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FLAME STRUCTURE 2014
8th International Seminar on Flame Structure

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On Behaviour of the Premixed Flame Propagating across the Varied Composition Field in a Rectangular Duct.

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Abstract

Flame propagation through a rectangular duct has been investigated frequently in the past. This work is focused on the flame propagation in a channel when the air/fuel mixture composition along the channel length changes. Experiments were carried in the duct that has an aspect ratio of 25mm x 50mm and length of 1800mm. The duct is fitted with a spark plug at one (closed) end and an injecting nozzle located at 300mm from the spark plug end. This allows for the local injection of either fuel (local enrichment) or air (local leaning) of the air/fuel mixture in the channel. The exit end of the channel can be fully or partially open at different experiments. The channel initially can be filled with the air/fuel mixture of equivalence ratio of 1 and 1.1. The initial set of experiments was carried out to confirm repeatability of the previously obtained and published results for the uniform composition field in the channel. In the current work fuel or air is injected at the suspected location of the tulip flame formation, around 300mm from the ignition end. Injection timing with respect to the spark timing was also selected as well as the variations of injection durations were observed. Images of the moving flame front were captured using a high speed CCD camera to determine the flame evolution and speeds through the varying field of equivalence ratios. These results are compared with results from the uniform composition field.

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Introduction

Flame propagation has been studies for a long time. Flame propagation ducts of various cross sectional area have been used as far back as 1928 by Ellis [1]. He concluded that an aspect ratio greater than or equal to 2 would give rise to the well-recognized "tulip flame". The phenomenon attracted a number of studies with extensive publication record. In the recent past even more researchers have been looking at flame propagation in ducts [1-3][4]. All these investigations have been concerned with the tulip flame development and its explanation. The longer duct used in [4] allowed to observe the subsequent flame inversions that follow the tulip flame. In this paper development of both the tulip flame and the flame inversions is of interest under the open exit end condition and more importantly with varied equivalence ratio field along the duct.

Approach

The FPD shown in Fig.1 is a horizontal duct with a 180 cm in length and constant rectangular cross section, H = 2.54 cm x W = 5.08 cm (aspect ratio 1:2). The endplate at one of the ends (spark end) features threaded openings for a centrally mounted spark plug and pressure transducer. Initially, the duct is filled with air/fuel mixture of know composition, prepared using the partial pressure method. The fuel is Instrument Grade 99.5% propane and the oxidizer is dry air. The duct features two gaseous injectors located at 30 and 60 cm for the ignition, that serve the purpose of local injection of additional fuel or air and thus to change local composition of the mixture inside the FPD. The injection system includes also an injection timing control box and DC power supply. LabView program controls the injection timing and it allows triggering the injection with any required delay times with respect to spark ignition and recording times.

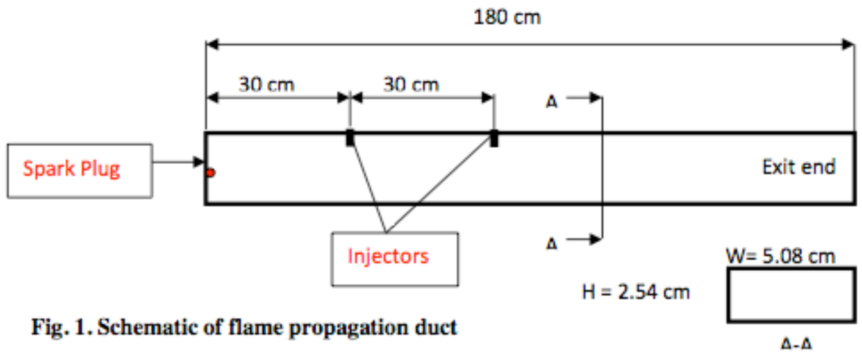

Fig. 1. Schematic of flame propagation duct

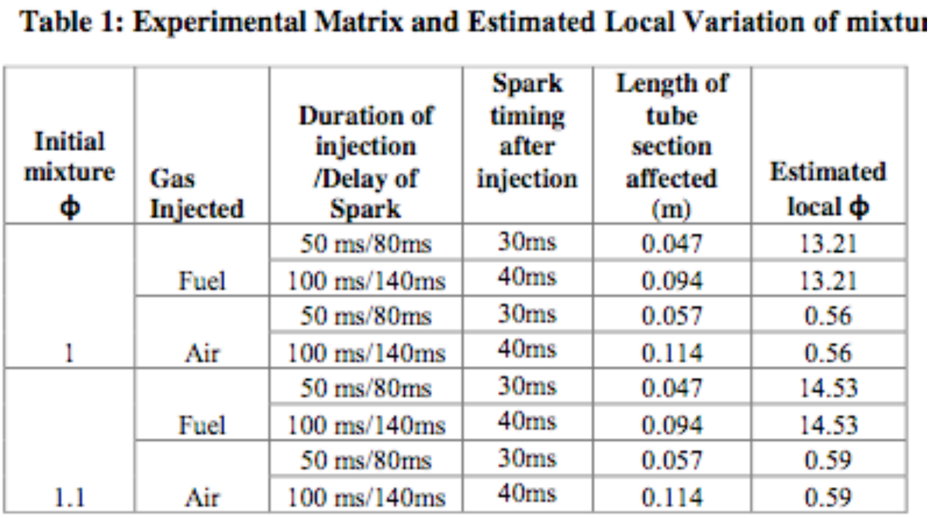

Table 1: Experimental Matrix and Estimated Local Variation of mixtu

Initial mixture Φ	Gas Injected	Duration of injection /Delay of Spark	Spark timing after injection	Length of tube section affected (m)	Estimated local Φ
1	Fuel	50 ms/80ms	30ms	0.047	13.21
		100 ms/140ms	40ms	0.094	13.21
	Air	50 ms/80ms	30ms	0.057	0.56
		100 ms/140ms	40ms	0.114	0.56
1.1	Fuel	50 ms/80ms	30ms	0.047	14.53
		100 ms/140ms	40ms	0.094	14.53
	Air	50 ms/80ms	30ms	0.057	0.59
		100 ms/140ms	40ms	0.114	0.59

eight conditions tested; two initial overall equivalence ratios 1 and 1.1 that were locally altered by air and fuel injection at times shown in Table 1. In addition the spark timing was varied. The injected air or fuel volume is expected to locally change the equivalence ratio. The ignition was delayed by 80ms from the start of injection for 50ms injection duration and 140ms delay for 100ms injection duration. This provides a settling time of 30ms for the 50ms injection and 40ms for the 100ms injection. Estimations of new local equivalence ratio and the length of duct containing the new mixture are show in the last two columns of Table 1. The set of results presented here is a bench marking exercise to identify the flame behavior with different injection timing and with different amounts of additional reactants for the future more focused experiments. The instantaneous flame speeds were calculated by evaluating the distance traveled by the flame at the height of the ignition electrodes towards the open end. The images were captured with a Photron Ultima APX-RS Fastcam camera at 10,000 frames per second (FPS). MATLAB code was used to calculate the displacement of the image towards the open end at each frame.

The instantaneous flame speed (fs) is the flame traveled at a time interval of s (at 10000 FPS).

Results and Discussion

Flame development in terms of flame speed, in a mixture with uniform equivalence ratio of 1, is shown in Fig.2 for two separate trials. The familiar from previous works [1-4] distinct pattern of flame behaviour can be seen. The tulip flame forms consistently around 500mm and independently of the equivalence ratio (results for Φ = 1.1 are not shown here because of the space limitation). The subsequent flame inversions are more random in both; their location and speeds they achieved.

Flame speed curves in Fig. 2 are later superimposed as the reference case in Figs. 3, 4, 5 and 6. This will help to differentiate between flame propagation pattern with the additional air and fuel injections.

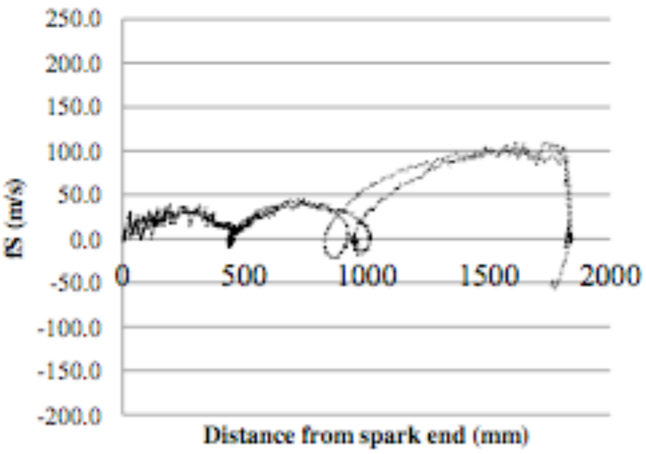

Fig. 2. Flame speed changes in two consecutive trials with 100 % open exit and mixture Φ = 1, no injection. Reference case at Φ =1.

Results shown in Fig. 3 are for the additional fuel injection and in Fig. 4 for the additional air injection. The injection was of 50ms duration and the spark was initiated 30 ms after the injection end. The speeds curves, in both figures, suggest that the flame behaviour has not noticeably changed from that in the reference case.

A dramatic change is observed in Fig. 5, for the additional fuel injection of 100ms duration and the spark release at 40ms after the injection ended. The tulip flame is still at the same location. However, the second inversion develops with very high propagation speeds and eventually the flame is quenched before reaching the duct exit end.

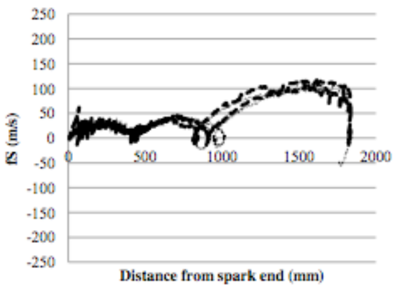

Fig. 3. Flame speed changes in three consecutive trials with fuel injection (50 ms) , with 100 % open exit and mixture Φ = 1. (Reference case is gray).

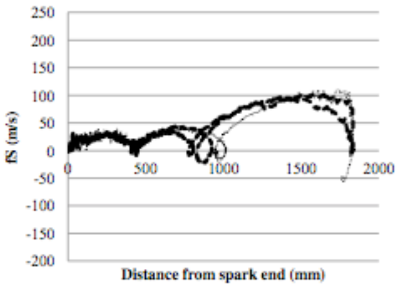

Fig. 4. Flame speed changes in three consecutive trials with air injection (50 ms) , with 100 % open exit and mixture Φ = 1. (Reference case is gray).

The flame termination could be attributed to the fact that the flame encounters a region of very rich mixture with the estimated equivalence ratio around 13.21 (from the initial of 1) over a duct length of 0.094 m (Table 1). The injection of air at the same conditions shown in Fig. 6, does not affect much the flame pattern, as the equivalence is only half of the initial one (in Table 1, change from 1 to 0.56).

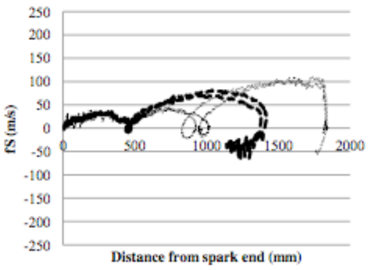

Fig. 5. Flame speed changes in two consecutive trials with fuel injection (100 ms), with 100 % open exit and mixture Φ = 1. (Reference case is gray).

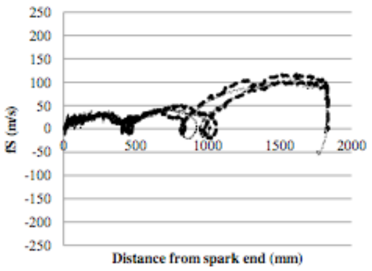

Fig. 6. Flame speed changes in two consecutive trials with air injection (100 ms), with 100 % open exit and mixture Φ = 1. (Reference case is gray).

Conclusions

The results provide strong evidence that the tulip flame development is quite insensitive to the changes in the initial and local equivalence ratio within the range of the tested conditions.

In contrast, the subsequent flame inversions show a varied degree of sensitivity to the local equivalence ratio changes, with the local enrichment having a bigger impact than the local leaning out of the mixture, leading, in some cases to the flame termination inside the duct. The initially rich mixtures also seem to be more sensitive to the local equivalence ratio changes.

The observed flame behavior (the flame inversions part) under these conditions is more of a random nature in contrast to deterministic pattern of the tulip flame development.

The research will continue to identify the set of conditions, in terms of injection duration times, split injections and ignition delay times, and additional injection locations along the duct, that have most destabilizing effect on the flame propagation.

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