

Gas Dynamics in the Inlets of a Valveless Micro Pulse Detonation Engine

Zu-Erh Chen¹ and Ming-Hsun Wu^{1,2}

¹Department of Mechanical Engineering, National Cheng Kung University, Tainan, Taiwan.

²Research Center for Energy Technology & Strategy, National Cheng Kung University
Tainan, Taiwan.

1 Introduction

A pulse detonation cycle typically begins with filling the detonation tube with fresh fuel/oxidizer mixture. The mixture is then ignited, and followed by detonation initiation and detonation wave propagation. The burned product is then purged out of the tube through a purging stage in which an inert gas or air is injected into the detonation tube. Timing of the stages in the cycle can be either regulated by mechanical valves or gas dynamics in the inlet manifolds, which is also called valveless pulse detonation [1,2]. Various studies have been made to study the gas dynamics of large scale pulse detonation engines to improve the pulsing frequency and propulsion performance [3-8]. Recently, interests have been further put on modifying the purging process in a valveless PDE to reduce the cycle period [6-8]. The purging gas, which can be either the oxidizer or a separate inert gas, was typically injected into the detonation tube before refilling of combustible mixture. It acts as a barrier or buffer zone between the hot combustion products and the fresh mixture that prevent the pre-ignition of fresh mixtures. The purging stage, like the filling stage, takes relatively long duration in a pulse detonation cycle. So, it would also be advantageous for further enhancing the operation frequency of a PDE if the purging stage can be left out or shortened.

Moreover, the addition of inert purge gas diluted the fresh mixture, which may cause quenching or unsteady detonation propagation in a millimeter-scale detonation channel, where the characteristic cross-sectional length scale approaches the cell size [9,10]. So, the existence of a purging stage in the pulse detonation cycle, especially when using an inert gas, can disrupt stable cyclic operation in a small scale valveless PDE. The feasibility of achieving high frequency pulsed detonation in a millimeter scale channel without using an inert gas for purging has recently been demonstrated in our previous work [11]. Detonation wave generation in the 1 mm × 0.6 mm channel is achieved through deflagration-to-detonation transition (DDT). DDT distance and time are significantly reduced due to the smaller cross-section area as well as the highly reactive ethylene/oxygen mixtures utilized [10]. The cyclic operation is based on a valveless inlet design in which oxygen was injected from one end of the reaction channel, and ethylene was injected from the sides in the present valveless inlet design. The pulsing frequency was over 100 Hz. The micro pulsed detonation engine was operating not only without mechanical inlet valves but also an inert purging gas.

However, emphasis of the previous work was on the application of a novel low temperature co-fired ceramic tape microfabrication technology to develop an integrated microthruster based on the

valveless pulsed detonation concept. It is nonetheless unclear how the fresh mixture is isolated from the burned gas in a millimeter-scale valveless PDE operating without purge process such that the fresh mixture is not pre-ignited to form a stable diffusion flame at the intersection of fuel and oxidizer inlets. The objective of the study is thereby to investigate the gas dynamics in the inlets that enable the valveless operation without the purging stage in the millimeter size pulsed detonation tube. A shadowgraph system is used to reveal the density variations caused by reaction front, shock, and interfaces between fresh mixtures and burned gas as well as between unburned fuel and oxidizer.

2 Experiment Methods and Setup

Figure 1(a) shows the exploded view of the pulsed detonation tube assembly, which consists of a channel plate sandwiched between plates made of transparent polycarbonate. On the channel plate, the detonation channel, the inlet channels of fuel and oxidizer, and the mixing section were machined on the 1 mm thick stainless steel channel plate as illustrated in Fig. 1(b) using electro-discharge machining (EDM). Channel width of the inlets and mixing section is 2 mm, while the mean width of the detonation channel with zig-zag sidewall is 3 mm. Oxidizer flowed into the combustion chamber from the end of the detonation channel, while fuel was injected from the sides at 30 degrees angle between fuel and oxidizer inlets. Fuel and oxygen were mixed in a 17 mm long mixing section prior to ignition. Ignition occurred right at the end of the mixing section through electrodes. Reaction front propagated in the 79 mm long detonation initiation section, which had a zigzag shaped wall for shortening the DDT distance [12]. Gas supply ports were installed on the back plate for injecting fuel and oxidizer into the detonation channel. A spark igniter was inserted from the backside into the channel for ignition. The ignition energy was less than 1 mJ.

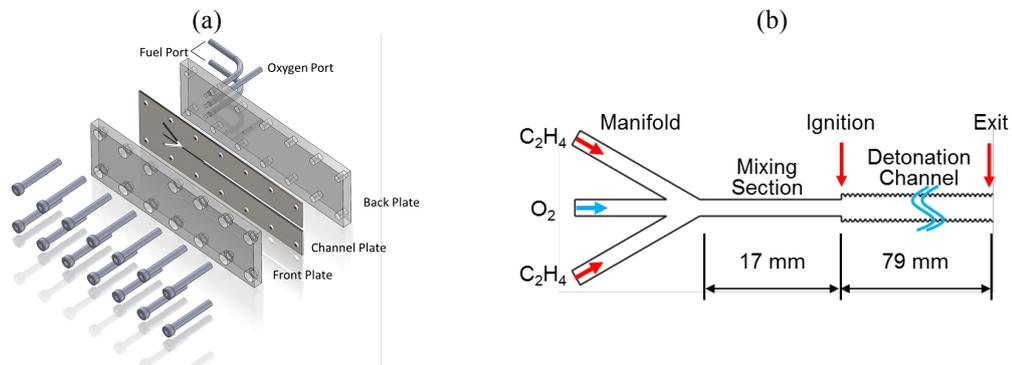


Figure 1. (a) Exploded view of the pulsed detonation channel assembly; (b) configuration of the detonation channel.

Table 1. Supply pressures for ethylene and oxygen.

Case No.	C ₂ H ₄ (kPa)	O ₂ (kPa)
Case 1	145	182
Case 2	242	295
Case 3	339	407
Case 4	436	520
Case 5	533	633
Case 6	630	745

In the experiments, ethylene was the fuel and oxygen was the oxidizer. Flow rates were regulated through choked orifices and supply pressures. The diameters of the choke orifices for ethylene and oxygen supply were 100 μm and 200 μm , respectively. The combinations of upstream pressures were listed in Table 1. Oxygen supply pressure is always higher in all cases.

Light source of the shadowgraph imaging system utilized was a 10W light emitting diode. The light was first focused into a pinhole with a focusing mirror (focal length = 5 cm), and then collimated by a

10 cm diameter convex lens with 15 cm focal length. A 200 cm focusing length mirror with was applied to de-collimate the light into a high speed camera (Phantom V12.1, Vision Research). The camera acquired images with the exposure time fixed at 285 ns at 260465 fps. Camera was triggered by the output signal of a delay signal generator (DG645, Stanford Research System), which was activated by the voltage breakdown of the ignition spark detected by a high voltage probe (P6015A, Tektronix).

3 Results and Discussion

High speed shadowgraph images in Fig. 2 show how reactant supplies are interrupted in the inlets under valveless operation in the . The red, blue, green, and orange arrows in Fig. 2 represent the location of the reaction front, the shock, the interface between fuel/oxidizer and unburned mixture, and the interfaces between fuel/oxidizer and burned gas, respectively. Before ignition, a clear interface between fuel and oxidizer at the cross-section of inlets can be observed in Figure 2(a) due to the density difference between ethylene and oxygen.

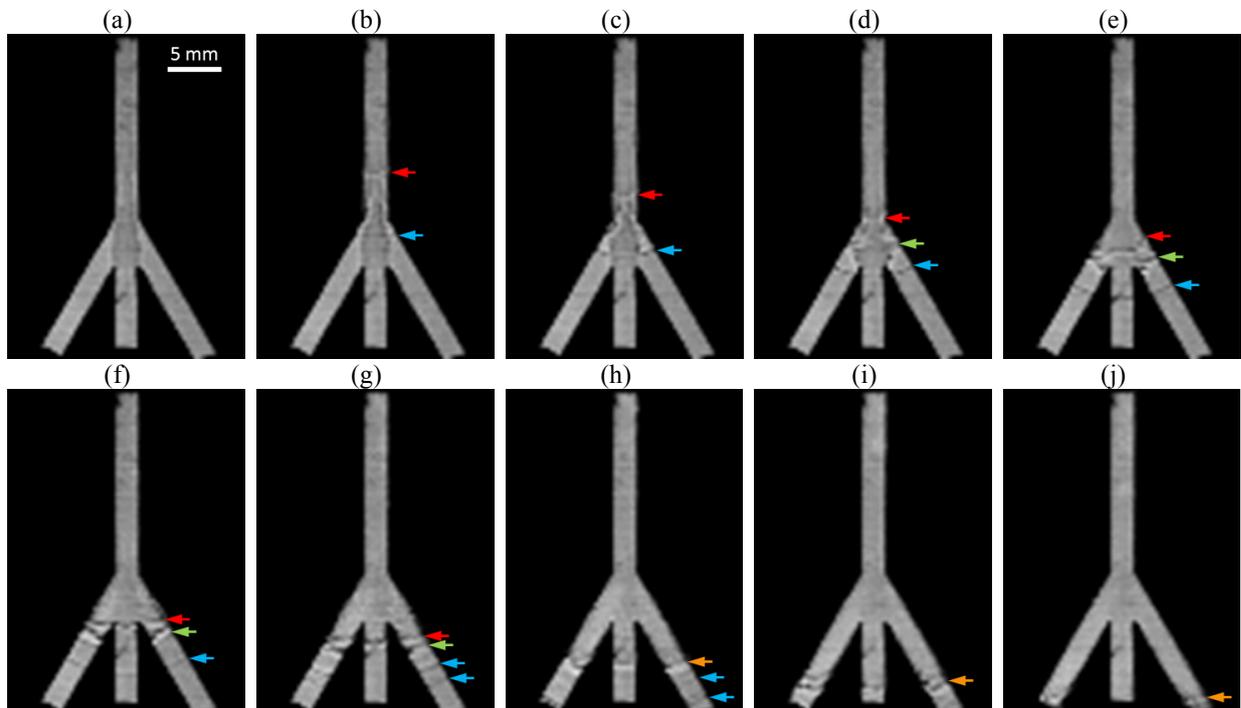


Figure 2. Shadowgraph image showing gas dynamics in the inlets at (a) before ignition; (b) 59.37 μ s; (c) 63.21 μ s; (d) 67.05 μ s; (e) 70.89 μ s; (f) 74.73 μ s; (g) 78.57 μ s; (h) 82.41 μ s; (i) 86.25 μ s; (j) 90.09 μ s after ignition of Case 1.

After ignition, the reaction would propagate both into the detonation channel downstream and the mixing section upstream of the ignition spot shown in Fig. 1(b). Fig. 2(b) shows that at 59.37 μ s, the reaction wave has propagated into the mixing section from the top of the figure. A leading shock wave is also formed due to the choking effect of the backflow induced by the backward propagating reaction wave. The shock wave diffracts and further propagates into the three inlet channels as shown in Figs. 2(c) and (d). At the same time, the interfaces between the ethylene and oxygen are perturbed resulting in mixing of the reactants, and this fresh unburned mixture is then pushed into the channel by the back flow. An additional interface between ethylene and the unburned mixture is therefore formed in the fuel inlet channels as shown in Fig. 2(d). Due to the existence of this unburned mixture section in the fuel channels, reaction is able to propagate into the inlet channels until the unburned mixture is consumed as shown in Figs. 2(f), (g) and (h). Multiple shock waves were found in Figs. 2(g) and (h) due to the reflections of the shock waves from the end of the inlet channels. In Fig. 2(h), a new

interface between fuel and burned gas as point out by the orange arrow is formed after the consumption of the unburned mixture in the inlet channels. The interfaces continue moving upstream in Figs. 2(h) and (i) until they reached the ends of the channels in Fig. 2(j), indicating that the downstream pressure is still larger than the supply pressures at 90.09 μs after ignition.

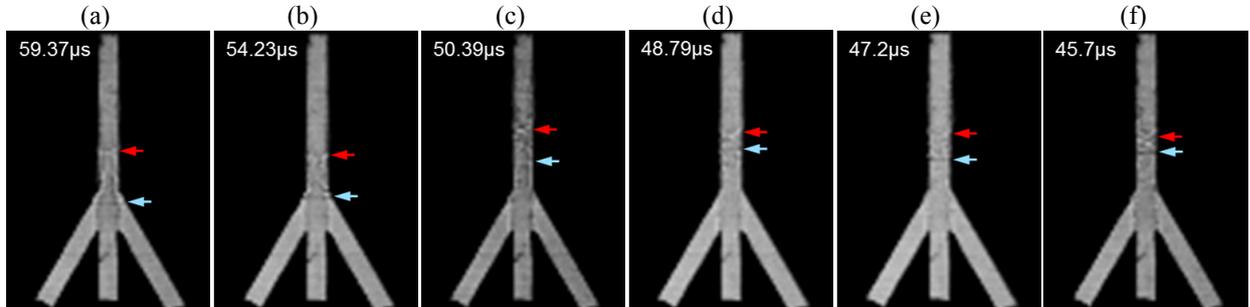


Figure 3. The shadowgraph image at the timing of shock formed under different supply pressure (a) case1; (b) case2; (c) case3; (d) case4; (e) case5; (f) case6.

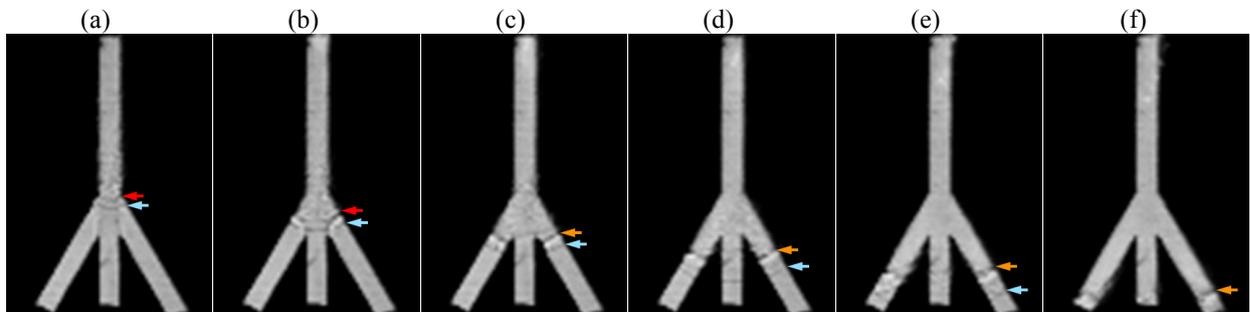


Figure 4. The shadowgraph image of reaction front propagation at inlet manifolds of valveless PDE at (a) 54.71 μs (b) 58.55 μs (c) 62.39 μs (d) 66.23 μs (e) 70.07 μs (f) 73.91 μs after ignition in case 5.

Figure 3 shows the effect on the propagation of the reaction and shock fronts in the mixing section after increasing the supply pressures. Acceleration of the reaction front in the mixing section was enhanced due to better mixing under higher supply pressures in which the supply flow rates were increased. As a result, no clear reaction front was observed in fuel or oxidizer manifolds at cases with ethylene/oxygen supply pressures higher than 436/520 kPa (Cases 4 to 6). This is because the shock formed in the mixing section was so close to the reaction front (Figure 4(a)) that almost no unburned mixture was pushed into the inlet channels before being consumed by the reaction front (Figure 4(b)). The reaction was terminated at the intersection due to lack flammable mixture in the inlet channels. The interfaces between burned gas and ethylene were therefore observed in Figs. 4(c) to (f). It also took shorter time for the interface to reach the ends of inlet channels.

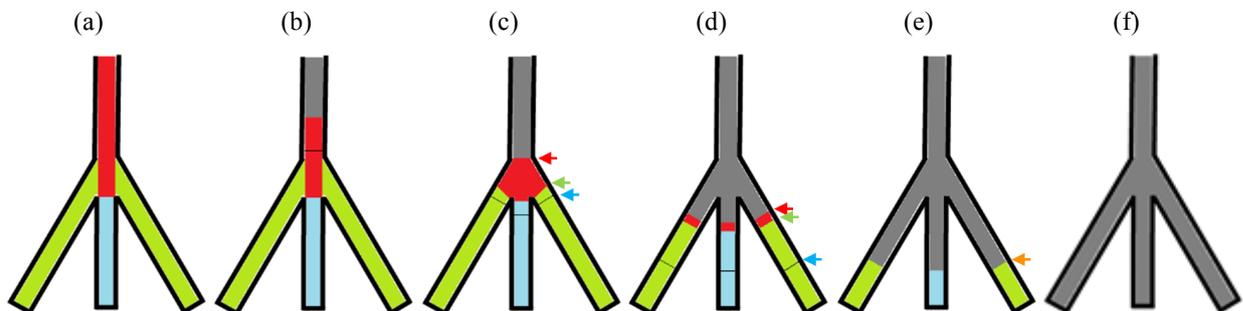


Figure 5. Illustrations showing the gas dynamics in the inlets of the valveless pulsed detonation channel during, (a) ignition (b) shock formation (c) shock wave propagating into the inlet channels, (d) reaction front propagating into the inlet channels (e) consumption of the unburned mixture in the inlet channels, and (f) burned gas back flowed to the ends of inlets. Red, green, blue, and gray segments represent unburned mixture, fuel, oxidizer, and burned gas respectively.

oxidizer, and burned gas, respectively.

In summary, key stages of the process observed in the high-speed shadowgraph is further illustrated in Fig. 5. Channel sections occupied by burned gas, unburned gas, ethylene, and oxygen are represented by red, gray, green, and blue segments, respectively. It seems that backflow of burned gas mixture into the inlet channels is crucial for the interruption of the reaction. If there is no backflow into the inlet channels, a steady diffusion flame may be stabilized at the intersection of fuel and oxidizer inlets as the reaction front propagates back. When the pressure in the inlet channel drops below the supply pressure, refill of the reactant begins. Refill of oxygen is going to occur earlier than ethylene due to the higher supply pressure. The oxygen filling would result in the cooling of the mixture near the intersection. The excess heat loss of the small channel further enhance the cooling effect. Consequently, pre-ignition would not occur as both the ethylene starts to reflow into the intersection. As the supply pressures increase, there would be no remaining unburned mixture (red segments in Fig. 6(d)) being pushed into the inlet channels, and the shut-off duration of the reactant supply is reduced.

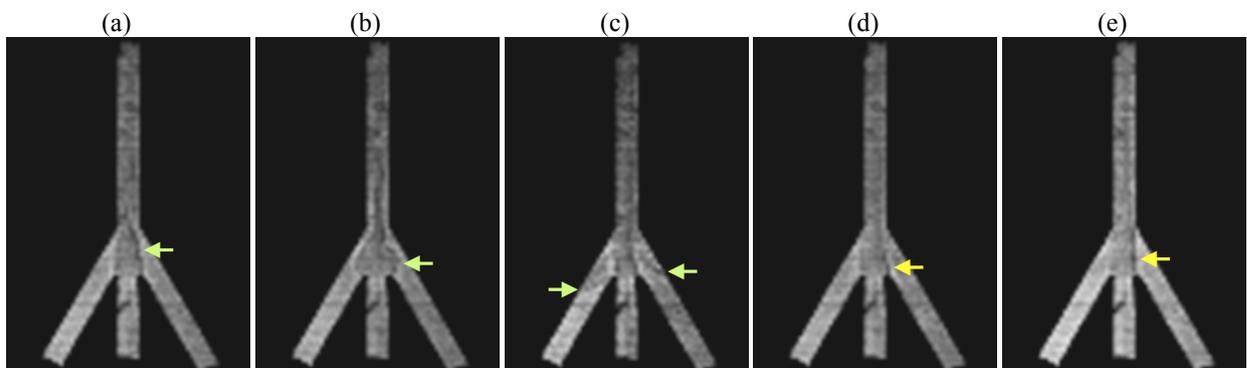


Figure 6. The shadowgraph image of refilling at inlet manifolds of valveless PDE at (a) 5925.80 μ s (b) 6870.27 μ s (c) 8183.30 μ s (d) 10402.41 μ s (e) 14756.16 μ s after ignition in case 1. Green and yellow arrows point out the location of interface between oxygen and burnt gas and interface between fuel and fresh mixture respectively.

Figure 6 shows refilling process in the valveless PDE under the lowest supply pressures (Case 1). Oxygen reflowed into the mixing section at about 5.93 ms after ignition, and an interface between burned gas and oxygen was formed as shown in Fig. 6(a). Local pressure of the oxygen stream was possibly larger than the pressure in the fuel inlets at the moment, so the interface expanded into fuel inlet channels (Fig. 6(b)). As the pressure in the fuel manifolds became lower than the ethylene supply pressure, ethylene refill into the fuel manifolds and the interface between unburnt mixture and fuel emerged as shown in Figure 6(c). At 14.76 ms after ignition, a clear interface between ethylene and oxygen, like the one shown in Fig. 6(a), was re-established (Fig. 6(e)), indicating the refilling of the valveless PDE was completed.

4 Conclusion

Gas dynamics in the inlets of a valveless micro PDE operating without the purging stage was studied using high-speed shadowgraph in this research. A transparent pulsed detonation engine was built for the high-speed visualization. Detonation channel, mixing section, and inlet channels were fabricated on a 1 mm thick stainless steel plate. Mean width of the 79 mm long detonation channel with zig-zag side walls was 3 mm, and the width of the 17 mm long straight mixing section as well as the inlet channels were 2 mm. The fuel channels intersect the oxygen channel from the sides at 30°.

It has been found that back flow of burned gas mixture into the inlet channels is crucial for the interruption of the reaction, and thereby stable pulsed detonation. Reaction may be stabilized at the intersection of fuel and oxidizer inlets if the mixing planes of fuel and oxidizer were not properly isolated from high temperature burned gas. Under lower supply pressures, small amount of unburned mixture was squeezed into the inlet channels that allowed the reaction to propagate further backwards into the inlets. At higher ethylene/oxygen pressures above 436/520 kPa, no reaction front was

observed in the fuel and oxygen manifolds due to the faster reaction front velocity that largely reduce the length of the unburned gas section between the shock and the reaction front, and all unburned mixture was consumed at the intersection. However, the back flowing burned gas would eventually filled the intersection and part of the inlet channels that interrupted mixing between fuel and oxidizer at the intersection in all cases. Refill stage of the pulsed detonation cycle was initiated by reflow of oxygen into the inlet channel. Cooling by the oxygen flow as well as the enhanced heat loss of the miniature channel reduce the temperature of the the mixture near the intersection. Thus, pre-ignition would not occur as ethylene also began to flow into the intersection, and the mixing plane was re-established.

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