Experimental study of hydrogen detonations in coaxial channels

Alexandre POYET, Hiroaki WATANABE, Vincent RODRIGUEZ, Ashwin CHINNAYYA

Institut Pprime, UPR 3346 CNRS, ISAE-ENSMA, Université de Poitiers
BP 40109, 86961 Futuroscope-Chasseneuil, France

1 Introduction

Hydrogen has been deemed an ideal candidate for the energy industry, for it appears to be a cleaner energy source that what is currently used. Hydrogen detonations have long been studied.

Nonetheless, hydrogen detonations have not been extensively studied in complex geometric-shaped channels. Although a lot of works have been done in the past using square channels and tubes, little work has been done using the coaxial channel, comparatively. In the latter case, a quasi two-dimensional geometry can be realized and side-effects can be avoided [1]. The present study aims to put into perspective the impact of the coaxial channel width w on the propagation of non-ideal detonations.

Marginal detonations can occur for multiple reasons, be it a low initial pressure, the addition of non-reactive to the mixture or by being too lean or rich. These detonations occur near the limit of the propagation of detonation, where different behaviors such as spinning, stuttering, and galloping have been observed [2]. However, there is currently no general theory for predicting the limits with general validity, which are specific to the studied geometry. For this reason, the limits of detonation have not been extensively studied in the coaxial channel.

Only one group has conducted numerical studies on this geometrical configuration [3], along with a limited number of experimental studies (Chao et al. [1], Gao et al. [4]), echoing the oldest of Voitsekhovskii et al. [5]. Chao et al. [1] showed that the generalized ZND solution was consistent with the experimental results for regular mixtures. Zhang et al. [6] highlighted that the typical criterion for detonation limit (the condition at which the cell width is equal to the perimeter of a channel) was inadequate for coaxial channels, particularly for the narrower widths. Tsuboi et al. [3] observed the occurrence of two-headed spinning detonation with the presence of an insert, whereas a single-headed spinning detonation was obtained in a circular tube, thereby confirming the findings of Voitsekhovskii et al. [5].

Section 2 presents the experimental apparatus. Section 3 presents the experimental results, with velocity deficits and soot foils in the marginal case. Last section summarizes the conclusions and perspectives.

2   Experimental methodology and setup

Figure 1 shows the experimental setup. It consists of three parts, the booster, the tube, and the test section. The booster, the tube and the test section are $1\,\text{m}$, $3.5\,\text{m}$, and $1\,\text{m}$, respectively. All are round tubes with the same inner diameter of $52\,\text{mm}$. The test section consists of two coaxial tubes forming an annular channel, of hydraulic radius $R_2 - R_1$, with R_1 the internal radius of the tube and R_2 the outer radius of the insert, corresponding to the width of the channel, and will be referred as w. The inner tube has an outer diameter between 20 and $40\,\text{mm}$ and is $2\,\text{m}$ long. Six shock pins and four pressure sensors are located in the last meter of the test section. The booster is a section where a gas will reach a high pressure thanks to a DDT. The pressure wave then breaks a diaphragm and a shock wave propagates in the test section. The gas used in the booster was $C_2H_4 + 3\,O_2$ at ambient temperature, with an initial pressure ranging from $10\,\text{kPa}$ to $50\,\text{kPa}$. A spark ignites the reactive mixture in the booster and a Shchelkin spiral is placed in the booster to accelerate the transition to steady detonation. The mixture in the test section was $2\,H_2 + O_2$ at an initial pressure ranging from 4 to $20\,\text{kPa}$.
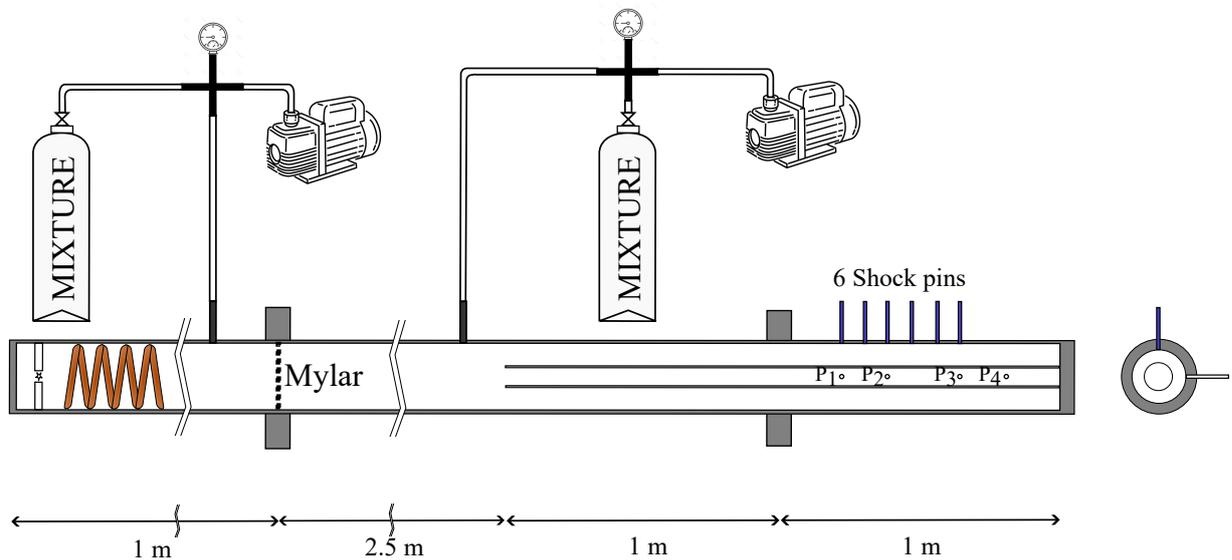

Figure 1: Schematic diagram of the experimental set-up. The distance between the shock pins is $8\,\text{cm}$. Distance between P1-P2 and P3-P4 is $16\,\text{cm}$, and P2-P3 is $24\,\text{cm}$.

Kistler 603B piezoelectric pressure transducers plugged into Kistler 5018A charge amplifiers are used to record the pressure signal. A National Instrument acquisition card is used to record the shock pins signals. Moreover, smoked foils are used to record the cellular structure of the detonation.

3   Experimental results

3.1   Detonation propagation in coaxial channels for $2\,H_2 + O_2$ mixture

In Fay [7] and following Chao et al. [1], boundary layers act as a sink by removing the mass from the flow, resulting in a flow divergence and a negative boundary layer displacement thickness δ^*. In the case of our study, two geometries were studied. The first geometry was that of the tube, with an area of $A = \pi(R + \delta^*)^2$ Then, one can easily show that:

$$\frac{d\ln A}{dx} = \frac{2}{R + \delta^*}\frac{d\delta^*(x)}{dx} \tag{1}$$

The coaxial channel is made of two concentric cylinders, where the inner diameter of the bigger cylinder is noted R_1, and the external diameter of the smaller diameter R_2. The area is then $A = \pi(R_1 + R_2)(R_1 - R_2 + 2\delta^*)$, which translates to

$$\frac{d \ln A}{dx} = \frac{2}{w + 2\delta^*} \frac{d\delta^*(x)}{dx}, \text{ with } w = R_1 - R_2 \tag{2}$$

As one can observe, the boundary layer losses of the coaxial channel are only dependent on the gap of the channel, which means that it is possible to compare results from different studies using this geometrical parameter, regardless of the radius of the tube. In addition, if we assume that the annular gap is significantly bigger than δ^*, it is possible to compare experimental data between tubes and coaxial channels with a consequent gap, as $R \simeq w$ and $\delta^* \ll w$.

The boundary layer displacement thickness relation used in our study is the turbulent version proposed by Gooderum [8]:

$$\delta^*(x) = 0.22x^{0.8} \left(\frac{\mu_e}{\rho_0 D}\right)^{0.2} \tag{3}$$

where μ_e is the viscosity, estimated in the post-shock state, ρ_0 the initial density ahead of the leading shock. The ZND model was built on the previous work of Veiga-López et al. [9], with the San Diego kinetic mechanism [10], and an initial temperature of $300\,\text{K}$.
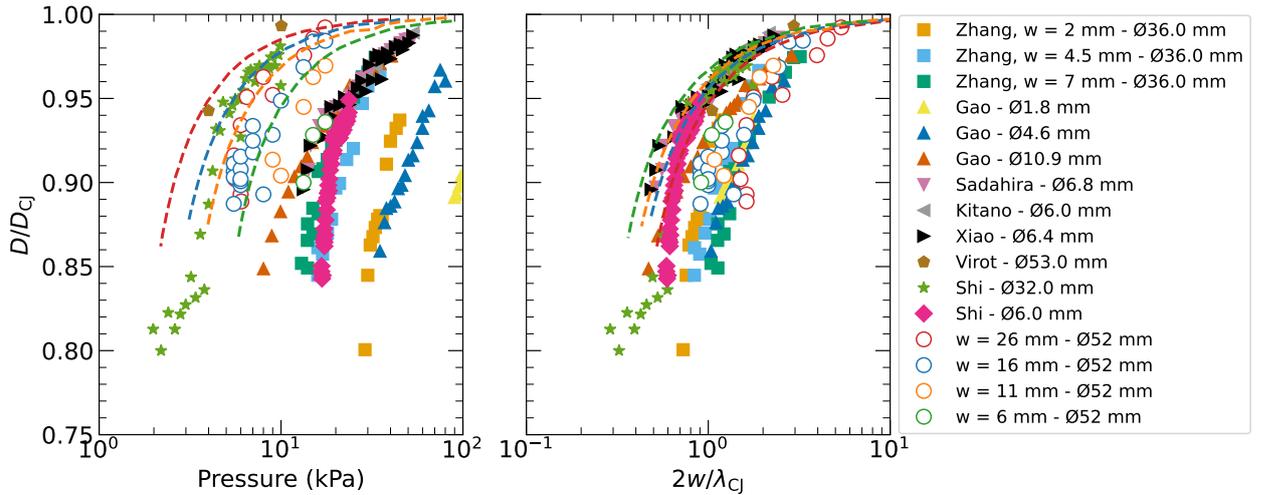

Figure 2: Velocity deficit as a function of initial pressure P_0, for the stoichiometric mixture $2\,\text{H}_2 + \text{O}_2$. Black empty markers are our experiments, for various coaxial channel widths. Coaxial results of Zhang et al. [11] are presented in orange, blue and green. For comparison with literature, narrow channel data from Gao et al. [14], Sadahira et al. [15], Kitano et al. [16], Xiao et al. [17] and Shi et al. [18] are presented, as well as data in tubes from Virot [19] and Shi et al.

Figure 2-left plots the velocity deficit as a function of the initial pressure for different hydraulic radii w. Our data (empty circles) were obtained without the use of a booster, and as such we are confident our velocity obtained are not for overdriven detonation. As the diameter of the tube increases, the velocity deficit for the same pressure is less important. Indeed, when we compare the results of Virot in a tube with a diameter of $53\,\text{mm}$, and Gao et al. in a narrow channel of diameter $10.9\,\text{mm}$, the velocity deficit for Gao et al. is more important than for Virot.

At first, a tube of inner diameter $d = 52\,\text{mm}$ was studied. It had been noted that for an initial pressure

of $P_0 = 10 \, \text{kPa}$, the velocity deficit dropped significantly. However, due to the limitation of the ignition system, the critical pressure could not be found. Then, the hydraulic radius was decreased to $w = 16 \, \text{mm}$. A similar behavior was observed, with a significant drop of velocity at a slightly greater pressure of $P_0 = 15 \, \text{kPa}$. The critical pressure was $7.5 \, \text{kPa}$. Near this critical pressure, both previous curves were close. With a hydraulic radius of $w = 11 \, \text{mm}$, a similar behavior has been observed, albeit shifted towards the higher pressure. The critical pressure has been estimated to be around $P_0 = 7.9 \, \text{kPa}$. Lastly, as for the hydraulic radius of $w = 6 \, \text{mm}$, detonation propagation was hardly possible, as the critical pressure rose up to $P_0 = 13 \, \text{kPa}$.

When the coaxial width was large enough, the detonation propagation was not sensible to the geometry. Similar observations than in the cylindrical were observed in all cases, with a global shift to higher pressures with a decreasing width. A limiting width seemed to exist for which no propagation was observed.

The ZND results are consistent with the experimental trends, that is, the decrease of the geometrical parameter w led to greater velocity deficits at the same initial pressure. The differences between the ZND results and the experimental data can be attributed to the fact that other phenomena such as friction and heat losses, as well as the cellular instabilities were not taken into account.

Another scaling proposed by Gao [4] used $2w/\lambda_{\text{CJ}}$, as shown in Fig. 2-right, where the ideal cell size λ_{CJ} was obtained from the interpolated data from Caltech Detonation Database [12]. By using this scaling, the experimental data collapsed toward a single curve.

3.2 Marginal detonations in coaxial channels for H$_2$ + Air mixture

Another experimental campaign was done using the $2\,\text{H}_2 + \text{O}_2 + 3.76\,\text{N}_2$ mixture. The goal of this campaign was to identify the different propagation modes of a marginal detonation, depending on the geometry of the tube.

Three soot foils are shown in Fig. 3, which were obtained for the same initial condition $P_0 = 11 \, \text{kPa}$. The soot foil on the left corresponded to the spinning detonation, classically observed in tubes. The trajectory of the triple point in white described an helix that spiraled along the circumference of the tube. Upon measuring the pitch of the helix, a length of about $150 \, \text{mm}$ was found, corresponding closely of the theoretical limit of $\lambda = \pi d$, where $d = 52 \, \text{mm}$.
In the middle, for a channel with $w = 16 \, \text{mm}$, a three-headed detonation was observed. The cells appeared to be irregular, with an average cell size of $\lambda = 113 \, \text{mm}$.
On the right, when $w = 11 \, \text{mm}$, only two triple points were present. One big cell, with a size of about the circumference of the channel, is seen. This can be considered as the final propagation mode before turning into a spinning detonation.

Spinning detonation occurred in the tube for a pressure range between 5 and 11 kPa, whereas double-headed detonation has been obtained for pressures as low as 8 kPa in the coaxial configuration. Experimental data suggested that spinning detonation occurred at much lower pressures than what was observed in tubes. As of today, we did not observe a spinning detonation in the latter configuration, although previous works [13] attest that it is possible. Moreover, they mention the occurrence of spinning detonation in the circular and coaxial configurations for the same initial pressure.

Furthermore, quenching was observed in the thinnest channel (w = $6 \, \text{mm}$) for pressures as high as $20 \, \text{kPa}$, whereas no quenching has been observed with pressures as low as as $8 \, \text{kPa}$ for the other two coaxial configurations.

Figure 3: Soot foils for the stoichiometric mixture $2\,H_2 + O_2 + 3.76\,N_2$, at the initial pressure $P_0 = 11\,\text{kPa}$. Left, tube with an inner diameter of $52\,\text{mm}$; middle, coaxial channel with $w = 16\,\text{mm}$; right, coaxial channel with $w = 11\,\text{mm}$. The trajectory of the triple points are drawn in white, to ease the interpretation.

4   Conclusion

Experimental data in coaxial channels were compared to a generalized ZND model, accounting for the boundary layer growth. Consistent results were obtained, even if some discrepancies remained, due to neglecting cellular structure instabilities. The ratio of the width to the ideal cell size was found to be an important parameter. Decreasing the width led to earlier quenching.

When a spinning detonation was observed in tubes, a multi-headed detonation was observed in the corresponding coaxial channels.

Additional experimental results will be presented during the oral presentation.

Acknowledgment

References

[1] Chao, J., Ng, H. D., Lee, J.H.S. (2009). Detonability limits in thin annular channels. Proceedings of the Combustion Institute, 32 2349-2354.

[2] Lee, J.J., Dupré, G., Knystautas, R., Lee, J.H.S. (1995). Doppler interferometry study of unstable detonations. Shock Waves, 5 175-181.

[3] Tsuboi, N., Daimon, Y., Hayashi, A.K. (2008). Three-dimensional numerical simulation of detonations in coaxial tubes. Shock Waves 18, 379–392.

[4] Gao, Y., Ng, H.D., Lee, J.H.S. (2017). Near-limit propagation of gaseous detonations in narrow annular channels. Shock Waves 27, 199–207.

[5] Voitsekhovskii, B.V., Mitrofanov, V.V., Topchiyan, M.E. (1966). The structure of a detonation in gases. English translation, Wright Patterson Air Force Base report FTD-MT-64-527 (AD0633821)

[6] Zhang, B., Liu, H., Yan, B. (2019). Investigation on the detonation propagation limit criterion for methane-oxygen mixtures in tubes with different scales. Fuel, 239, 617-622.

[7] Fay, J.A. (1959). Two-dimensional gaseous detonations: velocity deficit. Physics of Fluids, 2(3), 283-289.

[8] Gooderum, P. (1956). An experimental study of the turbulent boundary layer on a shock-tube wall. Technical Report NACA-TN-4243.

[9] Veiga-López, F., Weng, Z.F., Mével, R., Melguizo-Gavilanes (2023). Influence of low-temperature chemistry on steady detonations with curvature losses. Proceedings of the Combustion Institute, 39, 2925-2933.

[10] Williams, F.A. (2014). Chemical-Kinetic Mechanisms for Combustion Applications. San Diego Mechanism web page, Mechanical and Aerospace Engineering (Combustion Research), University of California at San Diego. https://web.eng.ucsd.edu/mae/groups/combustion/mechanism.html

[11] Zhang, B., Shen, X., Pang, L., Gao, Y. (2015). Detonation velocity deficits of $H_2/O_2/Ar$ mixture in round tube and annular channels. International Journal of Hydrogen Energy, 40(43), 15078-15087.

[12] Kaneshige, M., Shepherd, J.E. (1997). Detonation database. Technical Report FM97-8, GALCIT.

[13] Lee, J.H.S., Jesuthasann, A., Ng, H.D. (2013). Near limit behavior of the detonation velocity. Proceedings of the Combustion Institute, 34(2), 1957-1963.

[14] Gao, Y., Zhang, B., Ng, H.D., Lee, J.H.S. (2016) An experimental investigation of detonation limits in hydrogen-oxygen-argon mixtures. International Journal of Hydrogen Energy, 41, 6076-6083.

[15] Sadahira, K., Kitawaki, Y., Inaba, T., Susa, A., Matsuoka, K., Johzaki, T., Endo, T. (2013). Velocity Deficits of Ar and He diluted H_2-O_2 System in Small Diameter Tubes. 24th ICDERS.

[16] Kitano, S., Fukao, M., Susa, A., Tsuboi, N., Hayashi, A. K., Koshi, M. (2009). Spinning detonation and velocity deficit in small diameter tubes. Proceedings of the Combustion Institute, 32, 2355-2362.

[17] Xiao, Q., Weng, C. (2023). Unified dynamlics of hydrogen-oxygen-dilutent detonations in narrow confinements. Fuel 334 126661.

[18] Shi, X., Crane, J., Wang, H. (2021). Detonation and its limits in small tubes with ozone sensitization. Proceedings of the Combustion Institute 38, 3547-3554.

[19] Virot, F. (2006). Contribution à l'étude expérimentale et numérique du régime hélicoïdal de détonation dans les systèmes $H_2, CH_4, C_2H_6-O_2$ dilués ou non par N_2 ou Ar. Thèse pour l'obtention du Grade de Docteur de l'ENSMA, Poitiers.