Effect of Rehydration Ratio and Inlet Pressure on Shock Wave Focus in Hemispherical Concave Cavity

Wenrui Peng*

Science and Technology on Plasma Dynamics Laboratory, Air Force Engineering University, Xi’an, China, 710038

*Corresponding author: 3140103347@zju.edu.cn

Abstract. Shock wave focus is a phenomenon where energy is rapidly converged in a small area of the medium through the interaction of shock waves, resulting in extremely high temperature and pressure near the aerodynamic focus. Experimental and numerical studies are in progress using the high energy area generated by shock wave focus to induce detonation to study shock wave focus phenomenon, the experiments of shock wave focus in the hemispherical concave cavity was carried out. The emphasis is placed on the effect of ring vent width and inlet pressure. By comparing the peak pressure at the bottom of the concave cavity under different ring vent widths, it was found that the reflection of the incident shock wave formed in the channel decreased with the width of the ring vent as well as the intensity of the shock wave increased. The greater the intensity, the more likely it is to produce the focusing of the shock wave. When the subsonic speed airflow flowed into the cavity through the ring vent, it was found that under the influence of the reflection of the concave cavity and complex motion of shock wave, a local high temperature and high pressure area was formed. By comparing the pressure spectrum at the bottom of the concave cavity under different flow pressures, it was found that with the increase of the flow pressure, there were two whistling modes on the spectrum map, C1 and D1 modes, respectively. It was also found that the pressure pulsation in the concave cavity was more disordered and the magnitude was smaller when the inlet pressure decreased, which means the shock waves were not well focused. It can be concluded that in ignition experiments, inlet pressure is significant to shock wave focusing phenomenon and there is a prompt rehydration ratio which lead to better shock wave focusing.

Keywords: Hemispherical concave cavity, shock wave focus, rehydration ratio, inlet pressure, whistling modes.

1. Introduction

Pulse Detonation Engine (PDE) is a new concept engine that uses pulsed burst waves to generate thrust [1]. PDE has the advantages of high cycle heat efficiency, simple structure and high push-weight ratio, thus is an attractive propulsion device. Nevertheless, there is little information for key issues such as high-frequency reliable burst energy source technology, long DDT distance and so on [3, 4]. For further understanding on these problems, Levin et al. [2] proposed a two-stage pulsed
detonation engine (2-stage PDE), whose fuel can be continuously injected into conventional aviation kerosene without the need of additional ignitions and mechanical valves and has very high frequencies and very short DDT distances. The core of 2-stage PDE is that oil-rich combustion products mixed with the current amount of fresh air enters the concave cavity through the circular nozzle, and the annular centripetal supersonic jet generates shock waves in the concave cavity, forming a local high temperature and high-pressure area where the detonation is direct. Accordingly, it is necessary to study shock wave focus in the hemispherical concave cavity.

Japan and the United States have also carried out the research on the shock focusing detonation induced by the central jet collision. Leyva et al. [5] found that the flow in the cavity exhibits a high frequency self oscillation characteristic. Han et al. [6] studied the shock formation mechanism and influencing factors of the jet by using the prototype of binary 2-stage PDE. In the experiment, it was proved that the ultrasonic rapid jet collision can form periodic shock focus, and it was found that when the jet pressure ratio was lower than the critical pressure ratio, the shock wave cannot be produced. He et al. [7, 8] studied the effects of jet incidence angle, exit area of concave cavity, expansion angle of tail nozzle, distance between concave cavity and jet inlet on the frequency and pressure amplitude of aerodynamic oscillation in the cavity. Ou et al. [12] studied the effect of Atwood number on shock focusing and jet formation in shock tube by using the heavy-gas cylinder formed by soap film, and collected the image of the experimental process by using high-speed Schlieren system. The results show that when Atwood number is low, the shock focusing phenomenon appears outside the cylinder, not inside.

At present, the research on shock focused detonation is still in a relatively preliminary stage. There still exist many problems, such as the lack of proper theoretical explanation to the process of shock focusing, the difficulty in capturing the generated detonation wave and the unclear evaluation index of detonation performance. Therefore, the process of shock focusing in concave cavity was studied numerically. Besides, the effect of different rehydration ratios and inlet pressures on the shock wave focusing in the concave cavity was investigated experimentally.

2. Experimental
An annular jet concave cavity shock focusing experimental system was used to investigate the shock focusing phenomena under cold and ignition conditions. Under the cold conditions, a series of physical process mechanisms, such as propagation, reflection and focusing of shock waves, are studied in this paper. Under the ignition conditions, the fuel in the oil replenishing area is pyrolyzed to produce high active pyrolysis gas with the heat from pre-combustion zone. The progress of pyrolyzed gas with high temperature and high activity entering into the concave cavity and the detonation

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Figure 1. Schematic diagram of shock wave focus.
process is studied under the action of shock wave focusing. The experimental system is composed of gas supply system, oil supply system, experimental bench, shock wave focusing test section and test and data acquisition system. The schematic diagram is shown in Figure 1.

The experimental system of shock wave focus in concave cavity is used to explore the mechanism of the physical processes, such as the propagation, reflection and focusing of the shock wave. It consists of gas source, experimental bench, cold shock wave focus experimental apparatus and data acquisition system. The schematic diagram of it is shown in Fig.2.

![Figure 2. Schematic diagram the experimental system.](image)

The air supply system can provide compressed air with certain pressure, flow rate, flow stability and dryness in the experiment. It is mainly composed of air source, air tank, safety valve, air dryer, air filter, pressure gauge, electric control valve and pipeline system. Among them, the air source is screw air compressor (as shown in Fig.2), the volume of each air tank is 6m³, the maximum air storage pressure is 25Mpa. The air supply system is specially equipped with air filtration and drying devices to ensure that the normal operation of the test sensor will not be affected by the impurities and moisture condensation in the inlet during the experiment. The oil supply system mainly supplies fuel with stable flow and pressure in the pre-combustion area and the oil replenishment area. The oil tank is pressurized by a nitrogen cylinder, and the oil in the pre-combustion area and the oil replenishment area is controlled by two valves respectively.

The experimental section consists of a shell, a rectification cone, a concave cavity and a nozzle. The rectification cone and the shell are connected by four airfoil blocks. The concave cavity is installed at the tail of the rectification cone. The contact surface is sealed by a metal seal ring. The nozzle and the shell are connected by bolts. The contact surface is sealed by a high temperature resistant rubber seal ring. The ring is changed by adding or removing a metal gasket between the nozzle and the shell Seam width. The diameter of the concave cavity used in this experiment is 70mm. There are three specifications of threaded holes at the bottom center of the concave cavity, which are used to install the dynamic pressure sensor. The location of the arrangement is the same distance distribution in the radial direction. As shown in Fig.3, the measuring points from the center to the outermost side are named as points A, B and C. the radius of the measuring points A and B is 120 degrees with the radius of the measuring points a and C. The flow process in the experimental section is shown in Fig.4.
3. Analysis of flow field

In order to deeply understand the mechanism and principles of annular jet shock wave focusing, the flow field and shock wave motion process in concave cavity are calculated on Fluent19.0, and the formation mechanism of shock wave focusing is preliminarily analyzed. Because of the axisymmetric structure of the experimental section, the model of the experimental section is simplified to a two-dimensional model.

When using Fluent19.0 software, the separated solver is selected. The realizable $\kappa - \varepsilon$ model is used as the turbulence model. The standard wall function is used as the wall function. The algorithm is time splitting algorithm and the equation discrete scheme of the second-order upwind scheme is used. The inlet is set as the pressure inlet boundary, the inlet pressure is 0.5MPa, and the inlet temperature is 300K. The inner and outer areas of the concave cavity are filled with air at a pressure of one atmosphere and a temperature of 300K. The outlet is set as the pressure outlet boundary, the outlet pressure is 0.101MPa, and the outlet temperature is 300K.

![Figure 3. Schematic diagram of three measuring points in concave cavity.](image1)

![Figure 4. Schematic diagram of air flow process in the test section.](image2)
As shown in Fig. 6, the subsonic flow supplied by the gas source flows through the rectifying cone and forms a sonic annular jet through the annular nozzle, which produces a right-hand (positive direction is to point radially to the center of the cavity, defined as right-hand) moving shock wave $S$ (called the leading main shock wave). After the shock compression, the pressure and temperature after the wave increase, and vortex is generated at both sides of the entrance of the annular jet. Due to the lateral expansion of the leading main shock in the cavity, the strength of the leading main shock decreases gradually, and a left-hand disturbance wave is formed on the leading main shock. The left-hand shock wave propagates at the speed of sound and against the air flow. Because the air flow...
behind the leading main shock wave is supersonic, the left-hand shock waves move to the downstream of the diffusion pipe driven by the supersonic air flow. In the upstream of the left-hand wave head, the air flow is accelerated continuously only by the expansion disturbance caused by the expansion of the cross-section area, which is a steady sonic flow. It will produce more and more strong squeezing effect on the air flow which is decelerating continuously in front of it, so as to produce a downstream disturbance shock waves, and it will make the original shock wave of the left line stronger and stronger. This kind of strengthening effect is most concentrated in the wave head, so the left-hand shock waves are first superposed here to form a second shock wave also known as Mach disk or suspension shock wave, and the vortices on both sides of the entrance of the annular jet also expand with the jet advancing. The second shock wave is continuously strengthened in the process of downstream propagation. At a proper position, the velocity of the second shock wave relative to the air flow moving to the left is just equal to the velocity of the air flow itself moving to the right and remains relatively static, becoming a stationary shock wave with a fixed strength.

When the annular jet collides at the central axis of the cavity, the central air flow stagnates, resulting in the increase of pressure, temperature and density. According to the shock wave dynamics, the ring shock wave will collide in the center of the concave cavity, which is similar to the collision between the shock wave and the rigid wall, and the intensity of the reflected shock wave moving in the opposite direction is the same. At the same time, under the action of the pressure difference between the central high-pressure area and the undisturbed static gas in the front, the axial jet and the axial moving shock wave are formed. The axial moving shock wave is connected with the radial reflecting shock wave, and propagates to the bottom of the cavity in a cone shape. The central high-pressure area of the cavity is continuously expanded. At the same time, the axial moving shock wave is continuously compressed and reflected by the parabolic wall, and is close to the cavity. The space at the bottom shrinks rapidly, and the shock wave converges continuously, producing high temperature and pressure at the bottom of the cavity. The high temperature and high pressure zone is strengthened by the reflection shock wave, which further increases the temperature and pressure and moves to the low pressure zone at the opening outlet. As the shock waves at bottom propagates to the open outlet, the pressure decreases and the shock wave surface becomes flat due to the diffusion of the concave cavity. Shock waves near the outside expand and accelerate because they are close to the low pressure vortex region formed by the inlet jet. Due to the expansion of the low-pressure vortex region formed by the jet entering the inlet, the pressure of the external shock waves are lower than those at the center of the concave cavity. The velocity of the outer part of the nozzle is slightly higher than that of the center part due to the effect of the inlet jet and the diffraction at the outlet.

4. Influence of inlet pressure

The energy source of shock focusing in the concave cavity is the annular jet. The pressure of the annular jet will directly affect its under expansion and flow structure, thus affecting the shock waves and shock wave focus process in the resonant cavity. The pressure of the annular jet is closely related to the inlet pressure $P_{in}$. 


In order to study the influence of the inlet pressure pin on the shock focusing process in the concave cavity, the width of the ring vent was fixed at 4.1mm, the diameter of concave cavity is 70mm. The experiments were carried out under the conditions of the inlet pressure are 0.4MPa, 0.45MPa, 0.5MPa, 0.55MPa and 0.6MPa respectively. The experimental results are shown in Fig.8 (a)-(e). Generally speaking, the radiation noise of annular jet consists of three components: turbulence mixing noise, whistling noise and broadband shock wave related noise. It is known that in the radiation noise of the annular jet, only the whistling and broadband shock wave related noise are related to the shock wave. Therefore, in the analysis these two kinds of noise are discussed. It can be seen that there are a large number of noises in the low-frequency section under each inlet pressure.
condition. According to the known literature [13, 14], it is believed that these noises are mainly turbulence mixing noises, which usually appear in the low-frequency section and occupy a wide frequency band, covering the frequency band of 1kHz~3kHz, all these noises exist in the whole inlet pressure range, and the frequency is relatively stable. When the inlet pressure is 0.45MPa<P_{in}<0.6MPa, there is only one kind of whistling mode, its basic frequency is about 8700Hz, which is called C1 mode whistling in this paper. It has been known that one of the most important characteristics of whistling mode reflected in the spectrum is that it is often accompanied by harmonics, and sometimes even carries fourth or fifth harmonics [15, 16]. The second harmonic of C1 mode can be observed in the spectrum. It can be observed that the frequency of C1 mode whistling decreases with the increase of the inlet pressure. According to the small disturbance feedback amplification mechanism proposed by Powell [10], with the increase of the inlet pressure, the size of shock cell increases [11], and the acoustic feedback loop becomes longer, so the whistling frequency decreases. The basic frequency of wide-band shock related noise is slightly higher than that of squeal, and the frequency occupied is wider than that of squeal, and narrower than that of turbulent mixing noise. As shown in Fig.8 (a), the noise represented by the frequency bands near 10894Hz and 12499Hz is broadband shock wave related noise. In addition, it is composed of many uneven peaks with wide and flat background noise. When the inlet pressure P_{in} is less than 0.45MPa, the stable C1 mode whistling can not be observed from the spectrum, and the main noise is the broadband shock wave related noise. This may be due to the low pressure of the inlet, resulting in the insufficient energy of the annular jet to form a howl. When the inlet pressure increases to 0.6MPa, a new whistling mode can be observed from the spectrum. The basic frequency increased to 13002Hz, which is called D1 mode whistling. The reason of D1 mode whistling may be that the vibration of the jet collision surface and strong disturbance produced by the large instability wave of resonance. The disturbance draws energy from the larger instability wave, so the higher frequency whistling mode is excited.

![Figure 8. Comparison of pressure peaks at A, B and C points.](image)

The pressure data of point B and point C were also collected in the experiment, and the peak value of pressure fluctuation was compared with point A. It can be seen that when P_{in}<0.45MPa, the pressure peak value is generally low. Due to the insufficient energy of the inlet flow, intensity of shock wave caused by annular jet entering the concave cavity is not high enough and the compression of the air flow is insufficient. Therefore, pressure at the bottom of the concave cavity is not high enough and a high-pressure area was not formed. When inlet pressure is 0.5MPa, the value of pressure peak at the three points had a significant increase, it shows that when the inlet energy reached a certain value, through the complex motion of the shock waves in the concave cavity, a high-pressure and high-temperature area is formed at the bottom of the cavity due to the compression effect, which eventually increases the value of pressure peak. It can be seen from Fig.9 that the value of pressure peak reaches maximum when inlet pressure is 0.5MPa. When the inlet pressure continues to increase,
the pressure peak at the bottom of the concave cavity does not rise but falls, which shows that there is an optimal value of the inlet pressure that leads to the best effect of the shock wave focus in the concave cavity.

![Fluctuation of pressure signal at the bottom of cavity](image)

**Figure 9.** Fluctuation of pressure signal at the bottom of cavity when the inlet pressure $P_{in}=4\text{bar}$ and $P_{in}=5\text{bar}$.

With the inlet pressure decreases, the pressure fluctuation amplitude at the concave cavity bottom decreases from 1.8MPa to 0.2MPa. When the inlet pressure dropped below 0.45MPa, as shown in Fig.10 (b), the amplitude of pressure fluctuation decreases sharply. From the local enlarged figure of the corresponding inlet pressure, it can be seen more clearly that the pressure fluctuation becomes small and disorderly. This may be due to the fact that the energy of the annular jet is not enough to form a stable whistle mode when the inlet pressure is low. The main noise forms in the concave cavity is turbulence mixing noise and shock wave related noise in a wide frequency band, resulting in a small and disordered pressure rise at the bottom of the cavity.

5. Shock wave focusing test with ignition

In this paper, the test with ignition was carried out by means of pre-combustion and pyrolysis. The fuel was aviation kerosene RP-3. An experimental study was carried out to investigate the influence of the change of the oil replenishment ratio on the shock wave focusing at the bottom of the concave cavity by changing the size of the oil replenishment flow rate. In the experiment, a 90mm concave cavity was used, and the optimal width of the annular nozzle was selected. The variation curve of the incoming flow pressure was shown in Fig. 10.

![Change of inlet pressure](image)

**Figure 10.** Change of inlet pressure.
Because the inlet pressure is kept constant, that is, the mainstream flow rate remains unchanged, and the premixed oil flow rate remains unchanged, the equivalence ratio of the pre-combustion zone is basically unchanged, and the heat provided by the pre-combustion flame to the refueling zone is basically unchanged. Due to the offset of fuel nozzle at the beginning of injection, the equivalence ratio is high at the beginning (the same problem exists in the fuel replenishment ratio, and the same treatment method is adopted). The stable section should be selected for research (the slightly rich oil state is used for research in the experiment). The change of total equivalent ratio in the experiment is shown in Fig.11. In front of the annular nozzle, the aviation kerosene is thermally cracked by the heat of the pre combustion flame, and the pyrolysis gas with high activity is obtained. The pyrolysis gas enters the concave cavity through the annular nozzle and ignites and detonates under the action of shock wave focusing. The oil replenishment under various working conditions is shown in Fig.12.

Figure 11. Variation of total equivalence ratio under various working conditions.

Figure 12. Change of make-up oil ratio under various working conditions.

Figure 13. Pressure change at the bottom of concave cavity.
As shown in Fig.13, the pressure at the bottom of the concave cavity has no change in the first four working conditions, but a large pressure rise appears in the fifth working condition. It can be seen from Fig.10, Fig.11 and Fig.12 that the variation trend of incoming pressure is basically unchanged in the first four working conditions, which is about 0.75MPa; the pressure in the fifth working condition increases to 0.863mpa; the total equivalent ratio increases from 1.4 to 1.8; and the oil replenishment ratio increases from 4.85 to 6. According to the change trend of the bottom pressure of the concave cavity, the total equivalence ratio and the oil replenishment ratio have little effect on the bottom pressure of the concave cavity. The preliminary analysis may be due to the fact that the pyrolysis temperature of the refueling zone is basically constant when the equivalence ratio of the pre-combustion zone remains unchanged. Under the existing fuel replenishment ratio, the thermal cracking degree of the fuel has been saturated, even if the oil replenishment ratio is increased, it will not be further improved. The thermal cracking degree of kerosene and the cracking effect of fuel can not be further improved, and the pyrolysis temperature may not rise enough due to the excessive amount of oil replenishment, which weakens the shock wave focusing effect in the concave cavity. It can be seen from Fig.13 that the pressure at the bottom of concave cavity decreases under the first four working conditions. In fifth condition, when the inlet pressure increases to 0.863MPa, the pressure at the bottom of the concave cavity increases rapidly. It can be concluded that the pressure has a significant impact on the pressure at the bottom of the concave cavity. This is because the inlet pressure will affect the temperature and pressure of the local high temperature and pressure zone formed by the shock wave focusing at the bottom of the concave cavity, and then affect the initiation effect.

6. Conclusion
In this paper, based on the dynamic pressure changes at the bottom of the concave cavity during the shock wave focus process measured in experiments, the focus process of shock wave in hemispherical concave cavity is studied from two aspects: ring vent width and inlet pressure.

(1) The subsonic airflow enters the concave cavity through the annular nozzle. Under the reflection of the concave cavity and the action of complex shock waves, a high-pressure and high-temperature region will be formed;

(2) The reflection of the incident shock wave in the channel increases with the decrease of the ring vent width. The greater the intensity of the incident shock wave is, the easier to acquire focused shock wave.

(3) When the inlet pressure is 0.45MPa<P_{in}<0.6MPa, there is only one kind of whistling mode, called C1 mode whistling, the basic frequency is about 8700Hz. It can be observed that the frequency of C1 mode whistling decreases with the increase of the inlet pressure. When the inlet pressure increases to 0.6MPa, a new whistling mode can be observed from the spectrum. The basic frequency rises to 13002Hz, which is called D1 mode whistling;

(4) In the hot state experiment, the inlet pressure has a significant effect on the pressure at the bottom of the concave cavity, and there may be an optimal value of the oil replenishment ratio to make the shock wave focus better at the bottom of the concave cavity. The equivalence ratio and the oil replenishment ratio should not be too large, otherwise the shock wave focusing initiation effect will be affected.

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