The Stability of High Speed Turbulent Deflagrations in Fuel-Air Mixtures in Obstacle Fields

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INTRODUCTION

In the last twenty-five years, extensive experimental studies[1] have been made on the propagation of high speed turbulent deflagrations through obstacle fields. Although there is a fairly complete qualitative understanding of the phenomenon, the capability to quantitatively predict turbulent flame behaviour is still lacking. The ability to accurately estimate the over-pressures of turbulent flames is crucial in the effort to improve industrial safety in chemical plants and off-shore platforms where accidental fuel-air explosions can occur. Numerous computer codes have been developed to achieve this end;[2] however, they adopt physical sub-models that do not accurately describe turbulent flame propagation controlled by auto-ignition and shock wave interactions.[3] Therefore, more experimental work is needed to understand more clearly the propagation mechanism of high speed turbulent deflagrations in order to obtain more realistic modeling.

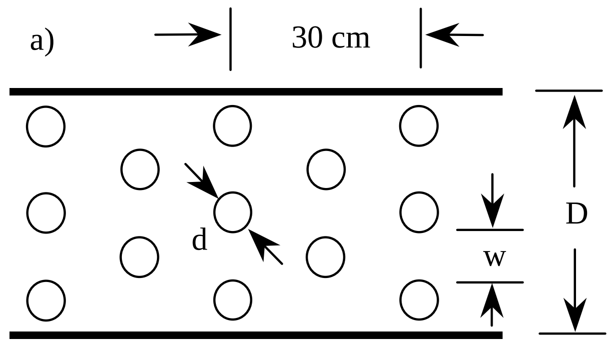
Experimental studies, to date, have been predominantly performed in circular tubes with regularly spaced orifice plates as obstacles. Distinct propagation regimes, based on steady terminal flame velocities over a few tube diameters or obstacle spacing, have been identified for different fuel-air mixtures with various tube diameters and obstacle configurations.[4] Little attention has been paid to local flame speed evaluated over a distance of about one tube diameter due to considerable fluctuations in the shape of the flame. To address this limitation, the present experiments have been performed in a square tube with obstacles of vertical cylindrical rods arranged in a staggered pattern. The dimensions of the obstacles and of the obstacle spacing (half a tube diameter) are smaller than the tube diameter, and the obstacles are evenly distributed across the cross-section of the tube. This arrangement of the cylindrical rods reduces the turbulent length scale in both all directions of the propagating flame. As a result, the flame fronts are more homogenous using the present set-up, and more meaningful local flame speeds at distances of about a tube diameter can be obtained. Local velocity measurements and their fluctuations from mean values will permit a more detailed study of the stability and of the propagation mechanism of high speed turbulent deflagrations and detonations.

EXPERIMENTAL DETAILS

Experiments are performed in a 30 cm x 30 cm square cross section steel tube. It is 7 m long, which corresponds to about 23 tube diameters. Two different sets of obstacles are used, both consisting of cylindrical rods arranged in a 3x2 offset pattern, spaced one tube diameter (30 cm) apart. The cylindrical rods in the larger obstacle array are 3.4 cm in diameter, resulting in an average blockage ratio (BR) of 0.41. The smaller obstacle array (BR=0.19) has cylindrical rods 2.2 cm in diameter.

Mixtures are prepared by the method of partial pressures in the initially evacuated tube. Commercial grades of methane, propane, ethylene, and hydrogen are used. A bellows recirculation pump is used to recirculate the mixture throughout the system for a sufficient amount of time to ensure homogeneity. An electrically fired igniter is used to initiate flames. Flame trajectories are monitored by ionization probes or by photo diodes spaced one tube diameter apart along the length of the tube. The slopes of the flame trajectories at steady state give the global averages of terminal flame speeds. Local flame velocities are calculated between adjacent arrival times.

A driver section was used to ensure that steady terminal flame speeds were achieved in as short a distance as possible. A circular tube 1.1 m with an inner diameter of 15 cm was used as the driver section. Orifice plates (BR=0.44) spanning the entire length of the driver section were used to promote flame acceleration. A thin Mylar diaphragm separates the driver section from the main flame tube, which permits a different mixture to be used in the driver. In general, a stoichiometric hydrogen-air mixture was used in the driver section and is prepared in the same fashion to the fuel-air mixture in the main tube with a separate bellows recirculation pump for mixing. Schematics of the experimental apparatus are shown in Fig. 1.



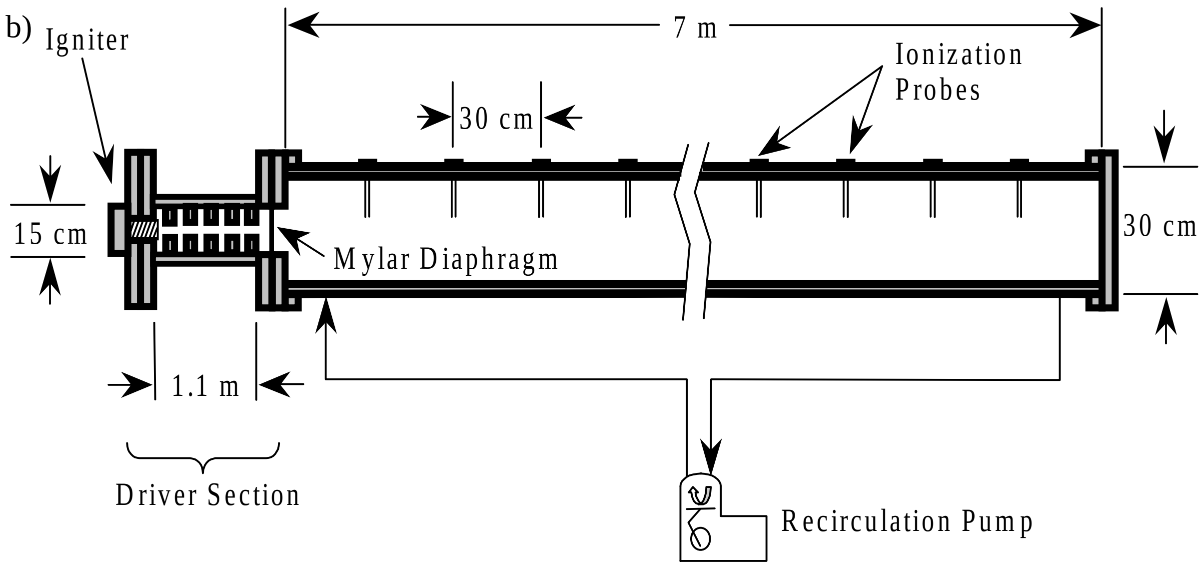


Fig. 1: a) Top view of obstacle configuration; b) Schematic of experimental apparatus.

RESULTS AND DISCUSSION

For very sensitive mixtures where the cell size is small compared to the transverse width between adjacent cylindrical rods (for a ratio of $w/\lambda>1$), a quasi-detonation will propagate at a velocity very close to the Chapman-Jouguet (C-J) detonation velocity with very little fluctuations. A plot of the local velocity along the length of the tube is shown in Fig. 2 for stoichiometric hydrogen-air. The average velocity is close to the C-J value of 2000 m/s with hardly any fluctuations. In this case, the cell size of the mixture (λ=1.5 cm) is much smaller than the transverse width between adjacent obstacles (w=6 cm). The obstacles have very little effect on the

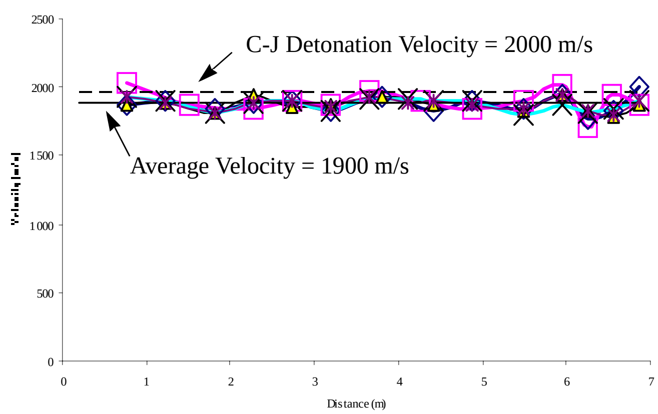


Fig. 2: Velocity vs. distance for hydrogen-air (ϕ=1.0, BR-0.41)

detonation structure. The same behaviour can also be observed for stoichiometric mixtures of ethylene-air (Fig. 3) and propane-air (Fig. 4). The velocities fluctuate very little about average velocities that are near C-J values (about 90% of C-J in both cases). The cell sizes (λ=2.5 cm and λ=5 cm for stoichiometric ethylene-air and stoichiometric propane-air, respectively) are smaller than the transverse width between adjacent cylindrical rods. The ratio w/λ is greater than unity for both mixtures. The propagation mechanism of the quasi-detonations is described by Teodorcyk et al.[5] in photographic studies. As a detonation propagates through the obstacle field, it diffracts and fails. Meanwhile, shocks colliding with the obstacles create hot spots that re-initiate the detonation. The small fluctuations observed in terminal velocities are results of the failure and re-initiation of the detonation as it propagates through the obstacle field.

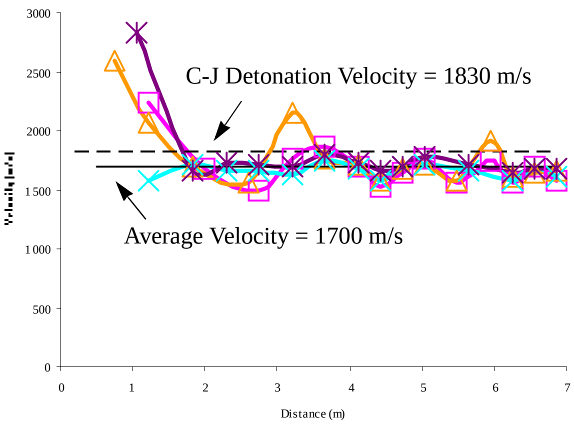


Fig. 3: Velocity vs. distance for ethylene-air (ϕ=1.0, BR=0.41)

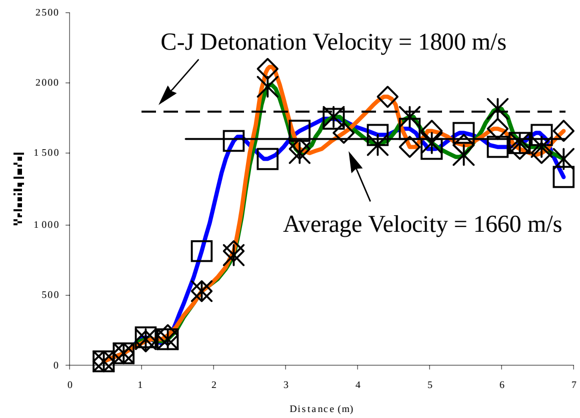


Fig. 4: Velocity vs. distance for propane-air (ϕ=1.0, BR=0.41)

The local velocity for a lean mixture of ethylene-air is shown in Fig. 5. For this mixture, the cell size is as large as the tube itself (for a ratio of D/λ=1). This high speed turbulent deflagration is unstable as it fluctuates significantly about an average velocity of 800 m/s. The obstacles serve to perturb the inner structure of the detonation cell. The combustion front is failing due to diffraction about the obstacles, but since the mixture is so insensitive, the hot spots generated by transverse shocks are insufficient to auto-ignite the mixture. Instead, portions of unreacted gas are trapped behind the combustion front by interacting shocks. These pockets of unburned mixture ignite at a later time, emitting pressure waves that drive the combustion front forward in pulses. In a study done by Makris[6] in porous media, open shutter

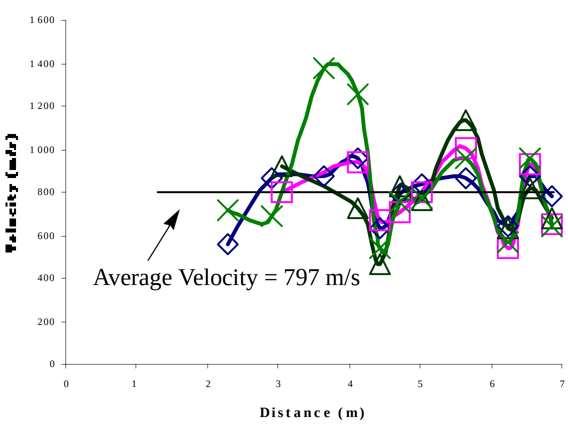


Fig. 5: Velocity vs. distance for ethylene-air (ϕ=0.6, BR=0.41)

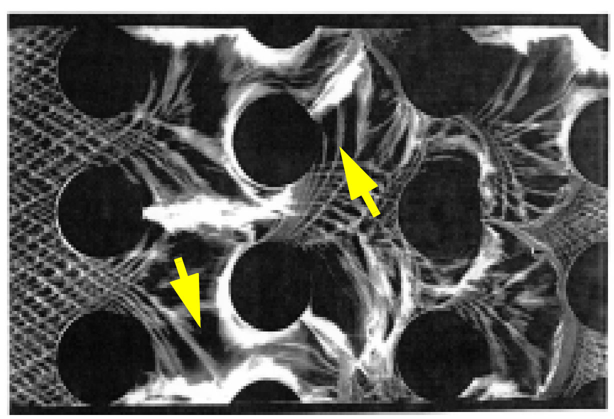


Fig. 6: Open shutter photograph of a detonation propagating through an obstacle field.

photographs of a detonation propagating in an array of staggered cylindrical obstacles show dark regions in their wakes where the characteristic cellular structure of the detonation dissappears (denoted by arrows in Fig. 6). In these regions, the detonation fails due to diffraction around the obstacles, creating pockets of unreacted mixture. Eventually, these quenched regions auto-ignite, which generate pressure waves that are responsible for the observed cyclical pulsation. The same behaviour in fluctuations is observed for all mixtures of hydrogen-air, ethylene-air, and propane-air where the ratio D/λ equals one for both blockage ratios tested in the present study.

When the sensitivity of the mixture is further reduced so that the cell size is greater than the dimension of the tube ($D/\lambda<1$), high speed turbulent deflagrations fail and propagate as slow turbulent deflagrations at 100-200 m/s. In Fig. 7, the average terminal velocity is plotted against equivalence ratio for propane-air and ethylene-air. The transition where there is a sudden jump from high speed turbulent deflagrations to slow turbulent deflagrations is indicated by vertical lines and corresponds to the criteria of $D/\lambda=1$. The high speed turbulent deflagrations just before the transition limits demonstrate large fluctuations in velocity. A similar plot is made for hydrogen-air in Fig. 8.

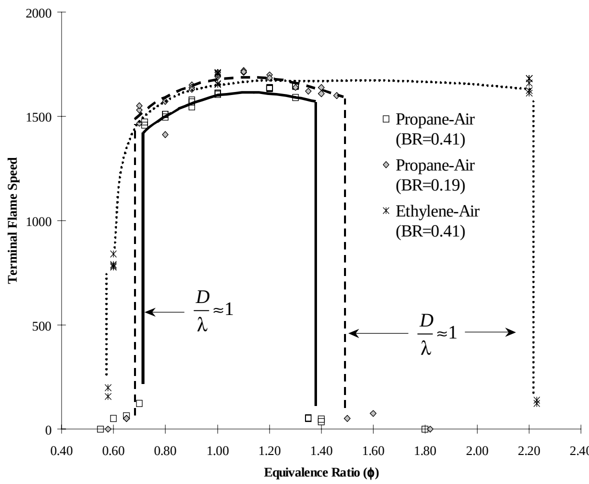


Fig. 7: Average terminal velocities for ethylene-air and propane-air.

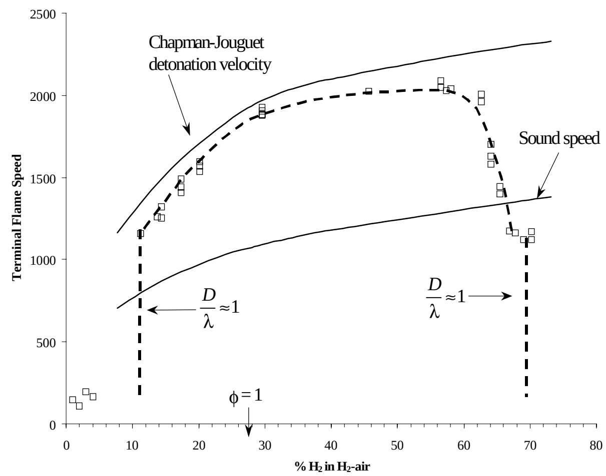


Fig. 8: Average terminal velocities for hydrogen-air.

For a stoichiometric mixture of methane-air, high speed turbulent deflagrations are observed even though $D/\lambda<1$. In Fig. 9, the velocity for stoichiometric methane-air is plotted against the distance along the tube. The high speed turbulent deflagration is unstable as the velocity fluctuates significantly about an average greater than the sound speed of the combustion products. The obstacles artificially sustain high speed turbulent deflagrations by enhancing turbulent mixing and by generating sufficiently strong transverse waves that create hot spots for auto-ignition.

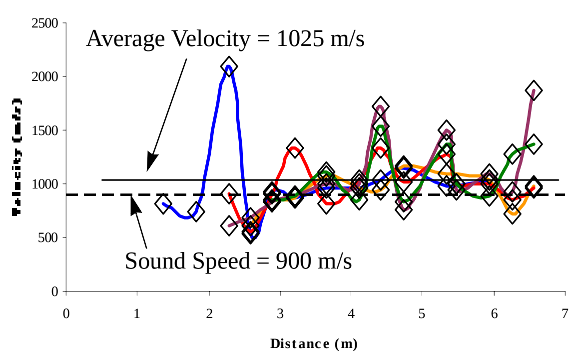


Fig. 9: Velocity vs. Distance for Methane-Air

CONCLUDING REMARKS

Detonations and quasi-detonations have been shown to be fairly stable with very little fluctuations in the propagation velocity. High speed turbulent deflagrations near the limit where $D/\lambda=1$ are unstable with large fluctuations in the propagation velocity. For these combustion waves, the fluctuations are due to the local explosions of quenched zones of unburned mixture that are isolated by colliding shocks. The pressure waves from the explosion of these pockets result in the pulsation of the combustion front. For less sensitive mixtures like stoichiometric methane-air where the cell size is larger than the dimension of the tube diameter, ignition is promoted by sufficiently intense mixing from the obstacle generated turbulence and transverse shocks. Due to the random nature of these auto-explosions regions within the turbulent flame zone, the flame speed behaves in an oscillatory manner. The present study indicates that the propagation mechanisms of high speed turbulent deflagrations are extremely complex, involving auto-ignition of pockets of unburned mixture in the turbulent flame brush.

ACKNOWLEDGMENTS

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