Study of plasma-assisted detonation initiation by quasi-direct current discharge

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Abstract
To study the effects of quasi-direct current discharge plasma on the initiation of a pulse detonation engine at multiple locations, we proposed a double-zones quasi-direct current discharge plasma ignition scheme. Based on the establishment of the plasma-assisted detonation initiation model, the process of detonation wave formation in the mixture of hydrogen and air by single and double ignition zone were studied by numerical method. The wave structure, component evolution history, and Zeldovich–von Neumann–Döring curve after forming a stable detonation wave were all discussed. The simulation results indicate that due to its higher total ignition energy and the synchronous propagation of multiple compression waves, double-zone plasma ignition has a 17.9% shorter deflagration to detonation transition time and 14.2% lower detonation distance compared to the single-zone scheme. The double-zone scheme does not modify the peak flow field temperature and pressure when the stable detonation wave is formed, resulting in smoother pressure and temperature increases.

Keywords
Pulse detonation engine, plasma ignition, quasi-direct current discharge, detonation wave, numerical simulation

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1. Introduction
Because a pulse detonation engine has the advantages of high thermal cycle efficiency, high thrust-to-weight ratio, low fuel consumption, and a simple structure, it is ideal for application to high-performance propulsion devices. The countries that lead the world in the aerospace field attach great importance to it and have made relatively large strides in theories, experiments, and simulations. However, detonation is a difficult core process, and indirect detonation is usually used in practice. Indirect detonation means a deflagration to detonation transition (DDT) occurs, which concerns series of physical and chemistry changes.1 Shortening the DDT distance and increasing the frequency as much as possible while ensuring reliable detonation is a research challenge.2,3

The emergence of plasma-assisted combustion and flame stabilization techniques provide new approaches for solving the pulse detonation engine detonation problem.4,5 Sinibaldi of the United States Naval Postgraduate School and Wang et al. of Southern California State University6,7 conducted in-depth experimental studies on the detonation wave formation in the transient plasma ignition (TPI) technique and noted that in comparison with conventional ignition devices, the TPI technique effectively shortens the time and distance of the DDT (the transition from slow combustion to detonation). Starikovskiy et al.8 of Princeton University also studied the influence of plasma on the DDT process. The experiment indicated that the energy of non-equilibrium plasma-assisted detonation ignition is lower than that for electric initiation by an order of magnitude and showed that the intervention of low-power discharge on the DDT process includes the two aspects of slowly moving flame formation and gas dynamic disturbance. Yu et al.9 conducted a two-dimensional numerical simulation on the transient plasma-assisted detonation ignition process and

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found that the time and distance needed for detonation initiation were shortened by 64% and 22%, respectively, compared to spark plug detonation ignition. By establishing the two-phase detonation model, Lin and Weng simulated and analyzed the influence of plasma jet energy and time on the DDT process and found that this ignition method can effectively transition from combustion to detonation.

There are currently few studies on the detonation wave of transient plasma-assisted detonation ignition, and most studies use nanosecond-pulsed discharge with coaxial electrodes scheme to generate non-equilibrium plasma. With these circumstances, the anode can extend only a finite distance into the detonation tube, which causes a relatively short plasma zone discharge length in the axial direction and presents the challenge of temperature resistance for the electrode and its insulating material in the high-temperature combustion environment. Therefore, a new discharge mode and layout should be adopted to solve these problems. In this article, we propose the use of quasi-direct current (DC) discharge by arranging the columnar electrodes on the detonation tube wall. A simplified plasma heat source model is established to study the single- and double-zone synchronous plasma-assisted detonation ignition processes and their effects by numerical simulation.

2. Physical model and numerical method

2.1. Quasi-DC discharge plasma ignition model

Quasi-DC discharge is similar to arc discharge, but this class of plasma discharge input power is much smaller than that of ordinary arc discharge, and the plasma channel temperature is much lower. Its macro-temperature is usually below 5000 K, while the macro-temperature of an arc plasma is more than 10,000 K. Thus, it is still a kind of non-equilibrium plasma. The physical discharge process is the plasma field emission process. A pulsed high voltage is loaded between the anode and cathode. When the emission current density reaches a certain level, the emission current gradually transitions to the charge-limit zone; when the current increases to a certain level, the emitting electrons heat the micro-tips to cause the molecules at the tip to vaporize, where they are immediately ionized by the emitting electrons, increasing the current. Next, a plasma sheath enclosing the cathode is formed, which expands toward the anode at a certain speed. Then, a short circuit occurs between the anode and the cathode; this is the quasi-DC discharge, which appears as a twisted long strip.

For quasi-DC discharge, by referring to the exploding wire principle, the pattern of internal energy in this high-temperature strip plasma zone can be described. By neglecting the fluid dynamics energy loss as well as the convective and conductive heat losses and assuming that the internal energy of the discharge medium is constant, the energy source term which is the power of the discharge plasma can be given in the form of equation (1)

\[ P = \varepsilon \sigma_b A T_{\text{pl}}^4 \]  

where \( A \) is the strip plasma surface area, \( \sigma_b \) is the Stefan–Boltzmann constant, \( T_{\text{pl}} \) is the plasma zone temperature, \( \varepsilon \) is the electrode material heat radiation coefficient, and the value is the heat radiation coefficient (0.81) of carbon as the commonly used material.

The Leonov team at the Institute of High Temperature, Russian Academy of Sciences, compared the experiments and simulation results and noted that the temperature rise caused by Joule heating is the main effect of the quasi-DC discharge plasma on the flow field. Therefore, according to phenomenological theory, the strip plasma zone can be simplified in the simulation. According to equation (1) for quasi-DC discharge plasma power, there is a relationship between the plasma heat source zone temperature and the plasma power, and therefore, we can establish the plasma phenomenological model: when we consider the effect of plasma, we treat the zone as a controllable heat source and equate the temperature in this zone to the quasi-DC discharge plasma temperature, which has been validated and used in references. However, we do not treat the zone under these conditions when there is no plasma present.

To study the effect of multi-zone synchronous plasma-assisted detonation ignition, we use the quasi-DC discharge electrode device described in Zhou et al. Two pairs of electrodes along the detonation tube’s axial direction are deployed. According to the type of the electrodes and their arrangement, and the flow status (i.e., it is static), the spatial shape of the plasma paths can be established in the way presented in Figure 1. The center-to-center distance between the two pairs of electrodes is 3 mm.

In this article, we select the equivalent heat source method, which is currently widely applied in pulse engine detonation simulations to simulate the detonation. For small diameter detonation tubes, because the strip plasma zone generated by the quasi-DC discharge is distorted in space and penetrates the entire tube diameter, diffusing its high heat rapidly all around, we initialize this TPI zone as a rectangular ignition zone in Figure 1 with a length of the tube diameter, a width of 3 mm (along the detonation tube axial direction), and a temperature of 3500 K, values aligned with relevant experimental parameters.

Because the plasma is dealt as a transient heat source as described previously, its energy input into the zone
can be calculated by the method for traditional heat ignition energy. Based on the internal energy of the ignition zone gas, we can calculate the ignition energy using the following equation 

$$E = \frac{4\pi p R^3}{3(y - 1)}$$  

where $E$ is the ignition energy, $p$ represents the ignition zone pressure (equal to the environmental pressure in this article); $y$ is the specific heat ratio (equal to 1.29 here); and $R$ is the ignition zone radius (calculated as $R = 3.83\text{mm}$ through volume equivalence). Therefore, the ignition energy of a single-zone reaches $82.3\text{mJ}$, and the ignition energy of a double-zone is $164.6\text{mJ}$.

2.2. Computation zone, grid division, and boundary conditions

The entire computation zone is shown in Figure 2, including a detonation tube closed at one end and a peripheral zone. The detonation tube is $300\text{mm}$ long and $10\text{mm}$ in diameter. Because the computation zone is regular, a structured grid is adopted. By comparing and analyzing the calculation results of multiple models with different numbers of mesh elements, we find that a detonation tube grid spacing of $0.15\text{mm}$ can capture the detonation wave propagation process well and obtain the detonation wave velocity and Von-Neumann peak pressure within acceptable tolerances, while still allowing a relatively small number of mesh elements. In the peripheral zone, assume the grid spacing follows an exponential distribution, becoming gradually sparse from the detonation tube outlet toward the computation zone outlet. To reduce computation resources, we selected the symmetric flow field axis as the axially symmetric boundary condition; the calculation includes a peripheral zone, which addresses the difficulty of determining the detonation tube outlet boundary conditions. The pressure outlet condition is set in the peripheral zone. The environmental pressure at the outlet is set to $1\text{atm}$, and the composition is air; all the tube walls and closed ends are non-slip and adiabatic; the detonation tube is filled with a hydrogen and air mixture at a ratio of 1:1, with an initial temperature of $300\text{K}$ and an initial pressure of $1\text{atm}$. The total number of mesh elements is $121,260$.

2.3. Model and calculation method

The conserved unsteady Reynolds-averaged Navier-Stokes equations with multiple compositions for reacting flow are adopted as the governing equations. As the realizable $k-e$ turbulence model has been widely used in detonation simulations and has shown good capability in capturing the DDT process, such as the studies reported in references, this model is adopted here together with the non-equilibrium wall surface function in order to better adapt to the pressure gradient and non-equilibrium flow. The finite rate chemical reaction model is used for the combustion simulation, and the reaction rate constant is calculated from the Arrhenius equation. Considering our research purposes and the plasma ignition model characteristics, a hydrogen/air one-step combustion kinetic model is adopted. One-step combustion kinetic models of hydrogen, methane, and ethylene have been tested and used to solve a variety of combustion and detonation problems, as given in references. Although the one-step kinetic model cannot exactly reproduce all properties of the hydrogen–air mixture for flames, detonation, and others, it can give a reasonable approximation of the length and time scales for the problem studied here based on the comparisons of the basic parameters of the detonation wave between the theory values and computational data.

The pressure implicit with splitting of operators algorithm, which is advantageous in the transient problem, is used to solve the control equations. To increase the computation accuracy and stability, the governing equations are discretized by the second-order upwind approach, and the time step is $5 \times 10^{-8}\text{s}$.

2.4. Method validation

The calculation results for the detonation tube flow field without considering the plasma indicate that the
stable, self-stained detonation wave forms in the tube after about $t = 100\mu s$. Through the National Aeronautics and Space Administration (NASA) Chemical Equilibrium with Applications program, based on C-J theory, the calculated theoretical reference velocity of the detonation wave is 1965 m/s, and the Von-Neumann peak pressure is 3.14 MPa. By comparing the detonation wavefront displacement at two different times after the formation of the stable detonation wave, the stable detonation wave velocity in the self-sustained state calculated by this article's simulation is 2000 m/s and the Von-Neumann peak pressure is 2.75 MPa. The wave velocity and pressure errors are 1.8% and 12.4%, respectively. Relevant studies have indicated that the wave velocity calculated from C-J theory is lower than that experimentally measured, and the pressure is higher than the experimentally measured C-J pressure by 10–15%. In addition, Figure 3 shows the pressure distribution on the computation zone axis at $t = 100\mu s$, demonstrating that the simulation results comply with the Zeldovich–von Neumann–Döring (ZND) detonation wave structure. The previous analysis indicates that the calculation methods adopted in this article are reliable.

### 3. Results and analysis

#### 3.1. Single-zone TPI detonation initiation

Figure 4 shows the flow field pressure distribution in the detonation tube for single-zone quasi-DC discharge plasma detonation. The simulation does have captured the basic dynamic changes and sub-processes happen in a DDT process. Based on the change in the flow field pressure at these four different characteristic times, we can clearly observe the DDT process of the transition from deflagration to detonation.

After the ignition at the closed end, because the tube is premixed with the hydrogen and air with a chemically appropriate ratio, the mixed gas experiences a short reaction delay in the high-temperature ignition zone and then begins to slowly burn, forming the deflagration wave. Because the combustion causes the expansion of medium volume in this ignition zone and works on the surrounding gas media, a series of compressional waves are generated to the tube ends. This causes the pressure and temperature behind the wave to rise, as shown at time $t = 10\mu s$ when the peak pressure is approximately 1.7 times atmospheric pressure. As time goes on, the compression wave propagates to the closed end of the detonation tube and is reflected back from the closed end. Because the temperature of waves rises due to combustion, the reflected compression wave propagating at the acoustic velocity is faster than the compression wave directly propagating to the open end and gradually catches up to the compression wave propagating toward the outlet. When the reflected compression wave catches the flame surface, it interacts with the flame surface and downstream. The flame burning rate increases under the influence of this wave.

As the reaction continues, the compression waves are gradually superimposed upon each other. At $t = 30\mu s$, the peak pressure behind the leading flow field wave has reached 6.9 atm. However, the intense combustion zone has not formed behind the leading wave system, and various compression waves are still in separate states. Specifically, the leading shock wave is still relatively weak. At $t = 60\mu s$, a large portion of the subsequent compression wave catches the leading shock wave, and the superposition makes the gas pressure swept by the wave surface rise significantly. However, by observing the given zonal flow field pressure distribution in the detonation tube, we see that the shock wave intensity cannot cause the mixing gas temperature to increase to the ignition point; the shock wave and reaction zone are not coupled together. At time $t = 100\mu s$ in the figure, the flow field pressure distribution is obviously different from the previous time, when the stable detonation wave has formed. The leading shock wave and the chemical reaction zone are tightly coupled together, and the strong shock wave triggers the combustion. The chemical reaction drives this shock wave and provides the energy needed for its propagation when the detonation wave pressure is approximately 25.7 atm.

The Taylor expansion wave follows the detonation wave. This reduces the pressure and causes the fluid to become motionless to satisfy the condition of zero velocity at the closed end.

#### 3.2. Double-zone synchronous plasma ignition detonation initiation

For double-zone synchronous plasma detonation ignition, the dynamic course of the flow field parameters
differs from that of single-zone plasma detonation ignition, as shown in Figure 5. The pressure distribution in Figure 5 is displayed for the same four characteristic times (10 μs, 30 μs, 60 μs, and 100 s), for easy comparison with the single-zone plasma detonation ignition in Figure 4.

We first observe the flow field at \( t = 10 \) μs. Compared to single-zone ignition, the pressure near the closed end is higher, and the high-pressure zone is wider. As the time goes on, part of the compression wave coming from two zones propagates to the open end of the detonation tube; the other part propagates to the closed end and is reflected back. The reflected compression wave also chases the front compressional wave, generating the superposition. However, due to the spacing between the two ignition zones, the strongest flow field wave system is not located at the front end at \( t = 30 \) μs, and there is a compression wave in front of the strongest wave system due to the large distance from the closed end to the ignition zone.

The reflected compression wave catches the leading shock wave from behind, causing it to accelerate. At \( t = 60 \) μs, the compression wave previously located in front of the leading shock wave has been superposed, and the surface of the leading shock wave can be clearly seen. The peak pressure behind the wave is relatively stable at approximately 25.7 atm. This is comparable to the flow field peak pressure at \( t = 100 \) μs, indicating that the leading shock wave begins to couple with the immediately following chemical reaction zone.

We again compare the pressure nephograms at different times in Figure 5 with those in Figure 4 and find that double-zone synchronous plasma ignition accelerates the DDT process. The superposition of compression waves is faster. The double-zone ignition at different times causes the front of the leading wave system to propagate faster to the open end, forming a stable detonation wave earlier.

### 3.3. Comparison of single-zone and double-zone plasma ignition detonation initiation

The proportions of reactants and combustion products can change significantly during the DDT process. To aid understanding the combustion wave changes, Figure 6 shows the \( \text{H}_2 \) and \( \text{H}_2\text{O} \) mass fraction distributions with respect to time for the two plasma ignition schemes. At \( t = 10 \) μs, for single-zone ignition, \( \text{H}_2 \) consumption occurs only in the zone adjacent to the closed end; two curves appear for double-zone ignition, which indicates that the combustion occurs at the same time in the two zones. As time goes on, the reactants are being constantly consumed behind the leading wave system, and their mass fraction discontinuity surfaces move forward. Similarly, the product \( \text{H}_2\text{O} \) also develops forward. These results are consistent with the pressure variation in the flow field discussed earlier and reflects combustion wave variation. At time \( t = 140 \) μs (when a stable detonation wave exists for both schemes), in single-zone ignition, the \( \text{H}_2 \) consumption and \( \text{H}_2\text{O} \) generation area is located 227 mm along the detonation tube’s axial direction, while for the double-zone ignition, it is located at 244 mm. The positions show the point of propagation of the detonation wave, indicating that the double-zone scheme allows for faster chemical reactions and a relatively high burn rate. The time needed for detonation is shorter.

To determine the DDT distance, Figure 7 shows the distributions of flow field pressure and temperature along the axis when the stable detonation wave is just formed, which complies with the ZND structure of a typical detonation wave. The analysis indicates that the DDT time and distance for the single-zone scheme are \( T_{\text{DDT}} = 95 \) μs and \( L_{\text{DDT}} = 134 \) mm, respectively, while the DDT time and distance for the double-zone scheme are \( T_{\text{DDT}} = 78 \) μs and \( L_{\text{DDT}} = 115 \) mm, respectively, shorter by 17.9% and 14.2%, respectively, than...
those of the single-zone scheme. The double-zone scheme is conducive to a shorter detonation tube and a shorter cycle time, enabling a higher cycling frequency. In addition, Figure 7 also indicates that compared with the single-zone scheme, the double-zone scheme has only a small influence on the flow field peak temperature and pressure behind the stable detonation wave, with smoother temperature and pressure curves.

Generally speaking, the plasma-assisted ignition detonation initiation process for single zone and double-zone schemes is the same. In both schemes, the shock

Figure 5. Pressure distribution in the double plasma ignition detonation initiation zone.

Figure 6. Mass fraction of species distribution along the tube’s axis at different times. (a) Single zone, H\textsubscript{2}; (b) single zone, H\textsubscript{2}O; (c) double-zone, H\textsubscript{2}; (d) double-zone, H\textsubscript{2}O.
wave is formed by constantly superposing the compression waves, which strengthens the subsequent chemical reaction; the chemical reaction also provides energy to the shock wave, forming a self-sustained stable detonation wave. However, for double-zone ignition, the compression wave’s propagation in the tube is more complicated at the initial stage of the DDT process and can be described by relative motion and penetration of compression waves caused by two zones. The analysis of pressure distribution in Figure 5 indicates that at certain times, a compression wave in front of the leading shock wave may exist with double-zone ignition but not in the single-zone ignition process.

This analysis indicates that the double-zone scheme can effectively shorten the DDT time and distance due to two factors: first, for double-zone ignition, the total energy available for ignition in the detonation tube is larger, reflected by the larger heat source zone area in the simulation; second, there is a certain spacing between the two zones; after the TPI begins, the two zones generate a compression wave in the two axial directions, causing three, compression waves to follow one front compression wave during the DDT process (specifically, the wave propagates to the right from the ignition zone adjacent to the open end in Figure 5). Due to the strong effect of two groups of compression waves originating from two zones, the burn rate is significantly enhanced, forming a stable detonation wave earlier.

4. Conclusions

In this article, we first propose the use of quasi-DC discharge as the discharge mode of TPI and preliminarily design single-zone and double-zone ignition schemes. Next, we conduct numerical simulation studies of the two ignition schemes, comparing and analyzing their detonation effects. The research results indicate the following:

1. For double-zone plasma ignition, the detonation tube wave system is more complicated than the single zone at the initial stage of the DDT, and a compression wave in front of the leading shock wave may occur. However, the DDT process of the two schemes is similar, both featuring compression wave superposition, chemical reaction intensification and shock wave coupling within a chemical reaction zone;
2. Compared with single-zone ignition, the double-zone scheme’s DDT time and distance are shorter, indicating its advantages for increasing the cycling frequency and shortening the detonation tube length;
3. Double-zone ignition has a small influence on the peak detonation wave ZND pressure and temperature in a stable state, and the temperature and pressure increase is smoother.

In summary, plasma ignition detonation using double-zone quasi-DC discharge has certain advantages, and the reasonable selection of the number and positions of discharge zones can enhance the detonation tube’s initiation performance.

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