Experimental observations of semi-confined steadily-rotating detonation

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1 Introduction

Studying detonation dynamics along the concave outer wall of a cylindrical chamber is helpful for understanding the possible detonation configurations in the combustion chamber of a rotating detonation engine (RDE). Only a limited number of studies into detonation in curved channels is available. Nevertheless, Kudo et al. [1] and Nakayama et al. [2, 3] have observed three types detonation behaviors after the transmission of an initially-multicellular Chapman-Jouguet (CJ) detonation from a straight tube to curved channel, i.e., the continuous multicellular transmission for the largest channel radii (supercritical configuration), the multicellular transmission with successive extinctions and ignitions near the inner lateral wall for intermediate channel radii (critical configuration), and detonation failure for the smallest channel radii (subcritical configuration). Additional works by Vidal et al. [4] have shown that this classification also applies to the transmission of an initially marginal detonation. Frolov et al. [5] have performed experimental and numerical studies on detonation and deflagration into circular tubes connected by one or two U-bends. Additional numerical calculations were made by Gwak et al. [6]. Edwards et al. [7] and Thomas et al. [8] carried out experimental studies on the interaction of a detonation front and a wedge and on the detonation propagation in a curved rectangular channel.

This work presents some experimental observations of the dynamical behaviors of a detonation along the concave outer wall of a cylindrical chamber without inner kernel. Attention focuses on the transmission of a multicellular CJ detonation from a straight tube to the chamber. Depending on the initial pressure, a detonation that steadily rotates along the outer wall is obtained. This detonation is considered as semi-confined since there is no kernel, i.e., no bounding inner wall.

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2 Experimental setup

The experimental set-up is essentially a concave cylindrical chamber with an 80-mm outer-wall radius and a 270° run angle (Fig.1). The top and bottom flat faces of the chamber were lined with soot-covered plates to record the detonation behaviors. The detonation entered the chamber from a straight channel connected to a 2-m long, 50-mm diameter tube. The initiation device was made up of an exploded wire and of a 50-mm long Shchelkin spiral to promote the rapid installation of a CJ detonation in the tube. The reactive gas was the stoichiometric mixture $C_3H_8+5O_2$ of propane and oxygen. The parametric study was carried out by varying the initial pressure P_0 from 60 to 150 mbar. The mean width λ of the cells that characterize the local unstable structure of a detonation front was used as a characteristic length for analyzing the observations.

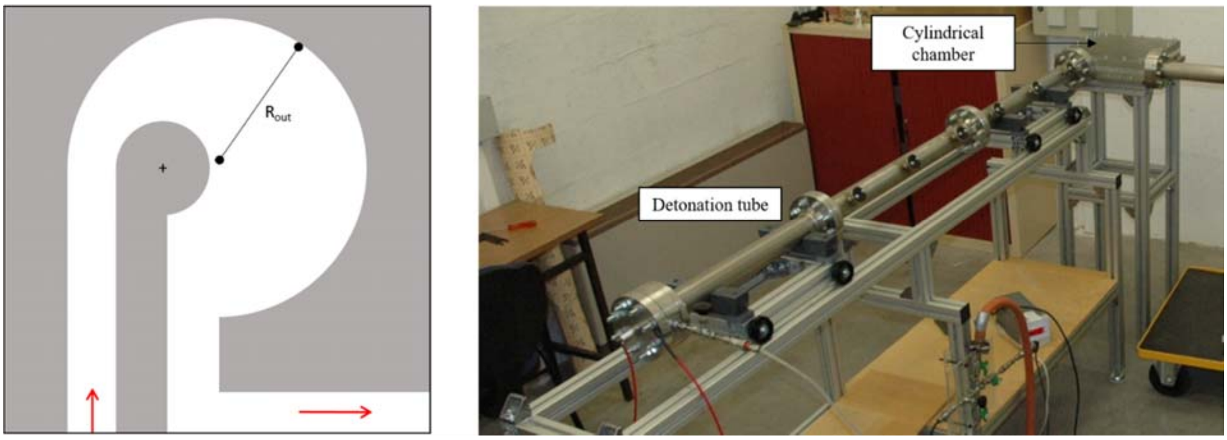

Figure 1: Scheme of the cylindrical chamber (left) (the arrows represent the propagation direction of the detonation). General view of the experimental set-up (right)

3 Results and discussion

Figure 2 shows sooted-plate records for the three initial pressures 80, 100 and 120 mbar. We observe that a steadily-rotating detonation is installed along the concave outer wall, in the last quarter of the chamber. We observe that the larger the initial pressure, the thinner the rotating-detonation layer, and that the closer to the outer wall, the smaller the detonation cells. The latter observation suggests that the rotating-detonation front is curved, and also that the smaller the initial pressure the larger the front curvature. Moreover, the detonation cells in the layer are always smaller than their value at the chamber entry and smaller than the mean cell width for the multicellular CJ detonation front at the same initial pressure. Before installation of the rotating detonation, transient phenomena associated with the transmission from the straight channel are observed. In particular, the initial detonation quenches at the inner wall of the channel due to the sudden lateral expansion of the reaction zone. However, this initial detonation continues to propagate at the outer wall due to the lateral compression. The interpretation is that the curved wall acts as a wedge with a continuously-increasing angle so that a Mach stem is formed when the chamber outer wall starts to bend [8]. Then re-initiation attempts are observed until installation of the rotating detonation.

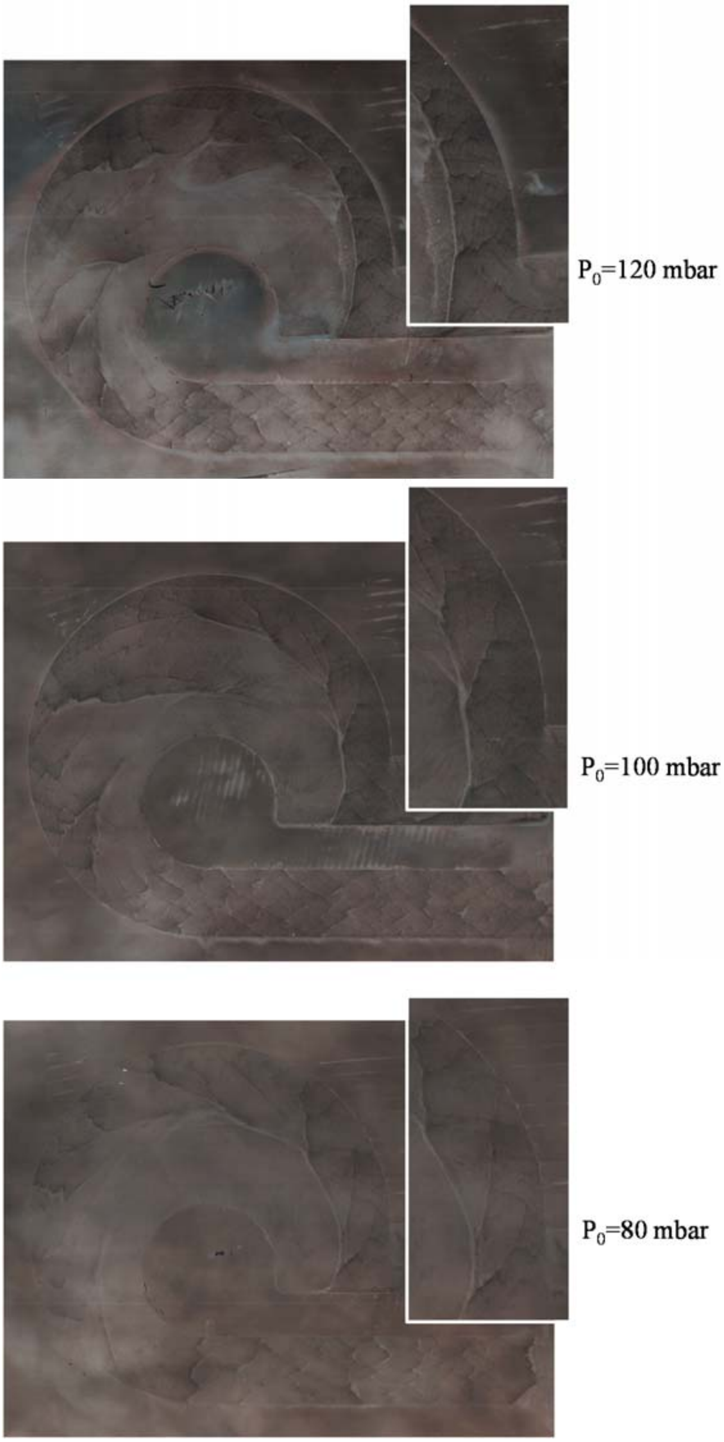

Figure 2: Sooted plates showing the history of the propagation of a steadily-rotating detonation front in the stoichiometric mixture $C_3H_8+5O_2$ for the three initial pressure P_0 80, 100 and 120 mbar. e: mean thickness of the rotating-detonation layer.

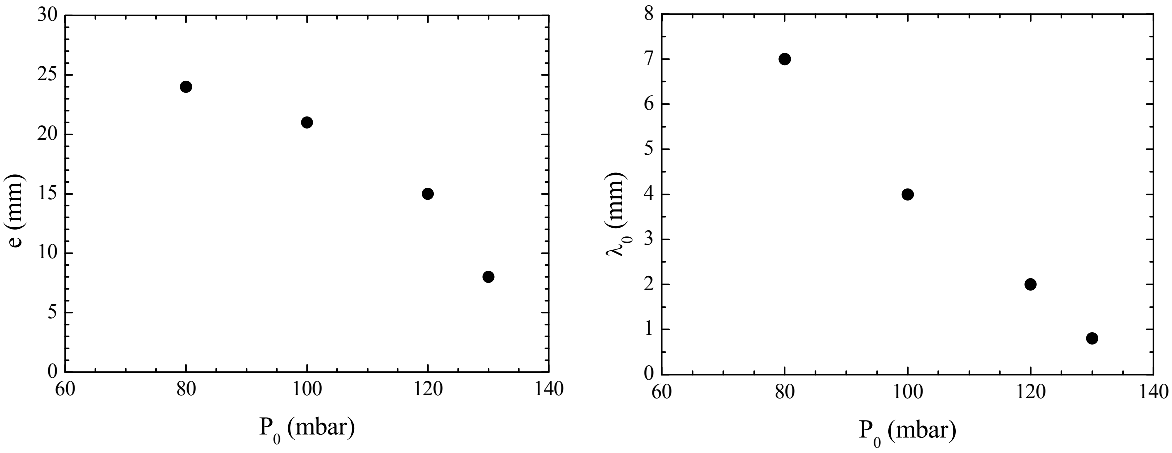

Figure 3: Width e of the rotating-detonation layer (left) and width λ_0 of the detonation cells on the rotating-detonation front at the chamber outer wall (right) as functions of the initial pressure P_0.

Figure 3, left, shows that the thickness e of the rotating-detonation layer decreases when the initial pressure increases. Figure 3, right, shows that the width λ_0 of the detonation cells of the rotating detonation along the chamber outer wall decreases when the initial pressure increases. Indeed, as a general rule, the larger the initial pressure P_0, the smaller the characteristic chemical lengths and, therefore, the smaller the cell size. The explanation is based upon the two results that the cell widths vary like P_0^{-n}, n~1, and like exp(E/RT), with E the activation energy of the global reaction of chemical decomposition, and T the temperature.

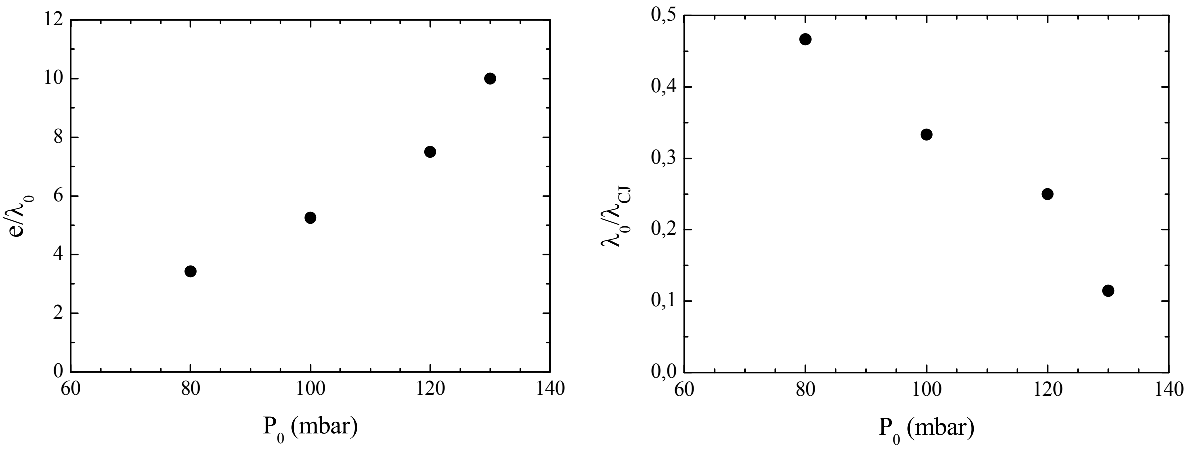

Figure 4: Ratio of the width e of the rotating-detonation layer to the width λ_0 of the detonation cells at the chamber outer wall (left) and ratio of the width λ_0 of the detonation cells at the chamber outer wall to the width λ_{CJ} of the detonation cells of the CJ detonation (right) as functions of the initial pressure P_0.

Figure 4, left, shows that the ratio of the width e of the rotating-detonation layer to the width λ_0 of the detonation cells at the chamber outer wall increases when the initial pressure increases. By comparing this trend with those in Figure 3, this means that the larger the initial pressure, the more cells in the rotating-detonation layer. Figure 4, right, shows that the ratio of the width λ_0 of the detonation cells at the chamber outer wall to the width λ_{CJ} of the detonation cells of the CJ detonation decreases when the initial pressure increases. This means that the width λ_0 at the outer wall is more sensitive to initial pressure than the width λ_{CJ}. The explanation is again based upon the two results that the cell widths vary like P_0^{-n}, n~1, and like exp(E/RT). Therefore, also considering that T varies like D^2, with D the wave front velocity, the larger D, the smaller the cell width and the larger the variation of the cell width with the initial pressure P_0. This demonstrates that the wave front velocity at the chamber outer wall is larger than the CJ velocity for the same initial pressure.

Therefore, in our conditions, the smaller initial pressures appear to be more favorable, assuming that combustion occurs only in the rotating-detonation layer.

4 Conclusion

We have conducted experiments on the dynamical behavior of the propagation of a semi-confined detonation along a concave outer wall of a cylindrical chamber. Depending on the initial pressure, a steadily-rotating detonation was observed along the concave outer wall. The records show that the larger the initial pressure, the thinner the rotating-detonation layer, and that the closer to the outer wall, the smaller the detonation cells. The latter observation suggests that the rotating-detonation front is curved. The detonation cells in the layer were always smaller than their value at the channel entry and smaller than the mean cell width for the multicellular Chapman-Jouguet (CJ) detonation front at the same initial pressure. This would indicate either that the rotating detonation front was over-driven, i.e., with a velocity larger than the CJ value, or that the transient phenomena associated with the detonation transmission from the straight channel to the chamber led to an increase of the initial pressure in the chamber before the rotating detonation could be installed. Nevertheless, these results demonstrate that a semi-confined detonation can rotate very rapidly in a narrow layer along a curved wall, with the consequence that not all the fresh mixture in the chamber is burned. This may participate in the set of explanations for the differences between some observed and predicted performances of RDEs.

Acknowledgements

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