INVESTIGATION ON THE EFFECT OF INJECTOR MODIFICATION ON INJECTOR ATOMIZATION AND U-BEND PULSE DETONATION COMBUSTION CHARACTERISTICS

by

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In order to shorten the deflagration-to-detonation transition (DDT) distance of the pulse detonation combustion chamber, an experimental study of the effect of pneumatic atomization injector modification on atomization particle size amd gas-liquid two-phase U-bend pulse detonation combustion (U-PDC) chamber was carried out. Gasoline and air were used as fuel and oxidizer, and the atomization particle size was tested and the detonation characteristics of the U-PDC were obtained using the pneumatic atomization injector before and after the modification. The results show that the atomization size range of the injector before the modification is 111.6~152.9 μm, after the modification of the injector atomization size range of 76.4~107.2 μm, atomization size than before the modification is significantly reduced. The U-PDC using the injector before and after the modification can achieve stable operation in the range of 10~30 Hz, and the DDT distance shortened with the increase in frequency. At an operating frequency of 30 Hz, the DDT distance of U-PDC with the injector before modification is about 676 mm, and the DDT distance of U-PDC with injector after modification is shortened by 8.9% to about 616 mm. In addition, under the same operating conditions, due to the better atomization effect of the injector after modification, The fuel flow rate of U-PDC with the injector after modification is 5~10% smaller than that with the injector before modification when the average detonation pressure reaches its maximum value during the adjustment of fuel-flow.

Key words: *pneumatic atomization injector, fuel consumption rate, DDT, pulse detonation combustion chamber, fuel atomization*

Introductions

Pulse detonation combustor is a new type of combustion chamber using detonation combustion, which has the advantages of self-pressurization of detonation combustion, fast combustion rate and low entropy increase. Pulse detonation turbine engine (PDTE) is a new concept engine that uses pulse detonation combustion chamber to replace the isobaric combustion chamber of traditional gas turbine engine, which can realize the transformation of gas turbine engine cycle from Brayton c+ycle to Otto cycle [1, 2].

Currently, aircraft engines use liquid fuel, which is atomized in the combustion chamber by fuel injectors and mixed with air to form a homogeneous mixture for combustion. As

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the core component of PDTE, the atomization performance of the fuel injector directly affects the ignition reliability of the combustion chamber and its operating stability. Poor injector atomization effect will lead to excessive fuel droplets, resulting in droplets attached to the wall, ignition failure, combustion flame backward, long DDT distance, fuel consumption rate and other problems [3], which is not conducive to the engineering application of the detonation chamber. Therefore, for the fuel injector atomization effect on the working characteristics of the pulse detonation combustion chamber, scholars around the world have carried out a lot of research. Japan's Watanabe *et al*. [4] argue that the prerequisite for generating stable and reliable liquid fuel detonation is a non-homogeneous mixture of detonation process. Kailasanath *et al*. [5] conducted experiments on liquid fuel in-tube detonation, the results show that due to the problems of atomization and evaporation of liquid fuel, detonation DDT distance, DDT time is longer compared to gaseous fuel. When atomization droplet size of two-phase pulse detonation is less than 10 μm, the C-J wave velocity of two-phase pulse detonation will be the same as that of gaseous pulse. Wang *et al.* [6] used pneumatic atomizing injectors instead of flat-hole type injectors, and demonstrated experimentally that as the atomization effect became better, the range of equivalent ratios of the pulse detonation combustion chamber became wider. Yan *et al.* [7] conducted different atomization injectors on the pulse detonation rocket engine, that has a larger atomization gas inlet diameter of the injector has better atomization effect, which in turn is beneficial to the ignition and detonation of pulse rocket motors. However, Wei *et al*. [8], Frolov *et al*. [9] in their studies on the effect of fuel atomization on the detonation characteristics of two-phase pulse detonation combustion chambers focused more on two-phase detonation compared to gaseous detonation, and the effect of injector atomization on detonation characteristics was often ignored.

At present, the two-phase pulse detonation combustion chamber generally use the adaptive fuel supply method, its low fuel supply pressure is not suitable for the use of pressure atomization injector which requires high fuel supply pressure, so most of the wo-phase pulse detonation combustion chamber use pneumatic atomization injector. The principle is through the injector inside the gas-liquid two-phase velocity difference will be torn into a film of fuel for primary crushing, then the air outside the injector will be sprayed out of the injector after the liquid film broken into liquid droplets, the process for the second crushing [10]. At present, there is less research on pneumatic atomization injectors for pulse detonation combustion chambers, and more research is conducted on pneumatic atomization injector structure, atomization mechanism*, etc.* Jiang *et al.* [11] for two-phase pulse detonation chamber improved a pre-film pneumatic atomization injector and began a comparative study of numerical simulations and experiments, the results show that the greater the radial pressure of atomized gas, the greater the difference in oil and gas velocity at the injector outlet, the better the atomization effect. On the atomization mechanism of pneumatic atomization injector, An and Yuming [12], Yao *et al*. [13], Ma and Zang [14], and Li and Wu [15] showed that the air-flow as well as pressure on the atomization effect than the fuel flow on the atomization effect is more influential.

The aforementioned studies have analyzed the effect of injectors on the detonation characteristics of pulse detonation combustion and the atomization characteristics of pneumatic atomization injectors, but injector studies are more based on traditional combustion chambers, for fuel atomization on the detonation characteristics of pulse detonation combustion less relevant research. Therefore, in order to investigate the effect of injector atomization on the detonation characteristics of the pulse detonation combustion chamber. In this paper, a new type of pneumatic atomization injector is designed, and atomization particle size tests are conducted on two types of pneumatic atomization injectors before and after the modification, and the

U-PDC with the injectors before and after the modification is used as the object of study. The experimental study of the detonation characteristics of U-PDC was carried out using gasoline and air as fuel and oxidizer to provide a reference for the improvement of pneumatic atomization injectors for two-phase pulse detonation combustion chambers and to promote the engineering application of pulse detonation combustion.

Test system and test method

Injector atomization particle size test system and measurement method

Injector atomization particle size measurement test system is shown in fig. 1, including fuel supply system, air supply system, pneumatic atomization injector and measurement system. In the test, the atomization gas pressure is controlled by adjusting the ball valve of the atomization gas line, and the fuel flow is controlled by the proportional valve. The fuel is sprayed out inside the injector under the action of atomization gas to form a spray field. Piezoresistive sensors P_1 and P_2 (range 0~1 MPa, accuracy 2.5% full scale (FS), frequency response 0~200 kHz) are installed on the atomizing gas line and gasoline line, respectively, to measure the atomizing gas pressure and fuel supply pressure. At the same time, a gear type flow meter (range 0.02~18 Lpm, accuracy ±0.3 R) is installed on the gasoline line to detect the fuel flow.

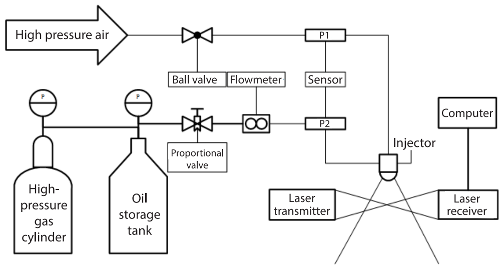


Figure 1. Schematic of the atomization particle size measurement test system

Figure 2. Battersize 2000 seconds spray laser particle sizer physical picture

The measurement of the atomization particle size is carried out with a Battersize 2000 seconds spray laser particle size meter shown in fig. 2, which uses a Fourier optical system to irradiate the sprayed droplets with a parallel laser beam, which receives the scattered light signal generated by the droplets through a large-aperture payoff lens, and transmits the signal to a computer to run the Mie scattering theory for inversion calculations to obtain the particle size distribution of the droplets. According to the axial distance from the injector to the ignition position in the U-PDC, the distance from the injector exit to the laser beam is 100 mm during the test. The distance between the laser emitter and the laser receiver is 600 mm, and the injector exit axis is located on the center line of both.

The structure of the pneumatic atomization injector currently used in the U-PDC chamber is shown in fig. 3. The atomized gas and gasoline enter the mixing chamber of the injector body through the atomized gas path and fuel path on the oil and gas base, respectively, the velocity difference between the gasoline and the atomized gas causes the gasoline to be sheared and broken, and is ejected at eight circular holes with a diameter of d_1, further broken into fine droplets. The modified pneumatic atomization injector structure schematic diagram is shown in fig. 3, the injector atomization gas and gasoline supply method is also through the oil and gas base, but the modified pneumatic atomization injector internal increase in the number of orifice plate, and the internal auxiliary atomization gas hole, the fuel through the orifice plate broken and further broken under the action of the atomization gas atomization, and finally the fuel droplets through the pitch of d_2 ring slit spray, forming a circumferential uniform atomization field. After the modification of the injector spacing d_2 annular slit area and before the modification of the injector 8 diameter d_1 round hole total area of the same.

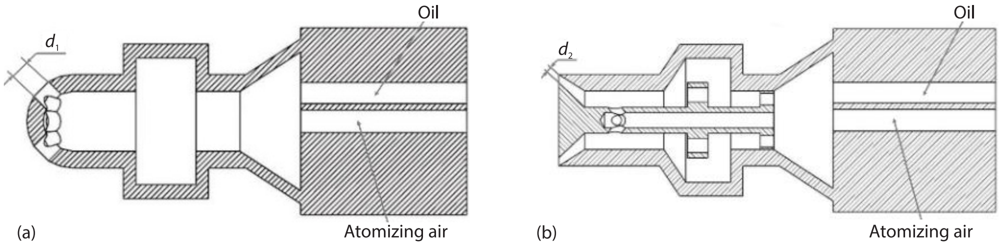


Figure 3. Schematic of the structure of the pneumatic atomization injector before and after modification; (a) injector before modifications and (b) injector and after modifications

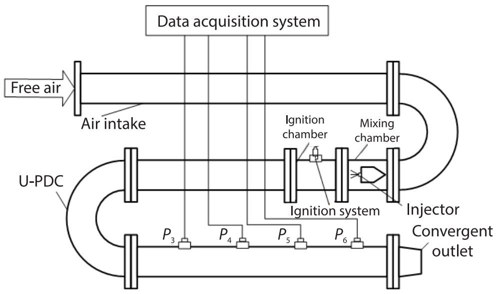


Figure 4. Schematic of the U-PDC system

The U-PDC test system and measurement method

After obtaining the injector atomization characteristics, the injector will be installed on the U-PDC for testing, U-PDC test system schematic diagram shown in fig. 4, by the inlet pipe, doping section, ignition section, U-bend detonation chamber and shrinkage injector composition. Among them, the pneumatic atomization injector installed in the head of the doping section, external atomization gas line and gasoline line. The 62 mm diameter inside the U-bend detonation chamber, the equivalent length of 726 mm. The distance between the front of the detonation chamber and the ignition position is 38 mm. Intermittent supply method to control the flow of gasoline in the test, the use of non-valve adaptive way to control the supply of air. The gasoline is mixed in the mixing section with the air-flowing in the air inlet duct to form a combustible mixture through the spray field formed by the pneumatic atomization injector and subsequently fills the U-bend chamber. The ignition section uses a hot jet ignition ignite the combustible mixture; the flame is accelerated by a Shchelkin spiral installed in the U-bend chamber to form a shock wave that travels outward through the constriction nozzle.

In order to detect the impact of different pneumatic atomization injectors on the detonation characteristics of the PDC, four piezoelectric sensors P_3~P_6 (SINOCERA CYD-205, frequency response 500 kHz, measurement error ±72.5 mV/MPa) are installed in the U-PDC to measure the pressure changes within the U-bend chamber to determine whether the normal detonation, where P_6 31 mm from the exit of the U-bend detonation chamber, P_5 and P_6 distance of 57 mm, P_4 and P_5 distance, and P_3 and P_4 distance are 60 mm. Pressure sensor signal through the signal conditioner processing and access to high speed data acquisition instrument, sampling frequency of 200 kHz.

Experimental results and discussion

Injector atomization effect comparison analysis

In this paper, the Sauter mean diameter, volume-surface mean diameter, SMD [3, 2], which is commonly used in aerospace and combustion fields, is chosen as a measure of atomization effectiveness. The SMD refers to the approximation of all droplets by the diameter of an equivalent sphere with the same surface area and volume. The atomization particle size of the pneumatic atomization injector before the modification and the pneumatic atomization injector after the modification were measured by a laser particle size meter under different fuel flow rates and different atomization gas pressures, respectively. The atomization gas pressure was selected as 0.35 MPa, and the trend of atomization particle size with fuel flow rate for both injectors under the same atomization gas pressure is shown in fig. 5. The fuel flow range is 4~24 ml/s. The atomization particle size of the injector after modification ranges from 76.4-107.2 μm. The atomization particle size of the injector before modification ranges from 111.6-152.9 μm. The atomization particle size of both injectors increases with the increase of fuel flow and the trend is basically the same. At the same fuel flow rate, the atomization size of the injector before the modification is about 1.5 times of the atomization size of the injector after the modification, indicating that the injector after the modification has a greater improvement in atomization size compared with the injector before the modification; the smaller the atomization size, the easier the fuel droplets volatilize and burn, which is more conducive to the full combustion of fuel.

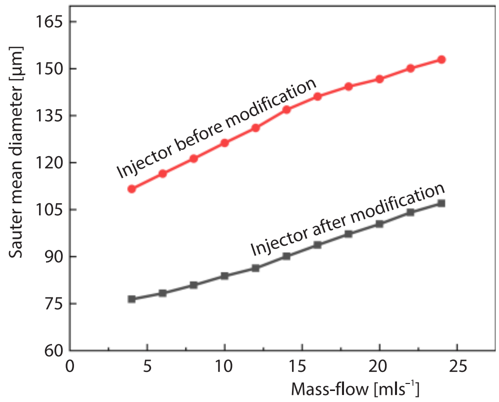


Figure 5. Trend of atomization particle size with fuel flow

The fuel-flow rate was fixed at 10 ml/s, and the atomization gas pressure was from 0.2-0.45 MPa. The trend of atomization particle size with atomization gas pressure for both injectors is shown in fig. 6. Both injectors atomization particle size decreases with increasing atomization gas pressure, but the atomization particle size of the modified injector is much smaller than that of the pre-modified injector. The U-PDC usually use the gas of the inlet section as the injector atomization gas, in order to ensure the stability of the U-PDC work, the injector needs to have a better atomization effect under different atomization gas pressure, more conducive to ensure that the U-PDC in different operating conditions can be normal ignition.

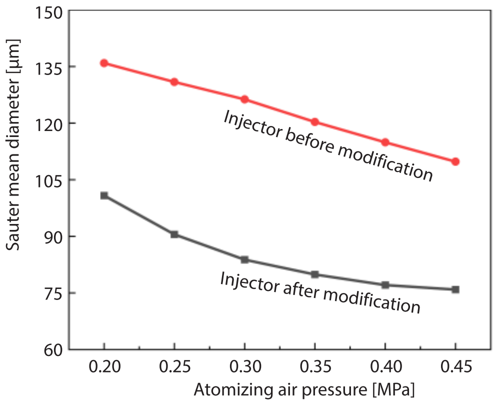


Figure 6. Trend of atomization particle size with atomization gas pressure

By analyzing the change trend of injector atomization particle size with fuel flow and atomization air pressure, we can find that the changing trend of atomization particle size of the two injectors is basically the same. Due to the simple internal structure of the injector before the modification, it does not produce large flow resistance loss, the fuel droplets have a high speed after being sprayed through the eight spray holes of the injector before the modification, and cannot be fully spread within a short distance. While the orifice plate structure inside the injector after the modification can play a breaking effect on the fuel, and produce a large flow resistance, so that the spraying distance through the injector after the modification is shortened. Finally, the circular slit outlet of the modified injector ejects the atomized droplets inside the injector, and then uses the speed difference between the injector and the outside air to further break the droplets, thus forming a better atomization effect and a circumferential uniform spray field, and the overall atomization particle size of the injector after modification is about 33% smaller than that of the injector before modification.

The U-PDC detonation characteristics comparison analysis

The C-J detonation parameters of mixtures can be obtained by the chemical equilibrium application (CEA) calculation developed at NASA Lewis Research Center, but the software can only calculate the C-J parameters of gaseous fuels. Because of the complexity of gasoline components and the similarity of *n*-octane and gasoline properties, *n*-octane was chosen for this paper instead of gasoline calculation. In the gas C_8H_{18}/air mixture pressure 0.1 MPa, temperature 300 K, the calculated C-J detonation pressure, C-J pressure wave velocity of 1.88 MPa and 1793 m/s, respectively. But the actual two-phase detonation involves liquid fuel volatilization, atomization mixing and other issues, while the Shchelkin spiral inside the detonation chamber caused by the flow loss and avoid heat loss will be on detonation C-J parameters, so the detonation pressure and detonation wave velocity of the test value is usually lower than the theoretical value of C-J calculated by the CEA program. For gasoline/air two-phase detonation, the detonation wave speed is not less than 65% of the calculated value, that is, 1130.4 m/s, and the detonation pressure is greater than the C-J calculated value as the basis for determining whether to generate a detonation [16, 17] . The speed of the test detonation wave can be calculated by the time difference between the two piezoelectric sensors P_5 and P_6 than the two sensors feel the detonation pressure detonation. If the calculated detonation wave speed to meet the requirements, define the distance from the ignition location the location of the detonation wave generation as the DDT distance.

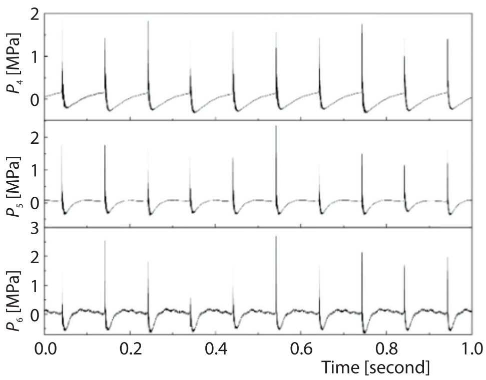


Figure 7. Pressure history of U-PDC using injector before modification at 10 Hz

Figures 7-9 shows the pressure variation curves of U-PDC using the injector before the modification at the operating frequency of 10~30 Hz. At an operating frequency of 10 Hz, the detonation pressure at P_4 is between 1 MPa and 2 MPa, and the detonation pressure at P_5, P_6 are greater than the theoretical value of the C-J detonation wave. As the wave velocity between P_4 and P_5 and P_5, and P_6 are 759.5 m/s and 890.6 m/s, respectively, which is less than 65% of the C-J detonation wave velocity, it is believed that the fully developed detonation wave is not formed at 10 Hz.

In the operating frequency of 20~30 Hz, detonation pressure at the P_4, P_5, P_6 are greater than the theoretical value of the C-J detonation wave. In the operating frequency of 20 Hz, P_5 and P_6 between the wave speed of 1117.6 m/s, close to 65% C-J detonation wave speed, that at P_6 has formed a fully developed detonation wave, DDT distance of 733 mm.

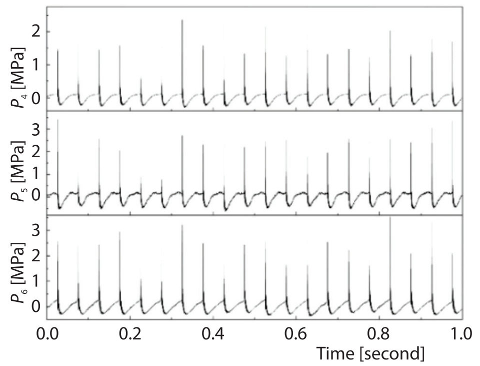


Figure 8. Pressure history of U-PDC using injector before modification at 20 Hz

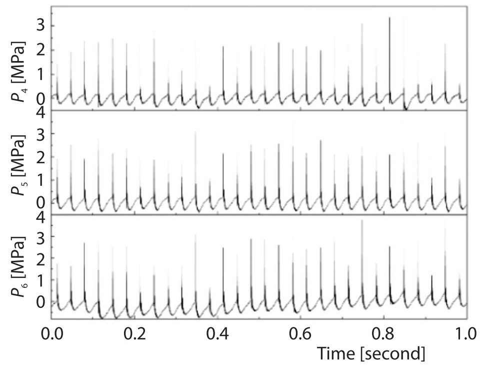
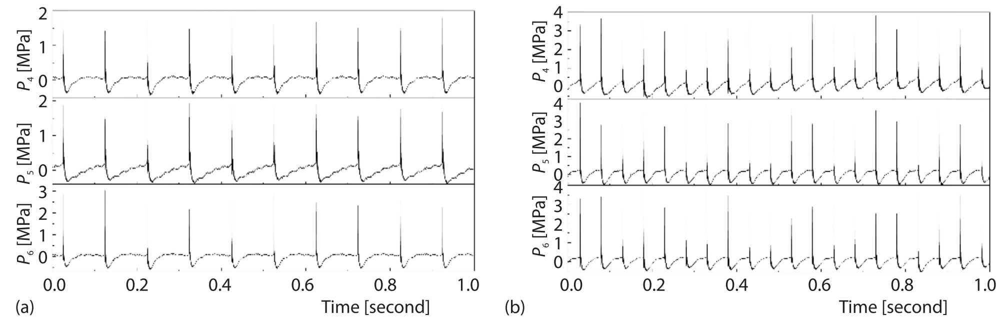


Figure 9. Pressure history of U-PDC using injector before modification at 30 Hz

compared to low operating conditions, the PDC wall temperature is higher, and U-PDC within the air-flow filling speed becomes larger, more conducive to flame propagation, more likely to form a sustained development of the detonation wave. The U-PDC in the operating frequency of 30 Hz, at the P_5 sensor has formed a fully developed shock wave, DDT distance of about 676 mm.

Figure 10 shows the pressure variation curve of the U-PDC using the modified injector at the operating frequency of 10~30 Hz. The U-PDC with injectors before and after modification has the same fuel flow rate at the same operating frequency, and a fixed atomization air pressure of 0.35 MPa. As shown in the figure, in addition the detonation pressure at P_4 at 10 Hz between 1 MPa and 2 MPa, the rest of the detonation pressure at different sensors at different operating frequencies are greater than the theoretical value of the C-J detonation wave. In the range of 15 Hz to 30 Hz using the modified injector U-PDC are stable operation and DDT distance from 733-616 mm.



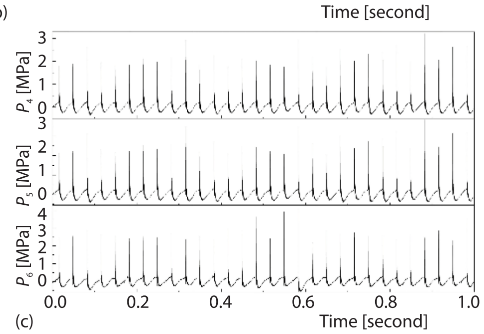


Figure 10. Pressure history of U-PDC using injector after modification at 10~30 Hz

The single detonation pressure waveforms at P_6 for the U-PDC with the modified injector at 10~30 Hz under the same incoming flow conditions and the same fuel flow rate are shown in figs. 11-13. At operating frequencies of 10~30 Hz, the detonation pressure at P_6 of the U-PDC with the injector after modification is 2.93 MPa, 3.65 MPa, and 3.76 MPa, respectively, which is 10~20% higher than that of the U-PDC with the injector before modification, indicating that the smaller fuel atomization particle size is conducive to full combustion of fuel and thus faster formation of fully developed detonation waves.

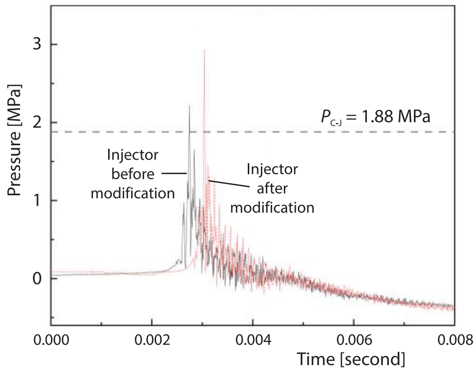


Figure 11. Comparison of single detonation pressure wave of U-PDC using different injectors at 10 Hz

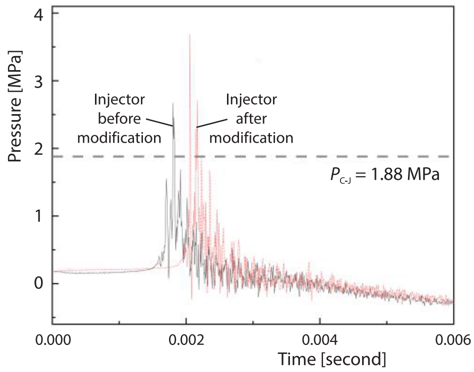


Figure 12. Comparison of single detonation pressure wave of U-PDC using different injectors at 20 Hz

Figure 14 shows the trend of the detonation pressure at P_6 with the fuel flow rate when the operating frequency is 10 Hz and the gas supply is constant. With the increase in fuel-flow, U-PDC fuel to gas ratio increases, P_6 at the detonation pressure shows a trend of first increase and then decrease. As shown in the dashed box, in a certain amount of air supply, the highest value of the detonation pressure at P_6, the detonation is selected to appear around 0.5 second time to take the average of the fuel-flow, that in the current operating conditions, the average detonation pressure under the fuel volume is higher.

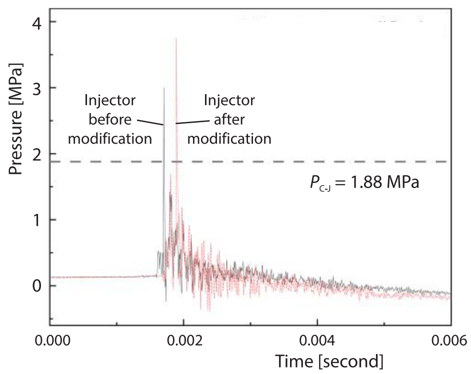


Figure 13. Comparison of single detonation pressure wave of U-PDC using different injectors at 30 Hz

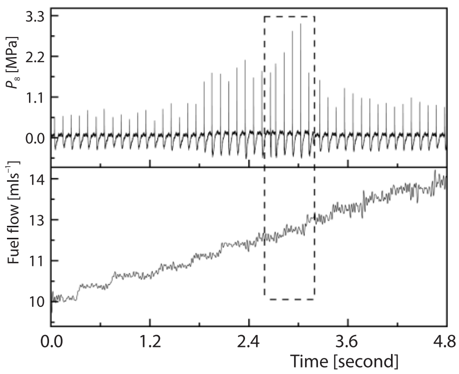


Figure 14. Detonation pressure changes with fuel-flow at 10 Hz

Figure 15 shows the comparison of U-PDC fuel flow rate with two injectors under the same incoming flow conditions and higher average detonation pressure at different operating frequencies. It is found that the fuel flow rate of U-PDC with injector after modification is 5~10% smaller than that of U-PDC with injector before modification at the same operating frequency, mainly because the atomization effect of modified injector is better than that of pre-modified injector. Under the same incoming flow conditions, U-PDC to achieve the same working condition requires fuel release energy is fixed. Fuel through the atomized droplets formed by the injector before modification particle size is large, large particles cannot be completely broken evaporation will lead to part of the fuel is not involved in combustion is discharged. Fuel through the injector after modification atomization form a better quality, more uniformly distributed spray field, the fuel is easier to evaporate to participate in combustion, and the corresponding U-PDC requires lower fuel flow to achieve the same working condition, so the modified injector helps to reduce the fuel consumption rate of U-PDC.

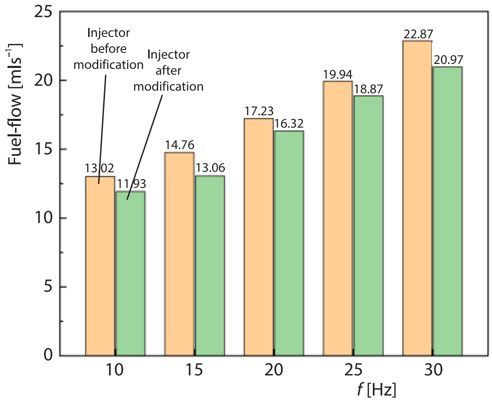


Figure 15. Comparison of U-PDC fuel-flow rate with different injectors

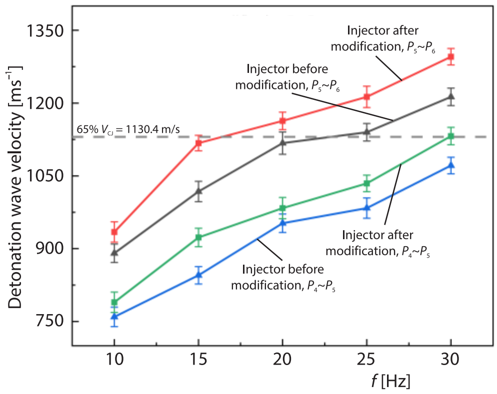


Figure 16. Detonation wave velocity under different working frequency

The U-PDC with the modified injector before and after the change in P_4, P_5, and P_5, P_6 detonation wave velocity with frequency is shown in fig. 16. Compared with the U-PDC with the injector before modification, the overall detonation wave velocity of the U-PDC with the injector after modification increases and the stable operating range becomes wider. At the same operating frequency, the fuel flow in a certain range, the modified injector atomization particle size is smaller, the fuel is easier to evaporate and participate in the combustion. At the same time smaller atomization particle size reduces the flame propagation process consumed in the atomization of evaporated fuel energy, which is conducive to accelerating the formation of the detonation wave. With the increase in operating frequency, the use of modified injector before and after the U-PDC in P_4, P_5 and P_5, P_6 detonation wave velocity are increased, which is due to the combustible mixture filling time is shortened, the filling speed increases, the turbulence of the filling air-flow increases in favor of flame propagation.

The same operating frequency U-PDC using a modified before and after the DDT distance comparison is shown in tab. 1. Due to the operating frequency of 10 Hz detonation chamber air-flow filling speed is low, turbulence is small, the wall temperature is not high, the U-PDC detonation wave speed using a modified injector before and after are to achieve 65% C-J detonation wave speed. In the operating frequency greater than 15 Hz, due to the modified injector has a better atomization effect, so at an operating frequency of 15 Hz, U-PDC in the use of modified injector can form a fully developed shock wave and DDT distance of about 733 mm. with the increase in fuel flow and air-flow turbulence in the PDC to enhance, the fuel droplets in the detonation chamber more uniform distribution, due to the injector after modification atomization of the formation of fuel droplets smaller particle size, the formation of a more uniform spray field, which is conducive to the full evaporation of fuel, combustion, more conducive to the formation and development of detonation waves. In the operating frequency of 20~30 Hz, U-PDC has a wider stable operating range when using the modified injector, and the DDT distance is shortened by 8.9% compared to the pre-modified injector.

Table 1. The DDT distance under the same working frequency of U-PDC using different injectors

Frequency [Hz]	Injector before modification DDT distance [mm]	Injector after modification DDT distance [mm]
10	–	–
15	–	733
20	733	676
25	676	676
30	676	616

Conclusions

In order to optimize the atomization effect of the injector used in the U-PDC and shorten the DDT distance, this paper carried out a design study of the pneumatic atomization injector modification, and analyzed the atomization effect of the pneumatic atomization injector under different conditions before and after the modification, as well as the effect of the injector on the gasoline/air U-PDC detonation characteristics before and after the modification, and the conclusions are as follows.

- After the modification of the injector atomization particle size range of 76.4-107.2 μm, before the modification of the injector atomization particle size range of 111.6-152.9 μm, after the modification of the pneumatic atomization injector under the same conditions of the atomization droplet particle size is smaller than the atomization droplet particle size of the pneumatic atomization injector before the modification. Its atomization effect is better and more conducive to fuel combustion.
- As the operating frequency increases, the DDT distance of the U-PDC with both injectors before and after the modification is shortened. The DDT distance of the U-PDC with the pre-modification injector is shortened from 733 mm to about 676 mm, and the DDT distance with the post-modification injector is shortened from 676 mm to about 616 mm due to the better atomization effect of the post-modification injector.
- The same incoming flow conditions and blast chamber operating conditions using the modified injector of the U-PDC fuel flow than the U-PDC using the modified injector in the same state of the U-PDC fuel flow is 5%-10% smaller. Fuel atomization particle size through the injector is smaller, easier to break, evaporate and participate in the combustion and fuel atomization particle size through the injector before the modification is larger, resulting in incomplete combustion.

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