

Investigations of the Dynamics of a Propagating Flame using High-Speed Imaging and Laser Sheet Tomography

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1 Introduction

In recent years, a revival of the pulse detonation combustor concept has taken place, due to the increased efficiency of near constant volume combustion. It is, however, inefficient to directly ignite a detonation. To this end, it is important to understand the fundamental characteristics of flame propagation and its role in DDT (Deflagration to Detonation Transition). Frequently, obstacles are used to bring about DDT (e.g., [3], [4]). In this study, obstacles of several geometries were investigated using high-speed laser sheet tomography. Additionally, the distance of the obstacles from the point of ignition as well as the separation distance, in the case of multiple obstacles, was investigated. Ionization probes were used on a different setup to capture front propagation at speeds at which high-speed imagery is more difficult.

2 Experimental Setup

In this study, several experiments were conducted on two setups. High-speed laser sheet tomography was conducted on a setup with a tube made of acrylic glass. Front propagation speeds were measured on another setup with ionization probes in a metal tube. The acrylic tube had an inner diameter of 30 mm and was filled with a stoichiometric hydrogen–air mixture whose composition was confirmed by two coriolis mass flowmeters. The mixture was given ten seconds to allow for turbulent dissipation, after which the contents of the tube were ignited using a sparkplug at the closed end of the tube imparting roughly 1.2 mJ to the mixture. The flame propagation was observed using laser sheet tomography. A fine mist of droplets (mean diameter of 1 μm) composed of silicone oil was produced using the combustion air before it was introduced into the flame tube. A laser sheet from a CW-laser was aligned along the axis of the tube with a thickness of 1 mm. In laser sheet tomography, the laser illuminates the oil droplets so that the unburnt gas may be seen. As the flame passes through the mixture, the droplets are burned with the gas and the combustion products no longer illuminated, resulting in a two-dimensional view of the flame front. Due to the light scatter from the oil particles, it was necessary to reduce the length of the tube to 350 mm in order to retain the required light intensity in the area of interest. This intensity allowed for images to be taken at a 16000 fps by a high-speed camera installed perpendicularly to the laser sheet. Pressure was not recorded on either setup and no visible density changes (indicating a pressure wave) were observed, therefore, interactions between the pressure waves and the flame were not investigated.

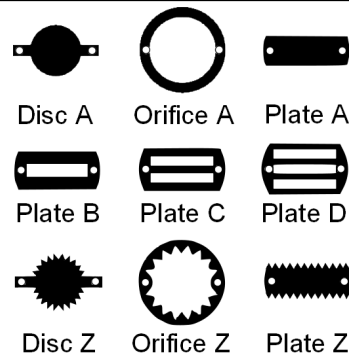


Figure 1: Obstacle geometries used in experiment, blockage ratio = 0.43.

Several obstacles of various geometries having a blockage ratio of 0.43 were installed in the tube to increase turbulence, resulting in flame acceleration. These obstacles were made of hard opaque plastic, in order to allow for ease of producing complex geometries. The blockage ratio was determined to be ideal for bringing about the deflagration to detonation transition, (e.g., [4] or [2]). The blockage ratio is determined as the area of the obstacle divided by the area of the cross-section of the tube. The geometries used are depicted in Figure 1. The obstacles were attached to two metal threaded rods outside of the plane of the laser with a diameter of 2.5 mm and held in place by nuts. This setup produces without a doubt additional turbulence, but it is assumed that this is minimal compared to that produced by the obstacles themselves. Despite this disadvantage, the setup was chosen due to the flexibility of installing the orifices at arbitrary and easily adjustable positions.

In choosing the geometries, the effect the obstacle would have on the turbulent length scales was also considered. Plates A-D, for example, all have the same blockage ratio but have a different number of slits, decreasing the size of the trailing vortices. Additionally, Orifice Z, Plate Z, and Disc Z are similar to their geometric counterparts, however, possess serrated edges (blockage ratio is, nevertheless, held constant). It was thought that these edges would function as vortex generators, increasing the amount of turbulence.

The same mixture was used on the second setup. Ignition was also achieved using the same system as in the previous experiments. Here, a steel tube with an inner diameter of 39 mm was used. Tube sections with smaller inner diameters were able to be inserted into this tube, changing the effective diameter of the combustion chamber. This resulted in inner diameters of 30 mm, 32.8 mm, and 39 mm. For the two smaller diameters inserts cut to the correct separation lengths were used as spacers between the orifices. Up to four orifices with blockage ratios of 0.43 were used in the experiments. For the largest tube diameter (without inserts), the orifices were installed exactly as in the experiments with the acrylic tube, with two threaded rods. The steel tube consisted of a mixing section of 110 mm in length and 22.5 mm in diameter followed by the flame acceleration and measurement tube, having a length of 1500 mm. Four ionization probes were installed at the far end of the tube at 910, 1110, 1310, and 1510 mm from the point of ignition, at the back wall of the mixing section. By measuring the time of flight between the probes, the front speed was able to be determined. An example is shown in Figure 2. At least ten test runs were taken for each parametric combination of tube inner diameter, number of orifices, and separation distance, resulting in roughly 500 test runs.

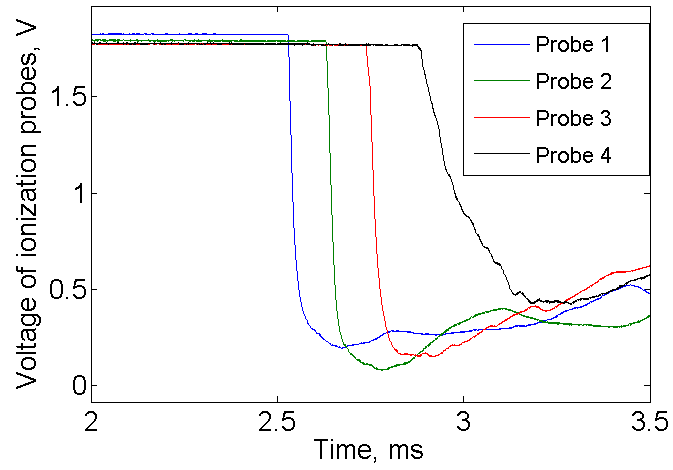


Figure 2: Typical signals from ionization probes

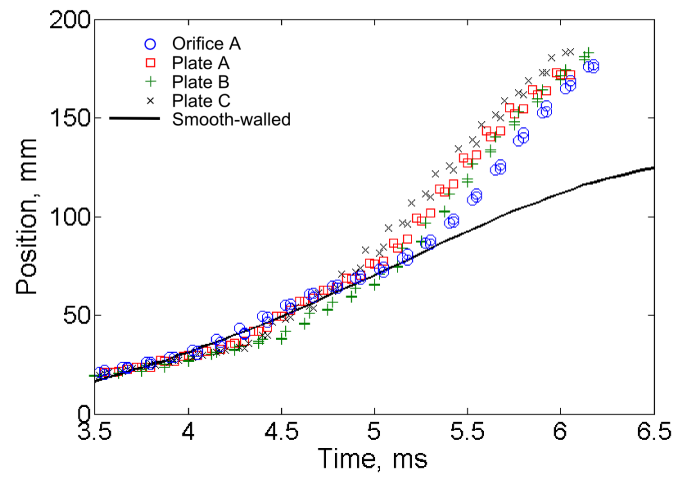


Figure 3: Flame propagation for various obstacles

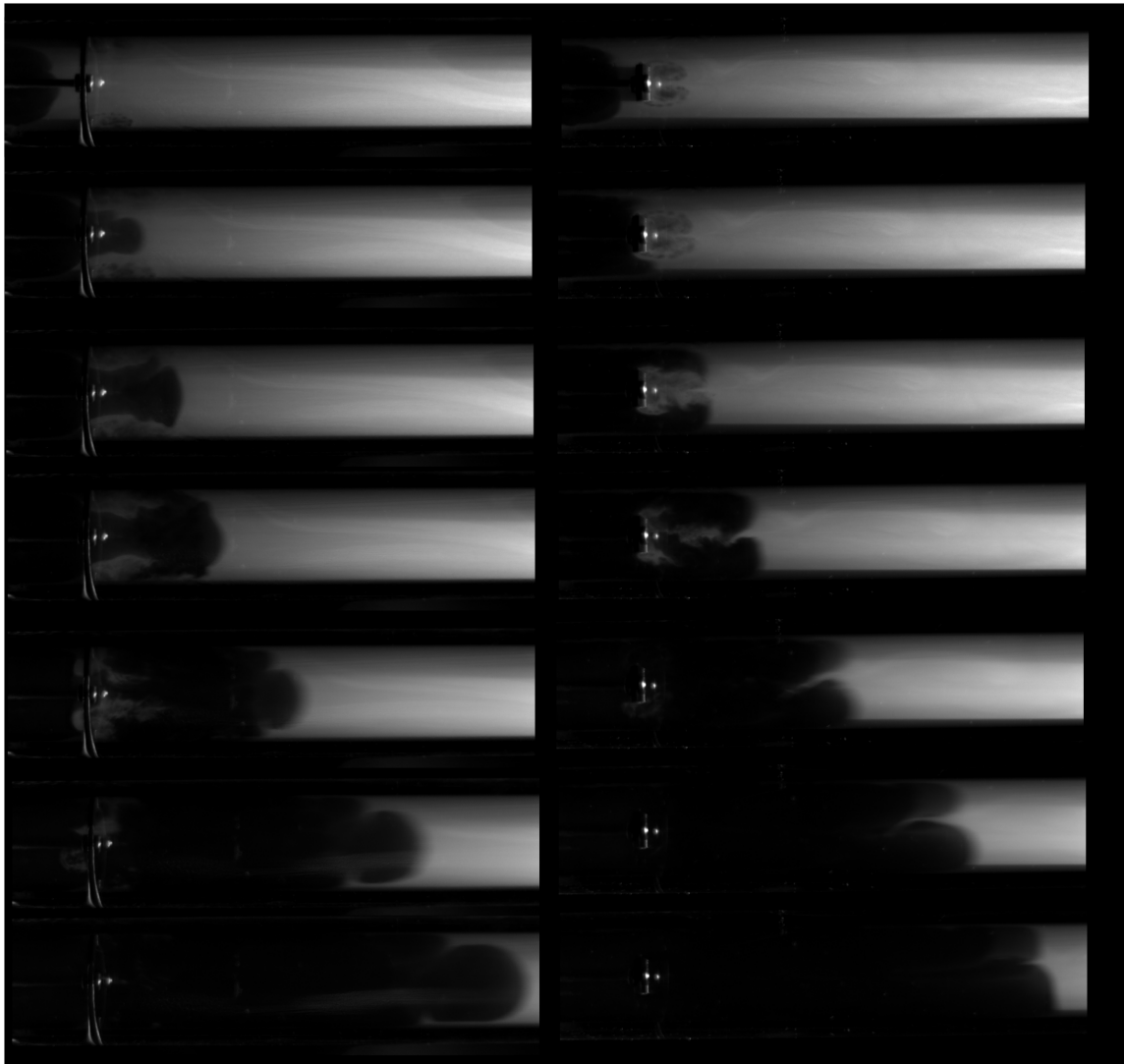


Figure 4: High-speed images of propagating flames using a single obstacle (Orifice A, left; Plate A, right), both having blockage ratios of 0.43. Each frame corresponds to $3 \mu\text{s}$.

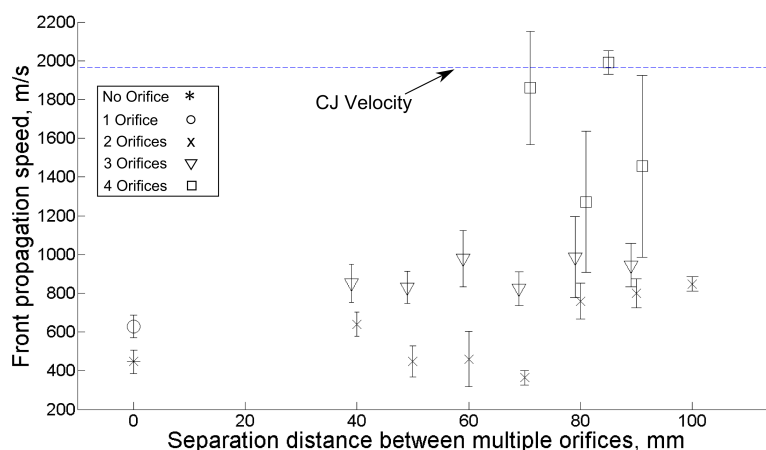


Figure 5: Front propagation with various numbers of orifices in a 39 mm tube. The bars indicate the standard deviation of each test series. Blockage ratio is 0.43.

2 Results

Let us first discuss the results obtained from the laser sheet tomography on flame acceleration. Individual obstacles were initially tested at a distance of 50 mm from the closed end of the tube. Several results are presented in Figure 3. An example of the flame propagation in a smooth-walled tube with no obstacles is presented for comparison. The propagation of this flame exhibits the typical "tulip flame" instability [1], resulting in oscillation and reversal of flame propagation (at later times not shown), drastically reducing propagation speed and increasing DDT length. Mounting any of the obstacles at 50 mm results in suppression of the "tulip flame" instability within the tube. Orifice A as well as Plates A, B, and C result in the highest flame acceleration, primarily directly after the obstacle, with a maximum propagation speed of around 120 m/s. Orifice A resulted in nearly the same flame propagation than those from the plates and with a similar final velocity, although just past the orifice, the flame shortly decelerates more than with the other obstacles. A series of images for Orifice A and Plate A are shown in Figure 4. In these images, the acceleration is nearly the same.

Plate D and Disc A resulted in similar flame propagation to Plates A-C. However, the propagation exhibited slightly more scatter and, thus, they are not shown in Figure 3 for the sake of clarity. The obstacles with serrated edges proved to show no improvement in flame propagation speed. In fact, Orifice Z produced a significantly lower propagation speed than Orifice A.

Orifice A was also investigated in more detail, as such orifices are frequently used in pulse detonation combustors. Since the orifice is in contact with the wall of the combustor, it allows for heat to be more quickly dissipated when cooled from the wall, decreasing thermal loading. First, the distance of the orifice from the closed end of the tube was varied from $1D$ to $3D$ in increments of $0.5D$, D being the inner diameter of the tube. The largest flame acceleration occurred when the orifice was at $2.5D$, resulting in a propagation speed of 111 m/s.

Finally, a series of two to three orifices were investigated and the distance between them was varied from $1D$ to $3D$. The first orifice was mounted at 50mm. A series of two orifices produced maximum speeds at $2.5D$ of 298 m/s. When a series of three orifices was mounted in the tube, the flame propagation speed increased from 266 m/s at $1D$ to 470 m/s at $2D$. When the distance between the three orifices was greater than $2D$, the flame speed increased so drastically, that it was no longer able to be detected.

Experiments with both two and three orifices suggest that the optimal distance lies somewhat above $2D$. The rule of thumb of a distance of $2D$ is frequently used in literature (e.g., [5]).

The experiments in the steel tube were conducted in order to confirm results seen in the previous experiments, now allowing DDT to occur in a longer tube. The first orifice was placed at 100 mm, roughly $2.5D$ for the largest tube, found to be advantageous in experiments in the acrylic glass tube. Of the three inner diameters, only that of 39 mm was able to consistently sustain a detonation. The tube with a diameter of 32.8 mm resulted in one instance of an overdriven detonation and the tube of 30 mm produced no detonations, whatsoever. The results of the tests with the 39 mm tube are shown in Figure 5. Here, it can be seen that a detonation occurs only after the use of four orifices. With three orifices, the flame is able to reach the "choking" regime discussed by Guirao [4]. The test series at 70 mm and 90 mm are at the boundary of producing a detonation. For example, 90 mm separation distance resulted in 8 detonations at roughly 2000 m/s and two choked cases at 1000 m/s, with no values inbetween. It is interesting that the 80 mm separation distance is suddenly no longer sufficient to produce a detonation, while a separation distance of 85 mm results in very stable detonation production.

2 Conclusions

Laser sheet tomography was conducted on a propagating flame in a tube with obstacles. Several obstacles were investigated. All of the obstacles, with the exception of those with serrated edges, seemed to perform equally well in terms of flame acceleration. In the case of single orifices, the highest flame acceleration was observed when the orifice was mounted at $2.5D$. In the case of two orifices, the highest flame acceleration occurred at a separation of $2.5D$. In the case of three or more orifices, drastic flame accelerations occurred for distances between orifices above $2D$, but not at $2D$ itself. This suggests that the ideal separation distance, at least for $D = 30$ mm, lies somewhere between $2D$ and $2.5D$.

Reliable detonations were only achieved with the 39 mm tube with at least four orifices. The remaining tubes seem to be too small for the detonation to propagate. In the largest tube, four orifices at a separation distance of 85 mm produced very repeatable detonations, while 70 mm and 90 mm separation distances resulted in the flames propagating in one of two regimes, that of the "choked" detonation and that of the CJ detonation. In this particular configuration, the best repeatability was found to be at $2.2D$, though the somewhat less than optimal reproducibility of the 70 mm, 80 mm, and 90 mm separation distances makes it difficult to say conclusively that this is the best separation distance.

References

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