On the Performance of Pulse Detonation Engines

D. Desbordes
and
B. Khasainov+, C. Canteins, F.Franzetti, and R. Zitoun
Laboratoire de Combustion et de Détonique, UPR 9028 CNRS.
Téléport 2 – BP 109 – 86960 Futuroscope Cedex , France.
e.mail: desbordes@lcd.ensma.fr
+Semenov Institute of Chemical Physics, RAS, Oulitsa Kossiguina 4, 117977 Moscow V334, Russia

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1) Introduction

PDE is a new concept of propulsion that can be used in air breathing and/or in rocket propulsion. The advantages claimed of PDE over conventional propulsion system are based on estimate of its performances. Due to nonsteady dynamics, analysis of such engine is more complex than that of steady ones and therefore the first estimations of performance given by computational and theoretical studies (/1/, /2/), vary widely. Recently, an extensive experimental and numerical efforts were undertaken in order to quantify the propulsion potential of this device. Ideal PDE configurations, in particular the single cycle tube experiment, are currently under study in different laboratories. Pulse functioning PDEs are also working but their global performances are not really known because unpublished. This paper reports the main significative past and recent results, available in the literature on PDE performance, and on parameters it depends. In this respect, up to now, many keys issues have not still been addressed.

Advantage of detonation regime over classical combustion lies in high rate energy release. It is about two order of magnitude faster than deflagration propagation (in internal combustion engine for instance). Moreover, detonation in propulsion systems does not need any pre-compression system (used to increase efficiency). PDE belongs to the class of unsteady alternative combustion engines. In this respect, a simple comparison of propulsion performance can be done between exhaust of combustion products into the atmosphere resulting from i) the adiabatic isochoric combustion, ii) the detonation of the same mixture (initiated at the closed end or at the open end of the detonation chamber of the same size as isochoric combustion chamber). The detonation regime gives a few percent gain over isochoric combustion (Fig.1). Our *2D* computations provide respectively *183s* and *176s* for the mixture-based specific impulse for $C_2H_4+3O_2$ mixture at standard conditions. In addition, as it is well known, thermal losses are important in the case of realistic isochoric combustion (long characteristic time) and remain limited in detonation regime (short characteristic time).

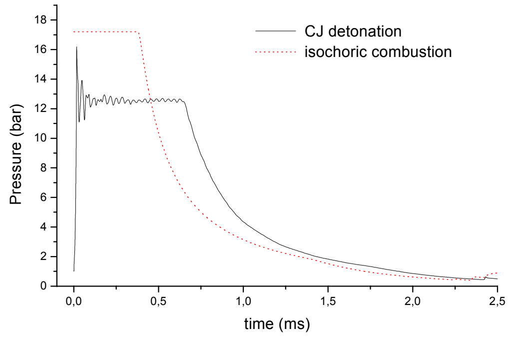

Fig.1 *TW* overpressure versus time for $C_2H_4+3O_2$ mixture

2) The ideal pulse detonation engine configuration

In order to quantify the maximum propulsion potential of a PDE, it is necessary to perform experiments that are very close to ideal situation. The ideal PDE is described as a cylindrical constant cross section tube

of i.d. d and length L detonation chamber, closed at one end by a plane normal wall, the so called "thrust wall" (or *TW*) and open at the other end (called the open end or *OE*) to the atmosphere of pressure p_0.
The detonation initiated directly at the thrust wall (from exploding wire or from detonation initiated by *DDT* mechanism emerging from a small tube) produces on the thrust wall a typical pressure variation depending completely on the unsteady *2D* axisymetric flow field induced. In the case of "short" tube with a sufficiently "large" i.d. the measured pressure on a single cycle can be reproduced numerically (*1D* and *2D* computation of the unsteady flow) with an excellent agreement /3/, /4/. Some typical experimental pressure signals are displayed in Fig.2, for the stoichiometric C_2H_4/O_2 mixture at standard conditions /5/. The quasi self-similarity nature of pressure profile appears clearly in Fig.3, when are used the non dimensional pressure $\pi = (p - p_a)/(p_k - p_a)$ versus non dimensional time $\tau = t/t_{CJ}$, (where $p_a = 1bar$ and $p_k = p_{CJ}\left[(\gamma+1)/2\gamma\right]^{2\gamma/(\gamma-1)}$ is the adiabatic pressure in detonated products at rest, and $t_{CJ} = L/D_{CJ}$ is the characteristic propagation time of the detonation). The main features of this signal are the following: after a jump to $p \sim p_{CJ}$ and a rapid drop, pressure follows a constant "plateau" $p \sim p_k$ for τ up to *3.25* (corresponding to the time elapsed from the beginning of the detonation propagation from *TW* to arrival of expansion wave from the *OE*), followed by the over-pressure decrease up to zero during the expansion of the detonation products. The overpressure vanishes at $\tau^+ \sim 9 - 10$. Then this positive overpressure phase is followed by a negative overpressure phase up to $\tau \sim 18 - 20$ ($\tau^- = 10$, Fig.2).

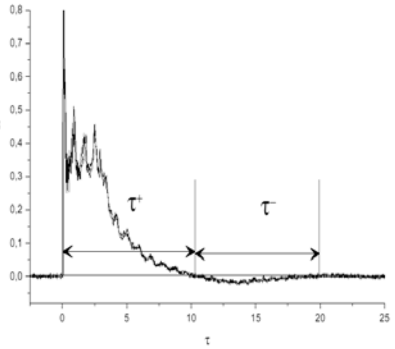

Fig. 2: Typical non dimensional *TW* overpressure versus time (C_2H_4+$3O_2$, *L =.1m and d = .05m*)

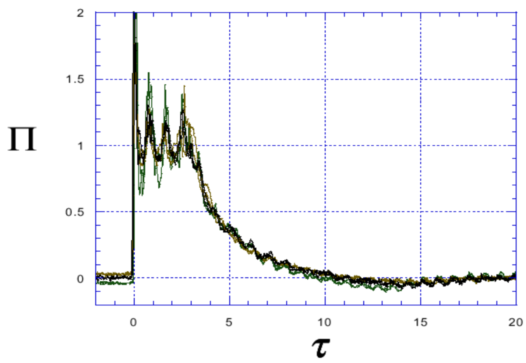

Fig. 3: Non dimensional *TW* overpressure versus time (C_2H_4+$3O_2$, C_2H_2+$2.5O_2$, C_2H_2+O_2, p_0 = *.7,1,1.5bar*)

This pressure profile (/4/, /6/) gives a relationship of the specific impulse expressed in term of the *CJ* characteristics of the mixture used:

$$I_{sp}^0 = K\left(p_k - p_0\right)/g\,\rho_0\,D_{CJ}\ ,$$

where K is a "constant" that can be determined experimentally and numerically. Values of *5.4* and *5.15* have been proposed in ref /3/, without considering the negative phase of over pressure (which represents *5%* of the impulse corresponding to the positive overpressure phase). It leads to a value of about *4.9* to *5.15* for total I_{sp}^0 for C_2H_4/O_2 system in tube of reduced length ($L < 0.41$ *m,* i.d. *5 cm*). For less energetic mixture such as C_nH_m/Air or H_2/Air (p_{CJ}/p_0 is smaller than in mixture with O_2) K is lower and ranges from *4.65* to *4.7* /8/. These values are very close to the one deduced from adiabatic unsteady flow field computation (K = *4.9* /3/ *4.85* /4/, Figs. 4 and 5 respectively). These results were used as a baseline for determining the PDE performance, in the case of an ideal cylindrical detonation chamber fully filled with reactive mixture. For an air breathing PDE, the fuel-based specific impulse of classical stoechiometric hydrocarbon-air mixture is about *1800s* and *4500s* for H_2/Air mixture.
The relative dispersion of the experimental values in the literature strongly depends on the characteristic size of the detonation chamber. A value of *4.3* is given by Winterberger et al. /6/ for a 1-m long tube device. This coefficient explains very well the results obtained on average thrust by Schauer et al. /7/ in multicycle operation with H_2/Air in 1-m long tube. So, 1-m long tube and more are penalizing for maximum efficiency, because wall thermal losses reduce the *TW* pressure level, see Fig.6. These losses can be neglected in the

heat release zone of the detonation (whose cell size is at least one order of magnitude smaller than diameter of the detonation tube) because the detonation velocity deficit to *CJ* remains in general below *1* or *2* percent. They become important in the unsteady flow field of the detonation products, if the working time during the expansion is long ($\tau = 10$).

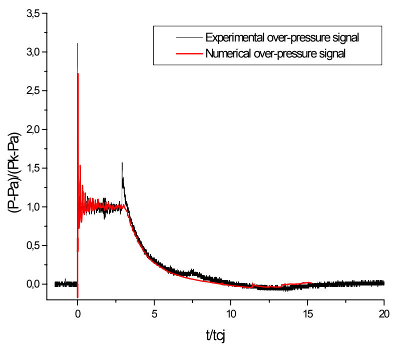

Fig. 4: Comparison of *TW* 2D numerical and experimental overpressure signal (C_2H_4+$3O_2$, *L =.1m and d = .05m*)

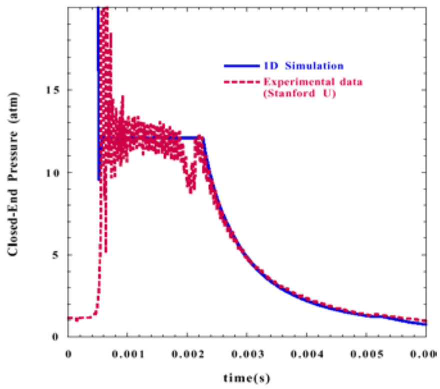

Fig. 5: Comparison of *TW* 1D numerical and experimental overpressure signal (C_2H_4+$3O_2$, *L =1.35m, from /4/*)

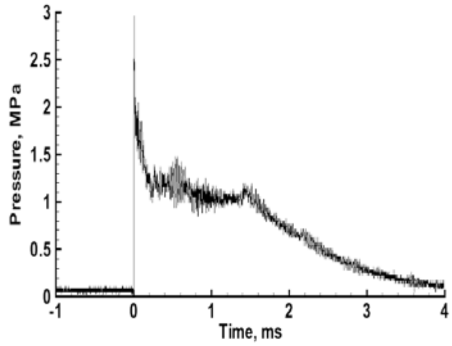

Fig. 6: *TW* experimental overpressure signal (C_2H_4+$3O_2$, *L =1m, d=.075, from /6/*)

Decrease of performance from the ideal configuration is caused by many factors (initial and boundary conditions):

- the reactive mixture is heated by hot wall,
- the thermal losses becomes non negligible,
- the detonation is not initiated directly, etc....

3) Improvement of Isp

The ideal configuration considered above does not necessarily provide the optimized PDE performance. Indeed that configuration, *1D* modeling and simulation of the unsteady flow field of detonation products, for the detonation initiated at *TW* or at *OE,* show that exhaust of detonation products at the exit surface is sonic during a great part of the cycle and thus limits the mass flow rate ejection /5/. The pressure at the exit section is $p_e = p_{CJ}\ \gamma^{2\gamma/1-\gamma}$, i.e $0.11 - 0.12 p_{CJ}$ which is generally higher than the atmospheric pressure p_0.

If the $p_e < p_0$ (because the reaction mixture is not sufficiently energetic), external pressure limits the exhaust mass flow rate.

If $p_e > p_0$, the return of detonation products to pressure p_0 in order to maximize I_{sp}, goes throught the optimization of the exhaust configuration. Addition of cylindrical straight nozzles of different lengths /5/,/9/, diverging nozzles of different shapes and lengths /5/, or external coaxial straight nozzle of different diameter and length may increase substantially I_{sp} /10/.

4) Factors decreasing I_{sp}

4-1 Air inlets effects

In the case of an air-breathing PDE air inlets have to be considered. They affect the PDE performance by increasing the discharge area during the expansion of the detonation products. It has been demonstrated experimentally (at mach number $M = 0$) that if the ratio α of the discharge area (normal to the detonation propagation) to the area of the rear exhaust cross section of the detonation chamber, is modified in the range of *0* to *1*, I_{sp} varies according to $I_{sp} = (1-\alpha/2)\, I^0_{sp}$. So if we consider $\alpha<0.2$ the decrease of I_{sp} remains small as it was indicated by computations /11/.

4-2 Partial blockage at the open end

Propulsion performance decrease by partial blockage of the exit section has been investigated /12/. Axially symmetric aerodynamical obstacles of the same diameter than the detonation chamber and of different shapes placed on the axis at different distances from the exit generally decrease I_{sp} and increase the time of over pressure application on *TW*. The shorter the distance, the lower is I_{sp}, and the larger is τ^+. These experiments confirm the negative effect of a converging nozzle.

4-3 Factors inducing Isp degradation.

In a general way, I_{sp} degradation finds its origin in a change of the initial mixtures, in the initial conditions and in the difficulty to attain detonation regime in the mixture used. A non exhaustive list of several important issues which control the PDE performance can be established:

- the non uniformity of concentration of fuel in Air or O_2 due to problem of mixing, fuel injection and eventually two phases mixing,
- incomplete ejection of detonation products and mixing with fresh reactive mixture,
- the thermal loading and the change of initial mean temperature and then the initial density of the mixture
- the length and delay of establishing the detonation regime in the chamber. These two parameters are closely linked to the three previous ones. Indeed, it has been demonstrated /6/ that partially detonated charge or charge supporting choking regime of flame propagation exhibits lower *Isp* with a dramatic increase of the cycling time.

5) Concluding remarks

In a general way, *Isp* is the key performance parameter of a propulsion system. Nevertheless in addition to *Isp*, *PDE* performance depends on thrust which is proportional to the mass flow rate; and then on the cycling time. Thus, high thrust requires a high mass flow rate and then a high frequency of cycling. This frequency is limited to the "shortest" cycling time which can be estimated on the basis of $\tau \sim$ *10 or 20* /6/. To compensate the limited flow and then thrust of *PDE*, it is possible to use multiple chambers that detonate on a sequential basis.

The PDE can be considered for application similar to those of rocket engine, utilising its inherent static thrust capability. Concerning air breathing engine at different flight regimes, only available results are given by modelling and simulation. The possible application to such a system to supersonic, and even to hypersonic flight, in addition to subsonic flight, have been addressed recently /11/, /13/.

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