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Flame Acceleration Enhancement by Distributed Ignition Points

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The investigation is reported of a novel method for promoting flame acceleration leading to detonation initiation in a tube. A common method used to initiate a detonation wave is via flame acceleration in an obstacle-laden tube. Previous studies with fuel–air mixtures have shown that the measured detonation run-up distance, and corresponding run-up time, is too long for a pulse detonation engine (PDE) application. The objective of the investigation is to enhance the flame acceleration process that leads to deflagration-to-detonation transition by using multipoint ignition. Experiments were performed in a 3.05-m-long, 14-cm inner-diameter tube equipped with a primary igniter mounted centrally on the tube endplate. Equally spaced orifice plates were placed in the first 2 m of the tube. A bank of four circumferentially equally spaced automotive spark plugs are located after each of the first three orifice plates. The firing time of each igniter bank is variable. The results indicate that flame acceleration is augmented early in the tube and maintained to the end. The reduction in the distance required for the flame to accelerate to a velocity on the order of the speed of sound in the combustion products is modest, on the order of 10%. However, the reduction in the time required to reach this velocity is much more pronounced, which has an impact on the PDE cycle frequency. Flame acceleration was further enhanced by replacing the first few orifice plates with perforated plates with the same total flow area, for example, the flame run-up distance was shortened by 30%. However, detonation initiation was not observed over the 3 m length of the tube in stoichiometric propane–air mixtures.

Introduction

IN the last decade, there has been substantial research activity in the development of pulse detonation engines (PDEs).[1,2] This interest is driven by the realization that PDEs represent a viable alternative to the turbo and ramjet engine for supersonic flight. PDEs operate by thrust produced by periodic detonation waves propagating within the combustion chamber. Thermodynamically, because the detonation process is similar to a constant volume combustion process, the PDE thermal efficiency is higher than that of a jet engine that operates under a constant pressure combustion process.[3] Furthermore, because a PDE does not require a compressor and turbine, it is more attractive than a turbojet engine from a manufacturing and maintenance perspective. This reduced complexity may be offset by advanced multitube intake and nozzle systems required for certain applications.

In general, there are two ways to initiate a detonation wave: either directly using a high-energy source, which is not practical for PDEs, or through a flame acceleration process known as deflagration-to-detonation transition (DDT). Rapid flame acceleration in a tube is accomplished by the use of repeated obstacles.[4–6] In independent studies investigating possible PDE detonation initiation systems Ciccarelli et al.[7] and Pinard et al.[8] used orifice plates and Lee et al.[9] used flat plates mounted in a helical pattern to promote flame acceleration and DDT. As a result of gas expansion across the flame, a flow is generated in the unburned gas. This unburned gas flow is distorted by the orifice plates to produce large-scale velocity gradients. The large-scale velocity gradients cause the flame to adjust to the radial velocity profile, resulting, in flame area enhancement, or flame folding. The flame area enhancement results in an increase in the volumetric burning rate, defined as the volume of unburned gas consumed per unit time, which increases the unburned gas flow ahead of the flame and feeds back to the flame folding process, resulting in flame acceleration.[4] As the unburned gas velocity increases with increasing flame velocity, a critical flow Reynolds number is reached at which point the flow becomes turbulent. The fine-scale turbulent fluctuations, that is, smaller than the flame thickness, enhance the thermal and mass transport rates, increasing the burning velocity. Once the flame achieves a velocity on the order of the speed of sound in the combustion products, a detonation may form if the orifice plate diameter is larger than the mixture detonation cell size.[10] If the orifice plate diameter is not sufficiently large the turbulent flame continues to propagate at this velocity, and the flame is said to be "choked."[11] As described by Lee et al.,[11] the propagation of a choked flame can be considered in terms of quasi-steady one-dimensional compressible flow in a pipe with friction and heat addition. Based on this argument, the choked flame velocity represents the maximum steady-state deflagration velocity possible. Chue et al.[12] developed a physical model treating the choked flame as an unsteady complex consisting of a flame and shock, each propagating at different steady velocities. In this model, the flame is treated as a Chapman–Jouget deflagration, that is, the flow is sonic at the end of the reaction zone. Empirical evidence to date has indicated that a quasi-steady choked flame has always been observed experimentally before the onset of detonation. For a given initial condition and boundary condition, the distance required for the flame to achieve the choked flame velocity can be considered a measure of the mixture detonability.

The DDT method of detonation initiation requires a combustion chamber length that allows for the flame acceleration process to proceed to completion. An engine performance penalty is paid by the added drag force produced by the flow around the obstacles[13]; thus, if this DDT method is to be used for a PDE detonation initiation system, then the length of the obstacle section must be as short as possible. Many detonation initiation systems currently used in

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PDE research rely on the sensitization of the fuel–air mixture by the addition of a more reactive fuel–oxygen mixture at the ignition point to enhance significantly the flame acceleration process and, thus, reduce the detonation run-up distance.[14] Although this method is effective, it requires an onboard oxygen supply, which is not desirable from an economic and safety perspective.

Previous studies have shown that flame acceleration obtained in a classically configured orifice plate-laden tube, that is, uniformly spaced and sized orifice plates with one end igniter, results in a relatively long detonation run-up distance for fuel–air mixtures. For example, DDT experiments performed by Pinard et al.[8] in a 15-cm tube with a stoichiometric propane–air mixture resulted in a detonation run-up distance of over 3 m. Propane is a common simulate for JP-10 because the detonation cell size for both fuels mixed with air is similar.[15] A large fraction of the run-up distance consists of the early flame acceleration phase where flame folding is the dominant mechanism. The effect of orifice plate blockage and spacing on this early part of the flame acceleration was investigated by Ciccarelli et al.[7] Experiments were carried out with propane air mixtures in a 14-cm inner-diameter tube filled with orifice plates, and the propagation distance required for the flame to reach the speed of sound in the reactants, roughly 340 m/s, was measured. The shortest distance measured for the flame to reach this velocity was six times the tube diameter. This was obtained when the plates were equally spaced at one tube diameter and the flow blockage ratio was 75%, defined as the ratio of the orifice plate frontal area and the tube cross-sectional area. With this optimum configuration, the flame reaches choked conditions after roughly 2 m of travel, and DDT was not observed in the instrumented length of the tube.

The effect of igniter spark energy and position on the flame acceleration process is also of interest. Sinibaldi et al.[16] performed experiments in a smooth 3.81-cm-diam tube varying the spark distance from the endplate and the spark energy. It was found that in general there was no effect of spark energy on the DDT run-up distance above 50 mJ. The maximum spark energy tested was 3 J. These investigators showed that locating the igniter one tube diameter away from the endplate resulted in the shortest run-up distance. When the igniter is located centrally at the endplate, a hemispherical flame ensues until the presence of the tube wall distorts the flame. When the flame is initiated away from the endplate, the flame develops spherically until the wall effects take over. The faster flame acceleration observed when the igniter is located away from the endplate is due to the higher volumetric burning rate associated with the larger flame area.

If sufficient energy is deposited in a reactive mixture by a condensed explosive or electrical spark, then a detonation wave can be directly initiated. The rapid energy release produces a blast wave that propagates away from the initiation site. If the energy released by the source is above the critical energy, the chemical energy release from the reactive gas couples with the blast wave and a detonation wave forms. The critical energy for propane–air is about 50 g of tetryl, or 214 MJ (Ref. 17). A PDE detonation initiation concept was proposed by Frolov et al.[18] based on accelerating a weak shock wave in a smooth tube by in-phase triggering of distributed electric sparks. The energy deposited by the spark behind the shock wave causes the shock wave strength to amplify to the point where a detonation is initiated. Experiments were performed in a 5.1-cm-diam tube with stoichiometric propane–air mixtures. Detonation initiation was achieved after 12–14 tube diameters using 11 igniters spaced at one tube diameter. The energy deposited by each igniter was derived from a 100-μF capacitor charged up to 2500 kV. The total theoretical energy deposited by the igniters was 1.68 MJ/m^2. Although this initiation concept works, the use of such a high-voltage system is not desirable for a PDE.

The objective of the present investigation is to enhance the flame acceleration process in a tube that leads to DDT by using multipoint ignition in conjunction with orifice plates. Tests were also performed with a combination of orifice plates and perforated plates, where an orifice plate has a single centered hole and a perforated plate has several distributed holes. This multipoint ignition concept is different from that of Frolov et al.[18] The igniters used are low-energy automotive-type spark plugs that ignite individual flames at discrete points within the tube. The energy released from the igniters does not directly amplify the leading shock wave. The leading shock wave is formed and then amplified by the enhancement of the volumetric burning rate resulting from flame area generation. A primary flame is created by an igniter centrally mounted on the endplate of the tube. Additional igniters are located down the length of the tube that initiate secondary flames that augment the primary flame area and, hence, the volumetric burning rate. It is postulated that if the ignition timing of the secondary igniters is optimized a flame can be made to accelerate faster than if only the endplate igniter is used. In this study, the metric used is the distance required for the flame to reach a velocity close to the speed of sound in the combustion products. Because of the limited length of the tube, detonation initiation was not observed in any of the tests. It is postulated that any reduction in the flame acceleration distance would result in a reduction in the detonation run-up distance. This hypothesis must be tested in a future study using either a longer tube or a more reactive fuel–air mixture.

Experimental Details

The experiments were performed in a 3.05-m-long tube with a 14 cm inner diameter. Flame acceleration was achieved through the use of orifice plates, equally spaced at one tube diameter, in combination with a multipoint ignition system. The orifice plate inner-diameter was 10.7 cm, and the orifice plate array was 1.8 m long. The orifice plates can be characterized by the blockage ratio defined as the ratio of the orifice plate frontal area and the tube cross-sectional area. For this size orifice plate, the blockage ratio is 0.42. To avoid end effects, flame velocity measurements were restricted to the array length that is shorter than the tube length. As shown in Fig. 1, each of the first three orifice plates at the ignition end of the tube have directly behind them four automotive spark plugs, equally spaced around the circumference of the tube. The spark energy of each of these spark plugs is approximately 250 mJ, which is slightly larger than that of a commercial automotive ignition system. The igniter banks are electronically connected to an ignition control system by which the firing time of each igniter bank can be independently set. The average flame velocity was obtained via flame time-of-arrival measurements made by equally spaced ionization probes. In the first 91.4 cm of the tube, ion probes were located at the orifice plate axial locations. This was done by cutting away a section of the orifice plate, equal in size to the probe diameter, and protruding the tip of the ion probe electrodes near the centerline of the tube. After this first section, the ion probes were located axially between the orifice plates and the electrodes protruded just outside the tube inner wall.

An additional series of experiments was performed where the first few orifice plates were replaced with perforated plates. The perforated plates have 22 equally distributed 1.5-cm holes as shown in Fig. 1 yielding a flow area identical to the 6.9-cm orifice plates. For this test series, a higher blockage orifice plate was used with an inner diameter of 6.9 cm, that is, blockage ratio of 0.75, and the array extended the full length of the tube.

The fuel–air mixture used in the experiments is stoichiometric propane–air. Propane was chosen because it has been shown to have a detonation cell size similar to that of JP-10 in air.[15] Following an air purging process to remove combustion products, the tube is evacuated to an absolute pressure of less than 0.1 kPa. The mixture is prepared by the method of partial pressures within the tube and

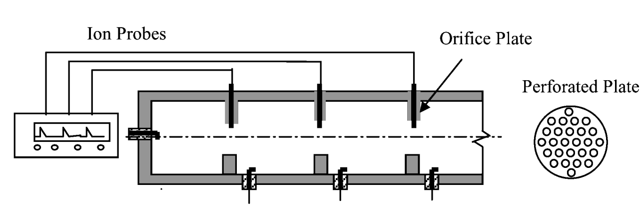

Fig. 1 Location of ion probes and spark plugs relative to the orifice plates, as well as perforated plate hole distribution.

then circulated for 20 min to ensure composition homogeneity. The pressure transducer used to measure the vessel fill pressure has an accuracy of 0.25% of full scale, or 0.25 kPa. Mixing in the tube was accomplished through the use of closed-loop recirculation from each end of the tube.

Results

Orifice Plate Experiments

A preliminary set of experiments was carried out with 10.7-cm inner-diameter orifice plates and a single igniter located at the tube endplate. The data from these experiments were used as a baseline to compare with subsequent tests using the multipoint ignition system. The average flame velocity vs propagation distance is plotted in Fig. 2. The horizontal error bars represent the 15.2-cm distance separating the ionization probes used to measure the flame time of arrival and from which the average velocity was calculated. The vertical error bars represents the scatter in the test measurements from nine experiments performed at the same condition. The magnitude of the error bars is based on the standard deviation of the measured average velocity data. The velocity scatter is very minimal, less than 5% for each data point, with the exception of the measurement at 0.8 m, which shows the high level of repeatability of these experiments. The experimental uncertainty in the measurement of the average flame velocity is associated with the finite thickness of the ion probe, 2-mm gap between the electrodes, and the time resolution of the oscilloscope used to measure the ion probe signal, that is, 1 μs. The largest uncertainty corresponds to the highest velocity where the flame transit time between adjacent ion probes is the shortest. This gives an uncertainty of 9 m/s for a velocity of 700 m/s.

To better show the acceleration trends in Fig. 2, a fourth-order polynomial fit was applied to the data. When examining this trend line, we see an inflection point at approximately 1.1 m. After this point, the rate of acceleration decreases until approximately 1.7 m, where the curve starts to level off at speeds between 680 and 700 m/s. This leveling off of the velocity corresponds to flame propagation in the choked regime. Theoretically, choked flames will propagate at the isobaric speed of sound of the products of combustion, that is, 890 m/s for a stoichiometric propane–air mixture.[11] The lower speeds observed experimentally are due to the momentum and heat losses from the flame to the orifice plates. Overall, the results shown in Fig. 2 are consistent with similar flame acceleration data found in the literature.[8] The time required for the flame to choke is 46 ms.

The time required for the flame initiated at the endplate to reach the first ion probe located at the first orifice plate was measured to be 36 ms. This time is important because the first igniter bank is located immediately after the first orifice plate, and thus, this time can be used as a reference for the triggering time of the first igniter bank. For example, if the first igniter bank is triggered less than 36 ms after the endplate igniter is triggered, it is clear that secondary flames will be produced at the first igniter bank spark plugs. If the delay is much longer than 36 ms, then the first bank igniters will be ineffective because the primary flame ignited at the endplate would have consumed the mixture around the igniters.

The first experiments performed in the orifice plate-laden tube with multiple igniters involved the endplate igniter and the first bank of igniters. The flame velocity vs distance was measured for different ignition delays between the endplate igniter and the first igniter bank. It was determined that enhanced flame acceleration relative to the baseline case was obtained when the first bank ignition delay was set between 23 and 27 ms relative to the endplate ignition time. Spark plug ignition delays are represented by $I_{\#\#}$, where the subscripts represent the spark plug locations. (Endplate igniter is designated 0, the first igniter bank is 1, the second igniter bank is 2, etc.) Note this range of I_{01} is shorter than the 36 ms it takes the primary flame to reach the first orifice plate. The best result was obtained for the case of a first igniter bank ignition delay of 25 ms. Figure 3 shows the flame velocity vs distance for this case; also shown for comparison is the baseline velocity data corresponding to the single igniter located at the tube endplate presented in Fig. 2.

Note the first flame velocity measurement is at 0.41 m, corresponding to the velocity measurement between orifice plates 2 and 3. No velocity data point is given between orifice plates 1 and 2 because two different flame fronts arrive at the different ion probes, and therefore, a flame velocity is meaningless. Specifically, the primary flame generated at the endplate crosses ion probe 1, and the secondary flames generated at the first igniter bank spark plugs cross ion probe 2. Flame acceleration enhancement is observed in the two velocity measurements after the igniter bank position. The velocity enhancement is maintained over the next 0.5 m of flame travel but diminishes over the last 1 m of travel. The propagation distance required to choke the flame is shortened by 0.2 m compared to that obtained using the first igniter bank. The time required for the flame to choke is 37.5 ms, a reduction of 20% compared to the baseline case with no secondary ignition.

The next set of experiments performed involved using igniter banks 1 and 2 in sequence. Based on the results obtained using the first igniter bank, the first bank igniter delay was set to 25 ms. With this delay fixed, the optimum delay between the first and second igniter bank, I_{12}, was found to be 4 ms. Figure 4 shows the flame velocity data using the two igniter banks with a 4-ms delay between banks 1 and 2. For comparison, the two flame velocity data sets from Fig. 3 corresponding to the baseline and bank 1 data are also provided. Again the velocity data point between the igniter bank 1 and 2 is not shown because the ion probes are crossed by different flames. As was the case with the single bank of igniters, flame acceleration is augmented down the length of the tube relative to the baseline case; however, there is no noticeable improvement between the single- and two-igniter bank cases. The implementation of a third bank of igniters did not result in a noticeable improvement in the flame acceleration.

Without flow visualization, it is difficult to determine the exact nature of the evolution of the various flame fronts initiated by the

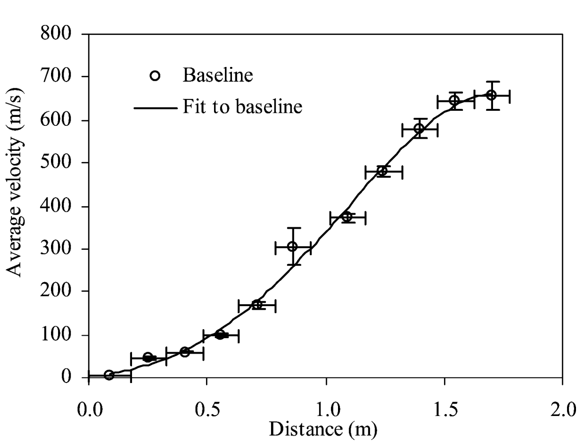

Fig. 2 Endplate ignition velocity profile for stoichiometric propane–air mixture in orifice plate-laden tube.

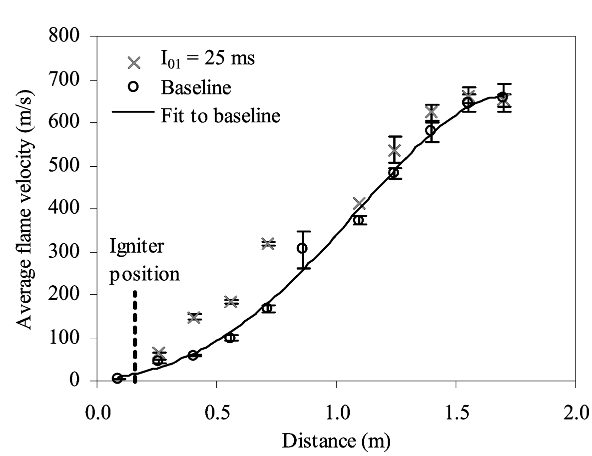

Fig. 3 Velocity profile showing acceleration enhancement obtained using first igniter bank.

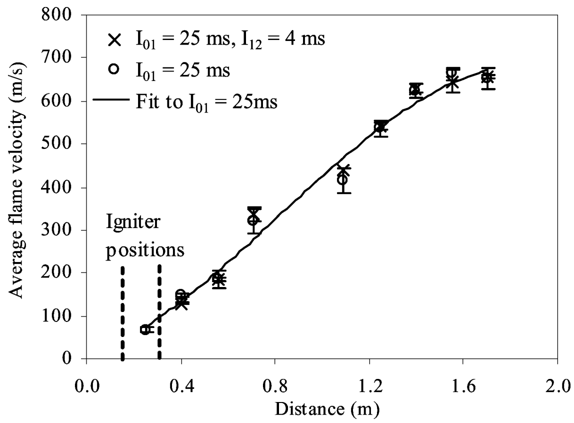

Fig. 4 Velocity profile with acceleration enhancement obtained from using first and second banks in sequence; I_{01} = 25 ms and I_{12} = 4 ms.

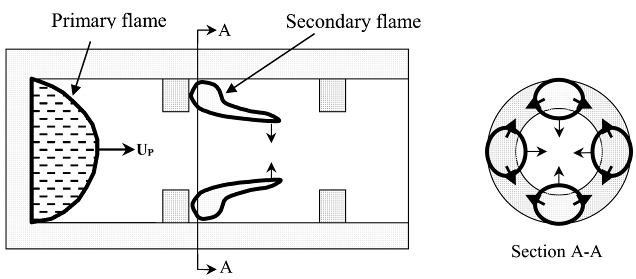

Fig. 5 Schematic showing the propagation of primary flame initiated at endplate igniter and secondary flames produced at first igniter bank. Cross-section view shows how the four individual secondary flames spread.

different igniters. However, based on the relative igniter timing and flame time of arrival, one can construct a simple representation of the phenomenon for the optimum ignition delays for the first and second igniter banks. The process starts with the firing of the endplate igniter, which produces a semispherical flame that spreads spherically from the igniter. The expansion of the combustion products produces a flow in the unburned gas ahead of the flame. The flow of unburned gas through the orifice plates sets up a recirculation zone downstream of the orifice plate where the igniter banks are located.[4] For the baseline case where the secondary igniters are not fired, the primary flame is convected through the first orifice plate, and then burns back into the recirculation zone.[19] When the first igniter bank is fired at 25 ms, the gas in the recirculation zone downstream of the first orifice plate is ignited at four distinct points, as shown in Fig. 5, before the primary flame arrives at the first orifice plate after 36 ms. The flames propagate circumferentially, eventually coalescing into a continuous reaction zone downstream of the first orifice plate. Because the flow velocity through the orifice plate is substantially larger than the laminar burning velocity of the mixture, the flame does not propagate back toward the endplate. The flame ignited at the orifice plate is then stretched downstream by the shear layer as shown in Fig. 5. The additional flame area associated with the secondary flames results in an increase in the volumetric burning rate, compared to the baseline case, which results in a higher unburned gas flow velocity through the second orifice plate.

The downstream surface of the secondary flame propagates with the flow toward the second orifice plate. The time required for this part of the flame to propagate to the second orifice plate is very short. For example, it takes about 8 ms for the flame ignited at the first igniter bank to reach the second orifice plate ion probe, compared to 36 ms for the transit time over the same distance from the endplate to the first orifice plate. The time for the flame to propagate from the igniter bank to the next orifice plate decreases for each subsequent orifice plate. As a consequence of the short time available, the secondary flames generated at the second and all subsequent igniter banks have insufficient time to produce enough flame area to enhance the volumetric burning rate. Therefore, this method of ignition is only effective for the first couple of orifice plates, this is corroborated by the flame velocity data that show no significant flame velocity enhancement for more than one igniter bank.

Perforated Plate Experiments

In an orifice plate-laden tube, a flame propagates continuously through the tube. The flame shape changes according to the unburned gas velocity field. If the orifice plate diameter is very small, the phenomenon changes to one of successive explosions between the plates. The explosions are caused by the rapid mixing of hot combustion products and unburned gas in the jet issuing from the orifice plate.[11] Ultimately, the volumetric burning rate is governed by the mass flow rate of the products through the orifice plate hole. To increase the volumetric burning rate, multiple holes can be used to have multiple jets that cover the full diameter of the tube. Experiments were performed using perforated plates in place of the first few orifice plates to boost the initial volumetric burning rate. This way, a high unburned gas velocity is produced through the subsequent orifice plates. This results in a high initial flame velocity at the start of the orifice plate section. The question is whether flame acceleration in the orifice plates section starts immediately or if there is a readjustment whereby the flame initially decelerates and then reaccelerates.

In these tests, the endplate central igniter is used to initiate a hemispherical laminar flame. As the primary flame propagates toward the first perforated plate, unburned gas is displaced through the perforated plate forming multiple turbulent jets. When the primary flame reaches the perforated plate, the combustion products flow through the holes producing flame jets. Flame transmission across the first perforated plate is one of ignition of the unburned gas after the perforated plate by the turbulent jet of hot combustion products. Note that there is no flame propagation per se between the perforated plates, but one can still define a combustion propagation velocity based on the ion probe signals. The volumetric burning rate is governed by the mixing rate of the products and unburned gas. In the case of multiple perforated plates, combustion is propagated down the tube by a sequence of explosions until after the last perforated plate, where normal turbulent flame propagation resumes. The perforated plate provides much more flow resistance than the orifice plate, and so it is not practical to use more than a couple at the ignition end of the tube. Experiments were performed to investigate the effect of replacing orifice plates nearest to the ignition endplate with perforated plates on flame acceleration.

The measured flame velocity vs distance for tube configurations with different numbers of perforated plates using only the endplate igniter is shown in Fig. 6. For the baseline case, no perforated plates were used, only 6.9-cm orifice plates, which have a higher blockage ratio than the 10.7-cm orifice plates used in the just described test series, that is, blockage ratio of 0.75 vs 0.42. The higher blockage orifice plates were used because a previous study indicated that in this tube 0.75 block ratio plates resulted in better flame acceleration.[7] As a result, the baseline velocity profiles given in Figs. 6 and 2 are

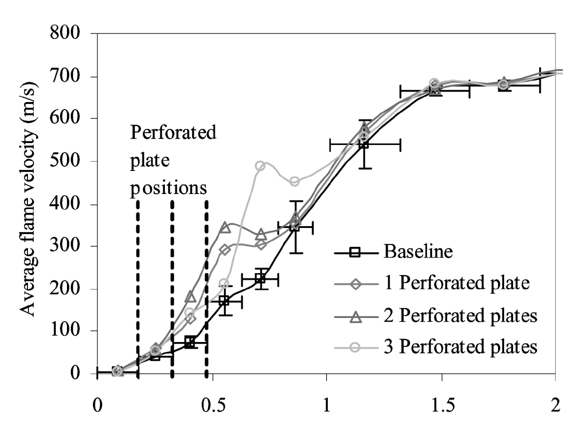

Fig. 6 Flame velocity profile for endplate igniter and different number of perforated plates replacing orifice plates.

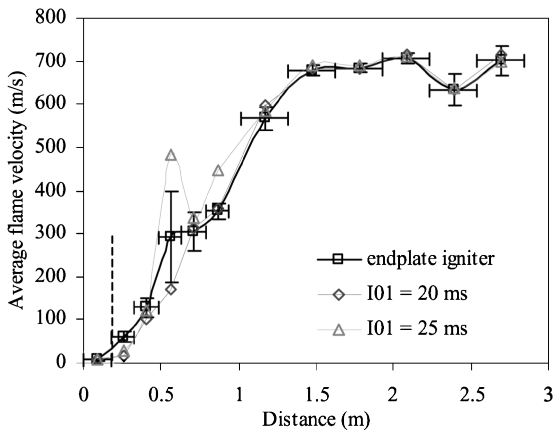

Fig. 7 Flame velocity profiles for single perforated plate with and without first bank of igniters.

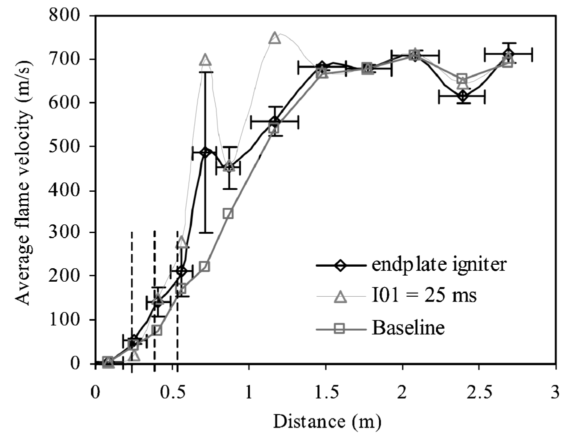

Fig. 8 Flame velocity profiles for three perforated plates with and without first bank of igniters and baseline case.

different. For the other three velocity profiles shown, the specified number of orifice plates were replaced with perforated plates. The perforated plate locations are shown in Fig. 6. For the baseline case, the vertical error bars correspond to the standard deviation of the velocity data from 10 experiments. To reduce the clutter in the graph, the error bars for the other data sets are not shown. Any flame acceleration enhancement produced by the presence of the perforated plate can be assessed by comparison with the baseline case. The flame time of arrival is measured immediately after the perforated plate. Clearly flame acceleration is enhanced downstream from the perforated plates. The flame velocity does not increase dramatically immediately after the perforated plate but is instead delayed farther downstream. For example, in the case of a single perforated plate, the first sign of flame velocity augmentation over the baseline is between the second and third orifice plates. This augmentation is sustained up to 1 m of flame travel, at which point the flame velocity profile merges with the baseline velocity profile. The use of additional perforated plates results in flame acceleration augmentation farther down the tube. For example, for three perforated plates a jump in the flame velocity is observed between the fourth and fifth orifice plates. However, in all cases the flame velocity profile eventually merges with the baseline case and steady-state flame velocity is achieved at the same location, for example, 1.5 m from the ignition point.

Additional experiments were performed with perforated plates using secondary igniters. The results obtained with a single perforated plate and the first bank of igniters with two different delay times is shown in Fig. 7. Also provided for comparison is the flame velocity profile obtained when a single perforated plate is used with the endplate igniter. The results indicate that flame acceleration enhancement is observed for an ignition delay of 25 ms but not for 20 ms. This enhancement in the flame acceleration is short lived. The flame velocity profile merges with the endplate igniter results after roughly 1.1 m of flame propagation. It is evident from the results obtained with the perforated plates, with and without secondary igniters, that any flame acceleration enhancement that is achieved occurs immediately downstream of the perforated plates. Once the flame leaves this region, it quickly readjusts to the flame velocity trajectory that is obtained in the absence of the perforated plates.

The only configuration tested where the choked velocity was achieved over a shorter distance was for the configuration including three perforated plates and a single igniter bank set to a delay of 25 ms. The flame velocity data is provided in Fig. 8. The results obtained with no perforated plates (baseline case) and three perforated plates with no secondary ignition (endplate igniter case) are also provided for comparison. As was the case for a single perforated plate (Fig. 7), there is a large jump in the flame velocity shortly after the last perforated plate. For the endigniter case in Fig. 8, there is a significant scatter in the flame velocity measured at 0.8 m, ranging from 300 to 670 m/s. This large scatter in the data is not observed for the same configuration with the first igniter bank set to an ignition delay of 25 ms. The scatter for this case, although not shown, is between 674 and 732 m/s, which is consistently above the velocity measured without the use of the igniter bank. This same trend in the data is observed in single perforated plate configuration, as shown in Fig. 7, only the jump in velocity occurs closer to the endplate. Independent of whether or not secondary ignition is used, the progression of combustion between the perforated plates is driven by the burning rate, which is governed by the turbulent mixing. It is not clear why there is such a large difference in the scatter in the velocity data, other than ignition by the igniter bank after the first perforated plate removes any variability in how the flame develops from the endplate igniter through the first perforated plate.

For the three perforated plates with a single igniter bank configuration, the flame reaches the choked flame velocity at roughly 1.2 m compared to 1.5 m of flame travel required with only the orifice plates, corresponding to the baseline case in Fig. 8. The time required for the flame to choke is 35 ms, which represents a 24% reduction in time compared to the baseline case using only 0.42 blockage ratio orifice plates. The results indicate that even though the flame reaches the choked flame velocity much quicker, DDT is still not observed over the 3 m length of the tube. Thus, it is not possible to comment on the ability of initiating detonation closer to the endplate igniter. Tests were only performed with propane–air, the influence of multipoint ignition and the use of perforated plates on the detonation run-up distance can be studied directly with a more reactive mixture such as ethylene or hydrogen–air, which readily detonates in the size tube used in this investigation.

Conclusions

The use of multiple igniters positioned after orifice plates was only moderately successful in enhancing flame acceleration. It was found that there was little improvement in flame acceleration with the addition of more than one ignition bank after the first orifice plate. The reduction in the distance required for the flame to accelerate to a velocity on the order of the speed of sound in the combustion products is modest, on the order of 10%. This distance was reduced by 30% by replacing the first three orifice plates with perforated plates and using a single bank of igniters after the first perforated plate. The reduction in the time required to reach this velocity is about 24% compared to just using orifice plates, which translates to a higher PDE operating frequency. This investigation has demonstrated that multipoint ignition and the use of perforated plates can enhance flame acceleration, but no direct evidence of a reduction in the detonation run-up distance was obtained.

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