Performance of Propellant Decomposition Products as Fuel in Airbreathing PDE

B. Veyssiere[1], B.A.Khasainov[1], P.Walton[1], E.Daniau[2].
[1]Laboratoire de Combustion et de Détonique (UPR 9028 CNRS), Université de Poitiers – ENSMA
[2]MBDA, Bourges

Corresponding author, Bernard Veyssiere: veyssiere@lcd.ensma.fr

1- Introduction

Different possibilities are foreseen for the choice of a fuel suitable to run an airbreathing PDE. Most of them regard liquid fuel as the best solution. However, use of decomposition products of a solid propellant can be considered as one of alternative solutions. Solid propellant presents the advantage of being easily loaded and transported safely. Its controlled combustion provides gaseous products containing several reactive species which can be used as a combustible and, mixed with an oxidizer (e.g. air), can form the detonable mixture running the PDE. Thus, it may be a good compromise to select a fuel with high potential detonation performance as well as a good stability. However, an important amount of solid carbon particles can be produced in the process of decomposition. Since those particles may represent a very important fraction of the total mass (eventually up to 50%), they can strongly influence the impulse yielded on the thrust wall and, to a greater extent, the engine specific impulse.

Going further in this perspective needs to predict more precisely the influence of these particles on the detonation parameters and evolution of the products behind the detonation front. From one hand, they decrease the heat released per unit of mass of the reactive mixture by increasing its specific mass. But a supplementary heat addition may be expected if an excess of oxidizer is provided to get the adequate oxygen balance allowing reaction of carbon particles, thus improving the detonation performance. However, the net effect of carbon particle cannot be predicted easily and the possible enhancement of the detonation depends on the characteristic time of particle burning. Results obtained by Veyssiere and Khasainov (1995) in modelling non ideal detonations in hybrid mixtures show that it depends on whether heat release from particle burning occurs inside the reaction zone of the gaseous detonation (before the CJ plane) or not.

In a first stage, we have studied the influence of solid carbon particles of variable diameter on the detonation parameters and evolution of detonation products of hydrogen-air mixtures (Walton et al., 2004). Particularly, we displayed that addition to a lean (r=0.6) hydrogen-air mixture of a suspension of carbon particles with a mass concentration of 50 g/m^3, is able to increase by 15% the pressure impulse on the thrust wall of a given PDE during one cycle, provided that the particles are sufficiently small (< 10µm): this case corresponds to particles releasing their heat in the reaction zone of the gaseous detonation. Increase of pressure impulse up to 10% can be obtained also with larger 20-µm particles. In this case, the detonation parameters are not augmented, but particles due to their late burning, downstream the CJ plane, induce an additional compression of detonation products providing the increase of pressure impulse.

Now, we study the effect of addition of carbon particles to a more complex reactive mixture, the composition of which is provided by the burning products of a solid propellant.

2- Estimation of the Optimum Detonation Performance of the Fuel

The solid propellant which is intended to be used in an airbreathing engine yields, after combustion, gaseous products having the following composition:

$$0.1324\ CH_4 + 0.0481\ CO + 0.2361\ H_2 + 0.0485\ H_2O + 1.5299\ N_2$$

This mixture will be called hereafter as mixture "A". Combustion of the solid propellant also yields carbon particles. Under working conditions, the quantity of solid particles is such that the composition of the whole mixture is:

$$A + 0.4876\ C$$

This corresponds to a mass particle concentration $\sigma_A = 101.3\ g/m^3$. The first step of the study consists in finding out the appropriate quantity of oxygen which is necessary to add to the mixture to obtain the highest detonation performance. For this purpose, we have calculated the CJ detonation characteristics of considered mixtures with air:

$$A + 0.4876\ C + x\ (O_2 + 3.76\ N_2)$$

where x is the number of moles of air added to the mixture. Calculations were performed with the thermodynamic code Quartet (Heuzé et al., 1987). Reaction products considered are: H_2, H, H_2O, OH, O, O_2, CO, CO_2, C, C(s), NO, NH_3, N and N_2. Value of x is varied from 0 to 0.5, i.e, from rich mixtures (r>2) to stoichiometric ones. Results are shown in Table 1 and Fig.1.

x	D_{CJ} (m/s)	P_{CJ} (bar)	T_{CJ} (K)	Equiv.ratio
0	1666	14.65	2126	2.131
0.1	1752	16.42	2485	1.73
0.2	1797	17.54	2723	1.456
0.3	1808	18.13	2847	1.257
0.4	1796	18.08	2866	1.105
0.488	1775	17.69	2842	1
0.5	1771	17.63	2825	0.987

Table 1. The CJ-detonation parameters of considered mixtures as function of the number x of moles of air added to decomposition products.

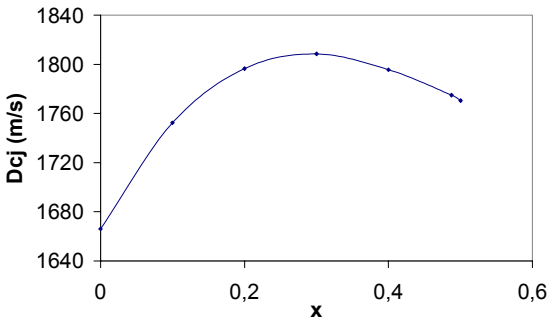

Fig.1. Variation of the detonation velocity as function of the number of moles x of air added to the decomposition products

It can be observed that the maximum detonation velocity is reached for x = 0.3. The same behaviour is obtained for the CJ pressure. As for the CJ temperature, its maximum is reached for x = 0.4. Therefore, the value x = 0.3 has been chosen for subsequent investigations, since it corresponds to the proportion of air addition susceptible to provide the highest detonation performance. This mixture is referred to hereafter as mixture "$A_{0.3}$" .

3- Influence of particle concentration

Choice of mixture $A_{0.3}$ allows to adjust at a fix value the optimum quantity of air to introduce in the chamber, in order to get the maximum detonation performance from the burning of carbon particles. However, the proportion of solid particles present in the whole mixture may be subject to variations (for example, on account of instabilities during the burning of the solid propellant). To estimate the influence of changes of particle concentration, we have studied the variation of CJ parameters of mixture $A_{0.3}$ as function of the mass particle concentration σ. Results are indicated in Table 2 and in Fig.2. Two concentrations of particles

are indicated; the first one corresponds to the mass of carbon particles released in the gaseous products; the second one is the concentration after dilution of the mixture by air addition.
As displayed by Table 2, the nominal concentration of σ_A = 101.3 g/m^3 in the initial mixture, becomes $\sigma_{A0.3}$ = 63.5 g/m^3 after dilution by the air. Fig.2 indicates that in this range of concentration, the detonation velocity is rather insensitive to changes in particle concentration. For example, when $\sigma_{A0.3}$ increases from 50 g/m^3 to 75 g/m^3, the detonation velocity diminishes only by 8 m/s. Thus, the chosen working conditions seem to be suitable to provide quasi constant values of detonation parameters.

σ (in A)	σ(in $A_{0,3}$)	n (mol)	D_{CJ} (m/s)	P_{CJ} (bar)	T_{CJ} (K)
0.00	0	0.0000	1594	13.08	2236
39.9	25	0.1919	1748	16.48	2711
79.7	50	0.3837	1805	18.02	2866
101.3	63.5	0.4876	1808	18.13	2847
119.6	75	0.5756	1798	17.9	2784
159.5	100	0.7675	1746	16.94	2561
199.3	125	0.9594	1675	15.78	2304
239.2	150	1.1512	1592	14.47	2040

Table 2. The CJ detonation parameters of mixtures $A_{0.3}$ as function of the mass particle concentration σ.

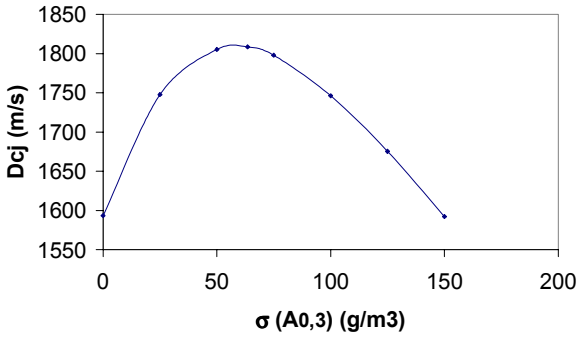

Fig.2 Variation of the detonation velocity in mixtures $A_{0.3}$ as function of the mass particle concentration σ .

4- Influence of particle size

Above calculations allow to predict the maximum effects which can be obtained by assuming instantaneous ideal reactions between all components (gaseous and gas particle reactions). However velocity and temperature relaxation times of particles behind the detonation front depend on their size. To take account of this effect, it is necessary to perform gasdynamic calculations. Numerical simulations have been performed with the EFAE code which allows simulating unsteady detonation propagation in two-phase reactive flows. Details of flow modelling can be found in Khasainov and Veyssiere (1996) and peculiarities of numerical methods for the considered problem in Veyssiere et al. (2002).

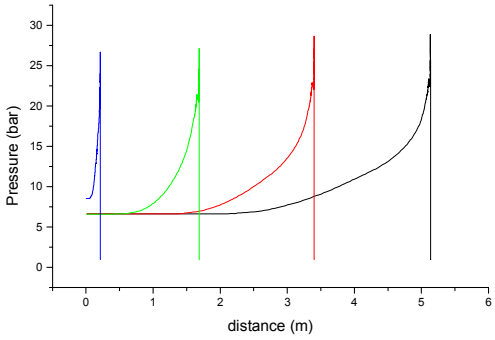

Fig.3. Pressure profiles at different stages of detonation propagation. Mixture $A_{0.3}$. Carbon particles : diameter 10 µm, concentration σ = 63.5 g/m^3.

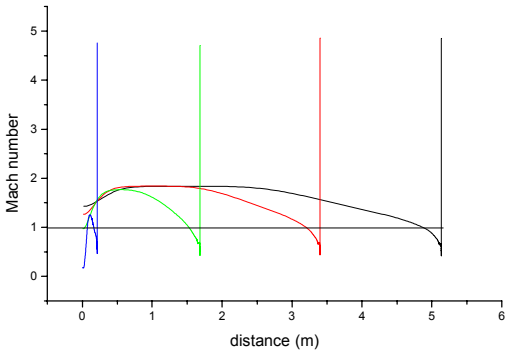

Fig.4. Mach number (*M=(D-u)/*s) profiles at different stages of detonation propagation. Mixture $A_{0.3}$. Carbon particles : diameter 10 µm, concentration σ = 63.5 g/m^3.

A first series of numerical simulations has been performed in a 6-m long tube in order to find out the conditions of steady detonation propagation in presence of particles. Typical results are shown in Fig.3 and 4 in the case of mixture $A_{0.3}$ with 10-µm carbon particles at σ = 63.5 g/m^3. Particularly, Fig.4 shows that the reaction zone behind the leading front is thickened, due to burning of carbon particles before the CJ plane: in this case, the CJ plane is located 28 cm behind the shock front.

5- Effect on PDE performance

Effect of carbon particles burning on the PDE performance can be evaluated by examining the changes induced on the impulse on the thrust wall during one cycle. Calculations have been made for a 600-mm long PDE tube. As seen in Fig.5, particles with a diameter smaller than 10 µm have close effects on the pressure impulse and may increase the maximum impulse up to 25%. Beyond 10 µm, increase of the maximum impulse by particle burning is not so efficient. Indeed, these particles have too long burning time and they are incompletely burnt when leaving the PDE chamber.

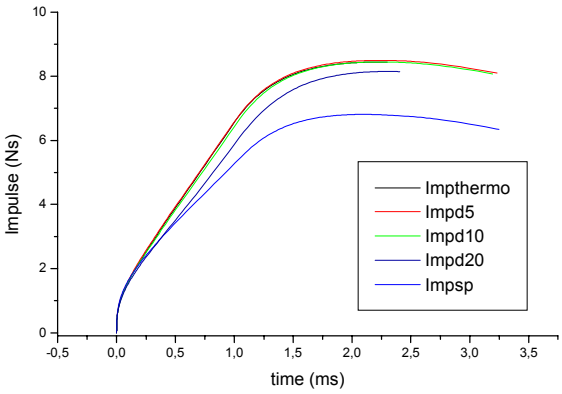

Fig. 5. Evolution with time of pressure impulse on the thrust wall for different particle diameters. Mixture $A_{0.3}$. Carbon particles, σ = 63.5 g/m^3.

6- Conclusions

In view of using the decomposition products of a solid propellant as a fuel for an airbreathing PDE, it has been shown that the presence of solid carbon particles (even in large quantity) in the decomposition products may be used to improve the performance of the engine. In the present study, increase of 25% of the pressure impulse has been predicted for sufficiently small particles (diameter less than 10 µm).

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References

Heuzé O., Presles H.N., Bauer P. (1987) Quatuor: a thermochemical code for computing thermodynamic properties of detonation and combustion products. 12ème International Pyrotechnics Seminar. Ed. Association Française de Pyrotechnie, pp.91-96.

Khasainov, B.A., Veyssière, B., (1996) "Initiation of detonation regimes in hybrid two-phase mixtures". Shock Waves, v6, p9-15.

Veyssière, B., Khasainov, B.A., (1995) "Structure and multiplicity of detonation regimes in heterogeneous hybrid mixtures". Shock Waves, V.4, p171-186.

Veyssiere B., Bozier O., Khasainov B.A. (2002) “Effect of a Suspension of Magnesium Particles on the Detonation Characteristics of Methane-Oxygen-Nitrogen Mixtures at Elevated Initial Pressures”, Shock Waves, Vol.12, pp.227-233, 2002.

WaltonP., Veyssiere B., Khasainov B.A., Daniau E. (2004), “Influence of Carbon Particles in Suspension on the Propulsive Performance of Hydrogen - Air Mixtures in Detonative Mode”, ISBN 5-94588-025-6, Ed. Torus Press.