A review of detonation studies applied to propulsion at Institute Pprime

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While most of the work carried out by the detonation team at Institute Pprime in Poitiers is essentially fundamental, a part of it aims at assessing the potential of specific applications at low technology readiness levels (≤ 3); those relating to propulsion have been developed for nearly 30 years. This presentation will summarize four including fundamental and/or applied contributions to (i) the combustion regimes behind a hypersonic oblique shock, (ii) flames and detonations in cryogenic H_2-O_2 gaseous mixtures, (iii) propulsive performance of pulsed detonations, and (iv) rotating detonations in annular chambers with constant or increasing cross section.

The combustion regimes behind a hypersonic oblique shock [1-4] were analyzed in H_2-Air and CH_4-Air mixtures, and Mach numbers ranging from 3 to 10. The oblique shock in the primary mixture was generated by the transverse expansion of the products of a detonation propagating in a secondary mixture parallel to the primary one. They were separated by a Mylar sheet which, due to the expansion of the products, acted as an oblique piston sustaining the shock as would a solid wedge. Regimes of turbulent flame and oblique detonation, transitions from the former to the latter, initiations at or away from the wedge tip were characterized experimentally; a strong dependence on chemical kinetics was observed. The regimes of detonation and some detached flames were found to be fairly well approximated using simple theoretical models (CJ secondary detonation, Prandtl-Meyer lateral expansion at the Mylar interface, oblique shock and 2-D oblique polars for the shock and the detonation).

Flame and detonation properties under cryogenic conditions were analyzed in stoichiometric and rich H_2-O_2 mixtures [5-6]. Fundamental burning velocities were measured on a Gouy burner, with initial temperature and equivalence ratios (ER) ranging from 123 K to 293 K, and 1 to 5, respectively. Detonability was quantified based on the critical ignition energy for direct initiation using a point source explosion, and on the mean cell width. Results at 123 K and 293 K show that lower temperatures favor detonation initiation. In the sub-atmospheric range, the lower the pressures, the clearer this effect is.

The specific impulse of pulsed detonations were analyzed experimentally in C_2H_4-O_2 and H_2-Air mixtures, and theoretically by means of the properties of the Taylor-Zel'dovich expansion behind a CJ detonation; a relation for computing simply the specific impulse was derived [7,8]. One-shot experiments in a suspended horizontal detonation tube (closed at one end and open at the other) were carried out to investigate the effect of ejectors, nozzles, incomplete filling of the chamber, and obstacles located close to the exhaust section, on the thrust and the propulsive performance. Measurements included pressure at the thrust wall, ballistic pendulum, schlieren visualizations, and cycle times for determining the upper limit of the mass flow rate. A multi-cycle set-up was designed and operated at a maximum frequency of 120 Hz for the considered mass flow rates.

Three demonstration chambers of continuously-rotating detonations were designed and operated:

I. *a constant-cross section annular chamber (2.5 to 5.5-mm width, 100 and 104-mm outer diameter, 5 to 10-cm length)* [9,10]. Mixtures of C_2H_4-O_2 at theoretical ER and total mass flow rates ranging from 0.5 to 3.5, and 10 to 35 g/s, respectively. The injection device at the chamber inlet consisted of 2 circular slots, one for the fuel, and the other for the oxidizer, arranged so that the two annular jets impacted each other. Steadily-rotating combustion regimes were obtained at atmospheric and sub-atmospheric pressures to mimic outer space conditions, and the effects of nozzles and restrictions at the exhaust was also investigated. Depending on the combination of parameters tested, 1 to 8 rotating fronts were observed. However, the wave front velocities were much smaller than the theoretical CJ values, reaching only 1 to 1.3 km/s, with associated pressure ratios of about 2 to 3. While this demonstrated the feasibility of establishing rotating combustion waves, these results stressed the need for better mixing of the fuel and oxidizer.

II. *an annular chamber (5 or 10-mm width, 70-mm outer diameter, 90-mm length) or with an increasing cross section (conical center body with 0° to 14.6° apex half-angles)* [11,12]. Mixtures of C_2H_4-O_2-N_2 with ER, total mass flow rates and dilution levels ranging from 0.7 to 1.5, 50 to 150 g/s and 0-0.5, respectively. The injection device at the chamber inlet consisted of 2 circular slots, one radial for the fuel, and the other axial for the oxidizer. Parametric results on ignition, combustion modes and stability were obtained. The main finding was that modifying the geometry of the center body, specifically decreasing the body length and increasing its conicity significantly improved the detonation velocities and pressures (up to 12 bar). In contrast, the N_2 dilution and the mass flow rate showed little influence. A numerical analysis suggested that dilution and heating of the fresh gases by detonation products could explain the measured deficits of pressure and velocity. A calculation of thermodynamic efficiency including a more realistic structure of the rotating detonation was performed.

III. *an annular chamber (5 to 20-mm width, 130-mm outer diameter, 100-mm length)* which is currently being investigated at total mass flow rates of around 300 g/s for various fuels (H_2, CH_4, C_2H_4) using O_2 and air as oxidizers [13]. The injection device is a set of small holes arranged on rings so that jets impact each other at the chamber inlet. The chamber inner and outer parts are water-cooled, the outer wall is optically accessible and is equipped with pressure, vibration, and temperature transducers; the propulsive performance are obtained using a scale on which the chamber is fixed.

A fourth setup consists of a curved flat chamber that allows for investigating one-shot rotating detonations [14]. The configuration is similar to that of Kasahara and co-workers, e.g., [15], but without an inner wall (i.e. there is no constant cross section channel, the chamber is empty with a concave outer wall). The front and back faces can be equipped with either soot foils (for recording the history of the transmission dynamics of a CJ detonation from a straight tube), or windows for high-speed schlieren visualizations. Tests were carried out with stoichiometric C_3H_8-O_2 mixtures at initial temperature of 288 K, and initial pressures ranging from 8 kPa to 15 kPa. The main observation is the existence of a range of initial pressures for which, after diffraction transients, a detonation can rotate normal to the outer wall with a constant angular velocity such that the normal front velocity at the wall is constant and larger than the CJ value. The height of the Mach front decreases, and its tangential (or angular) velocity increases with increasing initial pressure. This overdriven detonation results from the irregular reflection of the initially-oblique front as the outer wall tilts with respect to the front, similarly to shock propagation in a continuously-converging channel. The Mach triple-point moves away from the wall and stabilizes its trajectory parallel to the wall. This Mach front shows detonation cells parallel to the wall with a constant mean width significantly smaller than that of the initial CJ front. The analysis shows that this continuously-rotating overdriven detonation can be observed in a hollow curved chamber with outer diameter smaller than the minimum value necessary for stable rotation in a constant cross-section curved channel. The experimental observations are consistent with the experimental results obtained using RDE chambers without center body, or with linearly-increasing sections (see III. Above). Note that this configuration shows improved rotating detonation properties, compared to chambers with constant cross sections. Recent numerical simulations performed in our team confirm the validity of the initial interpretations/hypotheses, the main one being that the Mach front could be considered as a reactive discontinuity (i.e. there is no need to resolve the detonation structure) [16].

[1] Hamada L., Contribution to the study of the combustion behind a hypersonic oblique shock. Thesis, University of Poitiers, 1992

[2] Desbordes D., Hamada L., Guerruad C., Supersonic H2-air combustions behind oblique shock waves, Shock Waves, 4, 339–345, 1995

[3] Viguier C., Experimental study on the regimes of combustion induced by a hypersonic oblique shock wave in mixtures H_2-Air and CH_4-air mixtures. Thesis, University of Poitiers, 1996

[4] C. Viguier C., Gourara A., Desbordes D., Three-dimensional structure of stabilization of oblique detonation wave in hypersonic flow, Symposium (International) on Combustion 27(2):2207-2214, 1998

[5] Zitoun R., Desbordes D., Guerraud C., Deshaies B., Direct initiation of detonation in cryogenic gaseous H_2-O_2 mixtures, Shock Waves, 4, 331–337, 1995

[6] Zitoun R., Deshaies B., Burning velocities of rich H_2-O_2 flames under cryogenic conditions, Combustion and Flame, 427-435, 1997

[7] Zitoun R., Desbordes D., Propulsive Performances of Pulsed Detonations, Combustion Science and Technology, 144, 93-114, 1999

[8] Daniau E., Contribution to the study of propulsive performances of a pulsed detonation engine. Thesis, University of Poitiers, 2001

[9] Canteins G., A study of continuous rotating detonation: application to propulsion. Thesis, University of Poitiers 2006.

[10] Canteins G., Franzetti F., Zocłońska E. , Khasainov B.A., Zitoun R., Experimental and numerical investigations on PDE performance augmentation by means of an ejector, Shock Waves, 15, 103-112, 2006

[11] Hansmetzger S., On the continuous-rotation modes of detonation in an annular chamber with constant or linearly-increasing normal section. Thesis, University of Poitiers, 2018

[12] Hansmetzger S., Zitoun R., Vidal P., A study of continuous rotation modes of detonation in an annular chamber with constant or increasing section, Shock Waves, 28, 1065–1078, 2018

[13] This project is supported by the ANR through the EQUIPEX/GAP

[14] Rodriguez V, Jourdain C, Vidal P, Zitoun R., An experimental evidence of semi-confined, steadily-rotating, overdriven detonation, Combustion and Flame, 202, 132-142, 2019

[15] Nakayama H., Moriya T., Kasahara J., Matsuo A., Sasamoto Y., Funaki I., Stable detonation wave propagation in rectangular-cross-section curved channel, Combust. Flame, 159 (2), 859-869, 2012

[16] Melguizo-Gavilanes J., Rodriguez V., Vidal P., Zitoun R., Dynamics of detonation transmission and propagation in a curved chamber: a numerical and experimental analysis, Combustion and Flame, accepted, 2020.