PDE Performance Improvement by the Addition of a Coaxial External Nozzle

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1 Introduction

The pulsed detonation engine (PDE) concept is based on the repetitive detonation of a reactive mixture in a combustion chamber (CC) open into the atmosphere. To evaluate the performance of this engine, an experimental installation was developed to study a single-shot PDE functioning at $M = 0$ flight regime [1]. The detonation chamber consists of a cylinder open at one end to the atmosphere and closed at the other by a thrust wall (TW). The thrust, and thus the specific impulse, is derived from a pendulum system that integrates all mechanical efforts of detonation products on the structure [2].

It is now commonly recognized that the addition of a nozzle (straight or diverging) increases substantially the PDE performance. To improve the basic specific impulse I_{sp} of the PDE, some ejectors have been studied. The addition of a nozzle to the combustion chamber increases I_{sp} in interesting proportions (+150% with a nozzle 6 times longer than the combustion chamber). More particularly, a fast diverging nozzle provides an increase of I_{sp} without increasing the cycling duration, hence without decreasing the maximum cycling frequency [2]

This study aims at the performance improvement by adding a coaxial external nozzle on a single-shot PDE. It consists of a tube coaxially attached to the combustion chamber (Figure 1 and 2)

This coaxial nozzle causes two effects on the gas exhaust, schematized in Figure 1 :

- It confines the detonation products escaping from the detonation chamber ;
- A left-running shock wave propagates from the CC exit along the nozzle ; when it emerges outside, it diffracts and then air gets drawn inside the nozzle.

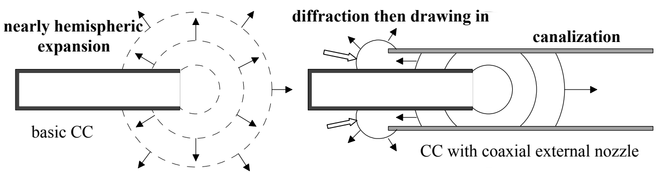

Figure 1: Ejector influence on the gas exhaust

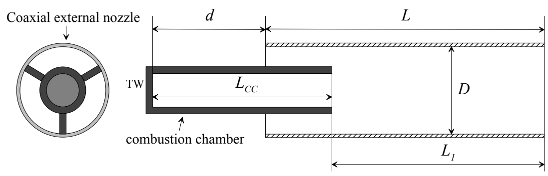

Figure 2 : Experimental arrangement

The most interesting point is the coaxial external air inlet. During flight, it could ensure the presence in the nozzle of fresh gas of higher density than that of detonation products. Therefore the mass ejected is more important if we use such an ejector rather than a standard nozzle. This circulation of air also favours the escape of detonation products. Finally, this assembling reduces drag if compared to standard nozzles. Such a Pulsed Detonation Rocket Engine could operate in the atmosphere.

The present work reports results for different nozzle lengths L and positions d relative to the thrust wall (Figure 2), for a given nozzle diameter. The combustion chamber dimensions remains constant. For each configuration, the specific impulse and the maximum cycling frequency are determined. Thus the performance gain in I_{sp} and thrust will be calculated and compared with the previous available results. 2D unsteady adiabatic numerical computations will complete this experimental work.

2 Experimental set-up

A single-shot PDE combustion tube is fitted out with a coaxial external nozzle and then suspended on steel wires constituting the ballistic pendulum. The detonation chamber is instrumented with a short rise time (1 μs) piezo-electric transducer (Kistler 603B) that registers the pressure signal on the thrust wall. The specific impulse is derived both from experimental measurements on this ballistic pendulum arrangement and from the pressure signal integration.

The dimensions of the combustion chamber are : 50 mm i.d., 72 mm o.d. and $L_{cc} = 480$ mm. The nozzle is a $D = 80$ mm i.d. and 5-mm thickness tube. Results will be given for different lengths L (400, 550, 700, 850 and 1000 mm). For each configuration, the position d of the ejector varies between 75 and 425 mm, by 50-mm increments.

A stoichiometric ethylene / oxygen mixture is used at atmospheric pressure. In a short cylindrical tube connected to the thrust wall, the detonation is initiated via DDT by ignition from a piston engine spark plug. The detonation can diffract in the CC because the initiation tube internal diameter is higher than the critical tube diameter 13 λ_{CJ} (λ_{CJ} is the Chapman-Jouguet detonation cell size). The CC is entirely filled with fresh mixture, initially separated from the ambient air by a thin mylar film (12 μm)

3 Results

3.1 Overpressure signal

Figure 3 presents the dimensionless overpressure time signal recorded on the thrust wall without and with ejector. P_{CJ} and P_a are Chapman-Jouguet and atmospheric pressure respectively and $t_{CJ} = \frac{L_{cc}}{D_{CJ}}$ where D_{CJ} is the Chapman-Jouguet velocity.

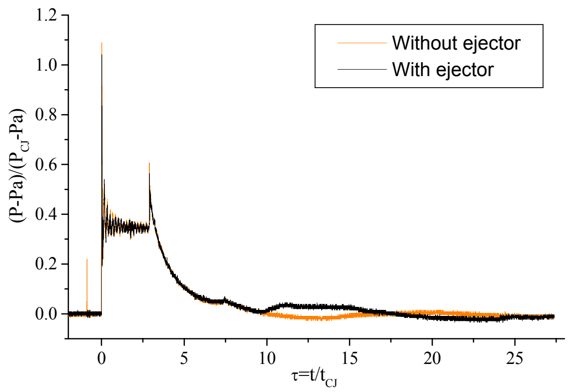

Figure 3 : Dimensionless overpressure signal recorded on the thrust wall

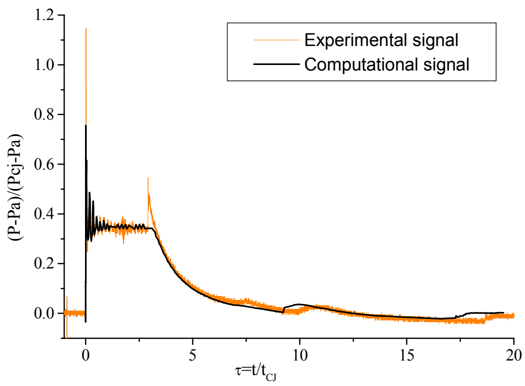

Figure 4 : Calculated dimensionless overpressure on the thrust wall

The first part of this signal, for $\tau < 7$, perfectly agrees with the previous results [1 , 2] and the calculations [3] (Figure 4). It consists of the Chapman-Jouguet peak, followed by a constant pressure plateau (0.34 P_{CJ} measured, compared to a theoretical value of $\left(\frac{\gamma+1}{2\gamma}\right)^{\frac{2\gamma}{\gamma-1}} P_{CJ} = 0.356\ P_{CJ}$ with $\gamma = \gamma_{CJ} = 1.138$) corresponding to the pressure of the detonation products at rest in the Taylor-Zeldovich expansion wave kernel. Then after the peak generated by the mylar rupture, we observe a two-step pressure decay until $\tau \approx 10$, corresponding probably to the reflection at the open-end of the two parts of the Taylor-Zeldovich profile. Without any ejector, the pressure drops below the atmospheric pressure, and then recovers again after roughly 18 t_{CJ}. The cycle duration is thus defined.

The confinement of the detonation products at the end of the combustion chamber is characterized by a secondary overpressure that appears at $t \approx 10\ t_{CJ}$ on the TW pressure signal. This phenomenon will increase the cycle duration.

The integration of the pressure measured only on the TW does not allow calculating the specific impulse because mechanical efforts are applied on other parts of the chamber.

3.2 Specific impulse

To evaluate the I_{sp} gain realized with the coaxial external nozzle, tests have been carried out on a basic detonation chamber without ejector. The mean specific impulse measured by the ballistic pendulum equals $I^o_{sp} = 164$ s with a standard deviation of 1%, in excellent agreement with the estimate from Stanford University experiments (163 s) [3]. This value is 18% smaller than in the previous results obtained with $L_{cc} = 100$ mm, which demonstrates the importance of thermal losses along the detonation tube. The TW pressure signal integration on the cycle duration provides $I_{sp} = 170$ s.

The values of I_{sp} obtained from ballistic pendulum versus d are given in Figure 5 for different nozzle lengths L. The curves of I_{sp} versus d exhibit a maximum for each value of L. The longer the ejector, the higher position of the curve. In the range of ejector lengths tested, the highest specific impulse (260 s) is obtained with a 1-m long ejector positioned at about 250 mm from the thrust wall. This provides an I_{sp} gain of 59% in comparison with I^o_{sp}.

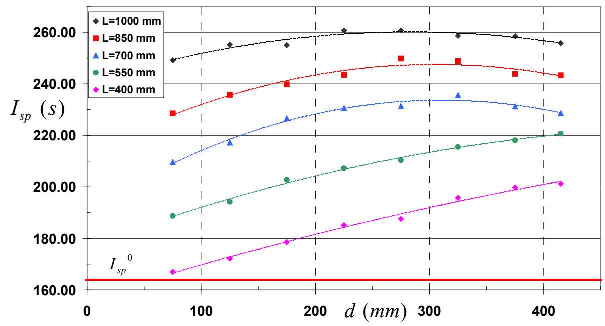

Figure 5 : Specific impulse I_{sp} versus the nozzle position d for different nozzle lengths L

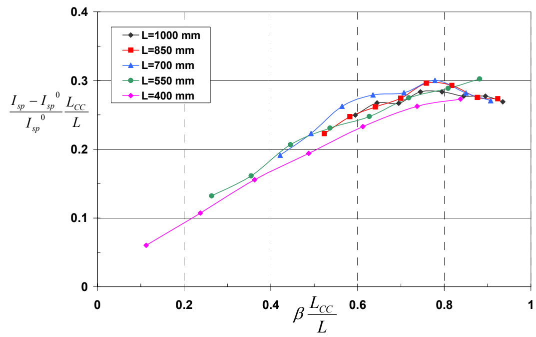

Figure 6 : Specific impulse gain in dimensionless parameters

Similar tests with a 110-mm i.d. ejector provided a curve of the same shape but with much lower specific impulse (between 180 and 200 s only).

Figure 6 shows the same curves using non-dimensional parameters : $\frac{I_{sp}-I^0_{sp}}{I^0_{sp}} \frac{L_{cc}}{L}$ versus $\beta \frac{L_{cc}}{L}$ where $\beta = \frac{L_1}{L_{cc}}$. At first examination of Figure 6, for an 80-mm i.d. ejector, a unique curve provides the specific impulse gain realized with a coaxial external nozzle whose length and position are known.

Moreover, this type of ejector provides a gain that is 75% higher than a straight cylindrical ejector for the same coefficient β (+42% against +25% with a straight cylindrical ejector) [2].

3.3 Maximum cycling frequency

The maximum cycling frequency is given by $f_{\max} = (t_{cycle} + t_{DDT})^{-1}$ with t_{cycle}: cycle duration and t_{DDT}: deflagration to detonation transition duration necessary for the initiation of detonation (the mean value of t_{DDT} is 0.17 ms with the present arrangement). This definition is based on the following consideration : the detonation chamber is entirely refilled at the end of the cycle, taking advantage of the low-pressure phase to refuel the CC with the mixture.

The pressure signal (Figure 3) allows us to measure two parameters : the duration of overpressure stage and the cycle duration, respectively t_+ and t_{cycle} . Figure 7 shows the variation of $\tau^+ = \frac{t_+}{t_{CJ}}$ and $\tau^{cycle} = \frac{t_{cycle}}{t_{CJ}}$ versus the coefficient β [2] .

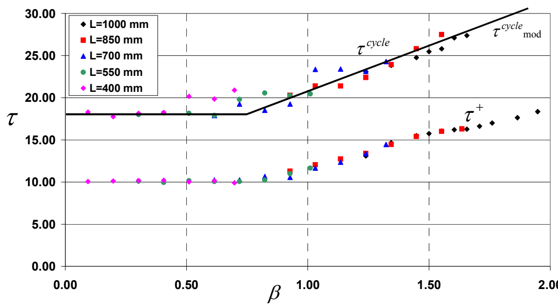

Figure 7 : τ^+, τ^{cycle} and τ^{cycle} simplified versus the coefficient β

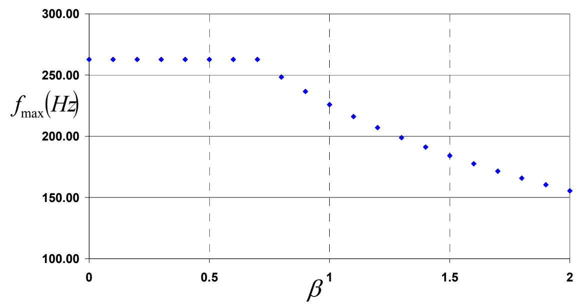

Figure 8 : Simple dependence $f_{\max}$ versus β

The cycle duration seems to depend only on β. A simplified dependence is then proposed for $\tau^{cycle}(\beta)$, and therefore for $f_{\max}$ (see Figures 7 and 8) depending only on the coefficient β. The highest value of $f_{\max}$ is 267 Hz for $\beta < 0.7$; this value is also that of a PDE without ejector.

3.4 Thrust

In pulsed detonation functioning, the maximum available thrust $F_{\max}$ is given by $F_{\max} = m_{mixture}\, I_{sp}\, f_{\max}$, with $m_{mixture}$ being the mass of fresh mixture contained in the CC. Using the experimental values for I_{sp} and the simple dependence of $f_{\max}$ on β (cf. Figure 8), the thrust was calculated versus β (Figure 9).

The best configuration for this combustion chamber is obtained with a 700-mm long ejector, positioned at $\beta \approx 0.7$ ($L_1 \approx 435$ mm) : the PDE would provide a maximum thrust of about 70 kg (685 N) at a frequency of 267 Hz in the ideal case, that is to say 28% more than the same PDE without ejector (55 kg,540 N). This result was obtained with an 80-mm i.d. ejector. The ratio thrust / weight for the present propulsive system is higher than 9 whereas the detonation chamber weight is not optimized.

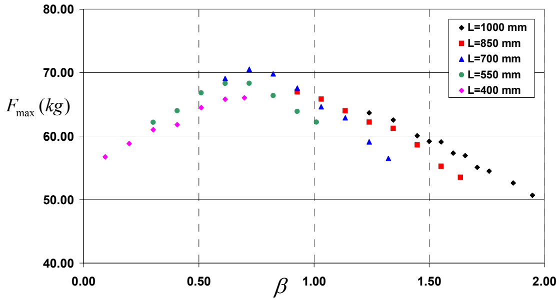

Figure 9 : Maximum thrust $F_{\max}$ of the PDE versus the coefficient β

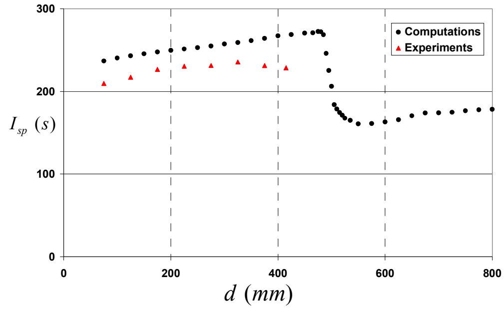

Figure 10 : Calculated specific impulse versus the position d of the nozzle

4 Computation results

Computation were conducted using a home-made 2D Euler unsteady adiabatic code ("efae" : Enhanced Fuel-Air Explosion) based on the Flux-Corrected Transport (FCT) method [4]. The configuration (geometry, mixture and initiation) calculated is exactly the same as the one used in the experiments, with $L = 700$ mm.

The pressure signal calculated on the thrust wall (in the same position as the pressure gauge) is in good agreement with the experiments (Figure 4).

The specific impulse was calculated by pressure integration on all the normal surfaces. It is roughly 15% higher than the experimental values : this is due to the heat losses on the inner wall, which were ignored in computations. If we consider the example of $d = 125$ mm, I_{sp} is thus composed by three contributions : 165 s on the TW, 12 s on the initiation tube end and 65 s (5 s without nozzle) on the CC end. This shows the origin of the I_{sp} gain : the gas confinement inside the nozzle increases the thrust applied on the CC wall thickness.

Calculations were performed for different relative positions d (Figure 10). The numerical results agree reasonably with the experiments. For $d > L_{cc} = 480$ mm, calculated I_{sp} drops quickly under I_{sp}^o because in that case the nozzle behaves like an obstacle.

5 Conclusion

This study demonstrates the performance improvement of a PDE by the addition of a coaxial external nozzle to the combustion chamber. The specific impulse was measured in a single-shot PDE by a ballistic pendulum method, for different lengths and positions of an 80-mm i.d. nozzle.

The addition of the ejector leads to an interesting augmentation of specific impulse : up to 60% in the best configuration studied, namely from $I_{sp}^o = 164$ s without ejector to 260 s with ejector. It is due to the confining of the exhaust gas at the end of the combustion chamber. On the other hand, the cycle duration remains constant for $\beta < 0.7$ and then increases, and so the maximum cycling frequency diminishes.

For the given nozzle internal diameter, the specific impulse gain can be determined with a simple curve if two dimensionless parameters are known, which are linked to the combustion chamber length, the ejector length and its relative position to the thrust wall.

The thrust gain in pulsed regime was estimated from the one-cycle experimental results. It reaches 28% with a 700-mm long ejector positioned at $d = 115$ mm : the PDE provides a 70-kg thrust (55 kg without nozzle).

The computations are in good agreement with the experiments concerning the pressure signal calculated on the TW, but the specific impulse is higher than the experimental one because heat losses were not considered.

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