Shock wave - boundary layer interaction driven autoignition and DDT

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1 Introduction and purpose

Detonation studies are very important in many aspects of science. One on the most important feature in a development of any new technology are basics. Once we can understand how does detonation, auto-ignition or deflagration-to-detonation transition (DDT) take place, we are able to create sophisticated, new, efficient mechanisms.

The detonation research started just at the beginning of 1880, but its fully detailed generation mechanism is still a mystery. Many experimental researchers in the early 1900s reported that the detonation is generated by the transition from deflagration, later known as deflagration-to-detonation transition. However, high performance laser allowing to see a detailed phenomenon was developed much later. Numerical simulation developed just a few decades ago, but it already became very powerful engineering tool taking over experimental research.

Recent text written by Lee[1] explain on DDT extensively. But not much about shock wave-boundary layer interaction in reactive mixture.

The purpose of this research is to investigate a chapter of detonation, namely shock wave – boundary layer interaction (SWBLI) triggered DDT and show that weak waves, which seems to be insignificant can promote uncontrolled explosions.

Hydrogen being an ecological fuel is very attractive now for engineers and is already actively used in rocket engines. However, peculiarities of hydrogen combustion kinetics, the presence of zones of inverse dependence of reaction rate on pressure, etc. prevent from wide use of hydrogen engines. The aim is also to confirm the numerical results with new and accurate experimental data.

2 The concept of auto-ignition in boundary layer

Numerical research were done using 2-D compressible Navier–Stokes equations for highly viscous and diffusive flow field in its early stage of deflagration. Stanford model with nine chemical species, H_2 , H, O_2 , O, OH, HO_2 , H_2O_2 , H_2O_3 , and N_2 , and twenty elementary reactions including a dependency of pressure with the Troe's formulation was used. The unsteady term is calculated with a Strang-type time splitting method, the convection term using a Harten–Yee non-MUSCL modified-flux TVD scheme, and the production term with a point implicit method.

Fig. 1 shows the scenario of an auto-ignition, DDT, and detonation development. Additionally, is some cases it is possible to observe a fast flame development prior to DDT. When we observe the process DDT, at first there is a the simple structure of a flame and a strong shock wave (a precursor shock), which travels in some unchangeable distance in front of the flame. After certain time due to interaction of weak shock waves produces by the flame with the boundary layer there is an auto-ignition between the flame and the shock wave. When the induction time is long enough, shock waves heat up the boundary layer causing the auto-ignition. The rise in the temperature is not that high behind just one single wave, nonetheless, there is one after another coming and keep on heating up this safety blanket up to a point where the gas mixtures ignites by itself. Sometimes from the point of auto-ignition a new supersonic flame develops on walls and after a few microseconds flames collide in the middle of the tube causing detonation.

Even though numerical research seems to be the best possible solution to analyze boundary layer problems, we want to show a validation with new experimental data.



Figure 1. The scenario of the auto-ignition, DDT, and detonation development [2].

3 Experimental facilities

The experimental tube is a 40 x 40 mm square 3.5-meter long tube with window through which we are able to observe a boundary layer. Fig. 2 shows the schematic of detonation tube system. The total length of detonation tube is 4500 mm. The length of the tube can be changed for purpose. A automobile plug is installed at the last end of the tube for ignition. The ignition timing is controlled by LabVIEW system. Near the closed end a Shchelkin wire is installed to enhance DDT. A dump tank is set at the other end of the tube to reduce the detonation power. A PET diaphragm of 25 μ m is set to keep the dump tank pressure to be vacuum condition. The test mixture is prepared by oxyhydrogen diluted with Argon to get a clear cell structure of detonation. Pressure transducers of PCB Co. (113A24) are used to get pressure and detonation velocity. An ICCD camera is used to get a DDT ignition in the boundary layer.



Figure 2 Schematic of detonation tube system

4 **Results**

DDT process is observed by three pressure transducers. Figure 3 is the pressure histories at x=375, 495, 735, 795, and 855 mm from the tube end where the ignition plug is located. The first pressure rises from the precursor shock wave at five pressure transducers are detected at each pressure transducer to show a broken line and its speed is 700 m/s. The pressure record from the flame front is not seen in the figure because of its near-atmospheric value, but the subsequent pressures caused from the flame front are seen behind the precursor shock wave. And near the DDT point, which is not seen in Figure 3, but can be obtained by the cross point of extending both broken lines, two pressure pulses of about 0.5 MPa, which is developed from the pressure behind the precursor shock wave, are seen from the pressure profile at the pressure transducer located at 855 mm from the plug-ignition point. The precursor shock wave propagation velocity is 650 m/s. Since the CJ detonation velocity for this mixture is about 1860 m/s, the wave does not reach to detonation yet. The second sharp and large pressure rises are also on a line, but are in the opposite direction from the first pressure rise. The second pressure rise is due to the retonation. From these results it is difficult to recognize a shock wave – boundary layer interaction.



Figure 3 Pressure records of five sensors; (a) 375 mm, (b) 435 mm, (c) 495 mm, (d) 735 mm, (e) 795 mm, (f) 855 mm, from the tube end (at the automobile plug type igniter position)



Propagating direction

Figure 4 Direct photograph of auto-ignition before DDT: the exposer time is $0.02 \ \mu$ s; the gain is 40; the delay time from the trigger is 50 μ s, the distance from the igniter is 2325 mm.

Figure 4 shows the direct photo of the ignition and flame propagation near the boundary layer (we cannot say the ignition occurs in the boundary layer from this figure). It is difficult to see the flame

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shape from Figure 4 (but the original figure can show the flame configuration with the auto-ignition near the boundary layer). The strong emission near the boundary layer shows the propagation of fast speed flame toward downstream along with the main flame. This fast flame has a bow shock wave at its front.

Figure 5 shows the direct photo of the different case with the same initial condition as that of Figure 4. This case is in the process of DDT. The auto-ignition occurs in the center region of the tube as well as that near the wall. The situation of this photo is later phenomenon than that of Figure 4. It is difficult to say there are transverse waves in the wave front or not, but the fast and strong flame propagation near the upper wall and the transverse wave-like phenomenon are seen in the figure.



Figure 5 Direct photo of DDT process: the exposer time is $0.02 \ \mu$ s; the gain is 40; the delay time from the trigger is 50 μ s, the distance from the igniter is 2375 mm. The initial conditions are the same as that of Figure 4.

The location of pressure transducer and its pressure record for the case of Figure 4 at the same initial conditions, but at the location of 2375 mm from the ignition plug are shown in Figure 6. The figure indicates clearly the precursor shock wave at the time of 7.5 msec, the time of auto-ignition at 8.9 msec, and the time of detonation transition at 10 msec during when the sequence of pressure rises by the weak compression waves caused from the flame front up to around 10 msec and when the DDT starts there where the sudden pressure rises to about 6.5 MPa. At the time of 10.6 msec the sharp pressure rise comes out, which is more than 10 MPa, but is probably caused by the reflected compression wave from the tube end and the window was broken at that time.



Figure 5 The location of pressure transducer and its pressure record for the case of Figure 4 at the same initial conditions, but at the location of 2375 mm from the ignition plug

5 Conclusions

The subsequent pressures caused from the flame front are seen behind the precursor shock wave. The experiment shows that DDT originated from the vicinity of boundary layer. That confirms our calculations on DDT origin as well as fast flame propagation with bow shock in front of it.

References

- [1] Lee JHS (2012) The Detonation Phenomenon, Cambridge University Press, Aug. 2008.
- [2] Dziemińska E, Hayashi AK. (2013). Auto-ignition and DDT driven by shock wave boundary layer interaction in oxyhydrogen mixture. Int. J. of Hydrogen Energy 38: 4185-4193.