Flame Inversions in a Rectangular Duct with 90ºBend

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INTRODUCTION

The problem of flame propagation in tubes has frequently re-appeared in combustion literature. In 1883 Mallard and Le Chatellier [1] have observed that after ignition at the center of the closed end of half-open tube, flame propagation and expansion of the combustion products create a gas velocity ahead of the flame and along the tube. The flame propagation is unsteady: both the flame speed and the gas velocity ahead of the flame decrease and a transition to a tulip flame occurs. During this process of flame inversion the shape of flame changes from a forward pointing, finger shape to a backward pointing cusp. More recently Clanet and Searby [2] have shown the transition to a tulip flame and explained this as a manifestation of Taylor instability, arising from deceleration due to the reduction in flame surface area when part of the flame reaches the tube wall.

It is interesting to note that various mechanisms that have been proposed [2, 3, 4, 5] to explain the formation of the tulip flame focused only on the first flame inversion. Schmidt *et al*. [6] in 1.09 m long square duct of 24 x 24 mm cross section and later Sobiesiak *et al*. [7] in a 1.6 m long rectangular of 25 x 50 mm cross section have demonstrated occurrence of several flame inversions. The apparatus in [7] included a 90° bend and a 0.3 m long vertical straight section. Flow in a curved tube differs significantly from that in a straight tube, owing to the presence of secondary flow by centrifugal forces. The secondary flow takes on the form of paired stream-wise oriented counter-rotating vortices. These large vortical structures evolve further with change in the flow conditions at the entry to the curved section. One can expect that the approaching flame and the bend vortical structures will interact to further modify flame appearance and velocity.

The main objective of this study was to investigate flame inversions during the flame progression along the duct under varying initial and boundary conditions.

EXPERIMENTAL APPARATUS AND PROCEDURE

The Flame Propagation Duct (FPD) shown in Fig. 1 consists of a 1.6 m long straight horizontal section, a 90º bend and a 0.3 m straight vertical section. The rectangular cross section of the FPD is H = 50. 8 x W = 25.4 mm (aspect ratio 2:1). In order to enhance formation of secondary structure in the bend a new apparatus was build with 1:2 aspect ratio, and with all other dimensions preserved. The surface area of the exit end of the duct can be varied in discreet interval to give 100%, 75%, 50%, 20%, 10%, and 0% open area.

The flammable mixture at required equivalence ratio was prepared in a separate bottle using the partial pressure method. The duct was filled to atmospheric pressure with the premixed propane-air mixture fed into the end of the longer straight section. The fuels used in the study were instrument grade propane, commercial propane HD5, and commercial propane with varying percentage of added oxygenated hydrocarbon, HD5-A (4%), HD5-B (2%), HD5-C (1%) and HD5-D (0.5%). The oxidizer used was dry air. The equivalence ratio (100% propane was assumed) was varied within the range of $0.7 < \Phi < 1.9$. For a given equivalence ratio the size of exit opening was varied from fully open to fully closed.

A high-speed Kodak Motion CCD camera was used to capture images of the flame along the duct. The recorded images of visible flame were processed using Matrox Inspector software and custom written programs to capture flame movement along the duct. In the duct of 1:2 aspect ratio pressure measurements were taken using a piezoelectric transducer mounted at the ignition end of the duct.

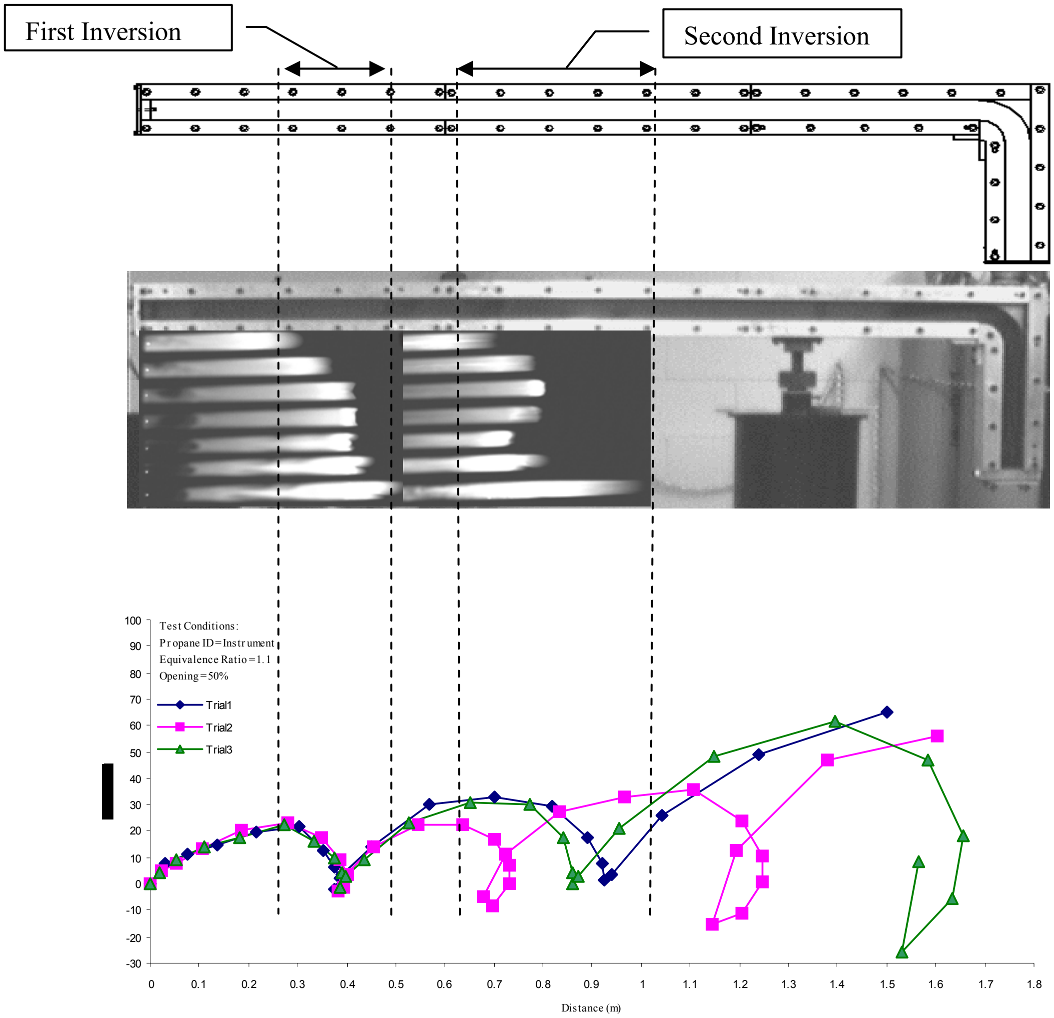

Figure 1. Schematic of the Flame Propagation Duct (at the top). Photograph of the FPD and images of the two flame inversions (in the middle). Plot of the flame speed versus the duct length (at the bottom) for three trials with instrument grade propane/air mixture at Φ =1.1, and 50% open exit.

RESULTS AND DISCUSSION

The Dynamics of the Flame Inversions

The flame propagation at given conditions was repeatedly filmed with a high speed Kodak CCD camera. The images were processed to provide data on speed of the flame front point located on the duct centerline and the most advanced point of the flame front. There are small speed differences between these two locations and all data reported in this work refer to the centerline speed. In Figure 1 examples of flame images are shown at two locations in the duct. These sets illustrate the first and second flame inversion. At the bottom of the Figure 1 the flame front speed along the duct length is shown for three trials at the same operating conditions (instrument grade propane, Φ = 1.1, 50 % open area). The first flame inversion is a classical tulip flame; a forward finger shaped flame becomes a backward facing cusp. The tulip flame is accompanied by radical flame speed changes. The speed graph shows that after initial acceleration the flame slows down to a total halt. Then, the flame moves backward, stops and reassumes a fast forward motion. Similar flame speed changes occur at two more downstream locations and they demonstrated additional flame inversions. The images of the second inversion show changes of the flame front shape, which only resemble the tulip flame formation. These distortions are not as ordered and can best be described as flame folding. The flame speed between the inversions increases in general and as the result the subsequent inversions occur at longer distances. The first inversion is a very repeatable occurrence in terms of flame speed and inversion location. There are more deviations in flame speed and scatter in inversion locations for the subsequent inversions. The results seem to indicate that the maximum flame speed and the deceleration process are critical in triggering the flame inversion. For the case illustrated in Figure 1 the last inversion is in front of the entry to the bend. The flame seed increases substantially in the bend and frequently the flame clears the bend in a few frames indicating speeds in excess of 80 m/s.

The Influence of the Mixture Equivalence Ratio

Laminar flame speed changes with mixture equivalence ratio and that relation has an impact on the observed flame inversions as illustrated in Figure 2. The maximum of laminar flame speed for propane-air mixture is at Φ = 1.1, and accordingly the flame speeds in the trial with Φ = 1.1 are the highest at each inversion. That in turn translates to fewer inversions than for the other equivalence ratios. All mixtures in the tested range of equivalence ratio produce the tulip flame at the first inversion. The flame speed decreases with departure of equivalence ratio from Φ = 1.1 and location of the first inversion moves upstream and concurrently the number of inversions increases. At very lean conditions, Φ = 0.7, the progression of the flame is very irregular and it is difficult to characterize the flame shape changes as ordered inversions.

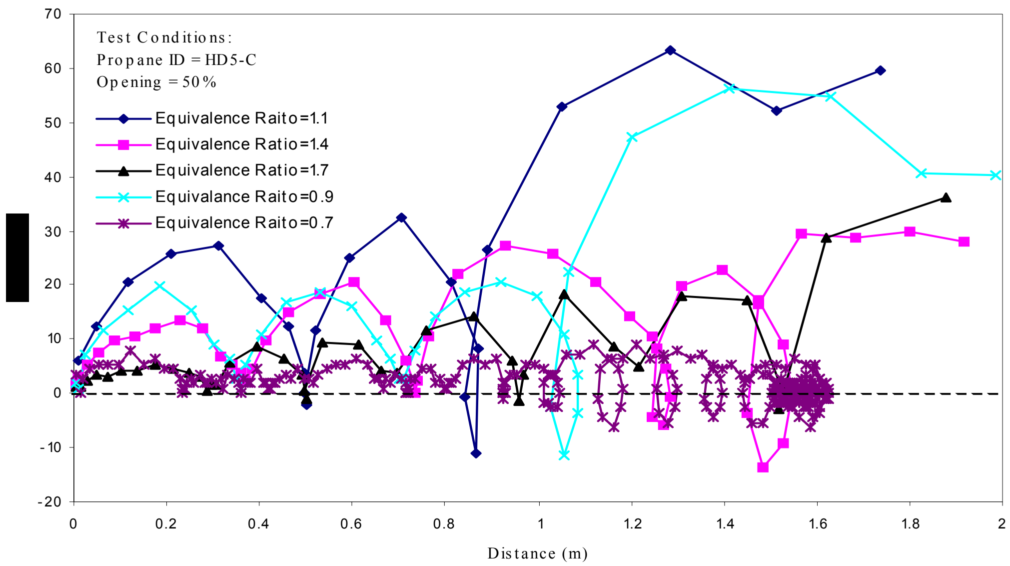

Figure 2. Flame speed changes along the duct length for varying equivalence ratio, HD5-C fuel/air mixture and 50% open exit.

The Influence of the Oxygenated Hydrocarbon Additive

To investigate an impact of oxygenated additives the commercial propane was mixed with a small percentage of an oxygenated hydrocarbon (up to 4%). The flame speed results are shown in Figure 3 for instrument grade propane, HD5, and HD5 mixes with additive. Fuel composition does change the laminar flame speed, although in this study the additive amounts are small. Nevertheless, the progression of flame with additives is much less repeatable than that for a fixed composition mixture at given equivalence ratio (such as in Figure 1). There are differences in the flame speed shortly after ignition and in the first inversion location. These differences amplify significantly as the second inversion develops. Interestingly enough mixtures with largest (HD5-A) and smallest (HD5-D) amounts of additive result in the longest for the first and second inversions.

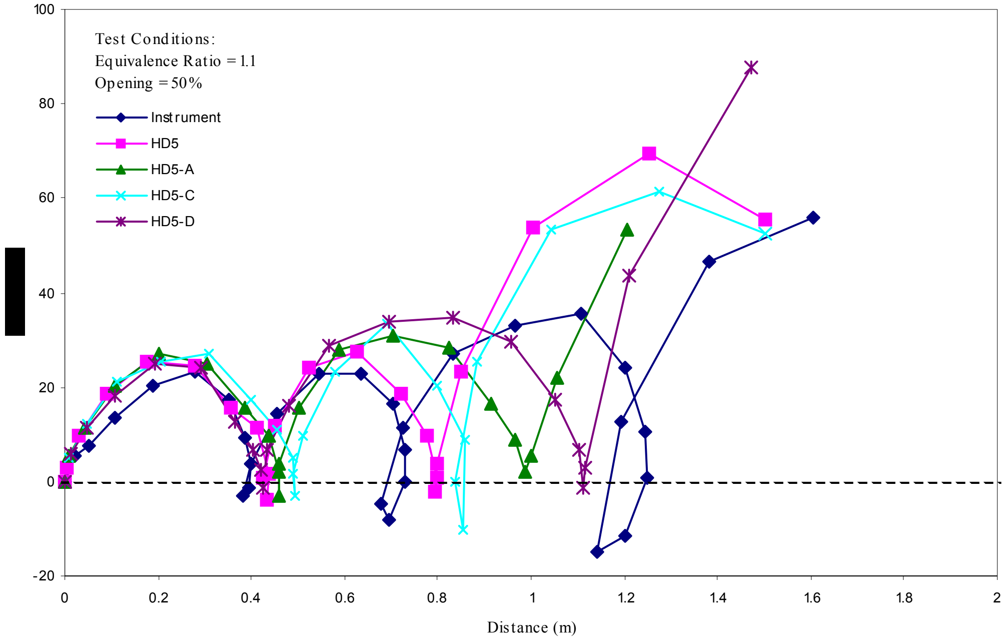

Figure 3. Flame speed changes along the duct length for varying percentage of additive in HD5 fuel/air mixture, Φ =1.1, and 50% open exit.

The Influence of the Open End Area

The features of flame progression in the duct described in the previous paragraphs are further modified when the surface area of the duct exit end is varied. The impact of such a boundary condition changes is demonstrated in Figure 4. The ordered flame inversion occur for large openings of 100%, 75%, 50%, and 25% and the point of the first inversion relocates upstream with decrease of the exit end area. The number of inversions increases with the exit area reduction, as does the flame speed in between the inversions. The progression of flame changes qualitatively when the area of the exit end is only at 10% or the exit end is closed. The first inversion still does occur however, the flame speed does not decrease to zero and there is no flame reversal of flame movement. The subsequent inversions are very weak and difficult to trace.

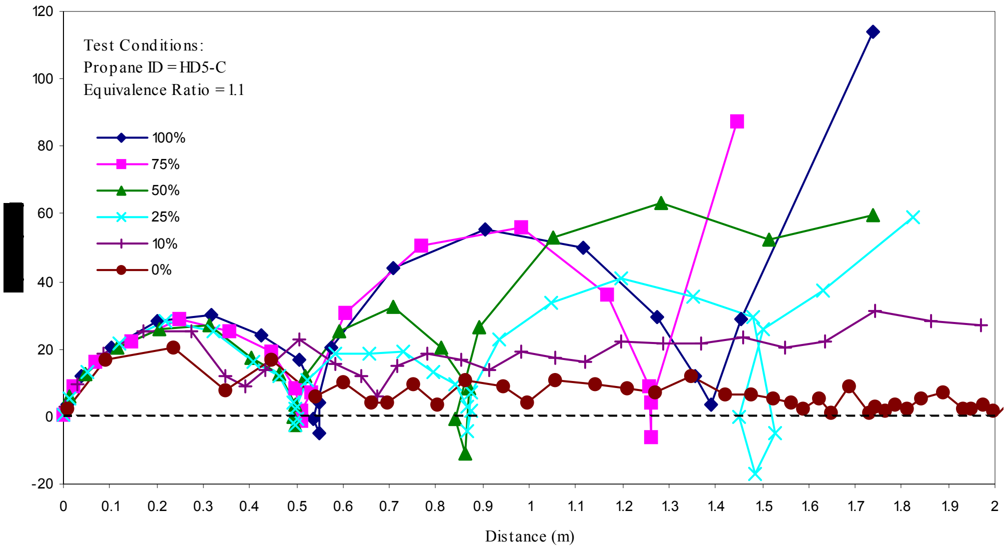

Figure 4. Flame speed changes along the duct length for varying percentage of the exit end open area for HD5-C fuel/air mixture, Φ =1.1.

The Influence of the Duct Aspect Ratio

The change in the duct aspect ratio from original 2:1 to 1:2 was implemented in order to improve triggering of secondary flow in the bend. In Figure 5 the flame speed results are shown for several trials for both set-ups. The three trials in the original apparatus demonstrate quite orderly flame progression by

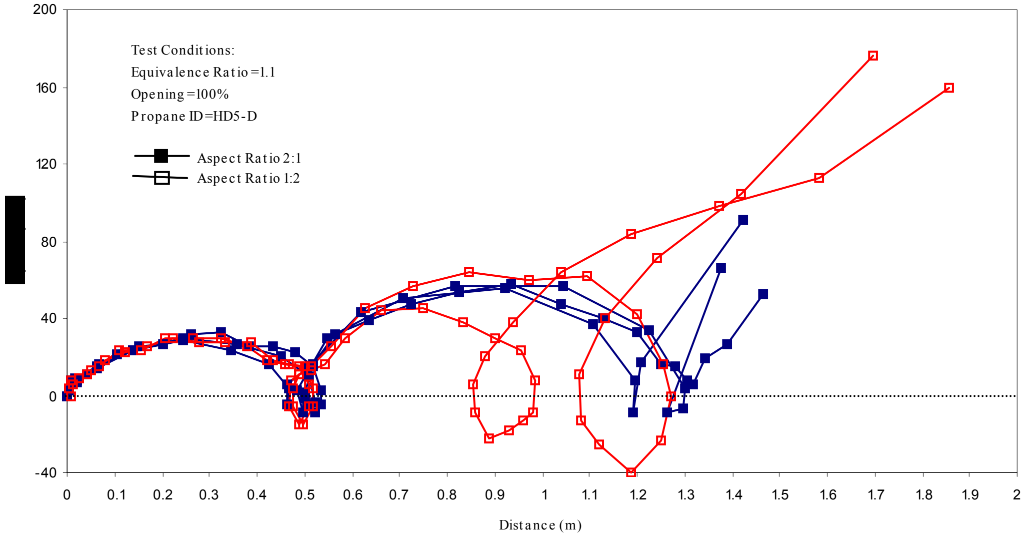

Figure 5. Flame speed changes along the duct length for the ducts with 2:1 and 1:2 aspect ratio, for HD5-C fuel/air mixture, Φ =1.1, and 100% open exit end.

way of two inversions. The initial progression of the flame and the first inversion formation is affected only marginally by the new 2:1 aspect ratio. However, the flame progression after the tulip flame stage is now very different. The two trials show much larger flame speed loop around the inversion point and there is large difference in that point location. The exit speed of the flame is much larger for both trials in the new apparatus. The new 1:2 aspect should promote the secondary flow in the bend and the dramatic increase of the flame speed in this area corroborates the postulate of the bend and flame interaction.

CONCLUSIONS

The progression of the flame front in rectangular duct is characterized by occurrence of several flame inversions. The forward propagating flame experiences periodic reduction or even reversal of its relative speed and concurrent radical change in the flame front appearance. The first inversion results in the tulip flame formation. The subsequent inversions are related to the tulip flame however; they are less orderly and take shape of large-scale flame folds. Changes in the initial (mixture composition) and boundary conditions (exit end open area and aspect ratio) influence strongly the flame inversions occurrence through the modification of the laminar flame speed first and then through the induced unburned mixture velocity ahead of the flame.

ACKNOWLEDGMENTS

The financial support of the Natural Sciences and Engineering Research Council of Canada, DaimlerChrysler Canada, and the University of Windsor School of Graduate Studies is gratefully acknowledged.

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