EFFECTS OF OBSTACLE SIZE AND SPACING ON THE INITIAL STAGE OF FLAME ACCELERATION IN AN OBSTACLE LADEN TUBE

G. Ciccarelli[1]

Queens University, Mechanical Engineering Department Kingston, ON, Canada, K7P 2M4

C. J. Fowler and M. Bardon

Royal Military College of Canada, Mechanical Engineering Department, Kingston, Canada

Key words: flame acceleration, DDT, PDE

Sustained flame acceleration in a tube can lead to deflagration-to-detonation transition (DDT). DDT has been studied extensively in the context of industrial explosion safety and more recently as a possible detonation initiation scheme for Pulse Detonation Engines (PDE). One of the difficulties associated with PDEs is the difficulty in initiating a detonation in a fuel-air mixture on a practical missile or aircraft engine scale. One of the most common methods for promoting flame acceleration in a tube and thus reducing the distance for detonation initiation is to place turbulence-generating obstacles such as orifice plates in the path of the flame. Under these boundary conditions the flame can accelerate from a velocity on the order of a few meters per second to a velocity close to 1000 m/s. This flame acceleration is caused by the interaction of the flame with the unburned gas turbulent flow and finite strength compression waves generated as a result of the expansion of the gas through the flame.

The initial stage of flame acceleration is characterized by flame area enhancement, commonly referred to as flame folding. Flame folding is caused by large-scale flow perturbations in the unburned gas generated by the orifice plates. At higher flame velocities small-scale turbulence generated in the shear layer downstream of each orifice plate edge enhances the local burning velocity and thus promotes flame acceleration. As the flame accelerates compression waves are radiated ahead of the flame. These waves strengthen as they coalesce, eventually leading to the formation of a strong shock some distance downstream from the ignition point. At the later stages flame front instabilities caused by reflected compression wave-flame interactions becomes the dominant mechanism for flame acceleration. Eventually the flame velocity reaches a maximum corresponding to the speed of sound in the combustion products, i.e. the flame chokes. There has been extensive research carried out looking at flame acceleration leading to flame choking and DDT (Lee et al. 1984, Kuznetsov et al, 2000). This investigation focuses on the effect of the orifice plate dimensions and spacing on the early stages of flame acceleration where the dominant mechanism is flame folding.

Experimental Setup

Experiments were conducted in a 15.2 cm diameter, 3.1 m length tube. Tests were performed with orifice plate spacing (S) of one-half, one, and one and one-half tube diameter (TD) (i.e., S = 0.5TD, 1 TD, 1.5TD). Traditionally the area blockage ratio (BR), defined as the ratio of the cross-sectional area of the tube blocked by the obstacle and the tube cross-sectional area, has been used to characterize the obstacle. For an orifice plate $BR = 1-[d/D]^2$, where d is the inner diameter of the orifice plate and D is the inner diameter of the tube. In this study orifice plates with BRs of 0.43, 0.6, and 0.75 were used. A weak electrical spark was used to ignite the mixture at one end of the tube. The spark was produced with the use of a standard automotive inductive system powered by a 12V battery, and supplied approximately 150mJ of

[1] Corresponding author, e-mail ciccarel@me.queensu.ca

energy. The flame time-of-arrival was recorded with a PC based high-speed data acquisition system, using ionization probes, extending to the tube centreline, outfitted every tube diameter for the first two meters of the tube. All experiments were performed with industrial grade propane (an established simulate for the military fuel JP-10) in air at normal atmospheric conditions (T=20C, P=1atm). For each test, the tube is evacuated with a vacuum pump for 30 minutes. The mixture is then prepared by partial pressures and is circulated for 15 minutes to ensure homogeneity.

Results

A sample of the measured flame propagation velocity data is provided in Figure 1. The data provided in Figure 1 was obtained from stoichiometric propane-air for three different blockage ratios and an obstacle spacing of 1TD. The vertical error bars on each curve represent the standard deviation of the average velocity from at least four tests. The speed that is obtained at a tube distance of two meters is close to that of the isobaric speed of sound of the combustion products, which for stoichiometric propane-air is 890 m/s. At this velocity the flame is choked and flame propagation beyond this point would continue at roughly a constant velocity. Flames in the higher blockage ratio tests propagate at a lower terminal speed than in the lower blockage ratio tests because of momentum and heat loses to the orifice plates. The results shown in Figure 1 indicate that initial flame acceleration is more robust for the higher BR plates. The flame acceleration is characterized by the distance L where the flame achieves a velocity of 400 m/s. This flame velocity is roughly half the choking speed and was found to correspond roughly to the inflection point of the flame velocity versus distance curve for all the conditions tested.

Figure 2 shows the normalized flame acceleration distance (L/D) as a function of the blockage ratio for the three obstacle spacings tested. Note as the blockage ratio is increased the distance needed to accelerate to 400 m/s decreases. For the smallest blockage ratio plates (i.e., BR= 0.43), the L/D is similar for the three different orifice plate spacing (i.e., L/D = 8), whereas for the largest blockage ratio (BR= 0.75) the 1 TD obstacle spacing shows augmented acceleration compared to the other two plate spacings. It is clear that increasing the BR results in enhanced flame acceleration for any plate spacing. However, more importantly Figure 2 shows that the influence of plate spacing on flame acceleration is negligible for the lowest BR and more pronounced for the high BR plates. In Figure 3 L/D is plotted for three mixtures (lean, stoichiometric, and rich) at the optimum obstacle spacing of 1TD. As expected the flame acceleration normalized distance is shortest for the stoichiometric mixture, representing the most reactive mixture. More importantly the slope of the L/D versus BR curves for each mixture is roughly the same, implying that the observation made from Figure 2 concerning the effects of plate BR and spacing on flame acceleration holds true for different mixture compositions.

Various correlations have been developed to predict the detonation run-up distance taking into account the BR of the orifice plates and the mixture properties. The following correlation was proposed by Veser et al. (2002) to predict the distance required for the flame to choke.

$$\frac{L_{choke}}{R}\left(\frac{10S_{lam}}{C_p}\right)(\sigma-1)\approx\frac{a(1-BR)}{1+b\cdot BR}$$

where L_{choke} is the measured distance for the flame to achieve 95% of the speed of sound in the combustion products C_p, σ is the gas density ratio across the flame, and S_{lam} is the laminar burning velocity, R is the tube radius and a and b are empirical constants. Figure 4 shows a plot of the stoichiometric mixture data from this study using the Veser correlation where L_{choke} is substituted by L_{400}, the distance for the flame to reach 400 m/s, a and b are taken as 2 and 0.5 respectively. The above correlation is successful in collapsing the data to within +/- 25%. This is similar to what was found for the data reported by Veser et al. (2002). The shortcoming of this correlation is that it does not explicitly include the plate spacing as a parameter, which experimentally was found to be important for large BR plates.

Discussion

In a smooth tube a flame ignited in a fuel-air mixture experiences very little flame acceleration. In an obstacle laden tube each plate is a source of perturbation to the flow ahead of the flame and thus the frequency of this perturbation will impact how fast the flame accelerates. At the limits, where the plate spacing approaches zero or the plate spacing approaches the tube length, the orifice plate-laden tube becomes a smooth tube. For example, as the plate spacing approaches zero the affective smooth-tube diameter approaches the orifice plate inner-diameter and as the plate spacing approaches the tube length the effective tube diameter approaches the tube inner-diameter. At these limits the flame acceleration would be equal to that of a smooth walled tube. As these limits are approached one would expect that the flame acceleration would no longer be influenced by the plate blockage ratio. Based on the results presented in Figure 2 the optimum obstacle spacing is 1TD and deviations from this value, such as 0.5TD and 1.5TD, tend towards this limiting behaviour, i.e., less flame acceleration.

Flame acceleration in the early stages is the result of flame folding. This is counteracted by heat loss from the combustion products to the tube wall and flame area extinction resulting from flame-wall interactions. As shown schematically in Figure 5 the flow field in the unburned gas is dominated by recirculation zones behind each orifice plate. The core flow outside the recirculation zones is characterized by flow expansion *between* the orifice plates and flow contraction *through* the orifice plates. This periodic flow expansion and contraction is responsible for flame area enhancement, or flame folding. The gas in the core flow is separated from the gas in the recirclation zones by a shear layer. The flame does not immediately penetrate the recirculation zone due to severe flame stretch in the shear layer and thus the recirculation zone represents a buffer for the flame from the wall. A similar yet much smaller recirculation zone exists ahead of each orifice plate. Based on these observations one would expect that if the recirculation zone is short compared to plate spacing a portion of the flame would come into contact with the tube wall and flame area would be compromised. If the plate spacing is too small the recirculation zone would extend completely between the plates compromising the core flow expansion and contraction. Therefore, the optimum condition should correspond to the situation where the recirculation zone length is roughly equal to the plate spacing. In order to check this hypothesis the L/D data from Figure 2 is re-plotted in Figure 6 as a function of the ratio of the plate spacing S and the orifice plate height H, or (D-d)/2. The data in Figure 6 indicates that for the lowest BR plates flame acceleration is independent of the S/H. For the larger BR plates the optimum flame acceleration is obtained for a value of S/H between 4 and 5.

Extensive literature exists on nonreactive flow over obstacles, or “fences”, in which the recirculation zone length is reported as a function of flow Reynolds number (Re#). For flow through a single orifice plate the recirculation zone length was found to be about 10 times the orifice plate height and independent of Re# for Re# greater than 1000 (Durst and Wang, 1989). In this study the Re# for the unburned gas flow ahead of the flame is estimated to be well in excess of 1000. For two fences in series Durst and Fonti (1988) showed that the recirculation zone length drops to 5 times the obstacle height since the turbulence generated from the first obstacle effects the flow over the second. Assuming that the value of 5 applies for many obstacles this corroborates the hypothesis that the optimum flame acceleration corresponds to the condition where the recirculation zone length is equal to the plate spacing.

References

Durst and Wang (1989) 7th Intl. Symp. on Shear Flows, Stanford University, pp. 10.4.1-10.4.2, August 21-23, 1989
Durst and Fonti (1988) Transactions of the ASME, Vol 110, pp. 48-54.
Kuznetsov, M., Alekseev, V., Dorofeev, S. (2000) Shock Waves, 10:217-223.
Lee, J.H., Knystautas, R., Chan, C.K. (1984) 20th Symposium on Comb, pp 1663-1672.
Gu, L.S., Knystautas, R., Lee, J.H., ISBN 0-930403-47-9, (1988)
A. Veser, W. Breitung, and S. Dorofeev (2002) “Run-Up Distance to Supersonic Flames in Obstacle-Laden Tubes,” 4th Intl. Symposium on Hazards, Prevention and Mitigation of Industrial Explosions, France, Oct. 2002.

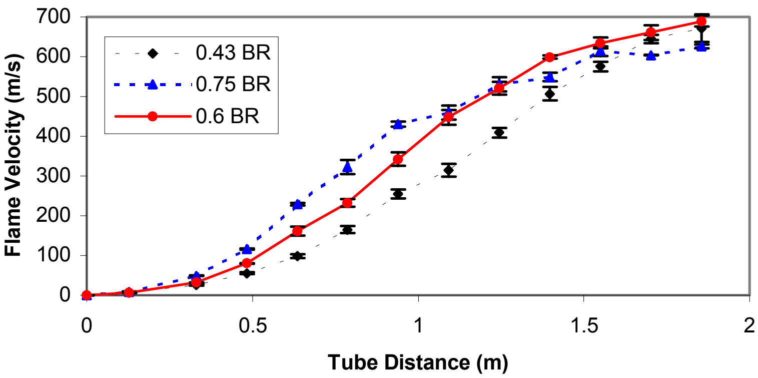

Figure 1. Flame velocity versus tube distance in stoichiometric propane-air at obstacle spacing of 1TD

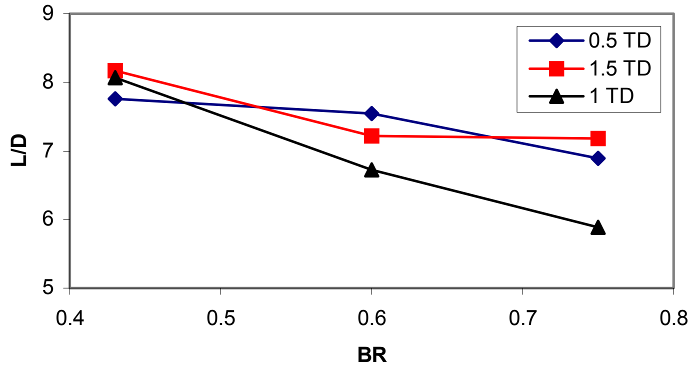

Figure 2. Run-up distance versus blockage ratio for three different obstacle spacings

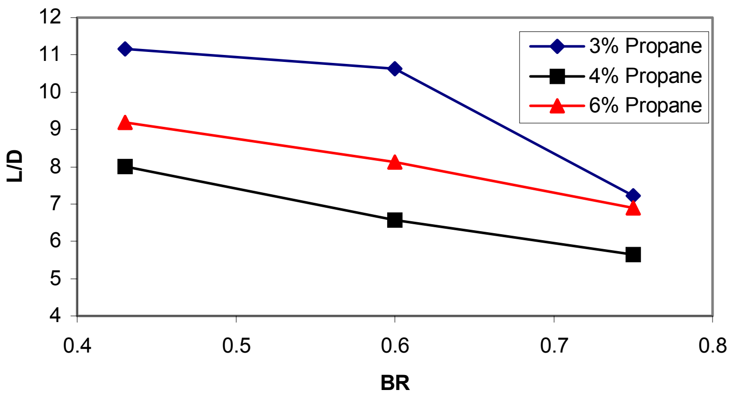

Figure 3. Run-up distance versus blockage ratio for three different equivalent ratios and 1 TD plate spacing

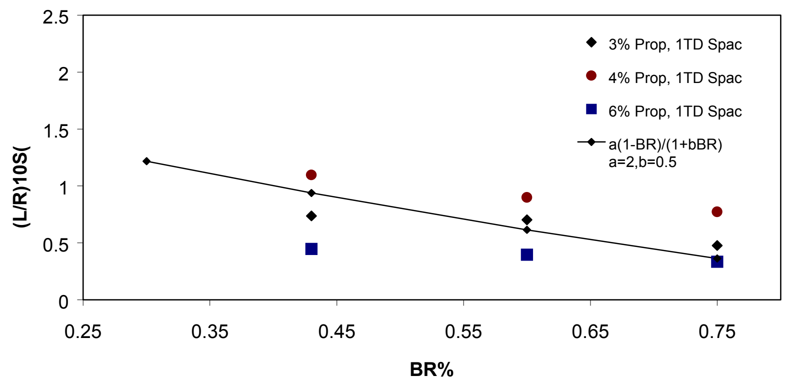

Figure 4. Measured and predicted normalized distance for flame to reach 400 m/s versus BR for three different mixtures with 1 TD plate spacing

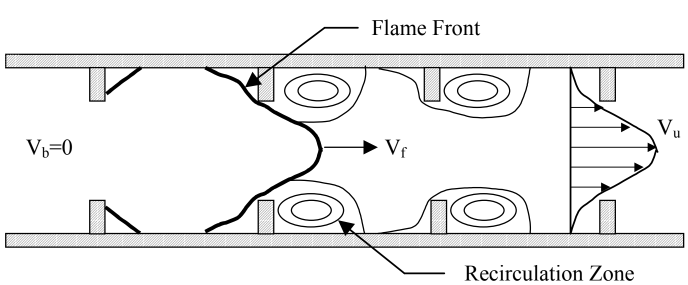

Figure 5. Schematic showing the unburned gas flow field ahead of the flame

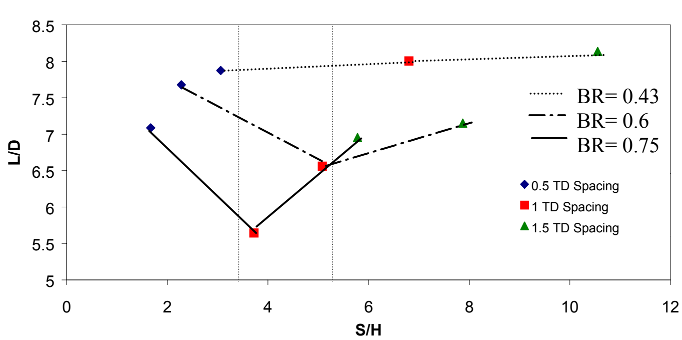

Figure 6. Flame run-up distance showing minimum L/D at S/H = 4