Research on detonation propagation in a 90-degree bifurcated tube

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1 Introduction

The study of successful and unsuccessful propagation of detonation waves in a bifurcated tube is very important. It can not only be used for the development of more compact Pulse Detonation Engines (PDE), but can also be used in energy and chemical industries for pipeline/tunnel design to suppress explosion hazards in chemical piping and mining tunnels.

From published literatures, there are relatively few studies on this specific research topic. In 1983, Murray et al. [1] conducted a series of experiments regarding detonation propagation from a small diameter long tube to a large diameter short tube with a front end wall. According to soot measurements, the successful re-initiation was found to start from strong reflection processes of the diffracted and undiffracted waves next to the front wall. The occurrence of a Mach Stem obviously plays an important role during the re-initiation, which would then expand until a stable detonation wave being completely formed, see Fig. 1. In 2013, Polley et al. [2] performed detonation reflection experiments similar to Murray's research [1], and the reflection re-initiation process was also observed. By employing several pressure sensors installed along the front wall, a new re-initiation mode was identified and termed multiple reflected re-initiation, which extends the successful re-initiation geometry range from those Murray [1] has summarized. Furthermore, Bhattacharjee [3] found the important effect of jet formation behind the Mach stem on the process of detonation re-initiation.

Since detonation has been reported to be successfully re-initiated after diffraction, we are also interested in using deflagration for attaining detonation transition with the same geometry, and seek the possibility to employ this bifurcated tube as a Deflagration to Detonation Transition (DDT) enhancement device. DDT phenomenon has been extensively investigated for decades, and various DDT devices such as orifice plates and Shchelkin spiral have been invented and tested. Other special geometries with bent shape, for example U tube and bent L tube, are also proved to be good DDT initiators [4]. In this study, we will mainly focus on the propagation of deflagration/detonation wave in this geometry, manipulate the wave inlet velocity approximated to or less than the corresponding C-J velocity, and try to find out the detonation re-initiation patterns and effectiveness of DDT process inside this geometry.

2 Experimental set-up and methodology

A bifurcation channel has been designed as shown in Fig. 2. A detonation wave generated in an initiation channel propagates from left to right, and then bifurcates into two directions with a 90-degree direction change. Pressure sensors (PCB112A24) were used to measure the pressure and wave speed before and after the bifurcation. The small metal components inside the channel can be easily replaced so that detonation propagation performance can be evaluated for various channel lengths, heights and widths. In this study, the channel cross section is 40mm (height)×20mm(width) in both vertical and horizontal directions.

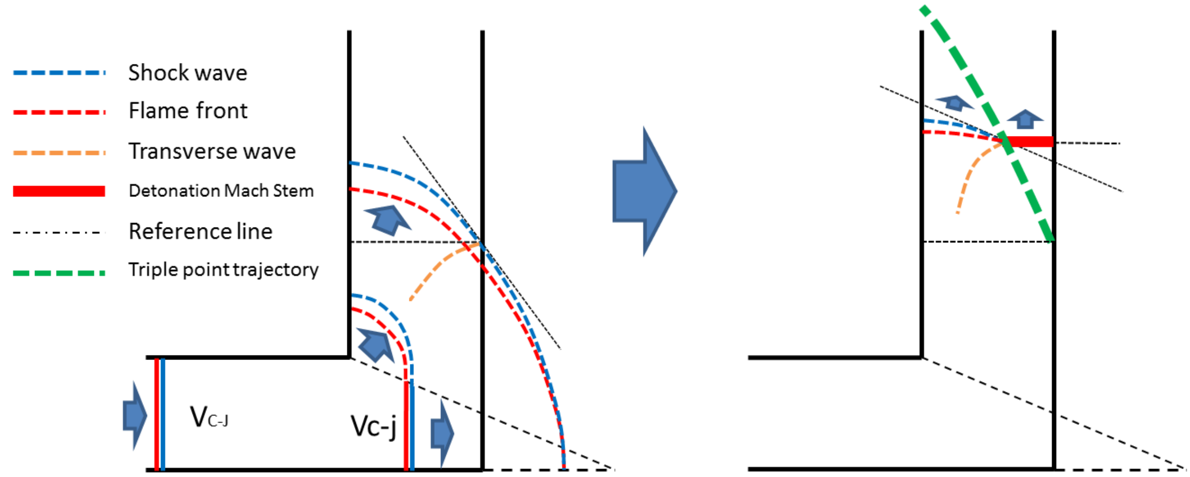

Figure 1. Conceptual sketch of detonation reflected re-initiation process [1].

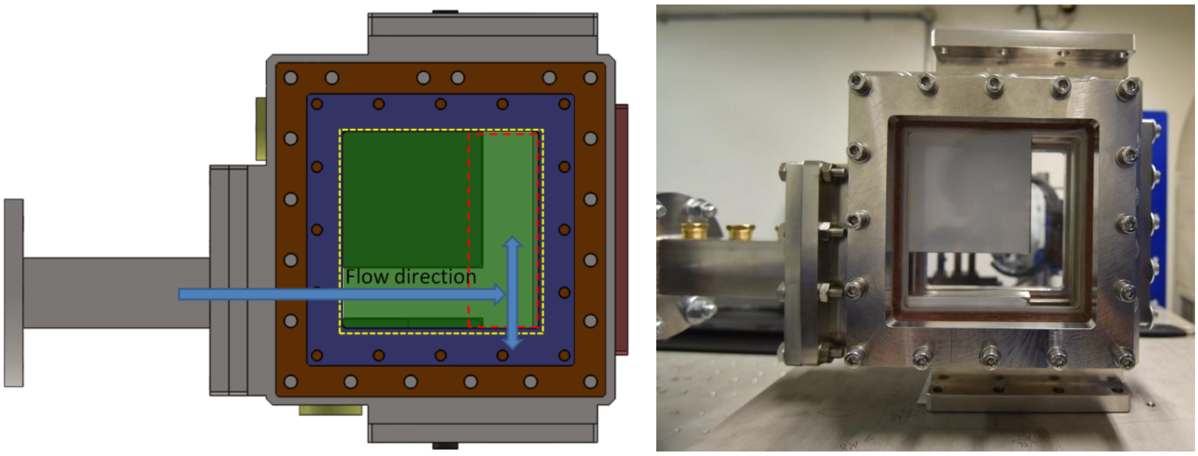

Figure 2. (Left) The detonation channel design. The yellow square represents the optical accessible area. The red rectangle represents the camera imaging area; (Right) Bifurcation test tube after assembling.

To better observe the phenomenon inside this geometry, measurement using the Schlieren technique was implemented. With the help of a high speed camera (Photron FASTCAM SA-Z), small and detailed structures on the shock wave and flame front can be captured, respectively. Ethylene and air mixtures were used as the reactants in this experiment.

3 Results and discussions

Detonation re-initiation

Some results using Schlieren imaging have been obtained regarding detonation re-initiation after reflection in this bifurcated tube. The experiment was conducted in this tube with an open end, and the reactants thus are near ambient pressure. A series of 16 orifice plates placed with 2 inches spacing were utilized as the DDT device to initiate a stable incident detonation wave before the bifurcated tube. The optical accessible area for Schlieren photography is shown in Fig. 2. Three Pressure sensors were installed 250mm downstream after bifurcation. The mixture equivalent ratio was set to be 1.2 for all cases.

Fig. 3 shows the typical results of an incident detonation case with its incoming wave speed of 1950m/s. In frame 1, the flame front and the leading shock wave are so close that they cannot be easily differentiated. Due to the wave's high velocity, the applied high speed imaging frequency was set to be 100,000frame/s with the resolution of 640×280. Right after detonation diffraction, the separation of shock and flame front can be easily identified from Fig. 3(4). After reflection in Fig. 3(4), a clear Mach stem can be formed which identified itself from the diffracted detonation flame front. As the Mach stem evolves, the distance between the Mach stem and the original diffracted detonation flame front increases, while the decoupled detonation becomes coupled again near back wall. The long reflection wave in Fig. 3(5) turns to be a short transversely moving wave which seems very likely to be a transverse detonation. A slip-line follows behind the transverse detonation and intersects with the diffracted detonation wave. After a secondary reflection on the back wall, the expanded Mach stem separates itself completely from the original diffracted detonation and the slip-line as shown in Fig. 3(9). Because of the lack of combustible mixture which is consumed by the newly generated detonation wave, the original diffracted detonation that follows behind will fade away. The images in sequence here show a close following feature of the reaction zone with the expanded Mach stem.

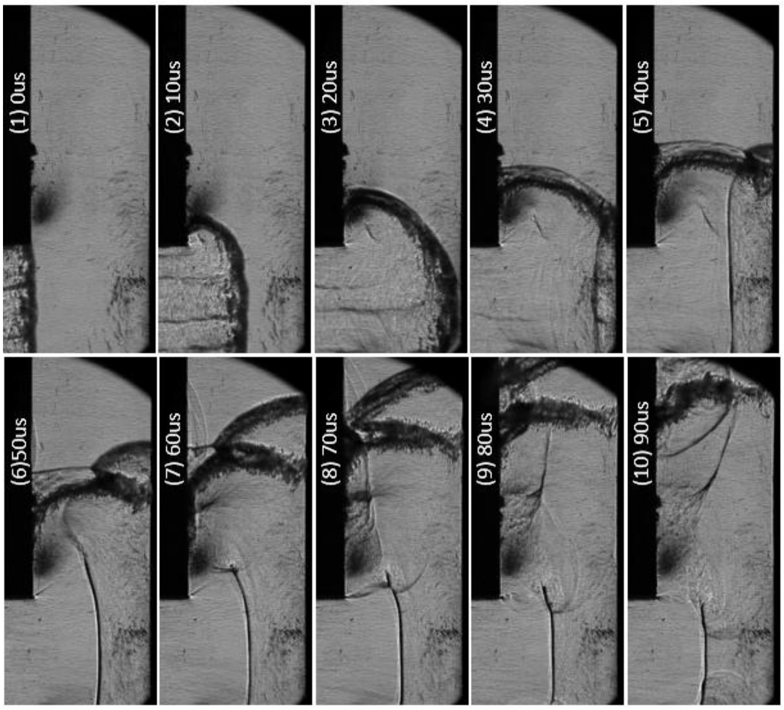

Figure 3. High speed imaging of detonation reflected re-initiation.

The velocities calculated at 250mm distance downstream using 3 pressure sensors show that most detonation shots can successfully re-initiate after diffraction and then transmit to the other end of the bifurcated tube. Under this testing condition, the cell size is around 15mm-20mm. The re-initiation can still be successful even though this cell size range is out of the successful regions as summarized in the studies [1-2]. It must be emphasized that the vertical tube length in this study is more than 300mm, which is far beyond those were used in both Murray and Polley's experiments [1-2]. This infers that detonation may not be able to re-initiate with one or two times of reflection when cell size is large. As shown in Fig. 3, immediately after the first reflection on front wall, even though the diffracted detonation can become coupled again, the induction length still keep increasing before the subsequent reflection on the back wall. In this case, several multiple reflections between the front wall and back wall may be necessary for a successfully detonation re-initiation. A CFD simulation in Fig. 5 conducted under the same condition with this experiment indicates comparable successful re-initiation result as shown in Fig. 3 when the tube is longer than 150mm, and also complies with those unsuccessful re-initiation cases in [1-2] when the vertical tube is short. However, there is another extreme result of Mach stem being decoupled under the same testing condition with inlet wave velocity of 1923m/s but outlet wave velocity of only 1250m/s. As shown in Fig. 4, the Mach stem gradually became much thicker from Fig. 4(1) to 4(6) with an increasing induction length, and was finally quenched with a much lower propagation speed recorded at outlet section. Currently, the reason leading to this extreme result is not clear.

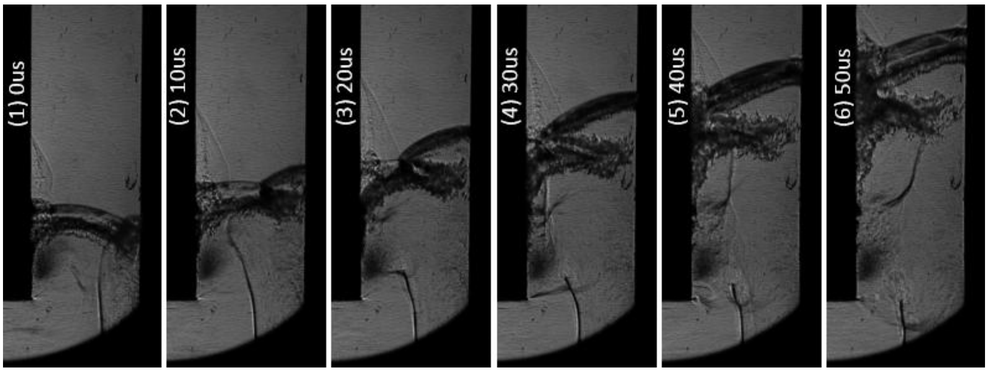

Figure 4. An extreme case of detonation quenching instead of re-initiation.

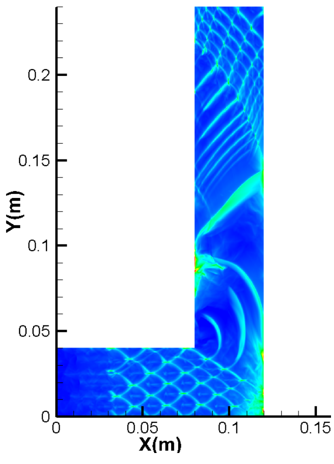

Figure 5. A CFD result of detonation re-initiation cell structure by maximum pressure.

Deflagration to Detonation Transition (DDT)

In order to investigate the possible occurrence of DDT in the bifurcated tube, an incident deflagration wave needs to be formed. This is implemented by moving the location of the spark plug further downstream, thus making the detonation initiation tube (with DDT orifices inside) not long enough for detonation to be achieved. Therefore a decoupled wave with speed less than the C-J velocity can be generated.

The inlet velocity within the range from as low as 600m/s to near C-J velocity was tested. Almost all shots in this range of inlet velocity were successful in transiting a low speed deflagration wave to a high speed detonation. Based on Schlieren imaging, there are two distinct categories of DDT processes classified by the inlet velocity. It was found that if the inlet velocity is less than around 1200m/s while still more than 600m/s, the DDT process would take place in the way as shown in Fig. 6. Since the velocity is relatively low, the leading shock and the flame front are completely separated for a long distance. As the leading shock front impacting on the front wall, it undergoes the regular shock reflection pattern, and then transit to Mach reflection at certain incident angle. After reflection, the shock is still propagating slowly along the vertical tube. As flame front comes later as shown in Fig. 6(8), a train of the multiple compression/shock waves ahead of the flame are also moving forward and undergo the same reflection process with the leading shock. These reflected compression/shock waves move faster forward until finally catching up and merging with the leading shock. The flame front behind also experiences a head-on reflection on the front wall. Because of the preceding compression/shock waves, the combustion induction time would decrease rapidly; so as to lead a much faster flame front after reflection which can be identified in Fig. 6(11-14) with the velocity around 2000m/s. Once the flame catches up with the shock waves ahead of it, a self-sustainable detonation can then be formed.

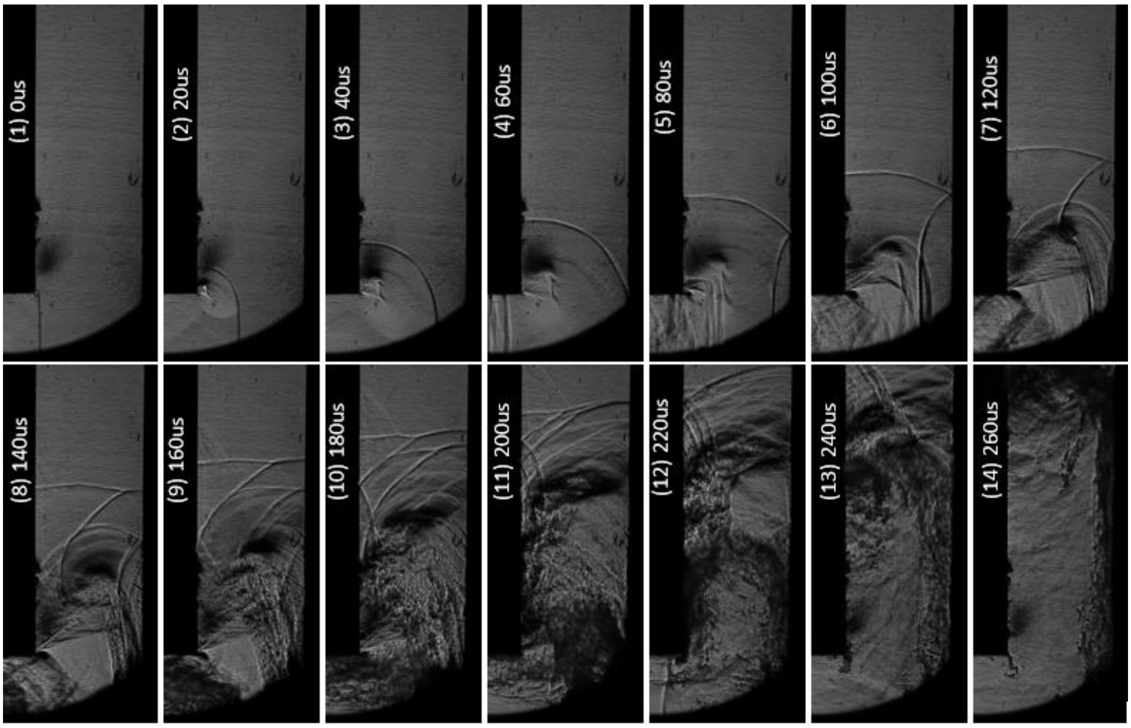

Figure 6. High speed imaging of the DDT process when wave speed is less than 1200m/s.

The other DDT process can happen when the incident deflagration velocity is less than the C-J velocity but larger than around 1200m/s. In this case, the DDT process is mainly driven by Mach stem. As shown in Fig. 7. The inlet wave is slightly decoupled with the moving speed of around 1300m/s. After diffraction, a clear gap between the leading shock and the flame front can be easily identified. Then a Mach stem is generated and then expands toward the back wall after the subsequent wave reflection on the front wall. With multiple reflections of diffracted leading shock and flame front between the front wall and back wall, a self-sustainable detonation wave driven by the triple point structure could be obtained at downstream. Compared with the detonation re-initiation case in Fig. 3(8), a clear difference can be found in this DDT process that during Mach stem expansion, there is no clear sign of the diffracted flame front and the slip-line as shown in Fig. 7(8). The diffracted flame front also coincides with the Mach stem. This could be attributed to the relatively weak strength of the shock wave before reflection.

4 Conclusions

The present study demonstrated an experimental research about detonation and deflagration waves propagating in a 90-degree bifurcated tube. Detonation re-initiation phenomenon and DDT process were observed using a high speed imaging system. Even though the inlet detonation wave cell size is around 15-20mm, based on measurement of the transmitted wave velocity, a self-sustainable detonation wave can still be re-initiated after multiple reflections. If the incident wave is a deflagration, two DDT processes were identified with different transition mechanisms. The results showed that, when inlet velocity is less than around 1200m/s, DDT occurs with flame front catching up with the leading shock which is caused by the reflection process of the leading shock and the several compression/shock waves generated. While if the inlet wave velocity is larger than around 1200m/s but still less than the corresponding C-J velocity, DDT is mainly driven by the Mach stem formation from reflection of the weakly decoupled inlet wave. Despite the phenomenon described above, there are still details and mechanisms remain to be elucidated such as the various thickness increasing speed of the Mach stem before re-initiation. Future work will be conducted to further address these details using a longer optical accessible tube and other optical measurement techniques such as PLIF.

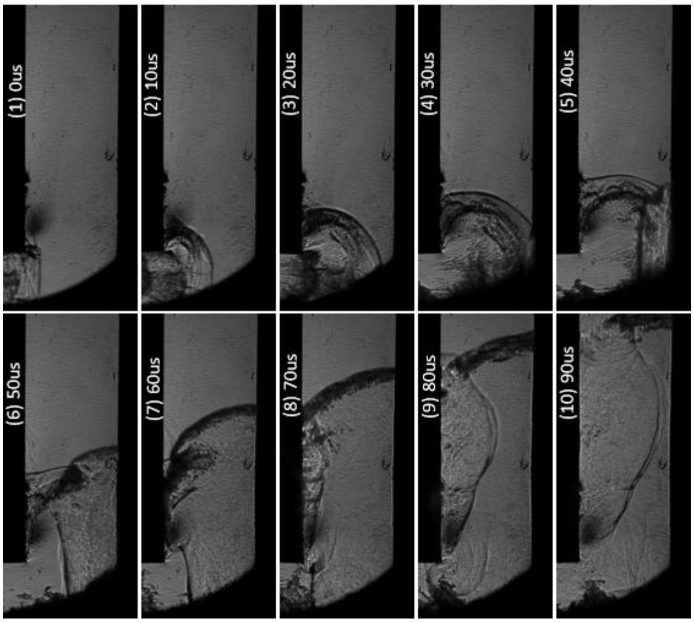

Figure 7. High speed imaging of the DDT process when wave speed is more than 1200m/s.

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