IGNITION ENERGY EFFECT ON DETONATION INITIATION BY SINGLE AND TWO SUCCESSIVE IGNITIONS

by

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In order to investigate the influence of two successive ignitions on the detonation initiation characteristics, the processes of detonation initiation by one ignition and two successive ignitions with different ignition energy and ignition time interval were simulated numerically. Stoichiometric propane-air mixture was used as the fuel-oxidizer. The simulation and analysis results indicated that a detonation wave could not be initiated in the smooth tube by single ignition with the current ignition energy range of no more than 10000 J, while a detonation wave was initiated successfully by two successive ignitions with a certain range of ignition time interval, even when the ignition energy of each ignition decreased to 100 J. As the ignition energy decreased, the range of ignition time interval in which the detonation wave could be initiated successfully decreased, while the time and distance of detonation initiation increased.

Key words: *detonation initiation, successive ignitions, ignition time interval, ignition energy*

Introduction

A pulse detonation engine (PDE) is a kind of unsteady power plant that is based on the high efficient detonation technology and the thrust is obtained by the burnt gas with high temperature and high pressure produced by intermittent or pulsed detonation wave. A PDE is one type of promising propulsion technology owing to the potential advantages including the high thermal cycle efficiency, simple structure, high reliability and wide operating range and so on [1-4]. Effective detonation initiation is one of the key topics for PDE research. There are two ways to initiate a detonation wave, direct and indirect detonation initiation methods. The direct detonation initiation is difficult to be realized in an applied PDE because of the huge energy and the high speed of energy release. For example, 4000J is required for direct initiation of hydrogen-air mixture and 26000J for some hydrocarbon fuel-air mixtures. The indirect detonation initiation is a promising way in a real PDE, in which a deflagration wave is generated firstly by weak ignition and then transited to a detonation wave through the deflagration-to-detonation transition (DDT) accelerator. Some researchers use a weak spark ignition in an optimally design geometry to promote DDT [5, 6]. Nevertheless, impractical long distance and time are usually

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required by this method. Besides, the reliability of weak spark ignition decreases in the case of high speed incoming flow [7].

Multi-point successive ignition [8, 9], nanosecond plasma ignition [10, 11], jet ignition [12, 13], and optical ignition [14, 15] are all ignition methods investigated for multi-cycle detonation condition. Multi-point successive ignition is an innovative means to initiate detonation waves, with which DDT was accelerated effectively. Authors in [8] pointed out that a detonation wave was generated by the movement external ignition sources under certain conditions. After the initial flame was formed by the first ignition source, the compression wave was strengthened continuously and turned to a shock wave, finally transited to a detonation wave by the successive ignition sources which were orderly distributed and ignited at the downstream direction of flame propagation [9]. The method of control the continuous ignition timing is equivalent to using the continuous movement ignition sources to accelerate DDT. The idea that triggers a detonation wave by using successive multiple ignitions to reduce the detonation initiation energy was firstly put forward by Zel'dovich *et al*. [8]. Thibault [16] *et al.* and Yoshikava *et al.* [17] carried out the relevant numerical simulation. The distributed external energy sources were artificially controlled and ignited one by one behind the weak compression wave to enhance the compression wave and form a detonation wave by simulating the strong coupling relationship between the shock wave and the chemical energy release [18-24]. Frolov *et al.* [20, 21, 24] and Frolov [22, 23] established several test systems with gas phase and liquid fuel to investigate the performance through the multi-point successive ignition method. The experiment results demonstrated that it was feasible to detonate the gas phase and two-phase combustible mixture with the multi-point successive ignition method. Frolov *et al.* [24] realized the detonation initiation in gas phase combustible mixture successfully at the distance of 0.6~0.7 m through the method of successive ignitions by experiment. The required ignition energy was lower than the energy required by single ignition. Sinibaldi *et al.* [10] conducted the experiment to shorten DDT time and distance by using two transient plasma ignitors. The experimental results indicated that the best triggering time interval of the two igniters was 550-610 μs. Dong *et al.* [25] simulated numerically the single-shot detonation initiation process in the hydrogen/air mixture through the multi-ignitions method. The results showed that the detonation initiation characteristics were significantly dependent on the ignition time interval of the ignitions. The influence of the distance between the two ignitions on the detonation initiation characteristics of propane-air mixture with the two successive ignitions was studied by Wang *et al.* [26]. The optimum distance between the two ignition sources was achieved to gain the best detonation initiation characteristics.

This paper addressed the numerical simulation on the detonation initiation characteristics by two successive ignitions with different ignition energy and ignition time interval. The detonation initiation process in stoichiometric propane/air mixture was analyzed by comparing the single ignition method with the two successive ignitions method. The ignition energy effect on the detonation initiation characteristics in the cases of single ignition and two successive ignitions with different ignition time interval was obtained. The simulation results provided the important and valuable reference to the research of the fundamental and applied PDE.

Physical models and calculation methods

The physical models established for the simulation of single ignition and two ignitions are shown in fig. 1. The 2-D axisymmetric model was used. The computational domain consisted of detonation chamber and external region. The left end of the detonation chamber was closed as the thrustwall, while the right end was open for exhaust. The inner diameter of the detonation chamber (represented by D) was 30 mm and the length was 60 0mm. The external region of $9D \times 6D$ was used to simulate the outlet boundary of the detonation chamber. The length of axial overlapping section between the external region and the detonation chamber was $3D$. The red zone with the width of 5 mm shown in fig. 1 represented the ignition region. As shown in fig. 1(a), there were twelve monitoring cross-sections in the detonation chamber, named as S1, S2… and S12, in order to monitor the status parameters along the chamber. The distances between the twelve cross-sections and the left end were 50 mm, 55 mm, 100 mm, 105 mm, 150 mm, 155 mm, 200 mm, 205 mm, 250 mm, and 255 mm, respectively. The L shown in fig. 1(b) represented the distance between the two successive ignitions and was fixed to 50 mm in this paper. The distribution of the twelve monitoring cross-sections in fig. 1(b) was the same with that shown in fig. 1(a).

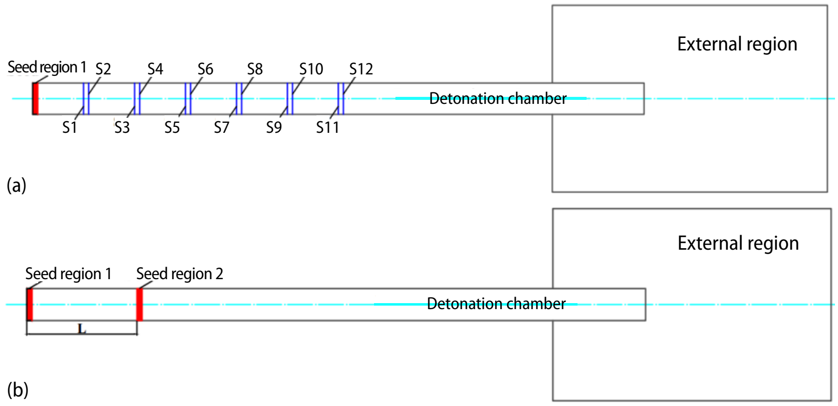

Figure 1. Schematic of the physical models; (a) physical model with single ignition and (b) physical model with two successive ignitions

The time interval between the time when the first ignition was triggered to ignite and the time when the second ignition was triggered to ignite was defined as ignition time interval (represented by Δt). The E represented the ignition energy. The numerical simulation in this paper was done at two steps: the effect of ignition time interval, Δt, on detonation initiation characteristics was obtained under a certain ignition energy and ignition distance ($L = 50$ mm) and the effect of ignition energy on the detonation initiation process was obtained by changing the ignition energy and repeating first step.

Unsteady 2-D flow simulations were performed by solving the compressible Navier-Stokes equations. The standard k-ε turbulence model was employed in all the simulations. In order to include the effect of the source term created by chemical reactions, a single-step irreversible finite rate chemical kinetic model was adopted in the present work. The results of reference [27] showed that single-step chemical kinetic model could be efficiently used to simulate the process of detonation initiation. Additionally, the adaptive mesh refinement method was used to refine the local mesh where there were huge temperature gradients. The gas was assumed as the ideal gas, and the wall was adiabatic and smooth. Stoichiometric propane/air mixture was used as the combustible mixture in the detonation chamber. The initial temperature was 300 K and the initial pressure was 0.1 MPa. The external region was full of air with the initial temperature of 300 K and the initial pressure of 0.1 MPa.

The grid-independent and experimental validation has been conducted in reference [27]. There were few differences between grid 0.5 mm and 0.2 mm, although the pressure peak values would be relatively more stable. Considering the much larger calculation expense and time for grid of 0.2 mm, the grid size of 0.5 mm was used in this paper.

Calculation results and analysis

The process of detonation initiation by using single ignition and two successive ignitions with different ignition energy and ignition time interval was simulated numerically. Five computation cases were selected as the examples and discussed in detail. Case 1 represented the case using single ignition and Cases 2-5 represented the cases using the two successive ignitions with different ignition energy, as shown in tab. 1.

Table 1. Computation condition in the five cases

Case	E [J]	L [mm]	Δt [μs]
1	5000	–	–
2	1000	50	50
3	500	50	52
4	200	50	50.3
5	100	50	53.4

Case 1: Single ignition with the ignition energy of E = 5000 J

Figure 2 illustrates the pressure contours at different time in the detonation chamber when single ignition with energy of 5000 J was used. When the ignition source at the closed end ignited, drastic combustion occurred in the combustible mixture near the ignition region through transitory induction time and led to the pressure increase. Meanwhile, a shock wave was generated and propagated to the open end. During its propagation, the shock wave was strengthened owing to the heat released by the drastic combustion and the pressure peak value increased to about 2.2 MPa at t = 10 μs. However, as the shock wave continued to propagate downstream, it was weakened gradually because of the weak combustion. At t = 120 μs, the pressure peak value decreased to about 0.8 MPa and was much smaller than that of the Chapman-Jouguet (C-J) gaseous detonation wave. The detonation wave was failed to be initiated. More simulation was done to confirm a detonation wave could be initiate or not with the single ignition at the increased ignition energy. The simulation result indicated that even the ignition energy increased to 10000 J, a detonation wave was still failed to generate.

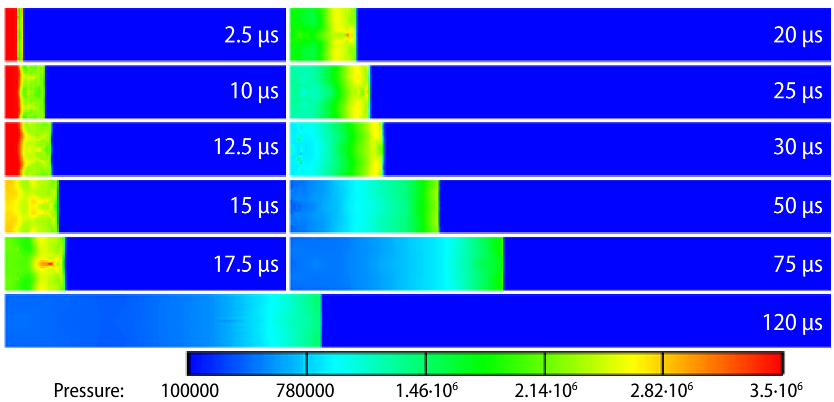

Figure 2. Pressure contours in the case of the single ignition with energy of 5000 J

Case 2: Two successive ignitions with energy of E = 1000 J, Δt = 50 μs

Figure 3 shows the pressure contours at different time in the detonation chamber when the two successive ignitions with each energy of E = 1000 J was used in the case of ignition time interval Δt = 50 μs. The compression wave formed by the first ignition source was weakened as

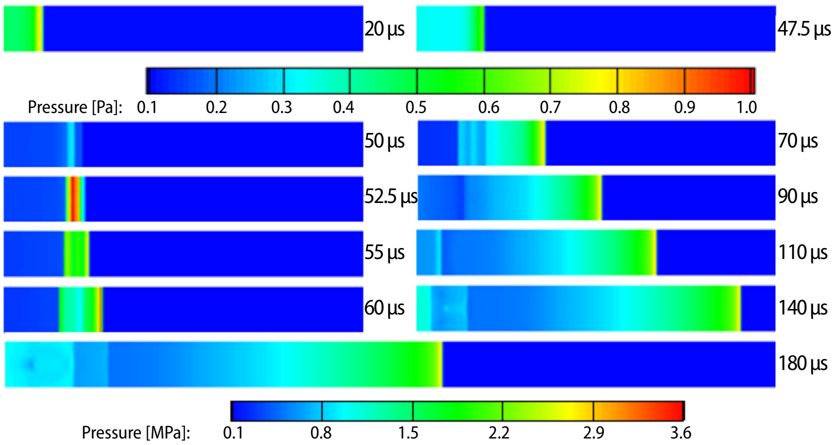

Figure 3. Pressure contours in the case of the two successive ignitions with energy of 1000 J

it propagated to the open end. The pressure of the compression wave decreased to 0.6 MPa at t = 47.5 μs. The second ignition source then ignited at t = 50 μs and led to the generation of the high pressure area at t = 52.5 μs. Upward and downward shock waves were driven by the high pressure area. The upward shock wave was weakened gradually during the propagation. The downward shock wave was weakened slightly firstly and then contained the intensity of about 2.9 MPa till it propagated to the outlet.

Pressure distribution along the axis of the detonation chamber at different time is shown in fig. 4. The pressure peak value in the detonation chamber was less than 1 MPa at t = 50 μs and then increased to about 2.8 MPa after t = 55 μs when the second ignitions was triggered. According to fig. 4, the shock wave arrived at the position of 89.5 mm, 127.5 mm, and 184.6 mm at the corresponding time of t = 70 μs, 90 μs, and 120 μs, respectively. The wave velocity was about 1900 m/s, which was greater than the C-J gaseous detonation wave speed of 1796.8 m/s for the stoichiometric propane/air mixture calculated by Chemical Equilibrium and Applications (CEA) code developed by NASA Lewis Research Center. The velocity of detonation wave in reference [18] was about 1800 m/s, which was close to the simulation results. Hence, according to the responding data of reference [18] and CEA, the simulation results were credible. Therefore, propane/air mixture in the detonation chamber was detonated successfully. According to figs. 3 and 4, the plane detonation wave was initiated at about t = 55 μs and the corresponding detonation initiation distance was approximately 61.2 mm.

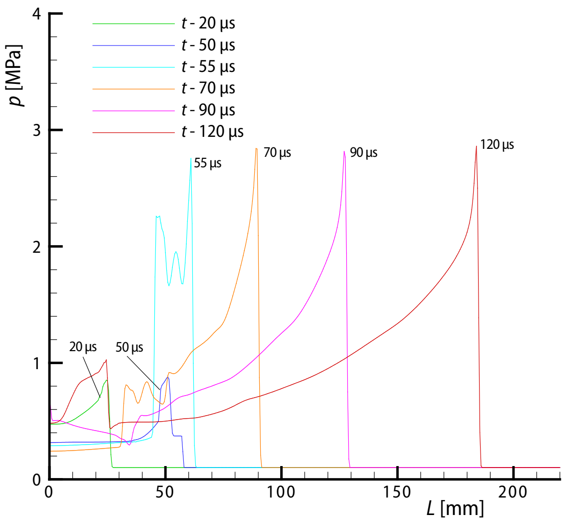

Figure 4. Pressure distribution at different time, E = 1000 J, Δt = 50 μs

Case 3: Two successive ignitions with energy of E = 500 J, Δt = 52 μs

Figure 5 illustrates the pressure contours at different time in the detonation chamber when the two successive ignitions with each energy of E = 500 J was used in the case of ignition time interval Δt = 52 μs. The compression wave formed by the first ignition source was weakened as it propagated to the open end. The pressure of the compression wave decreased to 0.7 MPa at t = 50 μs. The second ignition source then ignited at t = 52 μs and strengthened the compression wave. After 0.5 μs (at the time of 52.5 μs) a strong shock wave was formed and a high pressure area, in which the central pressure was more than 3.5 MPa, was formed at t = 55 μs. Upward and downward shock waves were driven by the high pressure area. The upward shock wave was weakened gradually during the propagation. The downward shock wave propagated to the open end with high pressure and velocity and was weakened slightly firstly. Transverse waves were generated when the downward shock wave collided with the top and bottom wall. The transverse waves then collided at the axis of the chamber and a stable strong combustion wave with the pressure of above 3.5 MPa was generated at t = 60 μs. The pressure was greater than the pressure of C-J gaseous detonation, so it could be judged that a detonation wave may be initiated.

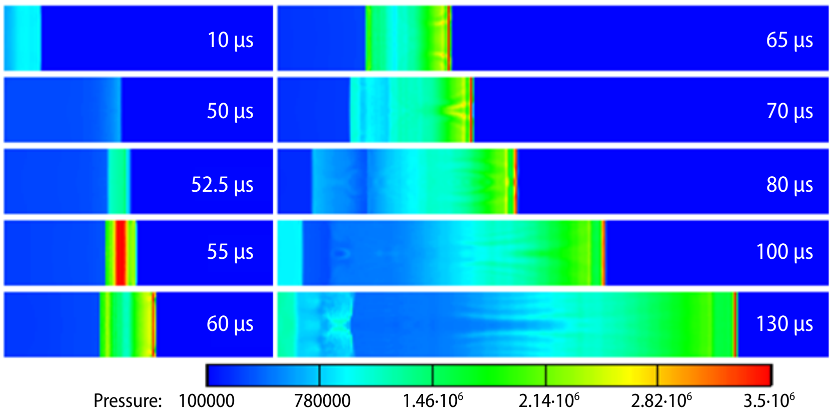

Figure 5. Pressure contours in the case of the two successive ignitions with energy of 500 J

Pressure distribution along the axis of the detonation chamber at different time is shown in fig. 6. The pressure peak value in the detonation chamber was about 5.3 MPa at t = 55 μs, corresponded to the high pressure area shown in fig. 5. The pressure peak value decreased to about 3.7 MPa at t = 60 μs and then kept nearly constant. According to fig. 6, the shock wave reached the position of 128.4 mm, and 208.2 mm at the corresponding time of t = 90 μs and 130 μs, respectively. The wave velocity was about 1996.4 m/s, which was greater than the C-J gaseous detonation wave speed of 1796.8 m/s for the stoichiometric propane/air mixture calculated by CEA. Therefore, propane/air mixture in the detonation chamber was detonated successfully. As shown in figs. 5 and 6, the plane detonation wave was initiated at about t = 60 μs and the corresponding detonation initiation distance was about 70 mm.

Case 4: Two successive ignitions with energy of E=200 J, Δt =50.3 μs

Pressure contours in the detonation chamber at different time by using the two successive ignitions with the energy of 200 J are shown in fig. 7. The compression wave triggered by the first ignition source was enhanced after the second ignition source ignited. Upward and downward shock waves were driven by a high pressure area. The downward shock wave propagated to the open end with high pressure and velocity and collided with the top and bottom wall. Local hot spots were formed when the downward shock wave collided with the walls at t = 65 μs. After that, the hot spots were strengthened continuously and local explosion occurred at t = 70 μs. The transverse waves generated by the local explosion propagated to the axis of the chamber and collided at t = 75 μs, which resulted in the strong shock wave with high pressure of 3.5 MPa. Actually it was an overdriven detonation wave and propagated upstream and downstream. The downward wave developed to a steady plane detonation with a slight lower pressure of 3 MPa at t = 90 μs. The pressure was greater than the pressure of C-J gaseous detonation, so it could be judged that a detonation wave may be initiated. Meanwhile, complicate reflection and collision occurred during the propagation of the backward shock wave.

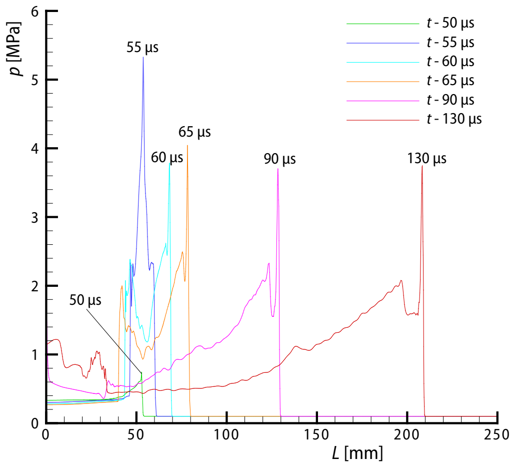

Figure 6. Pressure distribution in the case of the two successive ignitions with energy of 500 J, Δ*t* = 52 μs

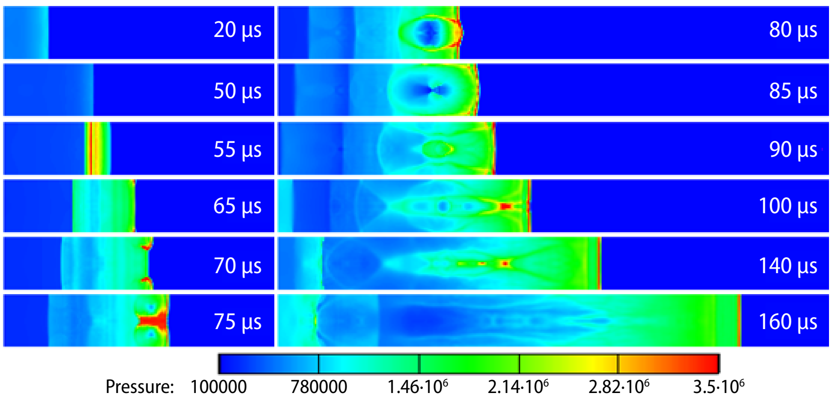

Figure 7. Pressure contours in the case of the two successive ignitions with energy of 200 J, Δ*t* = 50.3 μs

Figure 8 illustrates the pressure distribution along the axis of detonation chamber at different time in Case 4. According to figs. 7 and 8, the pressure peak value of 1.7 MPa at distance of 81.2 mm was corresponding to the local explosion. The pressure of the shock wave at the time of 85 μs and 90 μs was 3.4 MPa and 3.0 MPa, respectively. The pressure even increased to about 3.8 MPa at t = 100 μs and then kept nearly constant. Meantime, very high pressure occurred in the burnt region due to the reflection and collision of the transverse waves. The shock wave reached the position of 125 mm, and 144 mm at the corresponding time of t = 90 μs and 130 μs, respectively. The wave velocity was about 1900 m/s, which was greater than the C-J gaseous detonation wave speed. On the basis of figs. 7 and 8, a steady detonation wave was initiated in the propane/air mixture. The detonation initiation time was about t = 90 μs and the corresponding detonation initiation distance was approximately 125 mm.

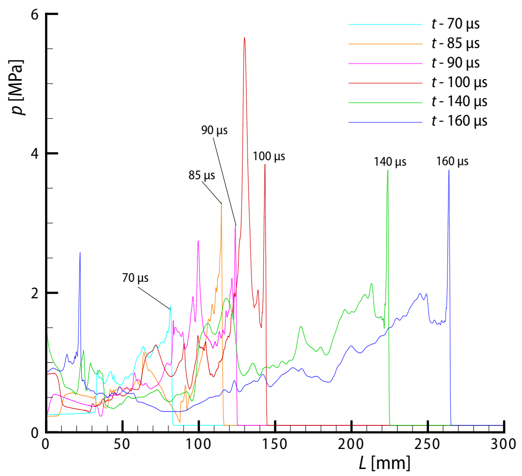

Figure 8. Pressure distribution at different time, *E* = 200 J, Δ*t* = 50.3 μs

Case 5: Two successive ignitions with energy of E = 100 J, Δt = 53.5 μs

Figure 9 shows the pressure contours in the detonation chamber at different time by using the two successive ignitions with the energy of 100 J, under the condition of Δ*t* = 53.5 μs. The compression wave formed by the first ignition source was weakened as it propagated downstream to the open end. The pressure of the compression wave decreased to less than 0.5 MPa at *t* = 52.5 μs. Shortly at *t* = 53.4 μs, the second ignition source ignited and the compression wave near the second ignition source was strengthened. A high pressure area with the pressure of above 3.5 MPa was formed at *t* = 60 μs. Upstream and downstream shock waves were driven by the high pressure area. The upstream and downstream shock waves were weakened during the propagation and the pressure of the upstream shock wave decreased quickly. The downstream shock wave propagated to the open end with high pressure and velocity and was weakened slightly firstly. Another high pressure region was formed at the center of the downstream shock wave at *t* = 67.5 μs. When it collided with the top and bottom wall, transverse waves were generated at *t* = 72.5 μs. The transverse waves then collided at the axis of the chamber at *t* = 80 μs. Finally, a stable strong combustion wave with the pressure of above 3.5 MPa was generated at *t* = 97.5 μs. The pressure was greater than the pressure of C-J gaseous detonation.

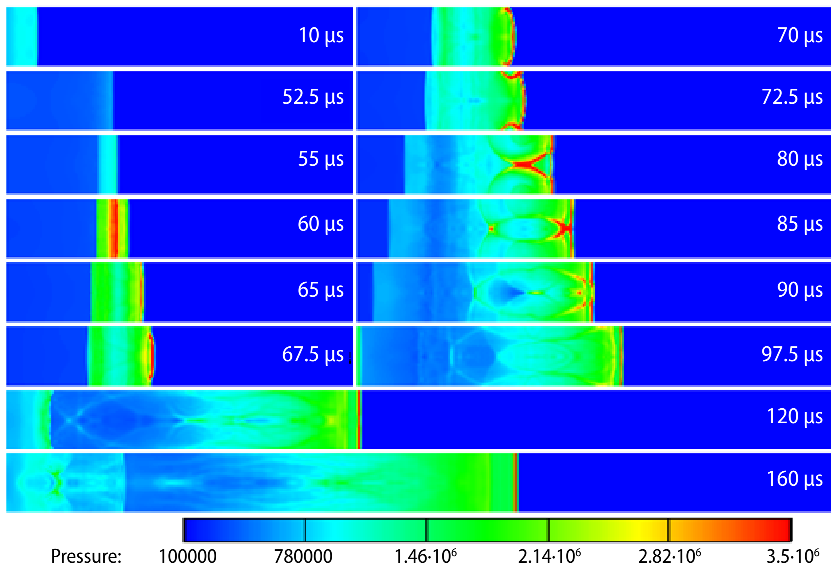

Figure 9. Pressure contours in the case of the two successive ignitions with energy of 100 J, Δ*t* = 53.4 μs

Pressure and temperature histories at the three monitoring sections of S1, S2, and S3 at different time are illustrated in fig. 10. It could be learnt from the curves of P-S1 and T-S1 that the flame front reached S1 at about t = 47 μs following the compression wave but the flame was decoupled with the compression wave according to the separate pressure and temperature curves. Similarly, the flame was also decoupled with the compression wave at S2. A detonation wave was not initiated at S1 and S2. According to the curves of P-S3 and T-S3, the flame was coupled with the shock wave and the pressure peak value was about 3.6 MPa. So it could be judged that a detonation wave was formed at S3. However, it was not a stable plane detonation wave, as shown in fig. 9. Figure 11 illustrates the pressure distribution along the axis of detonation chamber at different time in Case 5. The shock wave reached the position of 92 mm, and 136.5 mm at the corresponding time of t = 75 μs and 97.5 μs, respectively. The wave velocity was about 2000 m/s, which was greater than the C-J gaseous detonation wave speed. According to figs. 9 and 11, a plane detonation wave was initiated at about t = 97.5 μs and the corresponding detonation initiation distance was approximately 136.5 mm.

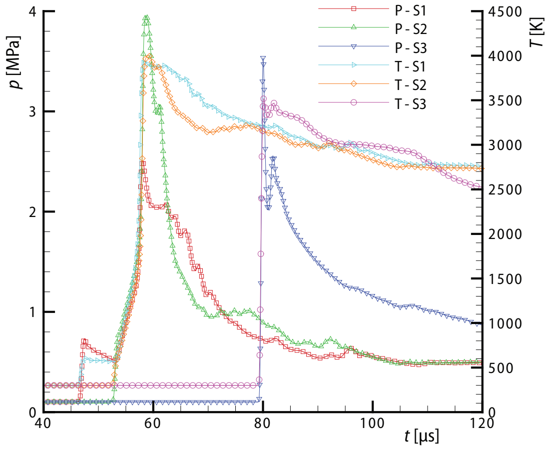

Figure 10. Pressure and temperature distribution at three locations at different time

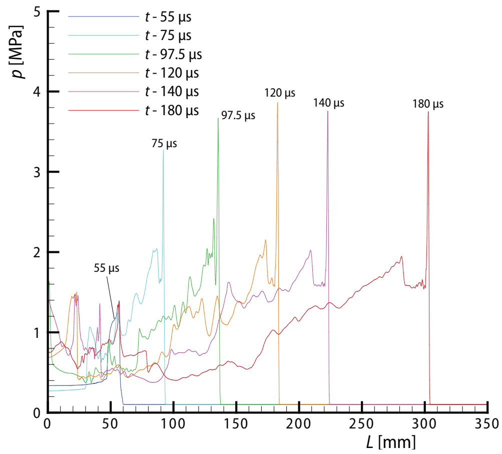

Figure 11. Pressure distribution at different time, E = 100 J

Calculation results in the cases of different energy and ignition time interval

Figure 12 shows the initiation time and distance of a stable plane detonation wave in Cases 2-5. The detonation initiation distance and time were both influenced by the ignition energy of the ignition source. It could be known that the shorter detonation initiation distance and time were obtained with the higher ignition energy. Lower ignition energy, shorter detonation initiation distance and time are all required for the application of a real PDE. Therefore,

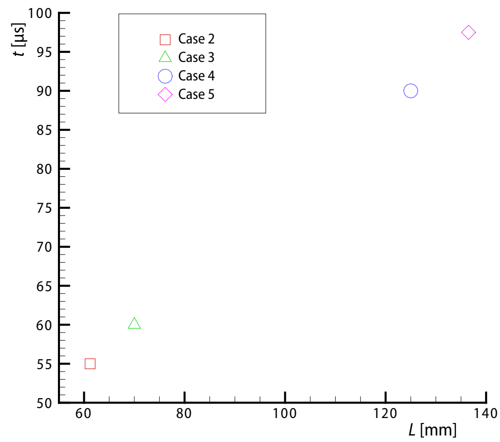

Figure 12. Initiation distances and times of a plane detonation in Cases 2-5

this conflict of conditions requires a compromise to be made so as to gain the best overall operating performance of a PDE.

Table 2 illustrates the calculation results when the two successive ignitions with the ignition energy of 1000 J, 500 J, 200 J, and 100 J were used under the different ignition time interval. A detonation wave could only be initiated successfully when the ignition interval time was within a certain range. The range of the ignition time interval with successful detonation initiation were 13.5 μs, 6.5 μs, 6.3 μs and 0.9 μs for the corresponding ignition energy of 1000 J, 500 J, 200 J, and 100 J.

Table 2. Simulation results of two successive ignitions with different energy and ignition time interval

E = 1000 J	Δt [μs]	40	46	46.5	60	70
	Detonation	No	No	Ye	Ye	No
E = 500 J	Δt [μs]	48.5	48.6	55	55.1	56
	Detonation	No	Ye	Ye	No	No
E = 200 J	Δt [μs]	50.1	50.3	56.5	56.8	57
	Detonation	No	Ye	Ye	No	No
E = 100 J	Δt [μs]	52	52.6	53.4	53.5	55
	Detonation	No	Ye	Ye	No	No

Figure 13 shows the fitting curve of the range of the ignition time interval with successful detonation initiation versus the ignition energy. The range of the ignition time interval with successful detonation initiation decreased at the decreased ignition energy when the distance of the two ignitions was fixed.

The experimental research of detonation initiation by two successive electric discharges was carried out in the smooth detonation chamber by Frolov *et al.* [19]. The experiment results are shown in fig. 14, in which successful detonation initiation in the detonation chamber is represented by "+" or unsuccessful detonation initiation is represented by "-". The range of

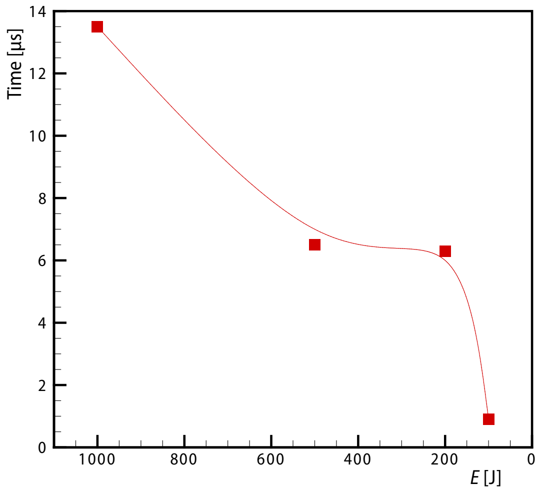

Figure 13. The fitting curve of the range of the time interval with successful detonation initiation *vs.* ignition energy

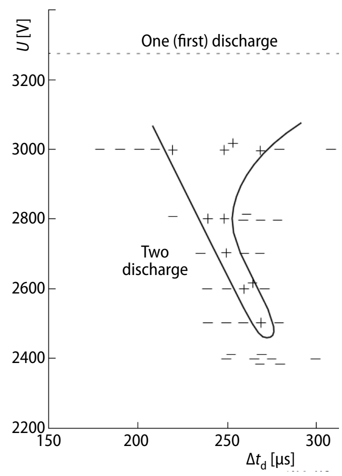

Figure 14. Detonation peninsula for *n*-hexane spray in air when detonation is initiated by two successive electric discharges [19]

ignition time interval decreased gradually as the ignition energy decreased due to the reduced discharge voltage. This result was consistent with the numerical simulation result by the two successive ignitions with different ignition energy in this paper, which proved that the simulation results in this paper were credible.

Conclusions

The numerical simulation of detonation initiation by the two successive ignitions with the same distance (L = 50 mm) but different ignition energy and different ignition time interval was conducted in this paper. Based on the analysis and discussion of the detonation initiation process, the results were obtained as the follows.

- A detonation wave could not be initiated by single ignition with the ignition energy of no more than 10000 J, while it was initiated by the two successive ignitions with the ignition energy range of 1000 J to 100 J.
- No matter how much the ignition energy of the two ignitions was, a detonation wave could only be generated successfully if the ignition time interval was within a certain range. Otherwise, a detonation wave would not be initiated when the time interval was out of the range.
- The detonation initiation distance and time decreased at the increased ignition energy of the two successive ignitions, which is beneficial to reduce the length of the detonation chamber and improve the operating frequency of a PDE. However, huge ignition energy is not easy to realize in a real engine. There is a compromise has to be made to achieve the optimum operating performance of a PDE.
- As the ignition energy of the two successive ignitions decreased, the range of ignition time interval with successful detonation initiation decreased under the constant distance between the two ignitions.

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Nomenclature

D – inner diameter of the detonation chamber, [μs]
E – ignition energy, [J]
L – distance between the two successive ignitions, [mm]
Si – monitoring cross-sections in the detonation chamber, i = 1, 2…12
t_d – detonation initiation time, [μs]
Δt – ignition time interval, [μs]

Acronyms

DDT – deflagration-to-detonation transition
PDE – Pulse Detonation Engine

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