KEY TECHNOLOGIES OF TWO-PHASE PULSE DETONATION COMBUSTOR

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The pulse detonation combustor is a new type of power device based on periodic high-temperature and high-pressure gas generated by detonation combustion as thrust. Due to its extremely fast heat release rate, detonation combustion has the characteristics of high thermal efficiency, low fuel consumption and low pollutant emissions. In recent years, relevant institutions have conducted extensive research on pulse detonation combustors. However, most research results focus on single studies where the fuel and oxidant are in the gas phase. Based on the vision of engineering application of pulse detonation combustors, the research progress of two key pulse detonation technologies, fuel atomization blending technology and rapid short-distance low-resistance detonation technology, as well as the research status of two-phase pulse detonation combustion based on kerosene are introduced. Regarding fuel atomization and blending technology, this paper mainly introduces the fuel atomization mechanism of two-phase detonation, fuel atomization technology and oil and gas blending technology. Regarding rapid short-distance low-resistance detonation technology, it mainly introduces obstacle-assisted detonation technology, spark plug ignition technology, hot jet ignition technology, pre-detonation tube ignition technology, shock wave focusing detonation technology and plasma ignition technology.

Key words*: pulse detonation; two phase; atomization blending;ignition; kerosene*

1. Introduction

The Pulse Detonation Engine (PDE) is a new jet propulsion system based on periodic high-temperature and high-pressure gas generated by detonation combustion as thrust[1]. Compared with traditional propulsion devices based on isobaric combustion, the extremely fast heat release rate of the detonation wave makes the detonation combustion process close to isovolumetric combustion. Therefore, PDE has high thermal efficiency, low fuel consumption and low pollutant emissions. In addition, due to the self-supercharging effect of detonation combustion, the engine structure can be greatly simplified and the PDE can fly at a wider flight Mach number. It is one of the ideal propulsion power systems for complex flight environments in the future. In recent years, it has received widespread attention from all over the world[2-6].

Compared with other forms of detonation propulsion technology, the current technological maturity of pulse detonation engines is relatively high. Depending on whether it carries oxidizer, PDE can be divided into Air-Breathing Pulse Detonation Engine (APDE) and Pulse Detonation Rocket

Engine (PDRE). According to different uses, air-breathing pulse detonation engines can be divided into pure pulse detonation engines, combined pulse detonation engines and pulse detonation turbine engines .

No matter which type of PDE, its core power device is the Pulse Detonation Combustor (PDC). The pulse detonation combustor generally consists of a mixing section, an ignition section and a detonation transition section. Fuel and high-pressure air are mixed in the mixing section, and after passing through the ignition section, rapid short-range detonation is achieved in the detonation transition section. A detonation combustion cycle is shown in Fig 1, which mainly includes: (1) filling of fuel and oxidant; (2) ignition; (3) generation and propagation of detonation waves; (4) expansion and exhaust; (5) scavenging ; (6) Fill the fuel and oxidant again and enter the next detonation combustion cycle. Compared with isobaric combustion, the organizational process of pulse detonation combustion is more complex and difficult.

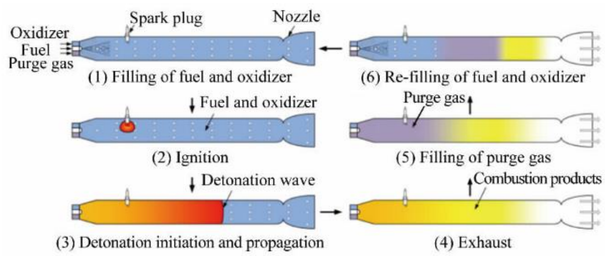

Fig.1 Detonation combustion working cycle diagram

In recent years, relevant institutions have conducted extensive research on pulse detonation combustion, but most of the research results focus on single studies where the fuel and oxidant are in the gas phase[7-11]. Compared with gas-phase detonation, researchers know less about two-phase pulse detonation combustors using liquid hydrocarbon fuel, and their early focus was mostly on the final propagation speed of the detonation wave[12-17]. However, due to the limitations of engine weight and length, in actual propulsion systems, the pulse detonation combustor must use liquid fuel with higher energy density and better storage performance. Compared with gas-phase detonation, two-phase detonation combustion has a very narrow detonation limit and a larger wave speed loss. The atomization and mixing of fuel, the organization of detonation combustion, the design of the ignition device and the arrangement of obstacles will all have an important impact on the performance of the pulse detonation combustor.

This article mainly introduces the research progress of two pulse detonation combustion technologies, fuel atomization blending technology and short-distance low-resistance detonation technology, as well as the research status of pulse detonation combustors based on kerosene fuel, laying the foundation for subsequent two-phase pulse detonation combustors.

2. Two-phase detonation atomization technology

In actual engineering applications, pulse detonation engines are limited by volume and weight, so they need to use liquid fuel with small volume and high density. When using liquid fuel, it is necessary to go through the process of fuel atomization, evaporation and blending, so that before ignition, the detonation chamber is filled with a well-atomized, fully mixed and evenly distributed explosive mixture within the explosive range[18]. Since the working process of the pulse detonation engine is unsteady, the filling time is very short when operating at high frequency, which poses huge challenges to the injection, atomization, evaporation and gas mixing of liquid fuel. In addition, the size and distribution of the initial fuel particles not only have a great impact on fuel evaporation and gas-liquid mixing, but also affect the initial reliability and subsequent DDT process. Therefore, it is of great significance to carry out research on the principle of two-phase detonation fuel atomization blending characteristics and key application technologies to deepen the understanding of the two-phase detonation mechanism and promote the engineering application of pulse detonation[19].

2.1. Two-phase detonation atomization technology

At the beginning of the 1960s, researchers began to study the mechanism of two-phase detonation atomization. In the early days, due to limitations of technical level, researchers' research on the two-phase atomization mechanism mainly focused on the construction of two-phase models and the impact of droplet size on wave speed loss.

Williams[20] studied the two-phase detonation process with reference to the ZND model. The research results show that only when the fuel evaporation rate is high enough and the fuel particle diameter is less than 10 μm, a stable and self-sustaining detonation wave can be formed. However, Webbert[21] and Cramer[22] pointed out that detonation can also be achieved. When the diameter of the fuel particles is large, and a large equivalence ratio is conducive to the self-sustaining propagation of the detonation wave. In the studies of Ragland and Debora[23-25], it was further confirmed that the droplet diameter directly affects the size of the two-phase detonation wave speed. The larger the droplet diameter, the greater the loss of the two-phase detonation wave speed. The wave speed mentioned here was calculated based on the ideal premixed gas phase detonation. They believe that after using liquid fuel, the width of the chemical reaction zone becomes larger, which will increase the heat dissipated by wall heat exchange, thus causing the two-phase detonation wave speed to decrease.

Some scholars also believe that wall heat dissipation is not the only cause of wave speed loss. The two-way propagation of detonation waves[26] and incomplete combustion of fuel[27] will all lead to an increase in wave speed loss. With the rapid development of computational fluid dynamics, researchers have used numerical simulation methods to further study the two-phase detonation fuel atomization mechanism. In the studies of Bowen[28] and Cheatham[29-30], it was found that when the diameter of the fuel particles is small enough, the detonation processes of two-phase detonation combustion and gas-phase combustion tend to be consistent.

2.2. Research on two-phase detonation atomization technology

Fuel atomization is the key to the successful detonation of two-phase pulse detonation. The smaller the initial diameter of the fuel particles, the larger the total surface area of the oil droplets, and the faster the fuel evaporates, the faster the exploding gas mixture can be formed within the limited filling time. Therefore, the design and selection of the fuel nozzle for the two-phase pulse detonation engine is very important. During the combustible mixture filling stage, it is not only necessary to ensure fast and efficient atomization of the fuel, but also to achieve the matching of the oil mist field and flow field in the detonation chamber. It meets the requirements for stable and reliable detonation of the engine in multiple cycles.

Brophy and Netzer[31] designed four different detonation devices to enhance the atomization effect of fuel during the two-phase detonation process. Research results show that better results can be achieved by using a combined structure of annular cavity and expanded steps on the head. Nabity[32-33] proposed that microelectromechanical technology (MEMS) can be used to build an atomizer structure with a scale of several microns to obtain very fine droplet atomization.

Northwestern Polytechnical University has conducted early research on two-phase detonation fuel atomization. Wang[34-36] conducted research on the effects of direct injection nozzles and pneumatic atomization nozzles on the atomization characteristics of gasoline and air two-phase pulse detonation engines. The results show that the atomization effect of the air-assisted atomizing nozzle is better than that of the direct-injection nozzle. The atomization effect of the detonation chamber using the pneumatic nozzle is 2 to 5 times higher than that of the detonation chamber using the direct-injection nozzle. In addition, they found that fuel atomization particle size affects the equivalence ratio of the detonation chamber for reliable detonation. The oil-gas equivalence ratio is directly proportional to the change in atomized particle size, and its value is generally greater than 1.

Zhang[37] conducted a head fuel atomization test study on the influence of head geometric parameters on the secondary atomization of a gasoline and air two-phase rocket pulse detonation engine, and compared it with the direct-injection fuel nozzle used in the experiment. The research results show that the head geometry has a significant impact on the secondary atomization process of fuel in the detonation chamber. The change pattern of SMD with fuel flow rate is opposite to that of direct-injection fuel nozzles that directly inject into the air, but the measured value of SMD is much lower than that of direct-injection nozzles.

Zhang[38] used his self-designed flash evaporation system (FVS) to heat the fuel temperature above the boiling point, causing it to undergo a phase change the moment it is ejected from the nozzle. The results show that this method can effectively improve atomization. Tan[39-40] studied the detonation characteristics of a single-tube pulse detonation combustor under different intake air temperatures. The test system is shown in Fig 2. Research results show that when the intake air temperature increases, the atomization and evaporation of gasoline are significantly improved.

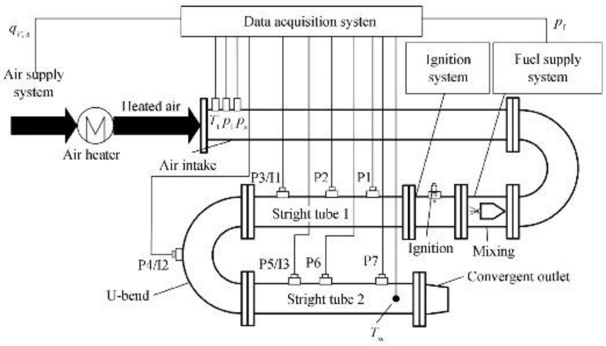

Fig.2 Schematic diagram of U-PDC test system

Jiang[41] from Nanjing University of Science and Technology used numerical simulation methods to study the influence of nozzle structural parameters such as side air injection angle, air channel diameter, mixing chamber outlet aperture and other parameters on the atomization effect of two-phase detonation fuel, which provides a basis for the optimal design of the pulse detonation combustor nozzle. Starting from the fuel supply requirements of pulse detonation engines, Zeng[42] carried out a study on the pressure-flow relationship of a new type of nozzle designed by herself through a combination of experiments and numerical methods. The results show that the designed centrifugal nozzle meets the working needs of the two-phase pulse detonation combustor.

Chen[43] used the VOF method to numerically simulate the cavitation flow characteristics inside the nozzle. The oil mist change process at the initial moment of fuel injection and the effects of air speed and gas-liquid ratio on liquid film breakup were analyzed. The mechanism of fuel-air assisted atomization in pulse detonation engine was clarified. Wu[44] of Nanjing University of Aeronautics and Astronautics designed an acoustic atomizer that can effectively reduce the atomization size and achieve multi-cycle detonation.

2.3. Research on two-phase detonation oil and gas blending technology

Researchers have also conducted a lot of research on the design of blending structures to enhance oil and gas mixing. Wang[45] conducted a numerical study on the influence of three air intake modes of the head, axial, radial, and tangential, on the mixing flow characteristics of gasoline/air two-phase PDC. Research results show that each of the three air intake methods has advantages and disadvantages. Tangential air intake can enhance mixing, but uneven distribution of oil and gas may lead to difficulty in detonation and the inability to achieve higher frequencies. The axial and radial air intake methods have relatively uniform oil and gas distribution, but poor mixing, which is not conducive to the transition from deflagration to detonation.

Gong[46] from Sun Yat-sen University through experimental research found that the use of mixing enhancement devices (such as orifice plates and reed valves) can effectively improve fuel distribution and reduce the impact of incoming flow on uniformity. Jiang[47-48] found that when the filling speed is accelerated, axial air intake is more conducive to droplet atomization and two-phase mixing than radial air intake, and the ignition and detonation distance and time are shortened. They used numerical simulation methods to study the influence of the venturi tube on the atomization mixing and detonation process in the pulse detonation combustor. The results show that the venturi tube has a significant promoting effect on the fuel atomization and two-phase mixing process, and thus significantly shortens the DDT distance and time. In addition, they also found that the DDT distance and time were shortest when the fuel nozzle was installed at the throat of the venturi. Guo[49] conducted a study on the effects of equivalence ratio and bluff body plugging ratio on fuel atomization and two-phase mixing for the atomization system of pneumatic valve-type PDE. The results show that when the fuel-gas ratio is at the stoichiometric ratio, the high-speed airflow at the throat is conducive to fuel atomization, but it will increase the ignition fuel-gas ratio. They pointed out that increasing the fuel-air ratio is beneficial to the atomization and mixing of fuel and the distribution of explosive mixtures in the detonation chamber. In addition, the bluff body maintains a certain blocking ratio, which is beneficial to atomized mixing. However, an excessive plugging ratio will affect the oil and gas distribution at the wall spark plug.

3. Rapid short-distance low-resistance detonation technology

Rapid short-distance low-resistance detonation is the key core technology of all detonation engines. In the actual working process, it is difficult to achieve direct detonation, that is, high energy to directly trigger the detonation wave. Generally, a weak spark is used to initiate slow combustion, and the transition from slow combustion to detonation is achieved through flame acceleration, which is the DDT process. How to achieve flame acceleration to complete the DDT process and quickly detonate two-phase fuel with short distance and low resistance is the core key technology in the design of pulse detonation combustor. This section mainly introduces the research progress of obstacle-assisted detonation technology and ignition technology in two-phase detonation combustion in recent years, providing reference for the design of two-phase pulse combustor.

3.1. Obstacle-assisted detonation technology

In the DDT process, in order to achieve flame acceleration and detonation wave transformation, some detonation-assisted devices are often required, such as orifice plates, spirals, shock wave reflectors, etc. The operating frequency of the vibration engine lays the foundation.

As early as the 1940s, Shchelkin[50] discovered that placing spiral obstacles in a smooth circular tube can greatly shorten the DDT process. This obstacle is called a Shchelkin spiral, as shown in Fig 3. Since then, scholars have conducted a lot of studies on the effects of different types of obstacles on the flame acceleration process and detonation characteristics in the detonation chamber [51-55].

Fig.3 shchelkin Helical structure

Lee[56] studied the influence of different spoiler sizes, spacing and structures on the DDT process in a mixture of hydrocarbon fuel and air, and found that the key factor for successful detonation is to spread the flame in the obstacle area within the detonation tube. The speed reaches half the speed of C-J. Wang Yun and others from Northwestern Polytechnical University[57-58] conducted experimental research on the impact of obstacles on the performance of pulse detonation engines. Research results show that Shchelkin spirals, spiral grooves and annular grooves can achieve detonation initiation and stable propagation, but the orifice plate cannot achieve detonation initiation. The thrust loss of the Shchelkin spiral is small, the DDT distance and DDT time between the spiral groove and the annular groove are longer, and there is no obvious thrust gain. Deng Junxiang[59] used numerical simulation methods to calculate the impact of annular obstacles on the detonation characteristics of a pulse detonation combustor. The results show that as the obstruction ratio of obstacles increases, the flow loss increases, and the unit fuel consumption rate increases. As it increases, performance decreases. Although obstacles are a necessary device for triggering detonation waves during the DDT process, the addition of obstacles in the detonation chamber inevitably causes a loss of propulsion performance. Studies have shown that the DDT time in a pipeline with an obstacle with a clogging ratio of 0.43 is 65% shorter than that in a smooth pipeline, but there is a 25% impulse loss[60].

In addition to solid obstacle-assisted detonation technology, many scholars[61-64] have also done a lot of research on fluid obstacle detonation technology. Fluid obstacle detonation technology refers to injecting gas into the flow field through slits or holes on the wall of the detonation tube, causing disturbance to the flow field in the tube and increasing turbulence, thus accelerating the detonation process and shortening the DDT distance. The jetted airflow can be regarded as a fluid obstacle, and its function is consistent with that of a solid obstacle. The advantage is that it can reduce flow losses to a certain extent. However, as a newer DDT enhancement method, there are still many problems that need to be solved, such as how to achieve stable and reliable detonation in multiple cycles, how to evaluate the flow loss of fluid obstacles, and how to quantitatively compare the detonation-promoting effects of fluid obstacles and solid obstacles, etc.

3.2. Spark plug ignition technology

The study of the detonation initiation process is very important both from the perspective of basic research and practical application. The currently widely studied pulse detonation engines have greatly stimulated the development of multi-cycle pulse detonation technology, especially detonation technology in liquid fuel and air mixtures with great application prospects. Many new ignition methods have emerged one after another. In addition to optimizing the detonation-assisted obstacles in the detonation chamber and improving the ignition conditions of the PDE, improving the ignition method is also one of the potential ways to shorten the DDT process. Good ignition methods can promote the rapid development of flames, thereby reducing dependence on obstacles.

Spark plug ignition technology is highly mature and simple in design. It is the ignition technology most used by researchers in the early days and even now. The spark plug ignition system is shown in Fig 4. It consists of a spark plug, an ignition vortex, an energy regulating device and a signal generator. The ignition zone structure can be changed by replacing the ignition scroll hole, and the energy adjustment device can adjust the energy delivered to the spark plug. Through the optimized design of the ignition zone and the transformation from deflagration to detonation, higher frequency detonation detonation can be achieved.

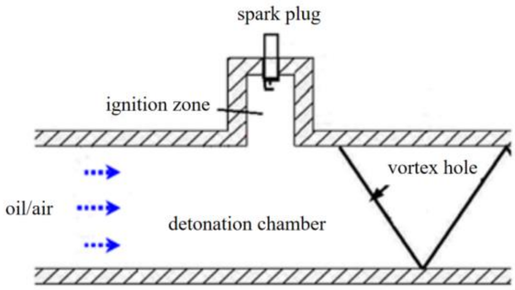

Fig.4 Spark plug ignition diagram

Northwestern Polytechnical University[65-66] early studied the impact of ignition energy on the detonation performance of pulse detonation combustors. The results show that with the increase of ignition energy, the detonation performance and thrust increase effect of the two-phase pulse detonation combustor are significantly improved, but at low ignition energy, the ignition frequency is greater than the detonation frequency. In addition, in the studies of Li[67] and Wang[68-69], it was found that two-phase detonation combustion will produce longer ignition delay time and DDT time. As the ignition energy increases, the ignition delay time and DDT time decrease. However, as the frequency increases, the influence of ignition energy weakens.

3.3. Thermal jet ignition technology

The schematic diagram of the hot jet ignition device is shown in Fig 5. Its basic working principle is that the oil and gas mixture passes through the draft tube and enters an ignition cavity for combustion. A flame jet is formed through the jet hole to ignite the combustible gas mixture in the detonation chamber. The DDT process is completed by a series of the flame acceleration mechanism. Relatively speaking, hot jet detonation is relatively less affected by the incoming flow and flow field in the detonation chamber, and is more reliable than spark plug ignition[70]. Currently, thermal jet ignition is divided into three categories according to the state of the jet[71]: 1. Quasi-detonation jet; 2.

Supersonic jet; 3. Subsonic jet. This section only discusses the currently most common subsonic thermal jet ignition.

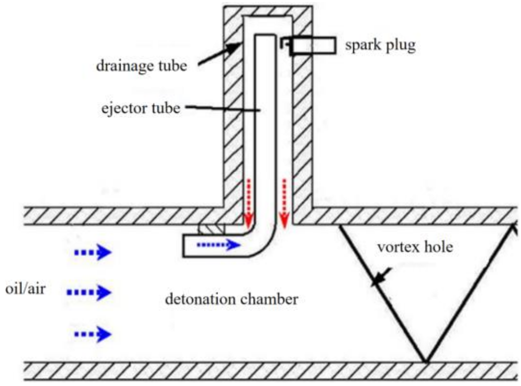

Fig.5 Schematic diagram of hot jet ignition

In addition, many scholars[72-74] have explored the impact of hot jet ignition technology on flame acceleration and DDT processes through experiments or numerical simulation methods. The results show that hot jet ignition can quickly form a strong turbulent initial flame in the ignition section, and the jet enhances the turbulence intensity of the downstream unburned gas mixture, which can promote the flame acceleration process. Under certain conditions, detonation can be directly triggered in the shear layer of the hot jet and the large-scale fuel mixing vortex.

Li[75] compared the influence of self-designed hot jet igniter and spark plug ignition on the detonation characteristics of the detonation chamber under the same conditions. Research results show that hot jet ignition can significantly shorten DDT time and DDT distance. Among them, the DDT time is shortened to about 1/4, and the DDT distance is shortened by about 40%. Zhao[76] studied the effect of hot jet ignition position on the initial flame propagation velocity and detonation pressure of the detonation chamber. Research results show that the impact of the ignition position on the flame propagation speed is closely related to its relative position to the reflow zone. The ignition position is within the reflow zone, and the impact is very small. The ignition position is outside the reflow zone, and the closer the ignition position is to the exit, the smaller the flame propagation speed. Tan[77] studied the influence of hot jet ignition and spark plug ignition on the ignition and detonation characteristics of U-shaped pulse detonation combustion chamber. Research results show that on the premise of achieving stable operation of U-PDC, the ignition energy required for hot jet ignition is smaller, only 0.05J, while spark plug ignition requires 1J.

3.4. Pre-detonation tube ignition technology

Judging from the currently publicly reported experimental results, both spark plug ignition and hot jet ignition have the problem of too long DDT transition distance. Pre-detonation tube ignition technology, that is, detonation jet, is an ignition method that has attracted much attention at present. In this ignition method, the exit jet of the pre-detonation tube is a detonation jet, and the ignition energy is stronger. In some cases, DDT time and DDT distance can be significantly shortened.

Chen[78] studied the process of the detonation jet detonating the detonation wave in the main detonation chamber under five pre-detonation tube arrangements through numerical simulation. The results show that the layout of the pre-detonation tube has a greater impact on detonation, and the orthogonal arrangement is beneficial to detonation. Zhang[79-80] designed a two-phase pulse detonation combustor that uses the same type of mixed gas (gasoline/air) as the working medium and is ignited and detonated by a pre-detonation tube, which can achieve stable intermittent operation with a maximum frequency of 66.7 Hz.

3.5. Shock wave focused detonation technology

The shock wave focused detonation technology uses supersonic jet to generate shock wave convergence in the concave cavity to detonate the combustible mixture.

Gross[81] made the first attempt to trigger shock-induced detonation, but no obvious detonation wave was observed in the experiment. In general, the triggering of shock-induced detonation waves mainly relies on the high-temperature and high-pressure points formed by the focus, convergence or reflection of shock waves to trigger detonation waves. At present, there are several forms of realization of SDT: strong shock wave induced detonation wave self-ignition as the form of oblique detonation engine ignition, mainly realized by oblique splitting[82]; supersonic jet in the two-stage PDE resonant cavity Collision and vibration trigger high-frequency detonation waves, with resonant frequencies as high as several thousand Hz; shock wave-induced detonation ignition is based on annular jets converging at the head of the detonation tube[83].

Researchers have conducted some studies on shock focused detonation[84-85]. At present, Russia has completed cold and hot state experiments on two test prototypes with diameters of 70 mm and 90 mm, and obtained stable thrust with a frequency of 10 kHz. Yang[86], Wang[87] conducted a study on the impact of shock wave focused ignition on the detonation characteristics of a two-phase pulse detonation combustor through numerical simulation methods. Research shows that the annular detonation wave can ignite the combustible mixture after reflection and convergence in the cavity of the detonation tube. Local explosions can be generated at obstacles to achieve self-sustaining propagation of detonation waves, effectively shortening the DDT distance.

3.6. Plasma ignition technology

The key issues that determine the development of pulse detonation engines include rapid and reliable detonation of detonation waves, shortening of axial distance, and increasing frequency. In recent years, research has shown that the use of plasma ignition can effectively detonate pulse detonation engines, and can significantly shorten the distance and time of DDT, and have a higher detonation success rate[88]. Applying plasma ignition technology to pulse detonation engines has a great effect on improving many performance indicators of pulse detonation engines.

If plasma ignition is to be applied to pulse detonation engines, it needs to adapt to the working characteristics of detonation engines, that is, the ignition should also be pulse type. The commonly used plasma jet ignition (torch ignition) is not suitable for direct application in the ignition of pulse detonation engines due to its slow response speed. Therefore, the plasma igniter used in pulse detonation engines is generally a relatively fast pulse igniter[89], as shown in Fig6.

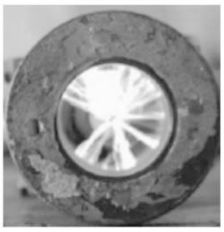

Fig.6 Schematic diagram of shock focused detonation

In order to study the feasibility of pulse detonation engine initiated by transient plasma ignition, Yu[90] designed a transient plasma igniter suitable for pulse detonation engine, and performed the discharge of transient plasma ignition and spark plug ignition. The process was compared and the transient plasma igniter had a larger ignition area.

Most of the research results are obtained through experiments[91-94]. From the public literature, there are few studies on multi-physics coupled plasma ignition simulation. Through experiments, test phenomena and test results can be observed more intuitively, and the data obtained are more realistic. Numerical simulation is also of great significance in explaining the physical and chemical mechanisms, influencing factors and change patterns of plasma ignition.

4. Pulse detonation combustion based on kerosene

Most of the appeals regarding the two-phase pulse detonation chamber fuel atomization blending technology and rapid short-distance detonation technology use gasoline as fuel and air as oxidant to study the working and propulsion performance of the pulse detonation combustor. However, gasoline has high volatility, which is not conducive to safe storage in military applications. Therefore, if the pulse detonation combustor is to be applied in aviation engineering, it still needs to use typical aviation kerosene with high energy density and easy storage as the material. However, kerosene and gasoline have different chemical properties and combustion characteristics, which have important implications for combustion chamber design and operation. Compared with gasoline, kerosene burns slowly and has poor volatility, requiring higher pressure and temperature to detonate. Under the same working conditions, its combustion efficiency is usually lower than that of gasoline. Therefore, how to improve the combustion efficiency of kerosene-based pulse detonation combustors by optimizing the design and operating parameters of the combustion chamber is a key core technology for future two-phase pulse detonation chamber design.

n recent years, relevant scholars have conducted a large number of studies on pulse detonation combustion chambers initiated by kerosene fuel. However, most of the oxidants are oxygen[95-103], and there are relatively few studies on kerosene-air two-phase detonation. Frolov[104] used 5 J spark plug ignition energy and obstacle-assisted detonation technology to successfully achieve kerosene/air two-phase detonation in a 51 mm diameter pulse detonation combustion chamber. The U.S. Naval Postgraduate School conducted research on two-phase detonation of kerosene, oxygen, and air, and successfully achieved detonation with a maximum frequency of 5 Hz.

Lv[105] quantitatively calculated the heat released by the complete combustion of aviation kerosene with a chemically appropriate ratio and the final temperature and pressure of the detonation chamber, and analyzed the relationship between the concentration of the reaction mixture and detonation. In a closed container with a certain volume, the volume fraction of the chemically appropriate aviation kerosene in the mixture is lower than the lower knock limit of aviation kerosene, and complete combustion of the aviation kerosene cannot cause knocking. To induce detonation in a two-phase mixture, the fuel concentration must be increased to within the detonation limit.

Zhang [106] conducted an experimental study on detonating a cylindrical rotary valve PDE using kerosene-air as fuel and oxidant. The results show that the engine can ignite successfully, but does not produce a stably propagating detonation wave. The improvement suggestion is to improve the stability of the on-duty combustion chamber and the coordinated performance of the engine.

Li[107-108] and others first conducted research on the knock characteristics of a two-phase pneumatic valve pulse detonation engine based on the explosive mixture formed by kerosene and low-pollution air. After heating the incoming air and kerosene, detonation combustion with a frequency of 10 Hz was achieved when the intake air temperature was 373 K and the fuel temperature was 363 K. However, the wave speed loss caused by the two-phase detonation and DDT process was not considered in the experiment. Only the theoretical wave speed was used as the test wave speed, which cannot explain whether a fully developed detonation wave was obtained. They[109-116] successfully shortened the DDT distance and time by installing reasonably structured obstacles in the detonation chamber to improve shock wave reflection and heat the gas fuel, and obtained a stably propagating detonation wave.

Zhu[117] conducted a numerical study on the influence of the refueling distance d and the fuel ratio R on the pre-combustion cracking effect for a two-stage pulse detonation engine. Research shows that the refueling distance d and the fuel ratio R have a great impact on the cracking effect of kerosene in the precombustion chamber. The larger the refueling distance d, the closer the second-stage fuel injection position is to the outlet of the pre-combustion chamber, which will reduce the residence time of the reactants and lower the output of each main active component; the larger the fuel ratio R, the smaller the pre-combustion chamber outlet. The temperature in the combustion chamber decreases and the residence time of the reactants is extended, which reduces the content of the main active components and weakens the knocking effect. Wang[118] conducted experimental research on the combustion characteristics of kerosene-air two-phase pulse detonation based on kerosene fuel. The research results show that the atomization fineness of fuel has a great influence on the ignition-detonation performance of PDE. When the atomization fineness of kerosene is low to a certain extent, detonation can be achieved without heating. Compared with gasoline/air propellant, kerosene/air PDE is more difficult to detonate, and the ignition-detonation time increases significantly. As the frequency increases, the difference in ignition-detonation time between the two gradually decreases. In addition, they[119] also studied the impact of ignition mode on the two-phase detonation characteristics of kerosene and air. The results showed that using pre-detonation tube ignition can shorten the DDT time to 2-3 ms and the DDT distance to 700 mm. Chen[120] conducted an experimental study on the impact of pre-injection fuel temperature on detonation combustion performance for a large-diameter PDE. The research results showed that the fuel temperature directly affects the DDT distance. The higher the temperature, the shorter the DDT distance. In addition, when the fuel is heated, the detonation chamber is more likely to detonate. Zhang[121] found in their research that a fully developed two-phase pulse detonation wave can be formed in a detonation tube whose inner diameter is smaller than the cell size of the mixture. By raising the temperature of kerosene and heating the wall of the detonation tube, it plays a very important role in promoting the ignition and detonation initiation process.

5. Conclusion

Although two-phase detonation combustion technology has achieved certain results in various aspects, there is still a certain gap between the engineering application of two-phase pulse detonation combustors.

In terms of fuel atomization and blending technology, researchers have done little research on the fuel atomization mechanism of two-phase detonation. They lack sufficient knowledge of the detonation wave structure, wave speed loss, explosive limit and DDT coupling process caused by fuel atomization. The atomization, evaporation and blending of fuel is also an urgent problem that needs to be solved to realize the engineering application of pulse detonation combustor.

In terms of rapid short-range detonation technology, using solid obstacles to assist detonation can shorten the DDT distance and achieve stable detonation, but it will increase flow resistance loss and reduce thrust. Utilizing fluid barrier technology can reduce performance loss, but the technology is not yet mature. Compared with spark plug ignition and subsonic hot jet ignition, which have mature technology but long DDT distance, at this stage, there is a lack of understanding of pre-detonation tube ignition, shock wave focused detonation ignition and plasma ignition. The installation and coordination of the ignition device and the detonation chamber are still difficult issues.

Regarding the research on two-phase detonation combustion, the fuel mainly uses gasoline fuel that is easier to detonate. In the research on detonation and detonation characteristics using kerosene fuel, most of them require external preheating and internal evaporator to achieve detonation. The integration of external equipment or breakthroughs in fuel atomization and blending technology are one of the key technical ways to achieve efficient detonation of kerosene.

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