Propagation of Near-Limit Gaseous Detonations in Rough Walled Tubes

Yiran Yan[1,2], Tianfei Ren[2,3], Huanjuan Zhao[1], John H.S. Lee[2†] and Hoi Dick Ng[4]

[1] State Key Laboratory of Ministry of Education of High-Efficient Mining and Safety of Metal Mines, University of Science and Technology Beijing, Beijing 100083, China

[2] Department of Mechanical Engineering, McGill University, Montreal, QC, H3A 0C3, Canada

[3] State key Laboratory of Explosion Science and Technology, Beijing Institute of Technology, Beijing 100081, China

[4] Department of Mechanical, Industrial and Aerospace Engineering, Concordia University, Montreal, QC, H3G 1M8, Canada

1 Introduction

Detonation limits refer to the conditions outside of which self-sustained propagation of detonation wave is not possible [1]. Experimentally detonation limits can be brought about by too lean or too rich a mixture composition, reduction in the initial pressure, increase in the concentration of an inert diluent, reduction in the tube diameter, and high concentration of a chemical inhibitor. In general, as the limits are approached, the detonation velocity decreases and the unstable cellular structure is driven to lower modes, i.e., from multi-headed to single-headed spinning detonations. Wall roughness has been found to have strong influence on both the propagation velocity as well as the structure of the detonation wave. In obstacle-filled tubes, detonation velocity can be reduced to as low as half the Chapman-Jouguet (CJ) value. Photographic observations also indicate that the detonation structure can be significantly perturbed. Numerous investigations have been carried out in the past few decades on detonation propagation in obstacle-filled tubes, e.g., [2-4]. Usually, the obstacles are in the form of circular orifice plates spaced periodically at about one tube diameter apart along the length of the tube. The orifice diameter as well as the spacing of the orifice plates are of the order of the diameter of the tube itself. Thus, it is difficult to call these orifice plates-filled tubes as rough walled tubes. Indeed, photographic observations indicate that the diffraction of the detonation through the orifice and reflections from the orifice plate and the tube wall of the diffracted front play major roles in the failure and ignition as the detonation propagates past the obstacles. It is appropriate to define rough walled tubes as those whose the dimensions of the wall roughness are small as compared to the tube diameter. In this way, the effect of the wall roughness creates only small perturbations on the detonation and the flow field associated with the detonation front.

In the original study by Laffitte [5], a strip of coarse sand paper inserted into the tube was used to create wall roughness. In the later study by Shchelkin [6], a long length of a spiral coiled wire inserted into the tube provided an easier way to generate wall roughness. The pioneering studies by Laffitte and Shchelkin are perhaps the genuine investigations of detonations propagation in rough walled tubes. Since both Laffitte and Shchelkin were concerned mainly on promoting DDT in rough walled tubes, relatively little information on detonation velocity and structure in rough walled tubes was obtained. The later study by Guénoche [7] contained more data on detonation velocity in tubes with wire spirals. However, Guénoche used only one mixture of $C_2H_2 + O_2$. Brochet [8] was the first to obtain streak schlieren photographs in tubes with spiral

†Correspondence to: john.lee@mcgill.ca

Y.Yan and T.Ren contributed equally and should be regarded as co-first authors coils inserted. He reported the important result that the spiral coil tends to drive the detonation to lower unstable modes. However, Brochet used only mixtures of C_2H_2 + $5O_2$ + $z{\cdot}N_2$ with various nitrogen concentration *z*. Teodorczyk *et al.* [9-11] also obtained framing schlieren photographs of detonations in $2H_2$ + O_2 mixture in a two-dimensional equivalent of a spiral coil in a channel. Some recent studies on detonation limits in rough walled tubes were also carried out, e.g., Starr *et al.* [12]; Zhang [13]. In the present paper, extensive information on detonation limits in rough walled tubes are reported. A variety of explosive mixtures, tube diameter as well as spiral parameters are used.

2 Experimental details

A schematic diagram of the arrangement of the experimental apparatus is drawn in Fig. 1. Three experimental setups with different scales were used. The first apparatus consists of 3 different inner diameter *D* brass tubes, each 1.5-m long. The driver section has D = 25.4 mm and 38 mm, and the test section has D = 50.8 mm. The second is made by three 1.5-m-long, 25.4-mm diameter polycarbonate tubes. The third is made by a 1.2-m-long steel tube as the driver section and a 1.8-m-long polycarbonate tube as the test section, the tube diameter of the driver section and test section is 76.2 mm. In all tubes, a Shchelkin spiral was put near the ignitor to facilitate detonation formation.

Pre-mixed mixtures of C_2H_2 + O_2, C_2H_2 + $2.5O_2$, C_2H_2 + $2.5O_2$ + 70%Ar and $2H_2$ + O_2 were used. However, not all the mixtures were studied in the different diameter tubes and spiral parameters so to reduce the number of experiments. The spirals are made with wire diameter of 1 mm, 2 mm, 3 mm for the 25.4-mm-diameter diameter tube, 1.5 mm, 3 mm, 6.2 mm and 9 mm for the 50.8-mm-diameter tube, 9 mm and 11 mm for 76.2-mm-diameter tube. The pitch of the spring is double of the wire diameter of each spring. For the less sensitive mixtures (e.g., $2H_2$ + O_2), detonation initiation may require the use of a driver section where a small slug of more sensitive C_2H_2+ O_2 mixture is used. Velocity measurements are carried out using optical fibers spaced at regular intervals along terminating at a photodiode (IF-950C). From the time-of-arrival data, detonation trajectories are obtained from which the averaged detonation velocity can be determined from the slope of the trajectory. The detonation cellular structure is recorded on a rectangular strip of glass plate inserted across the diameter of the tube where the cell size is large. When the glass plate starts to have an influence on the cellular structure, a smoked Mylar foil inserted into the tube is used.

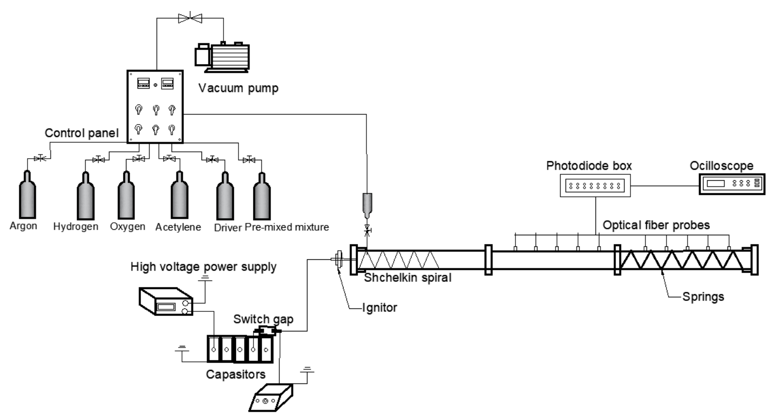
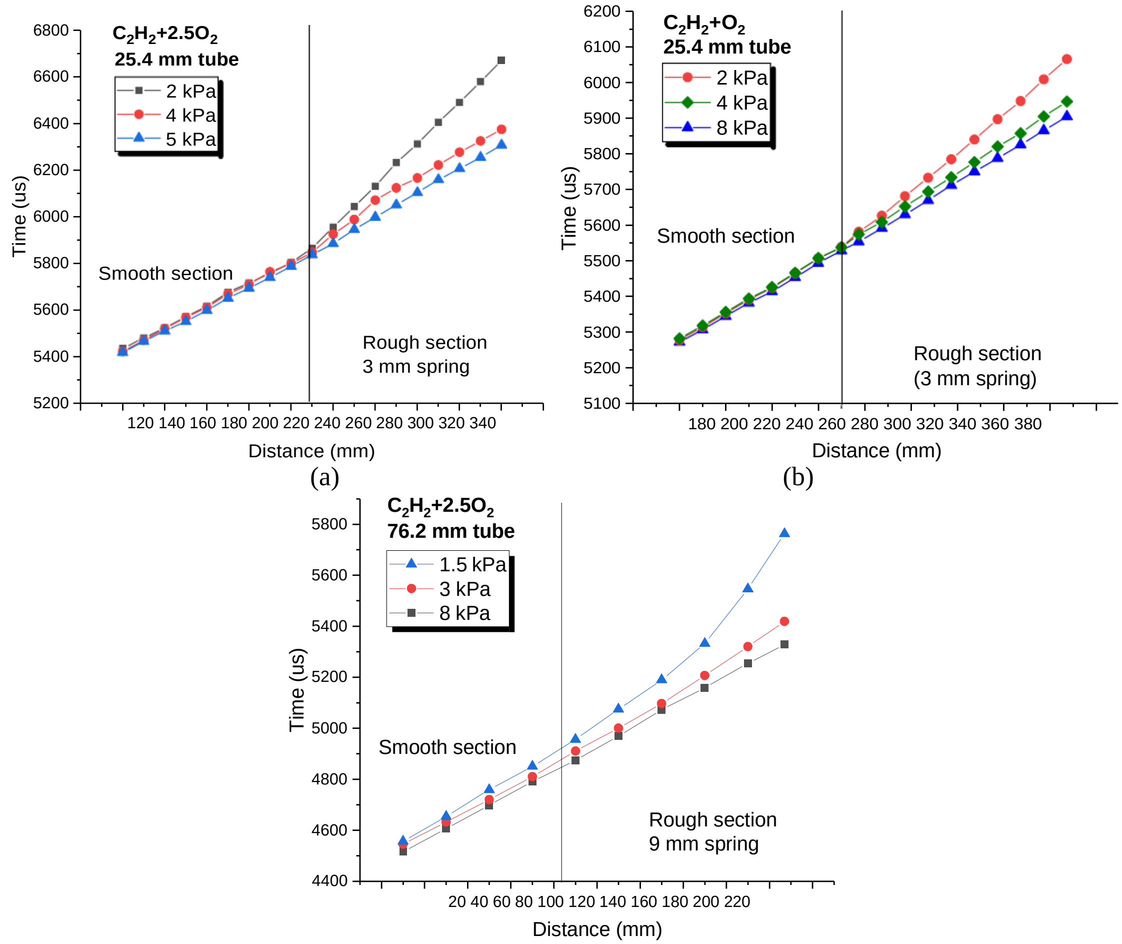


Figure 1. Sketch of the apparatus

3 Results and discussion

From the time-of-arrival data measured by the photo probes, the detonation wave trajectory can be plotted from which the averaged detonation velocity can be determined from the slope of the trajectory.

Figure 2 shows typical trajectories for C_2H_2+ 2.5O_2 in a 25.4-mm-diameter, C_2H_2+ O_2 in 25.4-mm-diameter tube, and C_2H_2+ 2.5O_2 in 76.2-mm-diameter tube, see Fig. 2 (a), (b) and (c) respectively. The vertical dotted line defines separation between the initial smooth section of the tube from the rough section where the wire spiral coil is inserted. The slope of the trajectory can be obtained to determine the averaged propagation velocity of the detonation in both the initial smooth section and in the rough section downstream with the spiral coil. The change in the slope of the trajectory indicates the decrease in the detonation velocity in the rough section. For decreasing initial pressures, the velocity deficit in the rough section increases. For high initial pressures (hence more detonable mixtures), the velocity in the rough section is found to be constant. However, for lower initial pressure, as shown in Fig. 2 (c), the detonation velocity is seen to decay as it propagates along the rough section (e.g., P_0 = 1.5 kPa).



(c)

Figure 2. Trajectories for (a) C_2H_2 + 2.5O_2 in a 25.4-mm-diameter; (b) C_2H_2+ O_2 in 25.4-mm-diameter tube; (c) C_2H_2 + 2.5O_2 in 76.2-mm-diameter tube.

From the trajectories, the detonation velocities in both the initial and the rough section downstream can be determined. Figures 3 (a), (b) and (c) show the cases of C_2H_2 + 2.5O_2 in the three tubes 25.4 mm, 50.8 mm and 76.2 mm diameter. For high initial pressures the velocity deficits are small, typically of the order of 90%V_{CJ} in the smooth section of the tube. For increasing roughness (i.e., larger wire diameter of the spiral), the velocity deficits are larger. Similarly, the velocity of C_2H_2+ 2.5O_2+ 70%Ar in 50.8-mm-diameter is shown in Fig. 3 (d). Generally, the decrease in detonation velocity with decreasing initial pressure is relatively small until near the limits when the velocity gets a rapid drop. The near limit velocity is also not steady and a large variation is observed in different experiments.

The local detonation velocity can be determined from the time interval between two photo probes. Thus, the velocity fluctuation $\delta = (V_l - V_m)/V_m$ where V_l is the local detonation velocity and V_m the average velocity over the length of propagation of the detonation along the tube. Figure 4 shows the variation of the velocity fluctuation δ with initial pressures in the different tubes and different spiral parameters (wire diameter). At high initial pressures, the velocity fluctuations are relatively small but increase as the initial pressure is decreased towards the limits. In the pressure range of the limits, the velocity fluctuations increase rapidly. This behavior is in accord with velocity results of Fig. 3 where as the limits are approached large variations in the mean velocity is observed. The use of velocity fluctuations to define detonation limits was first proposed by Manson *et al.* [14]. He recognized the unstable nature of the detonation as the limits are approached and set an arbitrary value of the velocity fluctuation of $\delta < 0.004$ (i.e., 0.4%) as the maximum allowable deviation from the mean for stable detonations. Manson's contribution is too restrictive and would exclude spinning detonations even though these propagate at a relatively steady velocity. Hence, Manson only considers stable detonations with velocity very close to the CJ value to be within the limits.

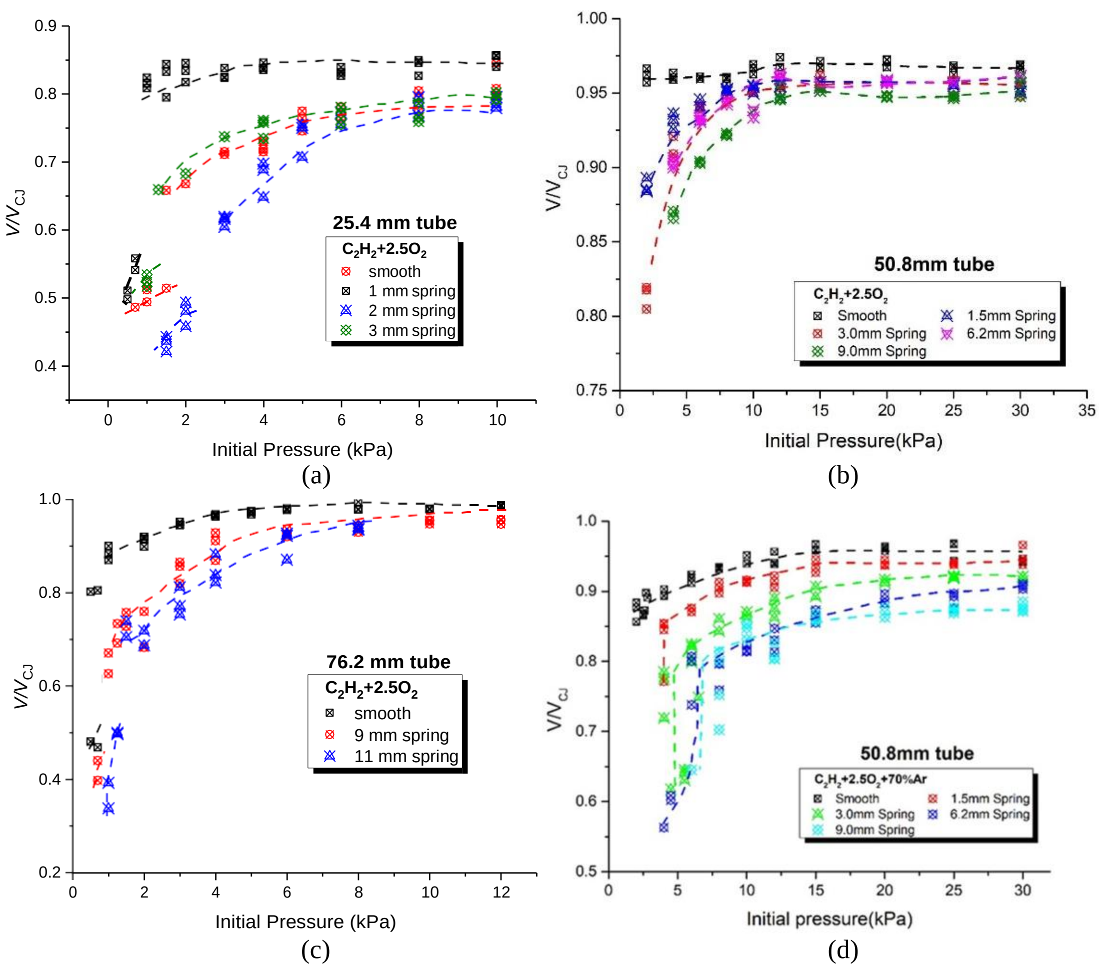


Figure 3. The normalized velocity of $C_2H_2 + 2.5O_2$ in (a) 25.4-mm-diameter tube; (b) 50.8-mm-diameter tube; (c) 76.2-mm-diameter tube; (d) the normalized velocity of $C_2H_2 + 2.5O_2 + 70\%Ar$ in 50.8-mm-diameter tube.

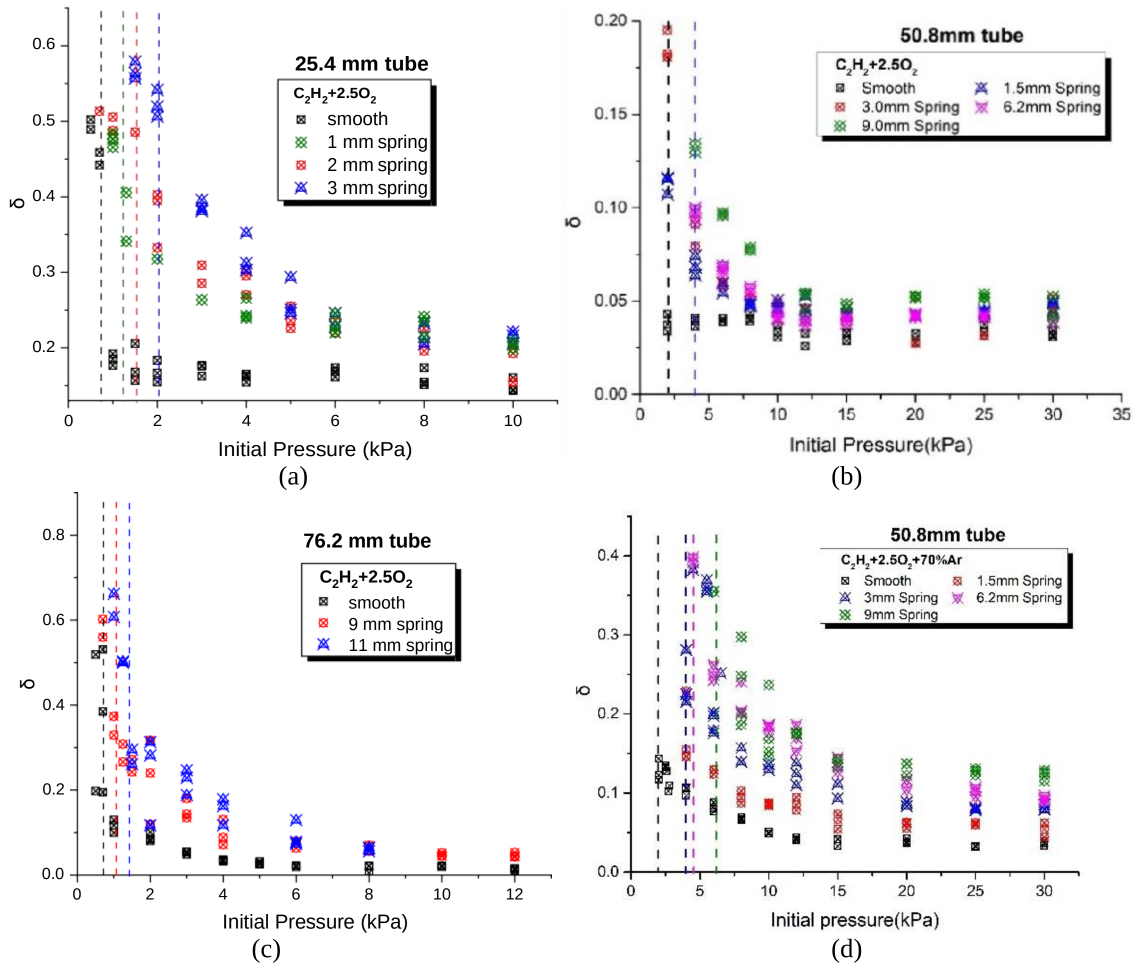


Figure 4. Velocity fluctuation as a function of initial pressure and spring diameters for C_2H_2 + $2.5O_2$ in (a) 25.4-mm- diameter tube; (b) 50.8-mm-diameter tube; and (c) 76.2-mm-diameter tube; (d) C_2H_2 + $2.5O_2$ + 70%Ar in 50.8-mm- diameter tube.

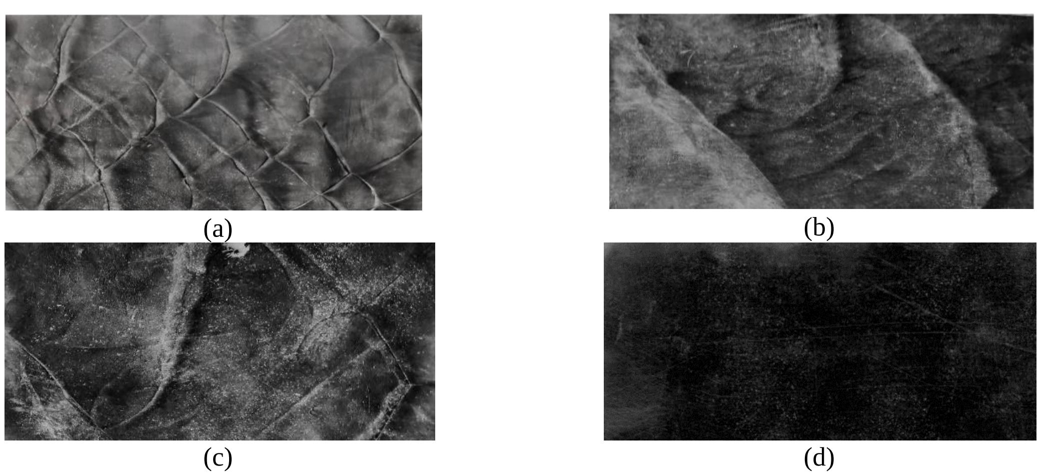


Figure 5. Smoked foils for $2H_2$ + O_2 with 6.2 mm spring in 50.8-mm-diameter tube (a) P_0 = 12 kPa; (b) P_0 = 11 kPa; (c) P_0 = 10 kPa; (d) P_0 = 9.8 kPa.

In the study by Brochet [8] and also in the paper by Manson *et al.* [14] streak schlieren photographs were used to observe detonations in a tube with a spiral coil inserted. The streak schlieren photographs revealed a strong influence on the structure of the detonation, particularly the spiral coil causes the cellular detonation to go to lower unstable modes. Past the lowest unstable mode of single-headed spinning detonation, no structure was observed even though periodic pressure fluctuations due to the interaction with the spiral coil can be identified. In this study, smoked foils were used to record the cellular structure. Figure 5 shows typical smoked foil records of detonations in $2H_2 + O_2$ in a spiral coil of 3.0 mm wire diameter. The pressure decreases from 12 kPa to 9.8 kPa. At P_0 = 10 kPa, multi-headed cellular structure is recorded which goes to single-headed spin wave, see Fig. 5 (c). At P_0 = 9.8 kPa, further reduction in the initial pressure suppresses all unstable cellular structure and nothing is registered on the smoked foil as shown in Fig. 5 (d).

4 Concluding remarks

Numerous studies in the past focused on the use of repeated orifice plates as obstacles. It was found that local reflection and diffraction of the detonation front past the orifice plates dominate the failure and re-initiation mechanisms. The present study employs spiral coil with wire diameter small as compared to the tube diameter. It is hoped that these tubes with spiral coil inserts can simulate a more genuine rough walled tube in contrast with the repeated orifice plates-filled tubes. Indeed, the present results are found to differ from those using repeated orifice plates. Of particular importance in the present study is the demonstration that wall roughness tends to drive the cellular detonations towards more fundamental lower modes. When limits occur, it is found that the detonation is devoid of cellular structure. Thus, this indicates that the development of cellular structure is essential to the self-sustaining propagation of detonation waves. Previous speculation of the role of obstacles to generate turbulence to sustain the propagation of detonations appear to be unsubstantiated. Whether in smooth or rough wall tubes, the ability of the detonation front to develop cellular instability is paramount to self-sustained propagation of detonations.

Acknowledgement

This work is supported by the Natural Sciences & Engineering Research Council of Canada (NSERC). T. Ren is funded by the International Graduate Exchange Program of Beijing Institute of Technology. Y. Yan is grateful for the financial support by the China Scholarship Council (CSC).

References

[1] Lee, J. (2008). *The Detonation Phenomenon*. Cambridge: Cambridge University Press.
[2] Gu LS, Knystautas R, Lee JHS. (1988) *Prog. Astronaut. Aeronaut.* 104: 230-247.
[3] Ciccarelli G, Cross M. (2016) *Shock Waves* 26: 587-597.
[4] Ciccarelli G, Wang Z, Lu J, Cross M. (2017) *J. Loss Prev. Process Ind.* 49: 739-744.
[5] Laffitte P. (1923) *C. R. Acad. Sci*. 176: 1392-1394.
[6] Shchelkin KI. (1940) *Zh. Eksp. Teor. Fiz.* 10: 823-827.
[7] Guénoche H. (1949) *Rev. Inst. Français Pétrole* 4: 48-69.
[8] Brochet C. (1966) *Contribution à l'Etude des Détonations Instable dans les Mélanges Gazeux*. PhD thesis, University of Poitiers, France.
[9] Teodorczyk A, Lee JHS. (1995) *Shock Waves* 4: 225-236.
[10] Teodorczyk A, Lee JHS, Knystautas R. (1988) *Proc. 22nd Symp. (Int.) on Combustion* pp. 1723-1731.
[11] Teodorczyk A, Lee JHS, Knystautas R. (1991) *Prog. Astronaut. Aeronaut.* 133: 223-240.
[12] Starr A, Lee JHS, Ng HD. (2015) *Proc. Combust. Inst.* 35(2): 1989-1996.
[13] Zhang B. (2016) *Combust. Flame* 169: 333-339.
[14] Manson N, Brochet CH, Brossard J, Pujol Y. (1963) *Proc. 9th Symp. (Int.) on Combustion* pp. 461-469.