Specific impulse of reactive mixture in detonation regime: Effect of the initial pressure.

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1) Introduction

The development and the design of the pulsed detonation engine (PDE) require the study of the propulsive performances of a reactive charge and their optimization in a single detonation mode. Only few experimental works are published in this field. Back and Varsi [1] have determined the specific impulse developed by the detonation of a solid explosive charge in straight or conical nozzles for propulsion in high density or pressure atmosphere. Zhdan et al. [2] have studied the effect of the ratio of the chamber length to the charge length on the specific impulse of the detonation of a reactive charge contained in a cylindrical chamber. In a previous work, Zitoun et al. [3] have investigated the effect of the position of the detonation initiation and of the length of the reactive charge on the thrust F(t) and on the impulse I(t). The results indicated that the specific impulse I_{sp} is independent of the position of the detonation initiation and that the flow in the combustion chamber is self similar. Consequently, for detonation initiation at the thrust wall TW, a scaling law was established for averaged thrust and a relationship between I_{sp} and CJ characteristics was obtained, (Zitoun et al. [4]). In the present work, we investigate the propulsive performances (thrust F(t), impulse I(t) and specific impulse I_{sp}) of a detonative mixture contained at different initial pressure p_0 in a combustion chamber of a given volume into the atmosphere at ambient conditions $p_a = l bar$ and $T_a = 293 K$. The effect of the chemical energy contained in the charge on F(t), I(t) and I_{sp} is studied by varying the initial pressure p_0 of the reactive charge. Three initial pressure are considered : i) lower than, ii) equal to, and iii) higher than the atmospheric pressure, namely $p_0 = 0.7$, 1 and 1.5 bar. These characteristics are determined using the pressure time history on the TW and the ballistic pendulum deflection and then discussed in terms of, (i) gain or deficit of specific impulse, and (ii) level and application time of thrust during a cycle.

2) Experimental set-up

The combustion chamber (CC) is an aluminum cylindrical tube with i.d. d = 50 mm, and length L = 100 mm (Fig.1a). One end of the CC is closed and forms the thrust wall (TW), the other end is open for the exhaust of the detonation products. The CC is initially separated from the ambient atmosphere by a thin mylar film (12µm) and then completely filled with the reactive mixture. We used a stoechiometric C₂H₄-O₂ mixture at 0.7, 1.0 and 1.5 bar. The Chapman-Jouguet detonation pressure and velocity of these mixtures are 23.56 - 31.10 and 51.91 bar and 2360 - 2377 and 2397 ms⁻¹, respectively. The detonation initiation is located at the TW, and is obtained by means of a deflagration-to-detonation transition (DDT) process in an additional tube of 12 mm i.d. The thrust F(t) produced by the detonation products on the TW and the corresponding impulse I(t) are deduced from the overpressure time history provided by a short-rise time KISTLER 603B pressure gauge located at the TW (i.e $F(t) = \int (p(t) - p_a) dS = S(p(t) - p_a)$ and $I(t) = \int F(t) dt$; S being the TW surface area, p(t) and p_a are the TW and the ambient pressure, respectively). The ballistic pendulum method (Fig.1b) is used to double-check the results obtained from the TW overpressure signal. In this case, the specific impulse (in seconds) is given by: $I_{sp} = \frac{M \delta}{m} (g L_p)^{-1/2}$, where M, δ , m, L_p and g are the overall device mass, the maximum horizontal deflection, the reactive mixture mass, the suspension wire length and the gravity acceleration, respectively.



Fig. 1b: Ballistic pendulum

3) Results and discussion

Reproducible overpressure profiles and pendulum deflections are obtained for different initial pressure. Examples of thrust F(t) and impulse I(t) time histories are displayed in Fig. 2a and 2b respectively. These profiles indicate that the level of the thrust and consequently the impulse increases with increasing initial pressure. However, the application time of the thrust remains quasi independent of p_0 . The results obtained from ballistic pendulum confirm this trend and show that the maximum impulse I_{max} increases linearly with increasing p_{θ} (Table 1).



Fig. 2a: TW overpressure time history for different p₀

Fig. 2b: TW impulse time history for different p₀

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	Results from pendulum		Results from TW overpressure	
p_0 (bar)	I_{max} (kg m s ⁻¹)	$I_{sp}(s)$	I_{max} (kg m s ⁻¹)	$I_{sp}(s)$
0.7	0.332	201	0.329	200
1	0.469	199	0.465	197
1.5	0.784	201	0.736	208

Table 1: Comparison of maximum impulse I_{max} and specific impulse I_{sp} values obtained from ballistic pendulum deflection and from TW overpressure time history.

In order to unify the analysis, the thrust and the impulse are expressed using dimensionless variables ie:

i) for time:

$$\tau = \frac{t}{t_{CJ}} \qquad \text{with } t_{CJ} = \frac{L}{D_{CJ}}$$
ii) for thrust
$$P(\tau) = \frac{p(t) - p_a}{p_k - p_a}$$

where p_k corresponds to the pressure level of detonation products at rest in the frame of the Taylor and Zeldovich expansion model. p_k (k for kernel) is given by:

$$\begin{split} p_k = & \left(\frac{\gamma+1}{2\gamma}\right)^{\frac{2\gamma}{\gamma-1}} p_{CJ} \\ J(\tau) = & \int P(\tau) d\tau \,. \end{split}$$

and iii) for impulse:

In the plane P, τ (overpressure-time history, Fig.3a) and in J, τ (impulse-time history, Fig.3b), the profiles obtained for different p_0 values are very close. It is interesting to notice that the mean value of constant level of P is about I, and is applied during $\tau = 3.25$. Then P decreases to 0 for τ roughly equal to 10 (10 - 11) depending on the initial pressure. Consequently J(t) increases linearly up to $\tau = 3.25$ and reaches it maximum J_{max} at $\tau = 10$ to 11. As it shown in Fig. 3b, J_{max} remains constant when the the initial pressure varies, it is roughly equal to 5.20 (with a discrepancy about 5%). I_{sp} can then be related to J_{max} using the classical relationship between I_{sp} and I(t), i.e $I_{max} = I_{max}$ with

 $I_{sp} = \frac{T_{\max}}{m g}$ with

$$I_{\max} = J_{\max} S (p_k - p_a) t_{CJ}$$

This leads to:

$$I_{sp} = \frac{J_{\max} (p_k - p_a)}{g \rho_0 D_{CJ}}$$

which provides values about 200 s for different initial pressure. This result is in good agreement with the value of I_{sp} obtained by pendulum method (cf Table 1).



Fig. 3a Dimensionless representation of TW overpressure time history for different p₀



Fig. 3b: Dimensionless representation of TW overpressure time history for different p₀.

Conclusion

In order to determine propulsive performances of a detonating mixture experiments were performed varying initial pressure p_0 of a reactive mixture (C₂H₄ + 3 O₂, $p_0 = 0,7 - 1$ and 1,5 bar) contained in the combustion chamber of a PDE into atmosphere at $p_a = 1$ atm. The different initial pressures p_0 of the same mixture simulate different detonating mixtures representative of C_nH_m/Air and C_nH_m/O₂ or other mixtures that could be detonated in the chamber at atmospheric pressure.

It has been observed that:

1) in the range of p_0 used, there is no effect of p_0 on I_{sp} . This is probably due to the very large value of p_k in comparison to p_a so I_{sp} remains constant and about 200s. The level of the thrust increases with p_0 and the application time is quasi constant.

2) I_{sp} can be calculated on the base of the CJ characteristics of the reactive mixture. It is related to $(p_k - p_a)$ by a constant factor $J_{max} = 5.20$.

3) the higher is the difference $p_k - p_a$ (i.e. $p_{CJ} - p_a$), the higher is the propulsive efficiency. So, the propulsion is favored by the use of mixtures presenting high density at atmospheric conditions, as gaseous monopropellant or hydrocarbon/heavy oxidizer mixtures.

References

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