

Fast Deflagration in the Smooth Tube in Hydrogen-Oxygen Mixture

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1 Introduction

Combustion velocities can be either subsonic or supersonic, and based on that we are talking about deflagrations or detonations. It is possible to achieve deflagration propagating with a speed higher than a speed of sound, nevertheless there is not much said about fast deflagrations (fast flame propagation) in the smooth tubes in the recent research. Even in existing reports about fast deflagrations the velocity of the flame does not reach the sonic speed in most of cases. In this paper we are going to show that flame can travel with the speed of Mach 1 and even higher in the H₂/O₂ mixture and additional phenomenon of ignition in the boundary layer can be seen.

The pioneers of visualization methods – Urtiew and Oppenheim – showed experimentally in 1960s that fast deflagration is possible. In 1978 Edwards et al. [1] referred to this kind of region of fast deflagration as quasi-steady shock-deflagration regime traversing tube with a quite high speed. Much later Chue [2] calculated that deflagration moves with velocity between 600 m/s and 1000 m/s without going to the detonation mode in rough tubes. According to Eder [3] probability for the onset of a fast deflagration is around 20%, and loaded with high pressure when reflected from the wall (over 200 bars). Very interesting work in obstructed tubes, and the closest to our results, was done by Kuznetsov [4] almost a decade ago. With the blockage ratio of 0.6, flame velocity in quasi-detonations regime in the hydrogen-air mixture reached 1600 m/s. He is mentioning that in the case of strong flame acceleration fast supersonic deflagration is possible due to generation of a strong compression and shock waves ahead of the flame. Liberman et al. [5] is using Navier-Stokes equation to solve the problem. In this case flame is propagating with more than sonic speed for a short

time just before DDT. Lee's group talked about the fast deflagration in many publications but one of the best summary of this problem can be found in [6], where fast deflagration is referred as a half speed of CJ value. As Lee and Liberman noticed from numerical analyses, the supersonic flame is the key to so called brush to detonation [6]. The details are written in the paper.

2 Numerical model and code verification

Our model is a smooth tube with dimensions of 2x60 mm with a structural, fine grid with adiabatic walls. Computational domain is divided into three regions as shown in Fig. 1, and corresponding initial conditions are set as shown in Table 1.

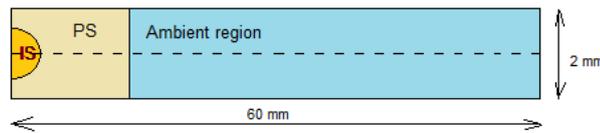


Fig. 1 Initial conditions for the model: IS – ignition source, PS – precursor shock, and ambient region.

Table 1 Initial conditions for model.

Region	Pressure [MPa]	Temperature [K]
Ignition Source	1.8	2000
Precursor Shock	1.048	682
Ambient Region	0.1013	300

The radius of the ignition source (IS) region is 5 mm. The second region called precursor shock (PS) is about 2 mm long measuring from the left edge. Grid is build out of 41.325 million points (75000x551). In the x direction width between them is constant and equals to 0.8 μm , while in the y direction the size increases from 0.8 μm on the wall to 5.5 μm at the center line which is also axis of the symmetry for the grid. With the higher grid density on the wall it was possible to register the phenomenon happening in the boundary layer.

To resolve this case Navier-Stokes equation and the Petersen and Hanson model with eight species and eighteen reactions is used. Ignition takes place on the wall on the left-hand side of the model and propagates towards the right-hand side. One of our numerical results were compared with Urtiew and Oppenheim's experiment [7] to verify the accuracy of the code. Both the experiment and numerical calculations are done for hydrogen/oxygen mixture.

3 Results

In the front of the flame with the structure like tulip-shaped flame, high temperature and high pressure region is obtained (Fig. 2) that leads to an explosion in the boundary layer (but not necessarily) and shortly after that to the deflagration-to-detonation transition and detonation. In this study DDT is not the theme, but the supersonic flame is the one we are interested in. In the deflagration phrase, flame is propagating with supersonic velocity of the value up to Mach 1.8 where Mach number is calculated at the local values, and the distance between the precursor shock and the flame is about 2 mm for the time frame captured in Fig. 2 and 3. The highest pressure is just in front of the flame, 14.8 MPa, and at the same time the highest temperature is 3552 K.

Additionally three different kinds of ignition have been observed. They are either connected with the fast flame propagation or the process that causes heating up in the boundary layer, but not the initiation of the flame at the left-hand side wall. Detailed analysis proves that the first hot spot causing explosion is created on the wall in the boundary layer. The second and third one that is the beginning of DDT is well observed at the tip of the flame. Pressure, temperature, and Mach number as well as other parameters corroborate that fact. However the mentioned problem is not the purpose of this paper, although it is the result of the supersonic flame.

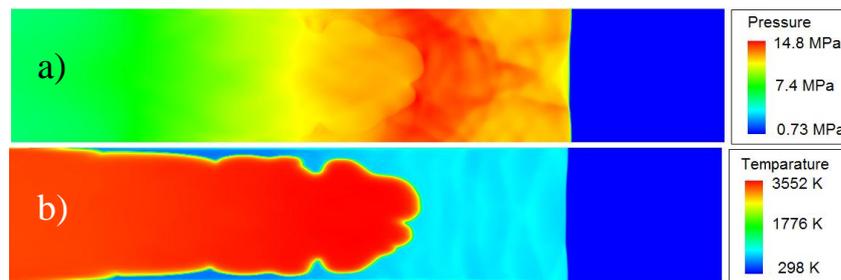


Figure 2. Pressure (a) and temperature (b) record for the time of 14.28 μ s. Bottom and top boundaries are walls. Shown piece is 2x11 mm at the time of 14.28 μ s.

Fig. 3 visualizes three different scales of Mach number for the same moment of 14.28 μ s, so it is easier to estimate the exact values of this presented part of the tube. In Fig. 1a the deep blue color is assigned to Mach 0 and the red to Mach 1.8. This is the lowest and the highest value of the velocity, respectively. Fig. 3b shows the shortened scale from Mach 0 to 1, where the deep red color is assigned to velocity equal or higher than Mach 1. And adequately to that in Fig. 3c the deep blue indicates equal or lower velocity than Mach 1. Finally in the part d) there is a graph presenting the actual values for this subtracted part of the tube where the vertical scale is the Mach number from 0 to 2, and the horizontal one is the tube's length measured from the left-hand side. Values are measured at the center line of the model, which is also the axis of symmetry for the grid. One can recognize that the high speed deflagration part in this graph is the region between the flame (the left-hand side slope) and the precursor shock wave (the right-hand side slope). The fast propagating deflagration is acting like a piston and causes compression waves of very high pressure, which are visible in pressure, temperature, and Mach number records. Once reflected at the wall with a big impact, there is an explosion in the boundary layer.

Newly created fast propagating flame in the boundary layer (after mentioned explosion) is generating a shock wave in the front. This shock wave is small, but with a very high impact, traveling on the tip of the flame. This flame is traveling faster than the main stream. This results in the increase of a burning rate and eventually the generation of a very strong shock. Moreover, the flame happens to propagate along the wall surface and this interaction causes additional instabilities within the flame. The distance between the flame and the compression wave shrinks along the wall. One can observe it in Fig. 2.

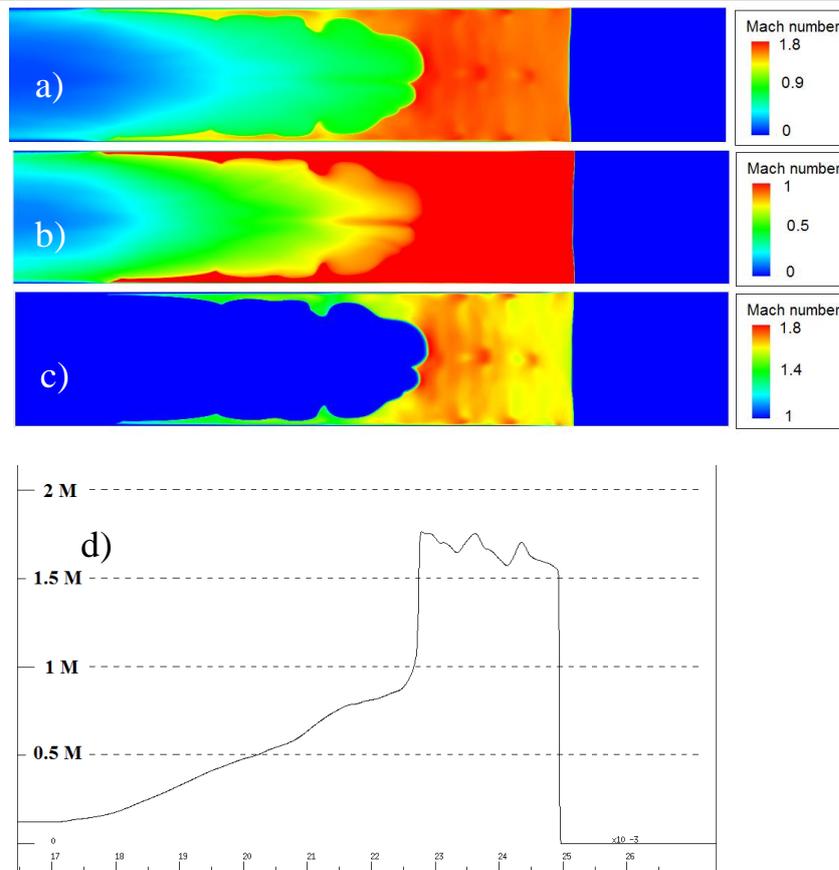


Figure 3. In a) b) and c) Mach number is visualized for the three different scales (for the same part of the tube like in Fig. 1a). Shown piece is 2x11 mm at the time of 14.28 μ s. Graph d) illustrates values for the Mach number for exactly the same part, distance here is measured with mm.

Just before the explosion in the boundary layer, the flame is propagating with Mach 1.83 and after it the additional flame starts propagating along the tube's wall with the velocity of Mach 1.86. High pressure and high temperature region which is pushed ahead by the piston effect one more time. Meanwhile the distance between the flame and precursor shock is constant, around 2 mm. In a very short time deflagrating flame is reaching almost Mach 2.

4 Conclusions

We proved that it was possible to simulate supersonic deflagration in case of hydrogen-oxygen mixture in the smooth tube. Propagating flame reaches velocities higher than Mach 1 and additional phenomenon, like explosion in the boundary layer, can be observed. Fast deflagration was noticed many years back by other researchers, either in experiments or numerical simulations. Though, nowhere else, such a supersonic speed of deflagration was mentioned.

Acknowledgments

This research was supported by KAKENHI(21360420) and collaborated with the JSS Systems in JAXA supercomputer system.

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