An Experimental Study on Flame Acceleration and Deflagration-to-Detonation Transition in Narrow Tubes

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1 Introduction

Recently, the prevailing of the microelectronic mechanical systems (MEMS) has attracted intensive and extensive research attention on the micro energy and power generation devices with significantly higher energy and power density than current lithium batteries can provide. Among the many possible power generation sources, combustion is still the most reliable and feasible method with specifically high energy and power density output for the micro power generation system. However, some problems will be encountered when the scale is decreased to micro scale, such as low temperature reaction and quench due to the enhanced heat loss. Nevertheless, if we consider a flame propagation system with a very high-speed reaction front, the heat loss from flame to the wall will be reduced to a minimum so that the existence of detonation wave propagation in the micro-scale systems may not be a question. Besides, the constant-volume combustion process provides higher efficiency. In general, the detonation wave can be generated by several ways including direct initiation, shock induced detonation transition (SDT), and deflagration-to-detonation transition (DDT). For practical consideration, the direct initiation and SDT methods need very high energy to obtain the detonation waves, so they are not appropriate for small tubes. However, DDT only needs a weak energy of ignition to generate a low speed deflagration and then with proper flame acceleration the flame may transit to detonation. The overall process may include flame acceleration, instabilities, high speed turbulent flame, shock pre-conditioning and finally a local explosion occurs [1].

To be Actual, detonation wave propagation in the micro scale tubes had been studied in 1960s [2]. This study mainly discussed the propagation of detonation in the micro tube, so that the detonation was already generated before entering the micro tubes. Recent researches revealed that several propagation modes were observed in the micro tube, including spinning, galloping, and low speed detonation [3,4] but these modes are not typical Chapman-Jouguet detonations. When the scale is reduced, negative effects on the flame acceleration due to enhanced heat loss through wall become pronounced and so does the viscous drags of wall.

In recent years, the feasibility of DDT in micro tubes or channels has been studied by several researchers [5, 6]. Their numerical results show that occurrence of DDT in the very narrow channels is possible, and proposed that heat loss and viscous force play important role on the flame acceleration. In 2007, an experimental research was performed with ethylene/oxygen mixture. The smallest tube size was 0.5mm. The results showed three propagation modes: stable, quenching, and low speed sub-

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CJ detonation [7]. However, not all of fuel and oxidizer mixtures can result in DDT in the micro tubes. A study in the relatively large scale was done by the researchers who used the turbulizing chambers to enhance the initial flame acceleration to reduce the DDT run-up distance [8]. In this study we investigate and discuss the phenomenon of flame acceleration and deflagration to detonation transition (DDT) in micro tubes, especially to achieve C-J detonation.

2 Experimental setup

In the experiments, we use stoichiometric hydrogen and oxygen as the gas mixture and use several straight quartz tubes of various tube sizes of 1mm, 1.5mm, 2mm inner diameters with fixed length of 80cm. A thick-wall tube of 2mm in thickness is used in order to prevent the damage of overdriven detonation. In other cases, for the expanded pre-chamber design, the quartz tube is connected to an aluminium chamber of 6 mm and 9 mm inner diameters and an automotive spark (NGK) is installed directly at the end wall of the pre-chamber. On the other hand, the igniters for straight tubes is constructed with two stainless wires as the electrode. The discharge voltage transmitted by a high voltage coil provides 2kV and is measured by a high voltage probe. The ignition energy is estimated to be less than 0.4 J. The fuel-air mixture is fed in the downstream of the tube for avoiding the influence of flow field by the feeding port. Before performing the experiments, the chamber is first vacuumed to 0.05 psia by a vacuum pump (UCLV). A high-speed camera (PCO. Camera, Cooke) which can take photos at the maximum frame rate up to 90000 fps is used to capture the position of flame fronts. In our experiments, the frame rate is 72900 fps with six pixels of height in the image and the exposure time is 10 μs.

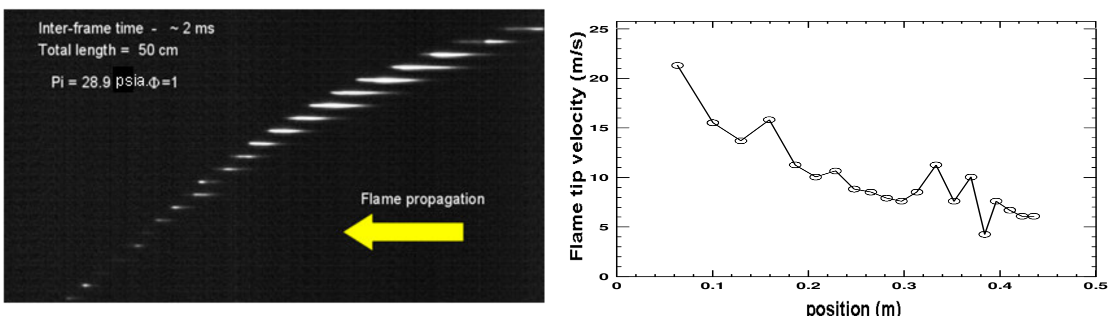

Fig 1. Flame propagation without generating of detonation at 28.9 psia.

4 Results and discussion

In the experiment, we first examine the onset of deflagration-to-detonation transition with H_2/O_2 mixture at atmospheric pressure in the straight micro-tube.The results show that with stoichiometric H_2/O_2 mixture in the 2mm tube the DDT phenomenon cannot be observed. In Fig. 1, with an increase of the initial pressure to 28.9 psia there still no trace of DDT. It's known that when the initial pressure increases, the possibility of DDT becomes larger and the run-up distance decreases. Figure 2 shows that DDT in the straight tube occurs when the initial pressure of the mixture exceeds 30 psia. and the oscillating phenomenon were also observed but due to the high frame rate the image of much lower speed flame is dim so that the position of flame is not defined. However, the reasons for the oscillating of flame will not be discussed in this article. The occurring of the detonation verified by the velocity of flame propagation measured by the high-speed camera. Below this pressure, low speed flame propagation is obtained and the flame does not accelerate but quench in the downstream of the tube. It can be explained by knowing that the product gas of hydrogen-oxygen flame is water with reduced mole fraction and especially in the small tube with high heat loss rates the condensation of water on the tube wall will decrease the product numbers so that the piston effect of the expansion gas behind the flame decreases. However, there exists a critical pressure to the occurrence of DDT. From Fig. 3, we can see the galloping flame propagation before the happening of the DDT at 31 psia and the light intensity emitted by the detonation wave become much higher than the deflagration. As the initial pressure increase to 36 psia., the run-up distance reduce obviously but galloping flame still observed

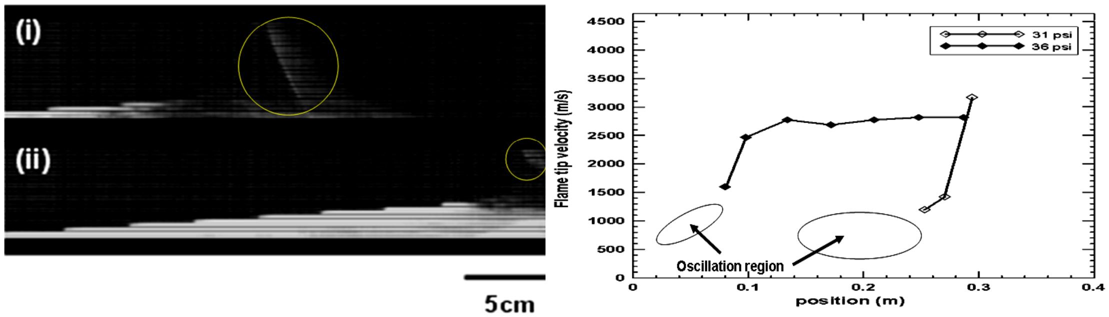

Fig 2. The onset of the DDT with initial pressure(i) 31 psia (ii) 36 psia

From above results, we can see the difficulties for H_2/O_2 flame propagation at low speed flame velocity and the importance of initial flame acceleration on the early stage of DDT. Due to these reasons, in this study we will further study methods to enhance the onset of DDT and we refer to the research by Smirnov of the concept of expanded chambers, or the pre-chambers to enhance the flame acceleration in the in initial stage of DDT.

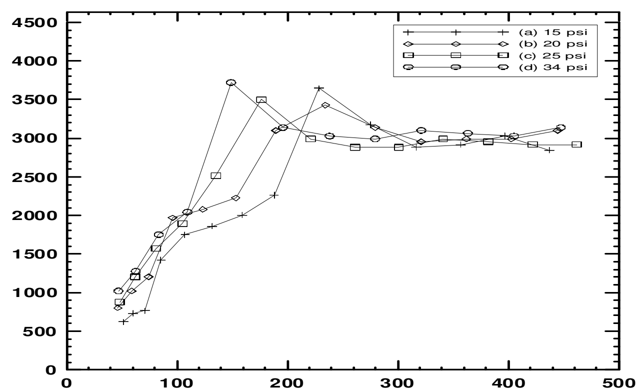

Figure 3. The propagation of flame in the 2mm tube with 6mm expanded chamber and initial pressure are(a)15 (b)20 (c)25 (d)34 psia

In our study, we use only one expanded chamber as the pre-chamber at the head end with the igniter. Effects of the pre-chamber size and the tube diameter on DDT will also be studied. In Fig 3., we can see that DDT occurs in the 2mm tube with 6mm expanded chamber for cases of various initial pressures from atmospheric and above and one can note that when the initial pressure is increased, the onset of detonation location moves upstream. Here we define the run-up distance of the DDT (X_{ddt}) as the ram-up velocity peak in the velocity-to-position plot, in other words, the location of the highest velocity of the over-driven detonations., we compare the X_{ddt} results in Fig. 2 and 3 and it shows that the existing of the expanded chamber in the 2mm tube can reduce the run-up distance efficiently nearly to half of that without the expanded chamber.

Figure 4 shows the results of the run-up distance for the cases of the smaller expanded chamber, 6mm, and three different tube sizes. The run-up distance decreases, when the tube size decreases and so does the initial pressure. However, for the larger chamber, except for one singular point for 2 mm tube at 20 psi, the tube size effect on the run-up distance is almost discernible. The effects of expanded chamber size are also shown in Figure 4, for 1 mm tube cases, there is no obvious change of the run-up distance (X_{ddt}) with initial pressure except for the atmospheric pressure for both 6 mm and 9 mm expanded chambers, but the larger pre-chamber has slightly smaller X_{ddt}. However, for the 2 mm cases, X_{ddt}

decreases obviously with initial pressure. The variation of run-up distance X_{ddt} with initial pressure for different expanded chambers on the 2mm tube is much larger than that on the 1mm tube. In other words, influence of the initial pressure is more obvious in the large tube than the effect of expanded chamber size. Also, in the smaller tubes, changing the expanded chamber size will almost produce no obvious change of the run-up distance especially when the initial pressure is increased. It is speculated that the volume of the expanded chamber may exceed a critical value so that the effects of expanded chamber size play a little role on the run-up distance when the size of expanded chamber is large enough.

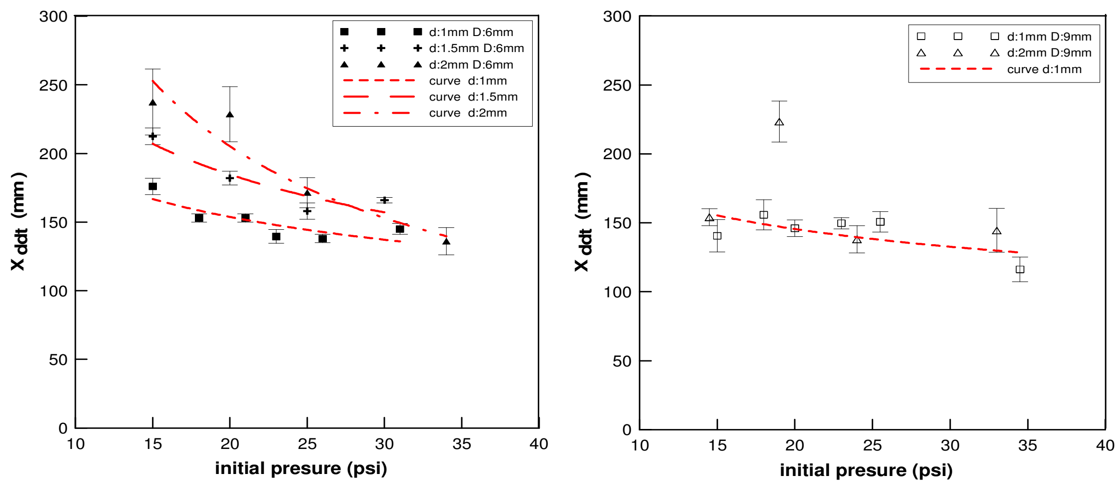

Figure 4. Relations between X_{ddt} and initial pressure of the different tubes with 6mm and 9mm expanded chamber

5 Conclusions

This study showed that with the configuration of an expanded chamber (pre-chamber) installed at the ignition section of the small tube detonation device of mm size can specifically promote flame acceleration and generate detonation wave via the deflagration-to-detonation transition (DDT). The hydrogen/oxygen flame can accelerate to detonation in the micro tube even at the atmospheric pressure condition with the installation of the pre-chamber. We also show in this study that generation of DDT in a straight micro-tube with the stoichiometric H_2/O_2 flame at atmospheric pressure is almost unfeasible.

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