Original article

A technique for promoting detonation transmission from a confined tube into larger area for pulse detonation engine applications

Navid Mehrjoo, Rocco Portaro, Hoi Dick Ng*

Department of Mechanical and Industrial Engineering, Concordia University, Montréal, QC, H3G 1M8, Canada

Abstract: A simple method of detonation transmission from a small tube to a large area is presented. This technique involves placing obstacles which create slight blockages at the exit of the confined tube before the planar detonation emerges into the larger space, thereby generating flow instability to promote the detonation transmission. In this experimental study two mixtures of undiluted stoichiometric acetylene-oxygen and acetylene-nitrous oxide are examined. These mixtures can be characterized by a cellular detonation front that is irregular and representative of those potentially used in practical aerospace applications. The blockage ratio imposed by the obstacles is varied systematically to identify the optimal condition under which a significant reduction in critical pressure for transmission can be obtained. A new perturbation configuration for practical use in propulsion and power systems is also introduced and results are in good agreement with those obtained using thin needles as the blockage ratio is kept constant.

Keywords: Combustion; Detonation; Pulse detonation engines; Diffraction; Perturbation; Reactive flow

1. Introduction

Recent focus on the development of detonation-based propulsion systems for high propulsive efficiency such as pulse detonation engines (PDE) [1-6], has led to a renewed interest in the problem of detonation diffraction, i.e., detonation waves propagating from tubes of one size or geometry into another variable cross-section [7-9], especially for the design of tube initiator geometries, e.g., when a detonation transmits from the small pre-detonator to the main thrust tube of the pulse detonation engine [10]. For the successful and steady operation of the PDE, repetitive initiation of detonation waves is required. The pre-detonator tube diameter should be made above a critical value known as the critical tube diameter [11], to ensure successful initiation in the larger detonation or thrust chamber tube and avoid detonation failure during diffraction. The objective of this work is to investigate the effect of hydrodynamic disturbance generated by small blockages on the detonation diffraction problem and propose a new practical design of the injector connecting the small tube section to a larger area, as it can have a beneficial effect for enhancing successful transmission of the detonation from different areas for PDE applications to aerospace propulsion and power systems.

Although no complete predictive theory has yet been developed, the criterion for successful transmission of a self-sustained detonation from a confined tube to an open area is often understood from the description of the failure mechanisms during detonation diffraction. Common hydrocarbon mixtures in which detonations are unstable with highly irregular cellular structures, successful transmission is often found to originate from a localized region in the failure wave, which is eventually amplified to sustain the detonation propagation front in the open area. Hence, failure is invariably linked to the suppression of instabilities at which localized explosion centers are unable to form in the failure wave when it has penetrated the charge axis [12, 13].

The importance of instability for detonation transmission was demonstrated recently by a simple experiment performed by Mehrjoo et al. [14]. This study investigates the effect of finite perturbation generated by placing a small gauge needle that serves as an obstacle with a small blockage ratio (BR = 0.08 defined as the cross-sectional area of the needle divided by the inside cross-sectional area of the confined tube) at the tube exit diameter just before the detonation diffraction, and observing the phenomenon's response. For special mixtures such as highly diluted argon mixtures which are stable with regular cellular patterns, the results using this small needle perturbation seem to exhibit little variation in detonation

*Corresponding author: H.D. Ng, Telephone: 1- (514) 848-2424 (ext. 3177), E-mail: hoing@encs.concordia.ca

Peer review under responsibility of National Laboratory for Aeronautics and Astronautics.

pressure for both perturbed and unperturbed cases. This can be attributed to the minimal effect of the perturbations on global curvature for the emergent detonation wave. However, results show that the small perturbation can have a significant effect in undiluted hydrocarbon mixtures resulting in the decrease of the critical pressure for successful detonation transmission. In other words, the disturbance caused by the small obstacle promotes transmission and this result supports that local hydrodynamic instabilities are significant for detonation diffraction in typical undiluted unstable mixtures considered for detonation-based propulsion systems. Using different needle arrangements at the exit of the confined tube, this study also demonstrates that the perturbation effect is independent of the blockage geometry, and suggests that it is only a function of its imposed blockage area. In other words, as the blockage ratio is kept constant, regardless of its configuration, the resulting perturbations show an almost identical behaviour for wave transmission in irregular mixtures whilst not affecting regular ones.

In this study, the effect of disturbance on the critical tube diameter problem in undiluted stoichiometric acetylene-oxygen and acetylene-nitrous oxide mixtures are investigated. The originality of this work is to systematically observe the effect of different blockage ratios with *BR* varied from 0.05 – 0.25. It is worth noting that the tested mixtures have a detonation instability nature representative to those potentially used in experimental PDE such as hydrogen or ethylene-based mixtures. Intuitively, it is anticipated that large *BR* will have an adverse effect due to excess momentum losses caused by the blockage and reduction of the “effective” tube diameter. Therefore, this work attempts to determine the optimal value of which detonation transmission is favourably promoted. Another novelty of this work is to introduce a different practical perturbation arrangement designed in an attempt to further promote the detonation transmission for PDE application in aerospace propulsion and power generation.

2. Experimental setup

The experiments were carried out in a modified high-pressure spherical explosion chamber of 20.3 cm in diameter and 5.1 cm in wall thickness. The chamber’s body is connected at the top to a 41.8 cm long vertical circular steel tube, of two different test diameters D = 12.7 mm and D = 9.13 mm. Figure 1 shows the schematic of the experimental setup.

Stoichiometric mixtures of acetylene-oxygen or acetylene-nitrous oxide prepared beforehand by the common method of partial pressure in separate gas bottles were tested. For each experiment, the setup was initially evacuated to approximately 100 Pa and then filled through the valve with mixtures at various initial test pressures p_0 by which the mixture sensitivity is varied. The initial pressure was monitored by an Omega pressure transducer (0-30 psi) with an accuracy of ± 0.25 % full scale. The lower pressure range is also checked with a more accurate digital manometer model HHP242-015A (0 to 15 psi) with an accuracy of ± 0.10 % full scale. A high-voltage spark ignition source initiates a planar Chapman-Jouguet (CJ) detonation that propagates through the vertical steel tube and emerges into the large spherical chamber. The procedure used to determine whether the emerging detonation from the confined tube is successfully transmitted into the open space is the same as described in [14-17]. Using the time-of-arrival (TOA) measurement from the piezoelectric shock pin (CA-1136, Dynasen Inc.) located at the bottom of the spherical chamber, it is possible to undoubtedly distinguish between successful detonation transmission or failure from the significant difference in the time scale of the phenomenon. In detail, the time of arrival of successful/unsuccessful detonation transmission measured by the piezoelectric shock pin is compared to the time of ignition in the vertical tube and hence, to deduce the wave velocity. For successful transmission, the wave velocity is typically obtained around 90% CJ detonation velocity. While for an unsuccessful transmission, the velocity of the diverging wave computed using the TOA signal from the shock pin is typically below 25% of the CJ velocity value, e.g., see [15]. In some shots, a photo probe located at the top of the spherical bomb (i.e., near the end of the vertical tube) is also used to record the time of arrival of the wave and check whether a successful detonation is first initiated in the vertical tube from the computed wave velocity. In the present study, the critical condition for each mixture is characterized by the critical pressure below which the detonation fails to emerge into the large spherical chamber.

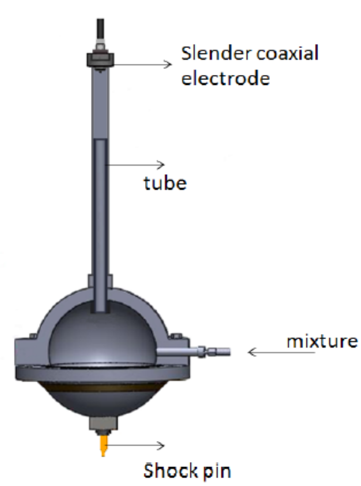
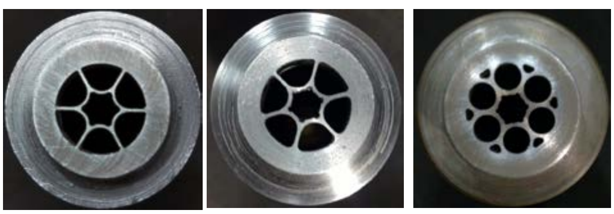


Figure 1 Schematic of the experimental setup

To generate small perturbations and identify the optimal *BR* ratio using which detonation transmission can be promoted from a confined tube into larger space, slender needles of different sizes are inserted at the exit diameter of the vertical tube to vary the blockage ratio *BR* from 0.05 - 0.25. In the second part of the study, a novel perturbation configuration is designed as shown in Fig. 2 instead of using needles as the disturbance generator. The present "injector" is made out of steel cylindrical rod. The design takes into account the manufacturing challenge and durability of the obstacles. This design retains symmetry and for the D = 12.7 mm tube, three blockage ratios of this configuration were studied with BR = 0.095, 0.13 and 0.25. For the smaller tube diameter D = 9.13 mm, the injector with BR = 0.098 was built and tested.



(i) (ii) (iii)

Figure 2 A new perturbation configuration with D = 12.7 mm. i) *BR* = 0.095; ii) 0.13; and iii) 0.25.

3. Results and discussion

For each *BR* ratio considered, initial pressure was incrementally decreased until the critical value below which the detonation wave cannot successfully transmit from the confined circular tube to the open area in the spherical chamber is determined. To ensure statistical convergence and reproducibility of the results, each experiment was repeated 8 times in order to identify accurately the critical pressure value above which successful detonation transmission can occur. In the present analysis, the critical pressure is defined by the upper limit boundary above which at least 75% of tests at the same initial condition gives a successful transmission of the detonation wave into the open space [14]. An example of one set of experimental results is given in Fig. 3, showing the Go/No-go plot (or successful/unsuccessful transmission) as a function of initial pressure with BR = 8%. In these plots, the overlap between the two symbols indicates that there is a mixed result between the 8 experimental shots repeated at that particular initial pressure. Such occurrence near critical conditions can be due to inherent sources of experimental variability and is typical for any detonation experiment. In this study of critical tube diameter, the range of uncertainty is quite minor compared to the measurement of critical energy for direct initiation and detonation cell size.

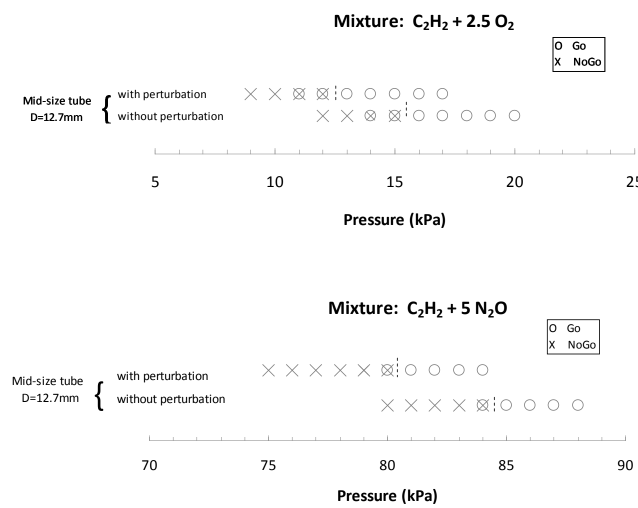


Figure 3 Sample Go/No-go plots as a function of initial pressure

Figure 4 summarizes the measured critical pressure limits for the stoichiometric C_2H_2/O_2 and C_2H_2/N_2O mixtures with needle perturbation of each different tested blockage ratio *BR*. A blockage ratio of zero refers to the unperturbed case. Also shown in each plot is the curve fit obtained using least-square regression. From the results shown in Fig. 4, it is observed that for sufficiently small blockage ratios, the needle obstacles can have a noticeable influence on the critical tube diameter phenomenon by lowering the critical pressure values for successful transmission. The maximum reduction in critical pressure caused from the needle perturbation for both stoichiometric C_2H_2/O_2 and C_2H_2/N_2O mixtures are 3 and 4 kPa, respectively (or equivalently about 18.8% and 4.8% difference where % difference is defined by [100% − (x/y · 100%)] where x and y are the lower and higher number). It is observed that for both mixtures tested that the optimal reduction in critical pressure locates at approximately less than 10% blockage ratio. For very large *BR* (BR > 0.18), excess blockage leads to a negative effect, causing too much of a momentum loss, consequently the emerging detonation front will not promote the detonation transmission in the open space and actually increases the critical pressure dramatically.

An equivalent series of experiments are then performed using the new perturbation configuration. Figure 5 first presents the results for the large diameter tube D = 12.7 mm using the new "injector" configuration with BR = 0.095, 0.13 and 0.25. The plot shows the Go/No-go data and the critical pressure limits. Once again, for each experimental condition (i.e., mixture composition, initial pressure p_o and blockage ratio), the experiment was again performed 8 times to ensure repeatability of the results. It is found that these results are in good agreement with those previously obtained with needles, as is illustrated in Fig. 4. The optimal reduction in critical pressure for successful transmission occurs with the blockage ratio of 9.5% in both tested mixtures. Similarly, the maximum decreases in critical pressure between the perturbed and unperturbed cases are respectively 3 and 4 kPa for the stoichiometric C_2H_2/O_2 and C_2H_2/N_2O mixtures. The present result indeed confirms previous observations which postulate that while maintaining a constant blockage ratio, the effect is shown to be qualitatively independent of the obstacle geometry for the typical irregular hydrocarbon mixtures, whereby all the results with different needle(s) perturbations show similar decrease in critical pressure for successful transmission [14]. Similarly as observed earlier, excess blockage to the flow (e.g., BR = 25%) results in an adverse effect, i.e., causing a significant increase in critical pressure required for detonation transmission.

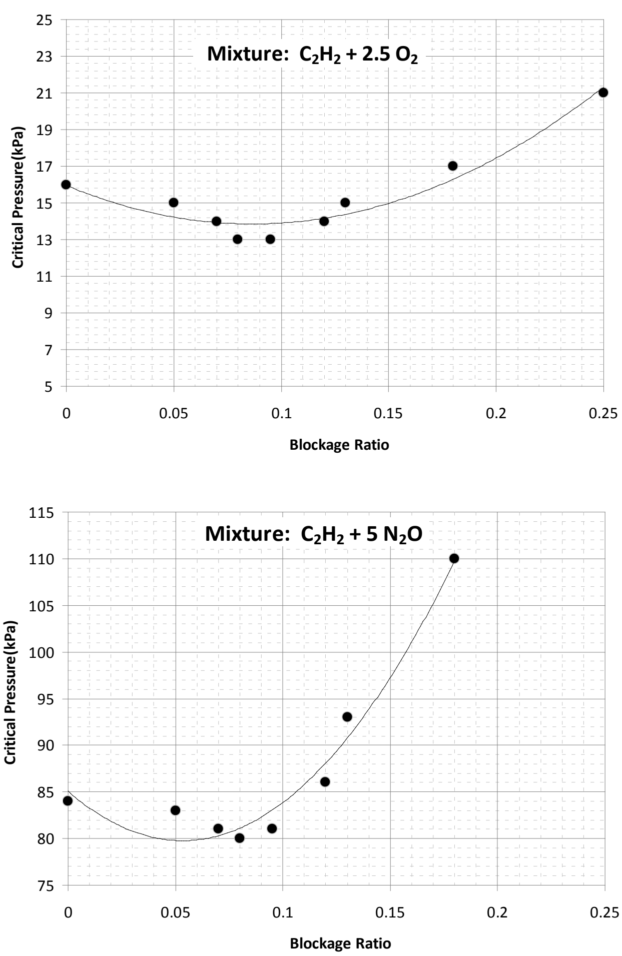


Figure 4 The effect of blockage ratio on the critical pressure for successful transmission.

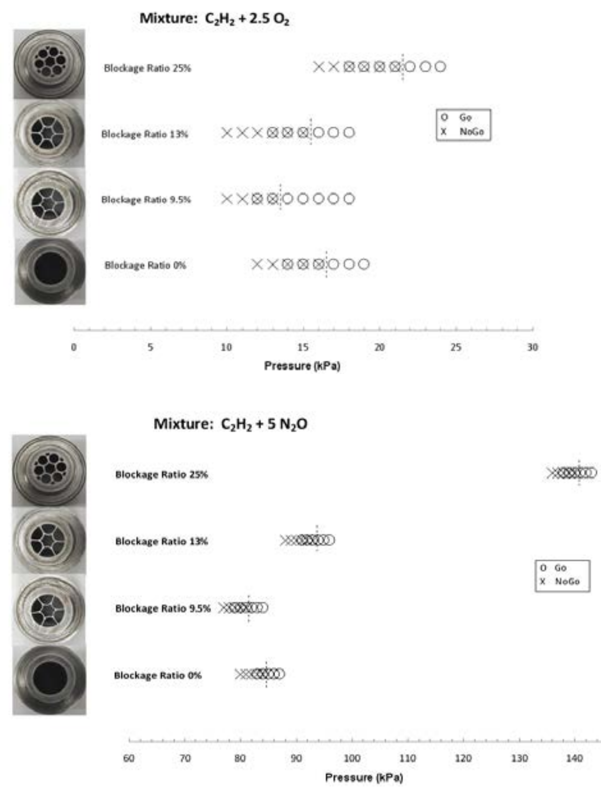


Figure 5 Summary of Go/No-go results for the two combustible mixtures with different BR of the injector and *D* = 12.7 mm

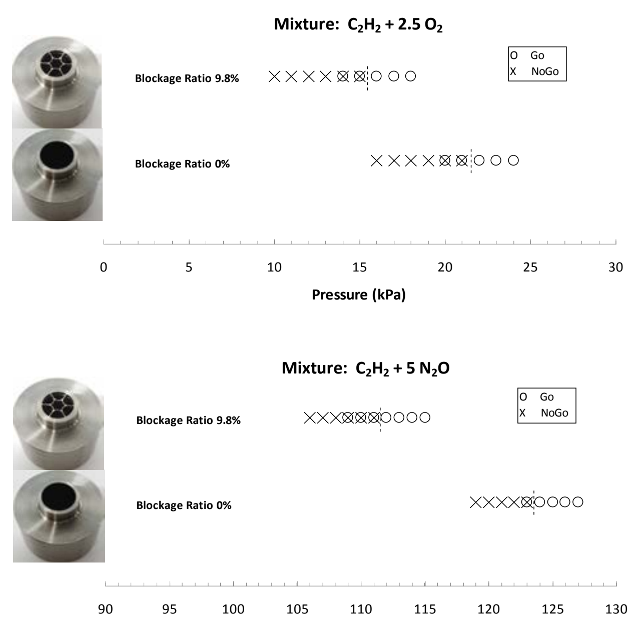


Figure 6 Summary of go/No-go results for the two combustible mixtures with BR = 9.8% and *D* = 9.13 mm

The last set of experiments was performed for the smaller tube diameter *D* = 9.13 mm using the same type of injector configuration. The significant decrease in critical pressures can also be observed but more clearly for this smaller tube diameter with BR = 9.8% as shown in Fig. 6, with a maximum reduction of 6 and 12 kPa (equivalently a difference of 28.6% and 9.8%), respectively for the stoichiometric C_2H_2/O_2 and C_2H_2/N_2O mixtures.

4. Conclusion

In this study, the effect of small perturbations with varying blockage ratio on the critical tube diameter problem are investigated in two unstable mixtures, typically with irregular cellular pattern as found in most hydrocarbon mixtures. Perturbations were introduced using both needle insertion at the exit of the tube before the gaseous detonation emerged into the free unconfined space and as "injectors" machined from steel rod. In all cases, it is found that the optimal blockage ratio is approximately 8 to 10%. Furthermore, the results agree with previous studies that demonstrate the effects of maintaining a constant blockage ratio. Moreover, the effect is shown essentially to be independent of the obstacle (or perturbation) geometry for the irregular mixtures where all the results show similar decrease (or increase with excess blockage) in critical pressure for successful transmission. These results can provide useful insight for practical application to the design of pulse detonation engines for aerospace propulsion and power systems.

Acknowledgements

This work is supported by the Fonds de Recherche du Québec – Nature et Technologies.

References

[1] J.A. Nicholls, H.R. Wilkinson and R.B. Morrison, Intermediate detonation as a thrust-producing mechanism, Journal of Jet Propulsion 27 (1957) 534–541.

[2] S. Eidelman and W. Grossmann, Pulse detonation engine: experimental and theoretical review, 30th AIAA Aerospace Science Meeting, Reno, NV, January 6-9, 1992, AIAA paper No. 92-3168.

[3] T. Bussing and G. Pappas, An introduction to pulse detonation engines, 32nd AIAA Aerospace Science Meeting, Reno, NV, January, 10–13, 1994, AIAA paper No. 94-0263.

[4] K. Kailasanath, Recent developments in the research on pulse detonation engines, AIAA Journal 41 (2) (2003) 145-159.

[5] K. Wang, W. Fan, Y. Yan and L. Jin, Preliminary studies on a small-scale single-tube pulse detonation rocket prototype, International Journal of Turbo and Jet Engines 30 (2) (2013) 145-151.

[6] F.K. Lu, Prospects for detonations in propulsion, Proceedings of the 9th International Symposium on Experimental and Computational Aerothermodynamics of Internal Flows (ISAIF9), Gyeongju, Korea, September 8-11, 2009, Paper No. IL-2.

[7] C.P. Li and K. Kailasanath, Detonation transmission and transition in channels of different sizes, Proceeding of the Combustion Institute, 28 (2000) 603-609.

[8] H.Y. Fan and F.K. Lu, Numerical simulation of detonation processes in a variable cross-section chamber, Proceedings of the Institute of Mechanical Engineer Part G: Journal of Aerospace Engineering 222 (5) (2008) 673-686.

[9] D.I. Baklanov and L.G. Gvozdeva, Nonstationary processes during propagation of detonation waves in channels of variable cross section, High Temperature 33 (6) (1995) 955–958.

[10] G.D. Roy, S.M. Frolov, A.A. Borisov and D.W. Netzer, Pulse detonation propulsion: challenges, current status, and future perspective, Progress in Energy and Combustion Science 30 (2004) 545-672.

[11] J.H. Lee, Dynamic parameters of gaseous detonations, Annual Review of Fluid Mechanics 16 (1984) 311-336.

[12] J.H.S. Lee, On the critical tube diameter, in: J. Bowen (Ed.), Dynamics of Exothermicity, Gordon and Breach, Amsterdam, 1996, pp. 321.

[13] A.A. Vasil'ev, Dynamic parameters of detonation, in: F. Zhang (Ed.), Shock Waves Science and Technology Library, Vol 6: Detonation Dynamics, Springer, Berlin Heidelberg, 2012, Chap. 4.

[14] N. Mehrjoo, B. Zhang, R. Portaro, H.D. Ng and J.H.S. Lee, Response of critical tube diameter phenomenon to small perturbations for gaseous detonations, Shock Waves, 2013, Accepted with minor revision.

[15] B. Zhang, H.D. Ng and J.H.S. Lee, Direct measurement and relationship between critical tube diameter and critical energy for direct detonation initiation, Journal of Loss Prevention in Process Industries, 2013, Available online. (http://dx.doi.org/10.1016/j.jlp.2013.07.011)

[16] B. Zhang, H.D. Ng and J.H.S. Lee, Dynamic detonation parameters in $C_2H_2/N_2O/Ar$ mixtures, Combustion and Flame 159 (9) (2012) 2944-2953.

[17] B. Zhang, N. Mehrjoo, H.D. Ng, J.H.S. Lee, and C.H. Bai, On the dynamic detonation parameters in acetylene-oxygen mixtures with varying amount of argon dilution. Accepted for Combustion and Flame. Nov. 2013.