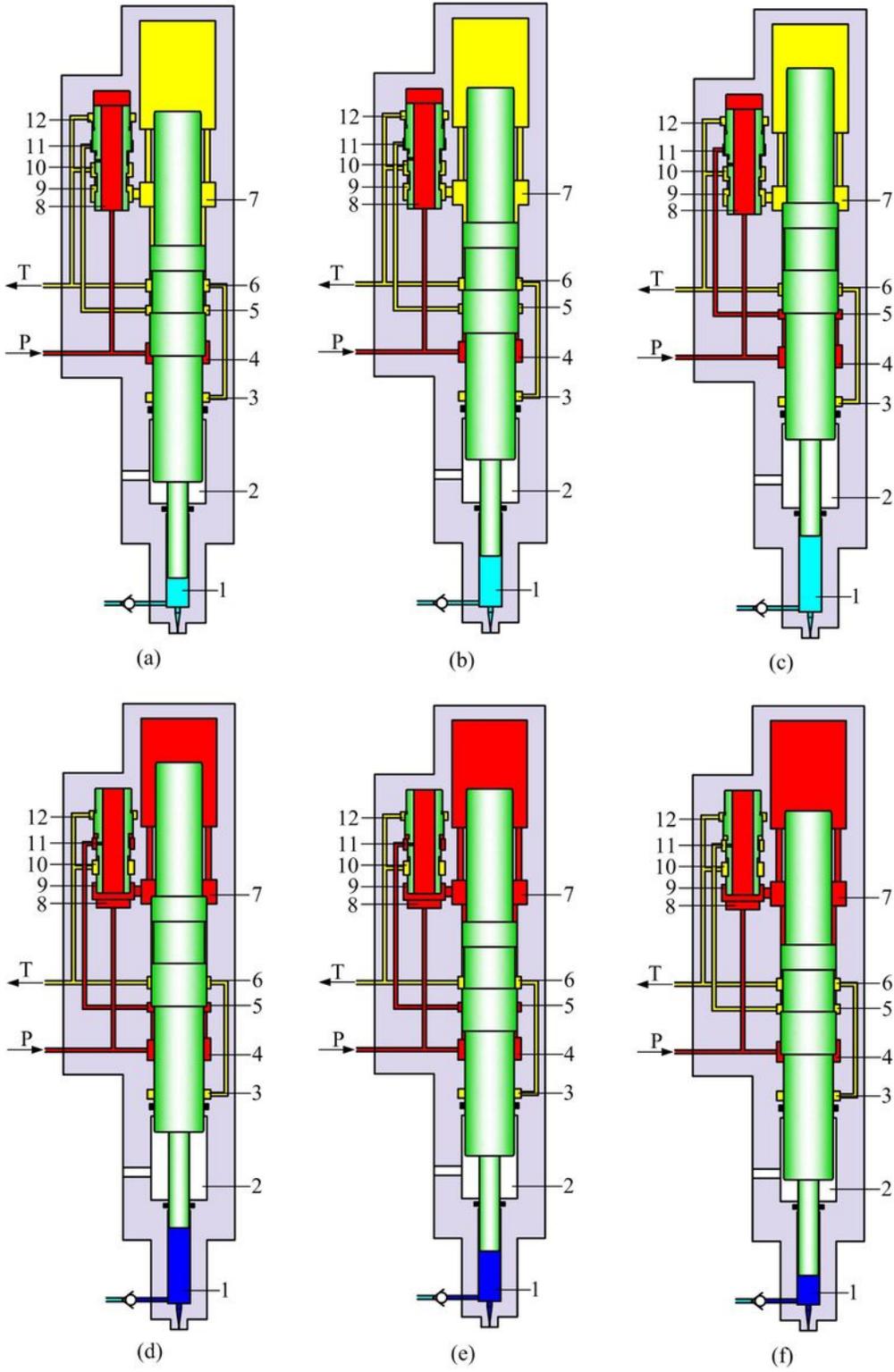


Figure 6

Working process of system

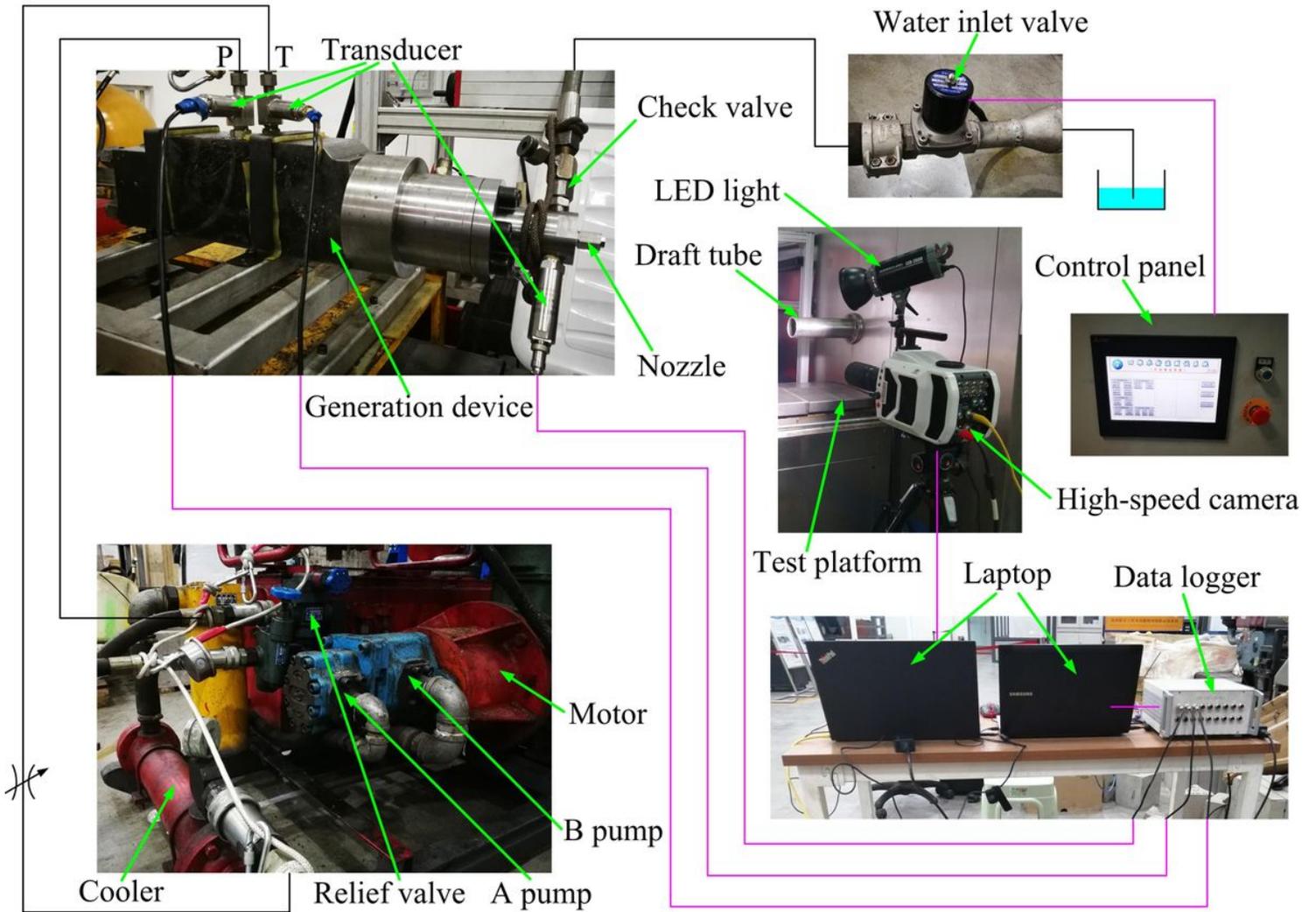
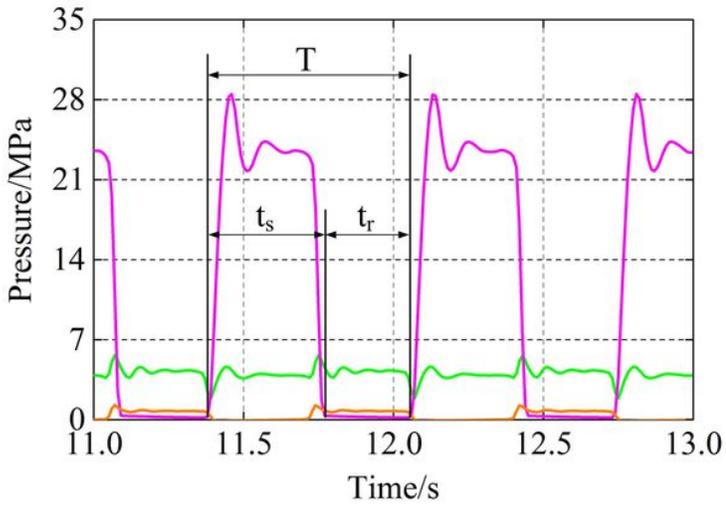


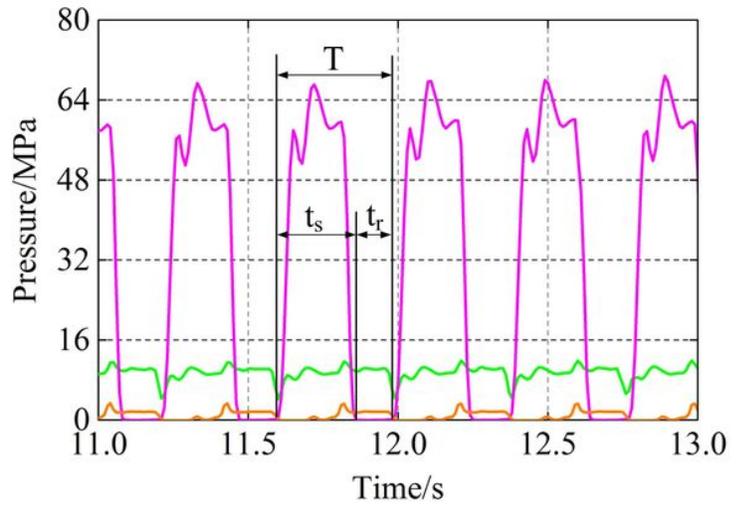
Figure 7

Physical connection diagram of experimental device

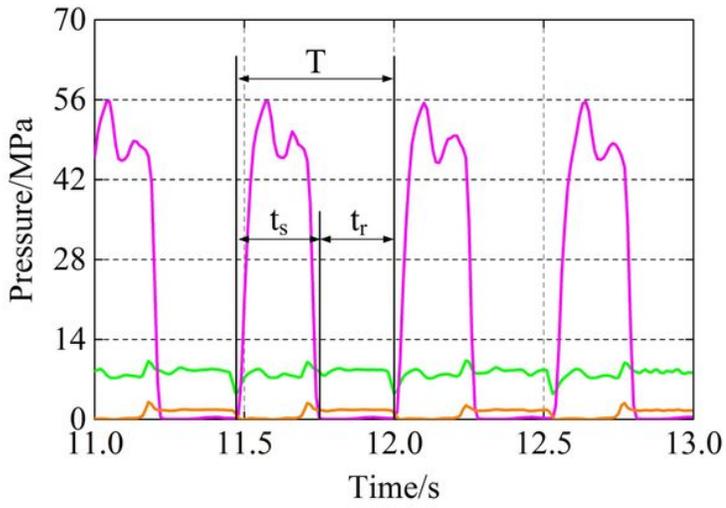
— Inlet pressure — Jet pressure — Outlet pressure



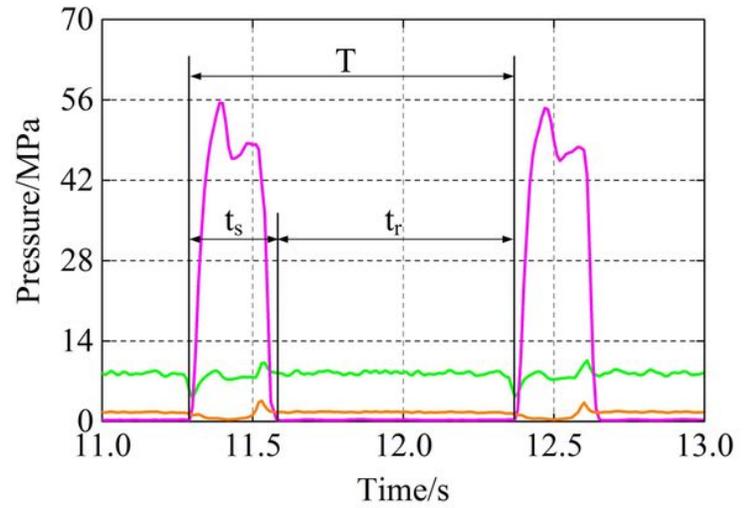
(a) p_{in} : 4MPa



(b) p_{in} : 10MPa



(c) q_{rin} : 5L/min



(d) q_{rin} : 1.6L/min

Figure 8

Inlet pressure, jet pressure and outlet pressure versus time curves

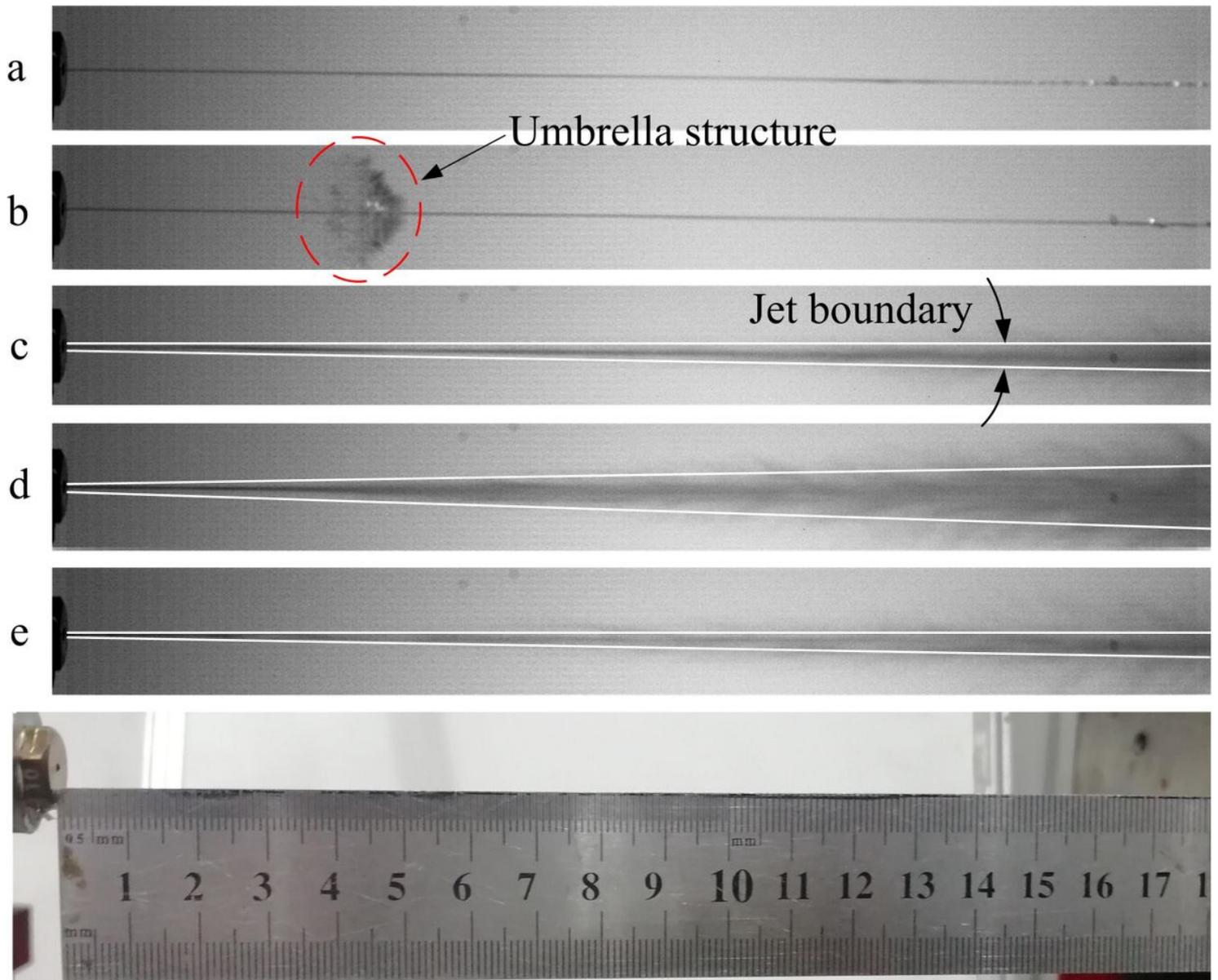


Figure 9

Picture of jet shape at different times of a single pulse

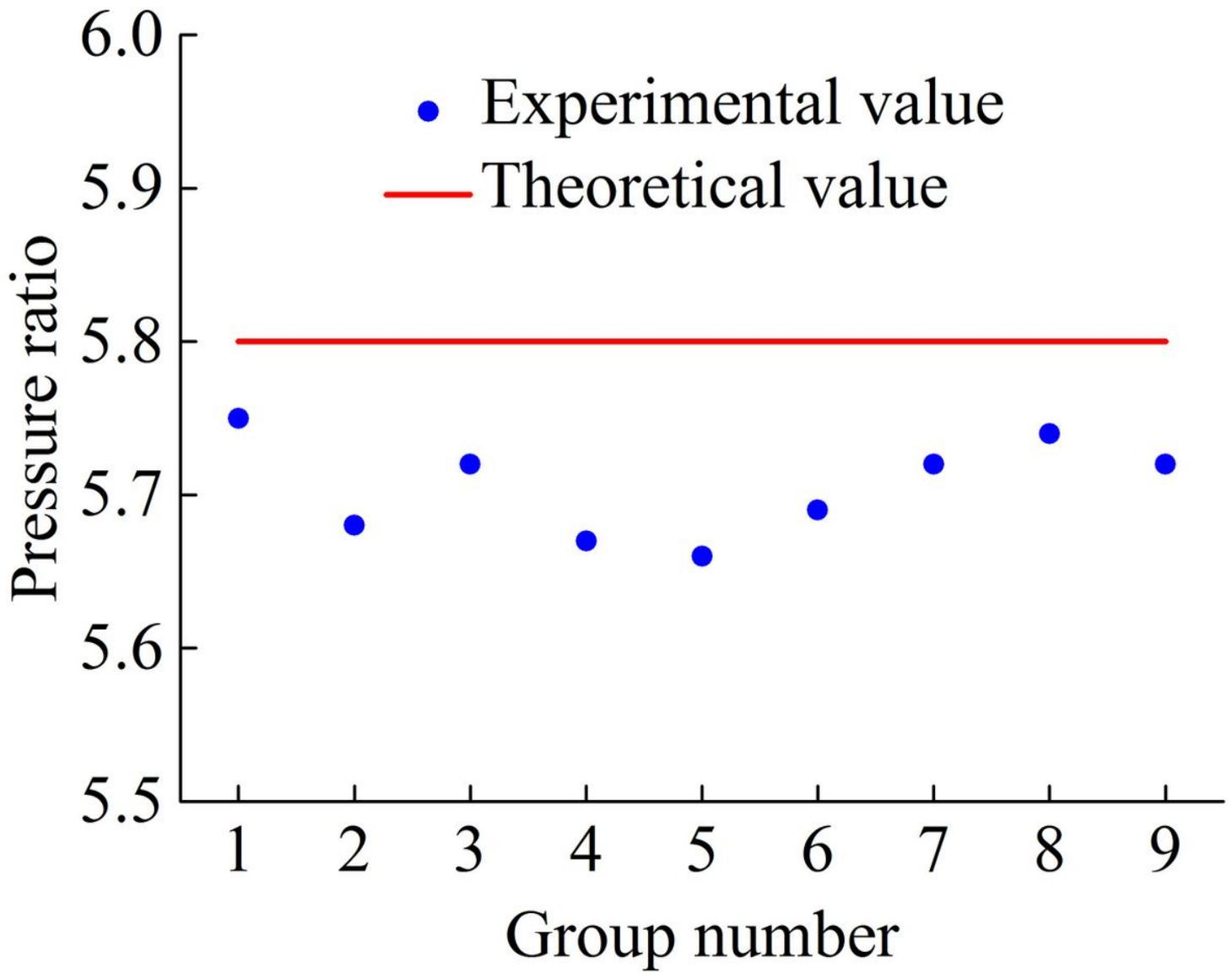
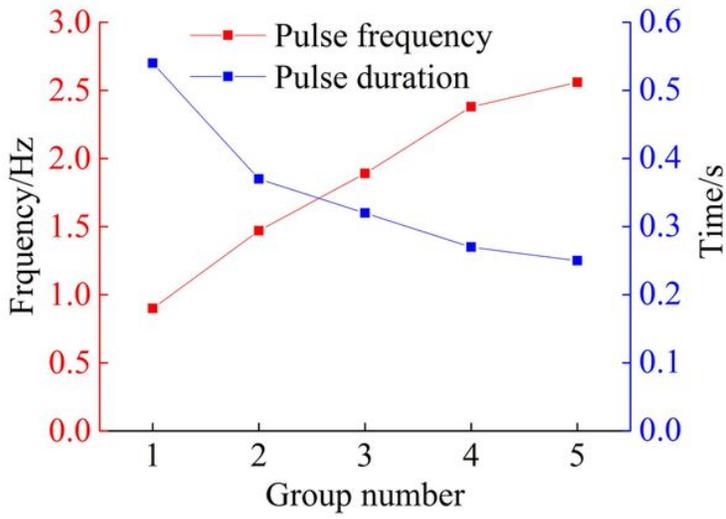
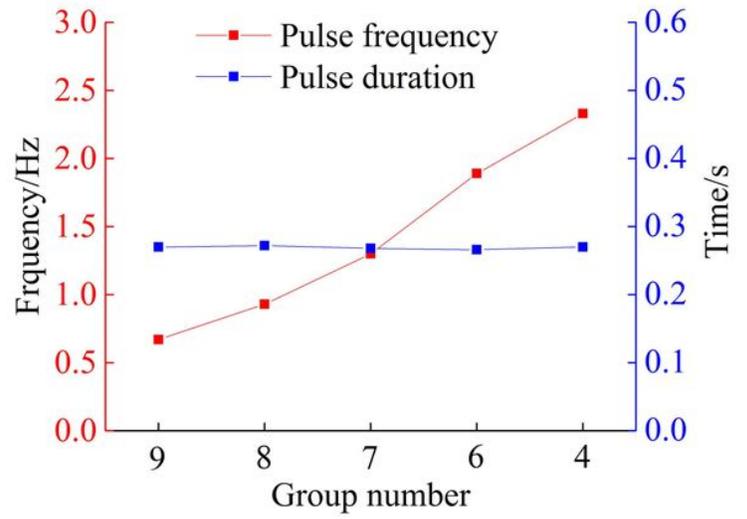


Figure 10

System pressure versus time curve under different outlet flow rate



(a)



(b)

Figure 11

Pulse frequency and pulse duration versus inlet flow rate curve