INFLUENCE OF TUBE AND OBSTACLE GEOMETRY ON TURBULENT FLAME ACCELERATION AND DEFLAGRATION TO DETONATION TRANSITION

J. Chao, M. Kolbe, J.H.S. Lee

Department of Mechanical Engineering
McGill University
Montreal, Canada

INTRODUCTION

Since the pioneering work of Laffitte[1], Chapman and Wheeler[2], Shchelkin[3], and Guenoche[4], the study of flame acceleration and the transition from deflagration to detonation in very rough walled or obstacle filled tubes has received considerable attention in the last two decades. Extensive experimental studies of a fundamental nature in both laboratory scale tubes and in large scale field tests more than an order of magnitude larger than laboratory tubes have been carried out. Numerical simulation of the flame acceleration process ranging from empirical computer codes to more sophisticated turbulent flame models have also been performed. It is observed in general that the transient turbulent flame acceleration process is extremely complex, and the experimental results show large local fluctuations even in small scale laboratory experiments with well controlled initial and boundary conditions.

Some universal trends based on circular tubes with circular orifice plates as obstacles, however, have been reported. Extensive experiments with tubes of different diameters and with obstacles of different blockage ratios and spacing have led to the establishment of certain “steady-state” regimes: quenching, weak turbulent flame deflagration, choking, quasi-detonation and Chapman-Jouguet detonation.[5] The quenching regime is of little interest since it corresponds to very large blockage ratios. The flame propagation process for this regime corresponds to the ignition and the combustion of a sequence of interconnected chambers; quenching occurs when the hot turbulent jet of combustion products from one chamber fails to ignite the cold unburned mixture in the neighboring chamber as it vents through. The weak turbulent deflagration regime correspond to off-stoichiometric mixtures where maximum flame speeds of a hundred meters per second are obtained. The pressures generated by such weak turbulent flames are insignificant in terms of structural damages. The flame propagation mechanism can be attributed to the wrinkling of an essentially laminar flame. No universal correlation of the flame speed with mixture composition and boundary conditions has been obtained for this regime. The flame speed in the choking regime appears to correspond closely to the sound speed of the combustion products, which is of the order of 800 m/s for most hydrocarbon-air mixtures. The average pressures developed are of the order of the constant volume combustion pressure of the mixture. The proposed mechanism is one of frictional and thermal choking, and the particular geometry of the tube and obstacles should not play an important role in this regime since the flame speed corresponds closely to the sound speed of the products. Therefore, it is governed by the energetics of the mixtures. The next regime of quasi-detonation also demonstrates some universality governed by the scaling of detonation cell size and dimension of the open area through the obstacle field. It appears that at least choking and quasi-detonation regimes display some universal behaviors that are amenable to scaling and theoretical descriptions.

All existing experimental data for these two regimes are based on circular tubes and round orifice plate obstacles placed one tube diameter apart; it is important, therefore, to investigate the effect of tube geometry and obstacle configuration in these two regimes to confirm their basic mechanisms of propagation. In the present study, a square cross-section tube with a two-dimensional obstacle array of circular tubes is used to investigate the effect of the onset of the choking and the quasi-detonation regime. As well, the dependence of the flame propagation and quasi-detonation speeds on tube geometry and obstacle configuration will also be investigated.

EXPERIMENTAL DETAILS

Previous studies[6] have indicated that large diameter tubes are necessary to realize detonations in the less sensitive fuel-air mixtures (particularly methane-air mixtures where the cell size is very large.) In the present experiment, a 30cm x 30cm (one foot nominal) square cross-section steel tube is used. The length of the tube is 7 meters long, corresponding to about 23 tube diameters. Previous studies in circular tubes have demonstrated that a steady state flame speed can be achieved in about 15 tube diameters, particularly with obstacles of high blockage ratios; therefore, the present apparatus should be adequate for studying all the common hydrocarbon-air mixtures.

The obstacles used are 3.4 cm diameter circular tubes spanning the width of the square tube. The obstacle cylinders are arranged in an alternating 3x2 offset pattern and spaced one tube width (30 cm) apart. The average blockage ratio of the 3x2 obstacle array is 0.41, corresponding closely to the blockage ratio of 0.43 used in the previous study in a 30 cm diameter circular tube.[6] The flame trajectory is monitored by ionization probes spaced one tube diameter apart along the length of the tube. Pressure transducers are also used at times to monitor the pressure development even though the pressure signals are extremely complex to permit much useful information to be obtained other than a global average. The mixture components are determined by the method of partial pressures. A bellows-type recirculation pump is used to recirculate the mixture through the system for an hour to ensure proper mixing. An electrically-fired chemical igniter is used to initiate the flame. Arrival times from ionization probes and pressure signals are recorded on a LeCroy oscilloscope. Commercial grades of the fuel gases (methane and propane) are used. A schematic of the detonation tube and obstacle configuration is shown in Figure 1.

RESULTS

The flame arrival times of stoichiometric methane-air mixtures are plotted along the length of the tube for a number of repeated shots in Figure 2. The flame accelerates rapidly to a steady state velocity of about 1000 m/s in about 6 tube diameters. As can be observed, the reproducibility of the data is extremely good. A plot of the final steady state flame speed for methane-air mixtures at different mixture compositions is given in Figure 3. The previous circular tube data and the sound speed of the product gases based on the adiabatic flame temperature are plotted for comparison. The present results are consistently greater than the corresponding values obtained previously in the circular tube experiment. Flame speeds are observed to be slightly in excess of the sound speed, indicating that these high speed flames may in fact be considered quasi-detonations. The limits whereby high speed deflagrations (or quasi-detonations) are observed are found to be much more narrow than those obtained in the circular tube. Similar results are obtained for propane-air mixtures (Figure 4). Again, the final steady state flame speeds (i.e. quasi-detonations) are found to be higher than those in the circular tube and to be about 10% below corresponding Chapman-Jouguet detonation velocities, which indicates that these high speed deflagrations are of a detonation-like nature. The limits for this regime are found to coincide with those obtained previously in the circular tube.

It is interesting to note that both methane and propane do not appear to have choking regimes for the present obstacle arrangement. Either steady quasi-detonation, low speed turbulent deflagration (with large velocity fluctuations preventing meaningful steady state flame speeds to be obtained), or quenching (where the ionization probes fail to register a signal) is observed. Comparing the present results with those obtained previously with circular orifice plates, it appears that the presence of the obstacles generates transverse shock waves that enhance turbulent mixing and promote detonation-like combustion in the reaction zone. In the previous experiment, the circular orifice plates create a 23 cm diameter unobstructed core along the length of the tube where no mechanism to generate transverse shock waves exists. It may be concluded that the present staggered arrangement of obstacles generates an array of strong transverse shocks that render the propagation mechanism to resemble that of multi-cellular detonation. This is apparent for propane-air mixtures where the obstacle spacing is of the order of the natural transverse wave spacing of the detonation. Hence, the quasi-detonation velocities that are observed are very close to C-J values. For methane-air, where the cell size (λ=32 cm) is much larger, the obstacle spacing is too small in comparison; therefore, the presence of the obstacles can only enhance turbulent mixing, which results in higher flame speeds. Since the dominant mechanism (i.e. the enhanced turbulent mixing due to generated transverse shock waves) is similar to that of a normal detonation, it can be concluded that the phenomenon for methane-air is really one of quasi-detonation with velocities around 1000 m/s.

CONCLUSION

The present results indicate that the staggered obstacle array used in this experiment does have a significant influence on deflagration propagation regimes in an obstacle-filled tube. In both methane-air and propane-air mixtures, quasi-detonation was the only regime observed. The transverse shock waves that are generated by the dense obstacle array play the same role as the natural transverse waves of cellular detonations. This results in more efficient turbulent mixing, and detonation-like high speed combustion waves are promoted. On the basis of the present results, it may be concluded that the propagation of high speed deflagrations and of quasi-detonations appear to be dependent on the obstacle density.

ACKNOWLEDGEMENTS

This work is supported by NSERC Grant # A-3347. The authors would like to acknowledge the assistance of the members of McGill University's Shock Wave Physics Group.

REFERENCES

1. Laffite, M.P. "Chimie Physique sur la Propagation de l'onde explosif". Séance du 16 juillet, 1923.
2. Chapman, W.R., Wheeler, R.V. "The Propagation of Flame in Mixtures of Methane and Air". *Journal of the Chemical Society*, 1926.
3. Shchelkin, K.I. "Effect of Roughness of the Surface in a Tube on Origination and Propagation of Detonation in Gases". *Journal of Experimental and Theoretical Physics (Vol. 10)*, 1946.
4. Guenoche, H., Manson, N. "Influence des Conditions aux Limites Transversales sur la Propagation des Ondes de Choc et de Combustion". *Revue de l'Institut Français du Pétrole No.2*, 1949.
5. Lee, J.H.S. "Fast Flames and Detonations". *The Chemistry of Combustion Processes*, 1984.
6. Peraldi, O., Knystautas R., Lee, J.H.S. "Criterion for Transition to Detonation in Tubes". *21st Symposium (International) on Combustion*, 1986.

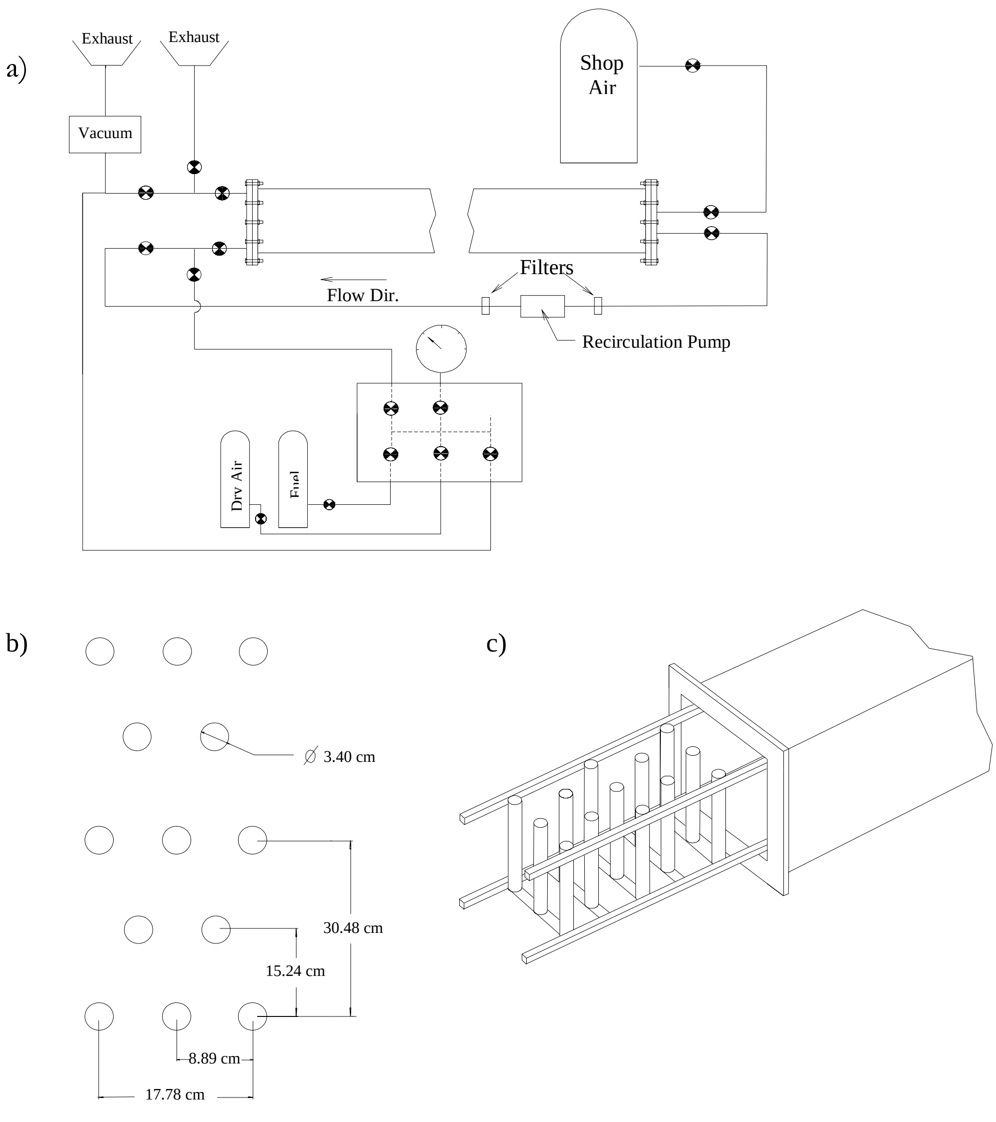

Figure 1: a) schematic of gas handling system b) plan view of obstacle arrangement c) 3-D view of obstacle-tube assembly

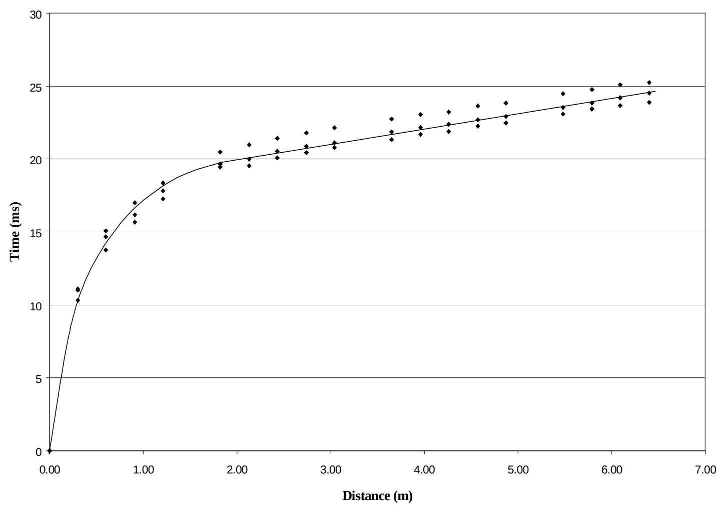

Figure 2: x-t diagram of flame arrival times for stoichiometric methane-air for repeated shots

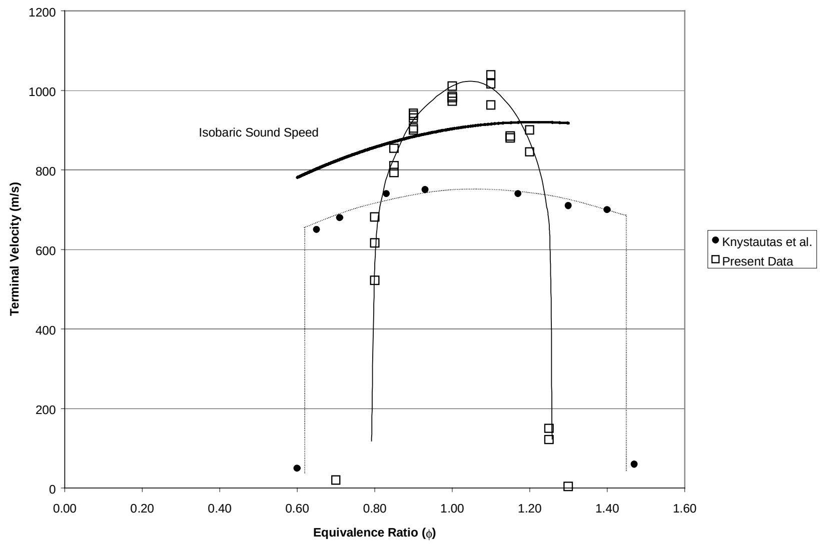

Figure 3: Terminal steady state velocities of methane-air at different equivalence ratios.

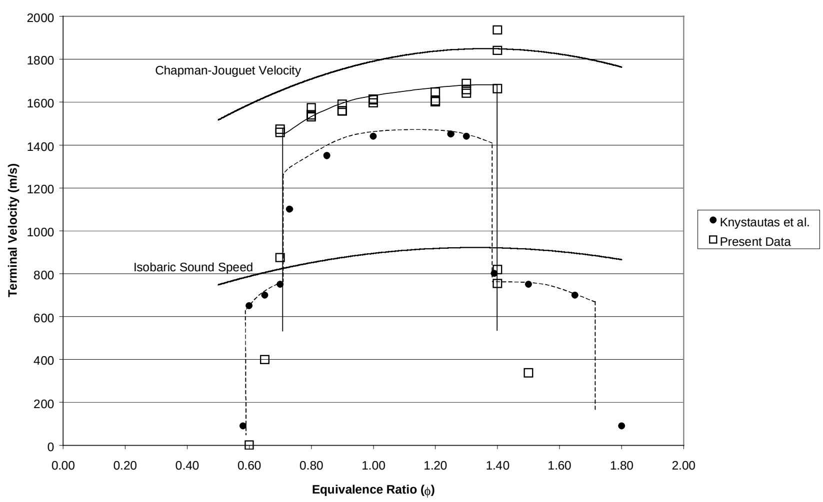

Figure 4: Terminal steady state velocities of propane-air at different equivalence ratios.