FALME PROPAGATION IN STRAIGHT CHANNEL WITH 90^0 CURVED SECTION

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Introduction

Flame propagation in channels has been one of the major subjects of research concerned with explosion hazards. Most studies in this area were conducted using straight channels and straight channels with internal obstacles to generate turbulence. In contrast, practical ducting systems usually include non-straight sections, such as bends, T-junctions and intersections. Furthermore, the majority of the studies on flame propagation in channels are concerned with fast flames, transitions to detonation, and detonation itself. In many instances however, the flammable mixture in the channel is initially stagnant and flow of the mixture is induced only after ignition, by the expanding combustion products. Flow in a curved channel differs significantly from that in a straight channel, owing to the presence of secondary flow caused by centrifugal forces. The secondary flow takes the form of paired, streamwise-oriented counter-rotating vortices.

Recently Sato *et al.* [1] investigated experimentally and numerically the flame propagation in a 0.02m x 0.02m square duct with a 0.1m long straight section and a 90^0 bend. They concluded that the features of the main flow of the unburned mixture primarily determined the flame behavior in the bend. Interestingly, there are no references in their work to the secondary flow and its impact on the flame.

The objective of this study was to examine interaction of the propagating flame with the secondary flow structures in a 90^0 curved section. Tests were conducted on a modified and scaled up version of the Sato experimental apparatus.

Flow development in a curved channel

Development of laminar flow in curved channels of rectangular cross-section has been studied experimentally by Humphrey *et al*. [2], Hille *et al.* [3], and Bara [4], and by mathematical modeling by Soh [5], Hille *et al*.[3[and Bara [4]. These studies revealed the presence of a symmetric two-vortex structure, which evolves into four-vortex structure when the entry velocity increases. These structures are manifestations of secondary flow and are known as Dean vortices.

In our experiments, the unburned mixture in the channel is initially stagnant. The flow in the curved section starts to develop after the ignition of the mixture at the closed end. As the flame propagates through the channel one can expect change in the mainstream velocity of the unburned mixture from zero to some maximum. For the given geometry of the channel, transient flow will exist for velocities up to 5 m/s yielding Re = 11286 and Dn = 7524. However, as pointed by Berger *et al.* [6] measurements and calculations of turbulent flows in curved rectangular channels exhibit many of the features observed in laminar flows, including secondary structures.

Experimental apparatus and procedure

The experiments were carried out in a channel of rectangular cross-section H = 5.08 cm and W = 2.54 cm, through the two straight sections (1.3 m and 0.5 m long) and curved section. The 90^0 curved section has internal and external radii of 5.08 and 10.16 cm respectively. This results in a curvature ratio R/a = 2.25. The longer straight section endplate features a spark plug. The endplate of the shorter straight section includes two openings. One opening is for the vacuum and fill piping connection. The other opening, 10 mm in diameter is open during experiments and serves the role of a partially open end.

Flammable mixtures of propane and air were used for all tests. The fuel was Instrument Grade 99.5% propane and the oxidizer was dry air. The one atmosphere pressure propane /air mixture was prepared by the partial pressure method. The equivalence ratios of the mixtures varied from $\Phi = 0.6$ to 1.8. For each specific equivalence ratio, at least ten trials were conducted and the average flame passage times were calculated.

The flame propagation was recorded by a series of photodiodes attached at specified locations along the channel centerline. Signals from the photodiodes were processed by custom made circuit and subsequently displayed on a digital oscilloscope. The resulting waveform distinguishes between individual photodiode signals and allows measuring of flame passage time between the photodiodes. A black and white, Motionscope 500 CCD camera with the frame rate of 500 frames/sec was used for recording the motion of the flame and the Schlieren imaging of unburned mixture and flame.

Results and Discussion

The trials have shown that for mixtures with equivalence ratio $\Phi \leq 0.85$, flame fronts are quenched either in the curved section or just in the entry of the vertical straight section. For the rich mixtures of $\Phi \geq 1.85$, quenching occurs in the curved section. Mixtures with equivalence ratio within 0.85 and 1.85 limits support continuous flame propagation through the entire length of the channel.

Flame velocity changes along the length of the straight section of the channel. Furthermore there is a strong dependence of the velocity profile variations on the mixture equivalence ratio. This is shown in Fig. 1 for moderately rich mixtures with an equivalence ratio $1.1 \leq \Phi \leq 1.4$

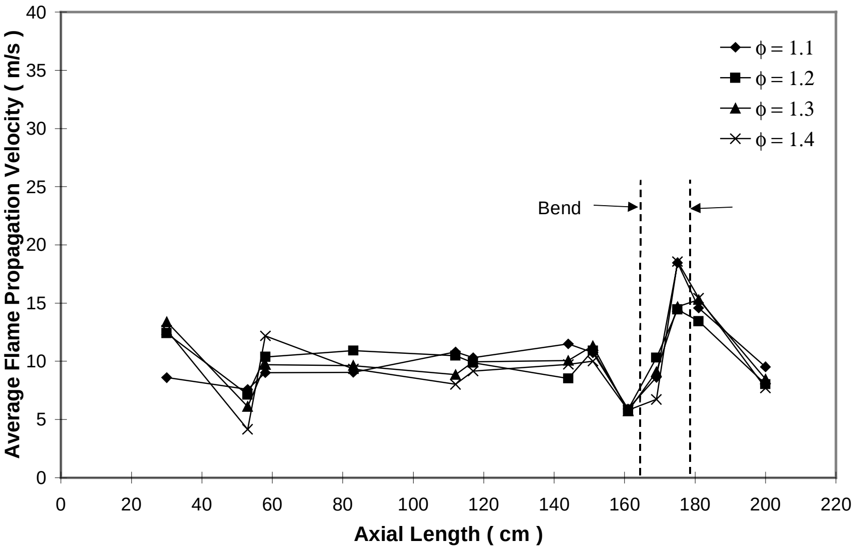

Fig. 1. Flame propagation velocity along the channel length for moderately rich propane/air mixtures.

However, for all equivalence ratios tested there is a distinct flame behavior around and in the curved section. Initially the flame slows down before entering the bend, then accelerates in the bend and it slows down when leaving the curved section. There are some departures from this trend for very rich, $\Phi = 1.8$, and very lean, $\Phi = 0.8$, mixtures.

Furthermore, lean mixtures with equivalence ratio $0.8 \leq \Phi \leq 1.0$, shown in Fig. 2, and rich mixtures with the equivalence ratio $1.5 \leq \Phi \leq 1.8$ (not shown here) exhibit a very unsteady velocity profile in the straight section of the channel, while for moderately rich mixtures with $1.1 \leq \Phi \leq 1.4$ flames assume almost a constant velocity (Fig. 1.). It is interesting to observe that despite of the local large variations there is no radical change in the velocity level with the equivalence ratio change. In contrast, Sato's [1] experiments show a substantial flame velocity decrease for lean mixtures and a gradual flame speed increase in the straight section throughout its length.

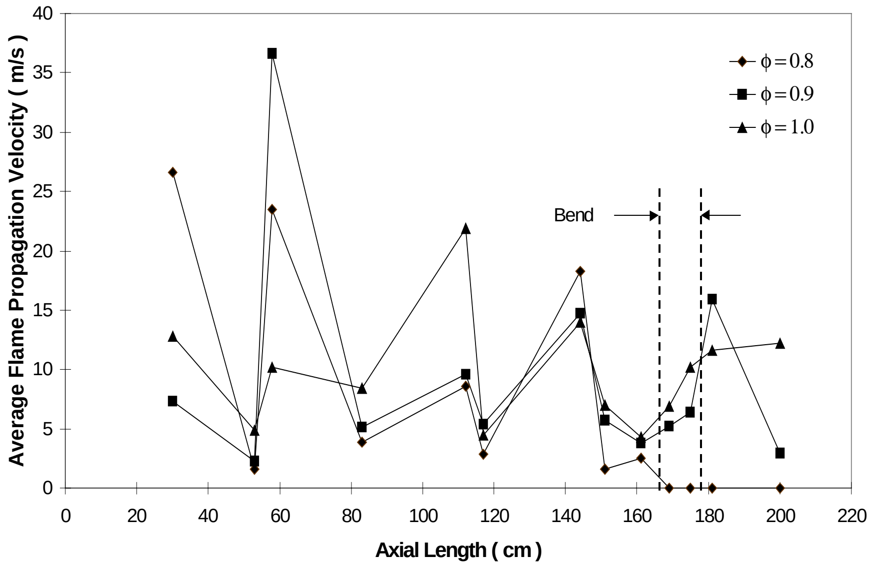

Fig. 2 Flame propagation velocity along the channel length for lean mixtures.

Flame propagation through the curved section of the channel is shown in Fig. 3 and it is representative of the observed flame behavior. In this picture the consecutive flame front contours are outlined for the mixture of equivalence ratio $\Phi = 1.2$.

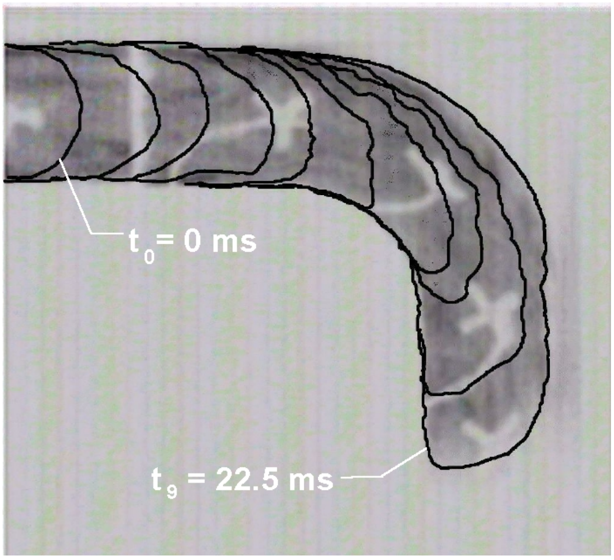

Fig. 3 Flame front contours for $\Phi = 1.2$, 400 fps. Time spacing between contours is 2.5 ms.

The flame fronts upon entering the bend have the tips of their leading edges either at the midplane level or tilted upwards. As the flame fronts proceed into the bend, the tip of the leading edge gradually moves toward the inner radius surface. By the time the flame fronts are halfway through the curved section, the tips are near the inner surface and much ahead of the flame remainder. At the outer radius of the bend the contour plots show an accumulation of the tightly spaced flame fronts. This becomes even more pronounced for mixtures of equivalence ratio above 1.3 and below 0.9. The high concentration of the contour lines is indicative of slowly (stationary in extreme case) propagating flame along the outer radius of the bend. This is further corroborated by calculated (from contour plots as in Fig. 3) flame propagation velocity at ¼, ½, and ¾ of the bend height and shown in Fig. 4.

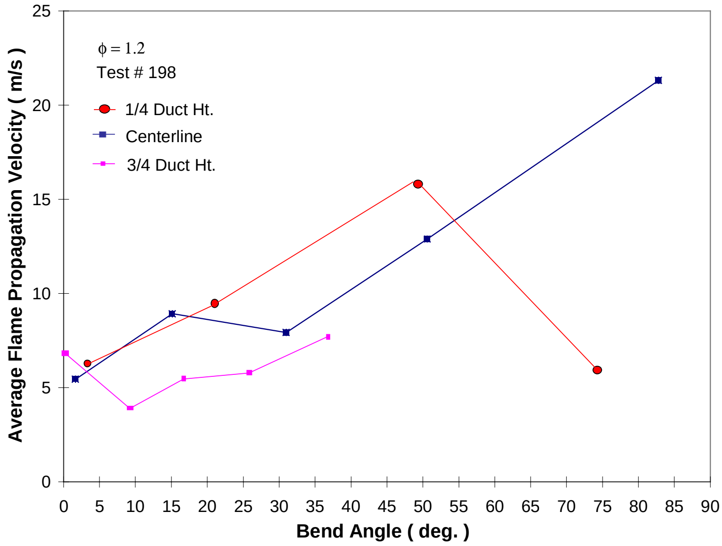

Fig. 4 Comparison of flame front velocities for Φ = 1.2 measured at ½, centerline and ¾ height of the bend.

Slowdown of the flame in the vicinity of the outer radius can be contributed to increased heat transfer due to the outer wall larger surface area and/or to the flame stretching by the Dean vortices and subsequent inability of chemical reaction to keep up with the heat removal. The negative flame stretch resulting from the Dean vortices and flame interaction at the inner radius could cause the fame acceleration at this location.

Conclusions

Trends in the flame propagation velocity in the curved section observed in our experiments follow patterns reported by Sato *et al.* [1]. In particular, the flame acceleration in the bend and subsequent slowing down at the curved section exit was confirmed in this research. The flame propagation velocity increase is considered to be related to large-scale vortical structures residing in the curved section of the bend. In the long straight section of the channel, rich and lean mixtures exhibit a fluctuating velocity profile, while for moderately rich mixtures flames assume almost a constant velocity. This finding is in a sharp contrast to the gradually increasing along the channel length flame propagation velocity reported by Sato.

Acknowledgments

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