Numerical Investigation of the Direct Initiation Mechanism of Double Point Laser Ignition

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1 Introduction

Gaseous detonation is one type of combustion phenomena in premixed gas, and has an aspect of self-sustaining propagation with interacting between shock and combustion waves. Detonation combustion has been paid much attention in the field of propulsion because of its high energy release rate and high thermal efficiency [1]. At present, pulse detonation engine, oblique detonation engine, rotating detonation engine and so on are widely studied in the world. One common feature of the detonation engine is that the airflow entering the combustor is supersonic and the residence time in the combustor is very short, so direct initiation is one of the effective ways to realize detonation combustion.

At present, the main ways to realize initiation are shock wave induced initiation [2], hot jet direct initiation and non-contact high energy laser direct initiation [2, 3]. With the development of laser technology, many scholars begin to pay attention to laser induced ignition and detonation [2-11]. Compared with the traditional ignition mode, laser ignition has a few advantages [6, 9]: non-contact over distance igniting does not cause direct interference in the flow field and can the ignition position can be control expediently; the energy density of time and space can be very high by focusing pulse laser; multi-ignition will be achieved easily, etc. It can be seen that laser ignition to achieve direct detonation has obvious advantages.

However, due to the limitation of laser focusing diffraction limit and gas absorption rate, the single point non-resonance ionization ignition is used to realize direct detonation, which requires a high pulse laser energy. This has some limitations on the wide application of this technology, so it is necessary to further explore the direct initiation method of low energy and high reliability laser ignition.

In order to realize the direct initiation of detonation with the lowest laser energy in premixed gas, the formation, development and initiation process of spark-core in multi-point laser ignition under different static pressure conditions were simulated specially in this paper.

2 Numerical Method and Simulation Conditions

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The governing equations are the compressible Euler equations with a chemically reacting gas system in a two-dimensional Cartesian coordinate system:

$$U_t + [F(U)]_x + [G(U)]_y = S \tag{1}$$

The equations consider compressible fluid dynamics and chemical kinetics of multi-component system. Considering the stiffness of the source terms, Strang splitting scheme [12] is used to couple the Euler equations to the chemical reactions [11], which consists of solving two separate differential equations:

$$U_t + [F(U)]_x + [G(U)]_y = 0 \tag{2}$$

$$U_t = S \tag{3}$$

where Eq. (2) is the 2D Euler equation for multi-species flow without chemical reactions, the thrid order TVD Runge–Kutta method [13] and the fifth order WENO-LF scheme [14] are employed to discretize the temporal term and convection term, respectively. Enthalpy and heat capacity for each specie are calculated from the data in the JANAF tables [15]. Eq. (3) is a purely reacting equation. For the chemical kinetic integration [16] is solved by the selected asymptotic integration method [17].

In this paper, the collision and initiation processes of two laser point sources in an open static space with different static pressure conditions are studied. In simulations with a static temperature of 298 K, the initial mole ratios of H2:O2:Ar are 2:1:3.76, respectively. The mixture is ignited by placing two laser point sources with diameter 3.0 mm, the distance between their centers is 4.0 mm at P=2×10^6 Pa and T=3000 K. Thus, the total energy input is 70J. The detailed chemical reaction model [18] containing 9 species and 34 elementary reactions are adopted.

3 Results and Discussions

The laser source with high temperature and high pressure produces a circular shock wave in combustible gas. Under above conditions with static pressure of 5×10^4 Pa, figure 1 shows the circular shock wave has been separated from the reaction zone at 20 us. In the region without any flame acceleration, after the shock wave is separated from the reaction zone, they will not be coupled again. Therefore, under the pressure of this study, the single point laser source cannot realize the laser initiation.

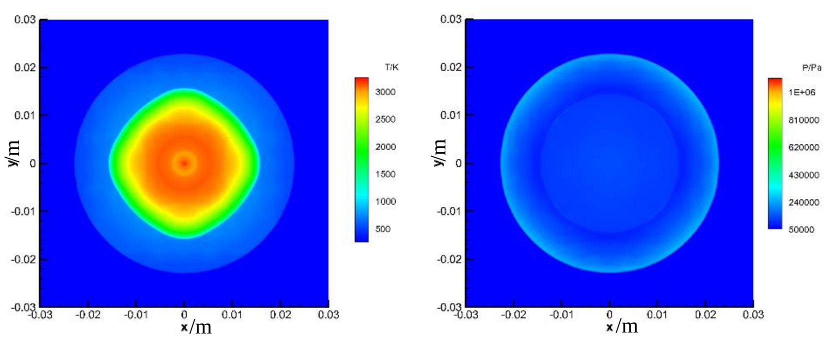
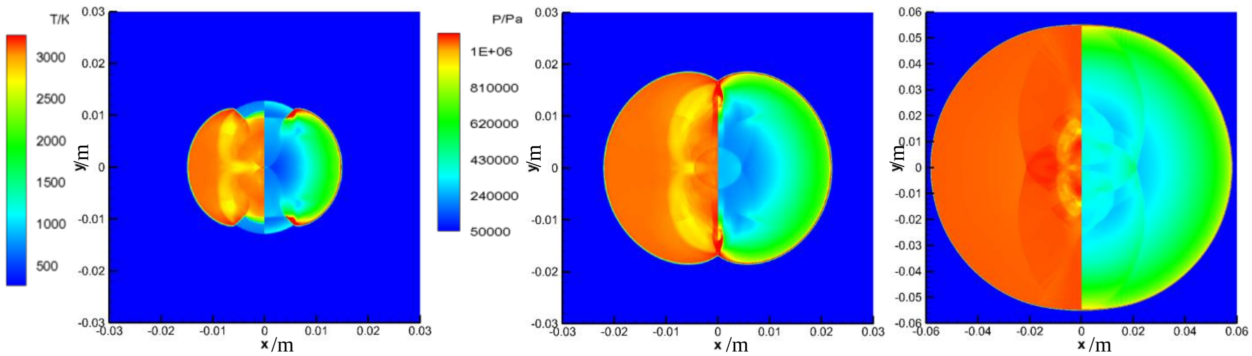


Figure 1. Contours of temperature and pressure at 20 μs

Figure 2 shows that the double point laser detonation is successfully realized by collision of shock waves in open space with static pressure of 5×10^4 Pa. The local detonation is realized in the place of shock wave collision, and the initiation is realized in the upper and lower directions under the influence of local detonation combustion in the left and right directions. It can be seen from fig. 2(c), the detonation front gradually develops from irregular shape to circle. Fig. 3 shows the change of temperature and pressure along the x direction, under the same conditions. The first curve in all graphs is 2 μs, the interval between each two curves is 2 μs. It can be seen that overdrive detonation wave gradually attenuates, and remains stable at last. If the space is infinite, the curvature of the detonation front will gradually decrease, and finally the plane detonation wave structure will be formed.



t=8 μs t=12 μs t=32 μs

Figure 2. Contours of temperature and pressure of detonation at different times

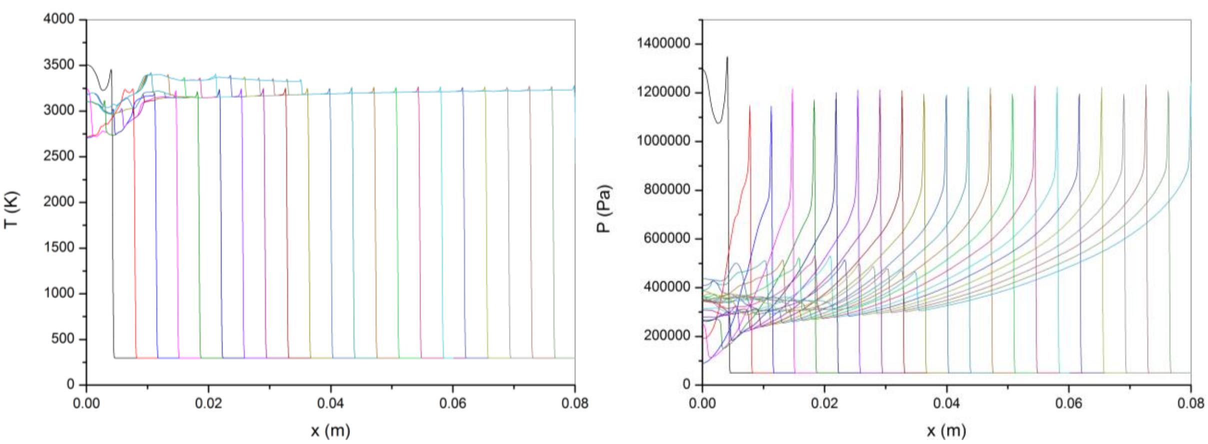
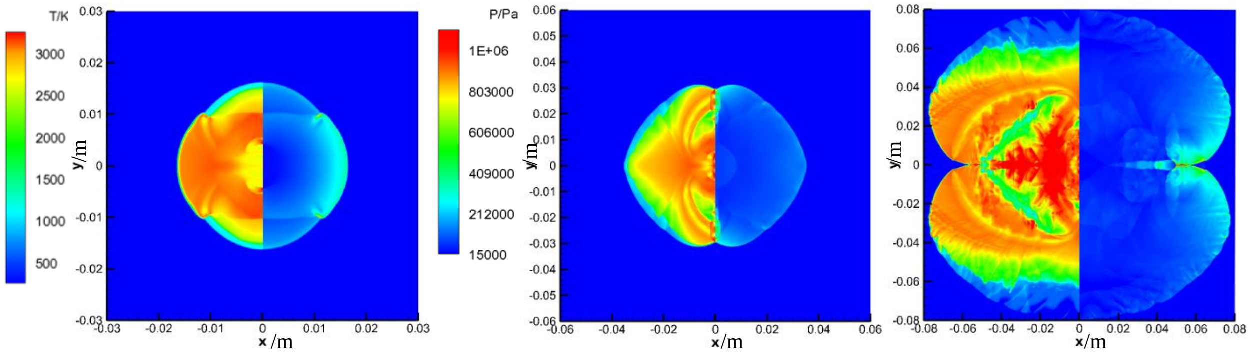


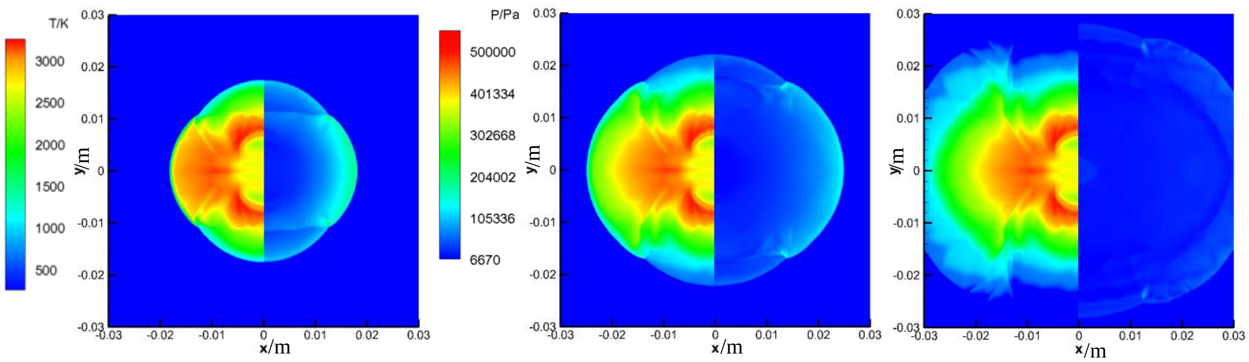
Figure 3. Temperature and pressure curves at different times in x direction

Figs. 4 and 5 show the temperature and pressure contours of the static pressure 1.5×10^4 Pa and 6670 Pa, respectively. It can be seen that the impact intensity of shock wave decreases with the decrease of ambient pressure. The reaction zone is separated from the shock front over time, and the initiation failure occurs at the static pressure is 6670 Pa.



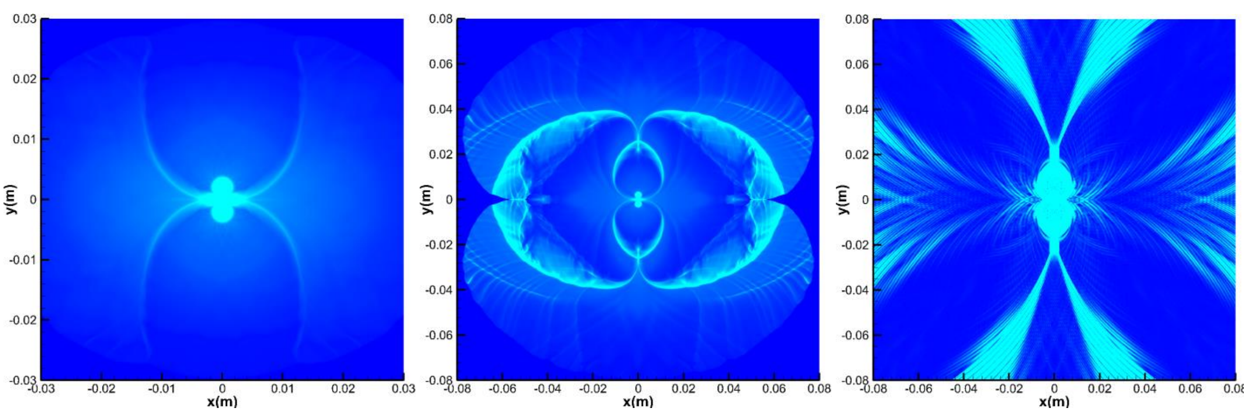
t=8 μs t=20 μs t=64.5 μs

Figure 4. Contours of temperature and pressure of detonation at different times



t=8 μs t=12 μs t=20 μs

Figure 5. Contours of temperature and pressure of detonation at different times



P=6670 Pa P=1.5×10^4 Pa P=5.0×10^4 Pa

Figure 6. Detonation cells at different static pressure

Figure 6 shows the detonation cells patterns at different static pressure. It can be seen that the higher static pressure the more frequent the collision of triple point. Because of the collision of the triple point, the detonation wave can maintain its own propagation. When the static pressure is lower, the collision period of the triple point becomes longer, and the energy loss is greater. The energy supply of detonation wave propagation is insufficient, the shock wave is decoupled from the reaction zone and detonation failures, finally.

4 Conclusions

Two points laser ignition process by the direct initiation were simulated at different static pressure. The environmental pressure has an obvious influence on the development process of flame-core and blast wave after laser-ignition. A higher environmental pressure increases the activity of the mixture, resulting in frequent triple point collisions. If we use the interaction of high-power multi-lasers to from strong reflected shocks in the airflow, it will help to realize direct initiation of detonation in stationary combustible gases.

Acknowledgments

The authors would like to acknowledge the Fundamental Research Funds for the Central Universities (Grant No. HEUCFP201719) for supporting this work.

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