Effect of a Suspension of Magnesium Particles on the Detonation Characteristics of Methane-Oxygen-Nitrogen Mixtures at Elevated Initial Pressures

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Introduction

Methane-oxygen-nitrogen mixtures at elevated initial pressure are used for projectiles propulsion in Ram accelerators. Projectile acceleration is the result of a complex process in which the material constituting the projectile may play a role. For example, it has been observed in the 30mm Ram accelerator at ISL that in the subdetonative mode, the terminal velocity of magnesium projectiles at the end of the Ramac tube is higher than the CJ detonation of the propellant gaseous mixture, whereas the projectile undergoes a mass loss during the propagation. In previous works [1,2], we have demonstrated that the experimental results could be explained satisfactorily by making the assumption that metallic particles ablated from the projectile react with the gaseous species and modify the performances of the propellant mixture.

Thus, addition of small magnesium particles in the reactive mixture during projectile propagation appears to be able to increase its terminal velocity in subdetonative mode. Prediction of expected performances is made for working conditions of the real 30 mm diameter 6 m long Ramaccelerator of ISL [3].

Thermodynamic calculations

First estimation of the effect of magnesium particles on the detonation is obtained by thermodynamic calculations. The gaseous mixtures considered for this study are two rich

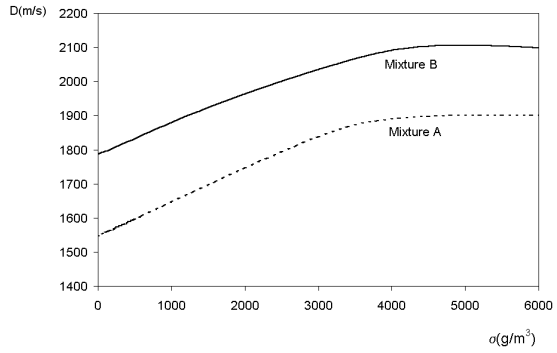


Figure 1 - Variation of the CJ detonation velocity as function of the mass particle concentration of magnesium. Thermodynamic calculations with Boltzman equation of state for burnt products.

methane-oxygen mixtures diluted with nitrogen: mixture A - 3 CH_4 + 2 O_2 + 10 N_2 (equivalent ratio: r = 3, ratio of nitrogen to oxygen mole number: Z_{N_2}/Z_{O_2} = 5) and mixture B - 2.8 CH_4 + 2 O_2 + 5.8 N_2 (r = 2.8 and Z_{N_2}/Z_{O_2} = 2.9), initially at 40 bar and 300 K. Calculations have been performed with the thermochemical code Quartet [4], using the Boltzman equation of state for the products. To calculate equilibrium composition of the products, the following species containing magnesium have been introduced in the database of the code: Mg(s), Mg(l), Mg(g), MgO(s), MgO(g), MgO(l), MgOH, $MgOH_2$, MgH, MgH_2, MgN. Data have been taken in the JANAF thermochemical tables [5].

The variations of CJ detonation velocity as function of the mass particle concentration of magnesium are plotted in Fig.1 for mixtures A and B. It can be seen that the detonation velocity increases from the value for the mixture without particles to a maximum. This maximum is reached for a magnesium concentration σ around 5400g/m^3 for mixture A, and 4800g/m^3 for mixture B. In the case of mixture A, detonation velocity increases from 1547 m/s to 1901 m/s, whereas it increases from 1786 m/s to 2106 m/s for mixture B.

Gasdynamic calculations

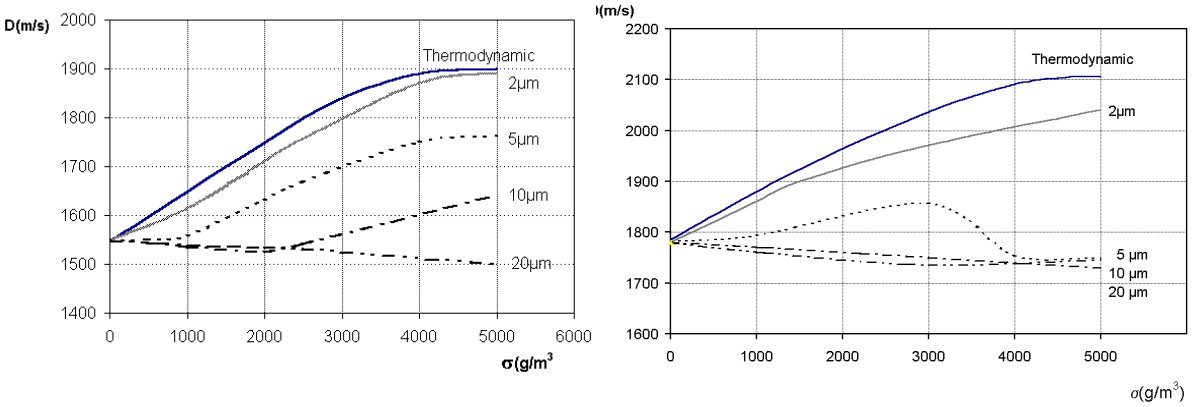
Better evaluation of the influence of particles requires to take two-phase flow effects into account, because relaxation of particles in the gaseous flow modifies the heat release process and leads to the propagation of non ideal detonation regimes. Thus, we have performed numerical simulations with the UKV code [6,7] designed to study the detonations of two-phase mixtures. The code treats unsteady 1D or 2D flows in eulerian coordinates. The two-phase flow is modelled by the classical two fluid flow method with mass, velocity and temperature different for the two phases, and modelling of interphase interactions by phenomenologic laws. Particles are supposed to have a spherical and the same diameter. Friction and heat transfer to the confinement walls are taken into account. Gaseous reactions and reactions between particles and gases are described by global kinetic laws. Ignition of magnesium particles is assumed to occur at the temperature T= 1103 K [8]. In a first approximation, the combustion time of particles is supposed to be proportional to the square of particle diameter.

Effect of addition of magnesium particles to the propellant mixtures has been studied as function of particle size and mass concentration, at initial pressure and temperature of 40 bar and 300 K. Dependence of the leading front velocity D on particle concentration σ is plotted in Fig.2 for different diameters of particles.

For mixture A, in the range of particle concentration under consideration (0-5000g/m^3) and for "fine" particles (2µm, 5µm), the detonation velocity D increases monotonously with augmentation of particle concentration. Maximum of D is reached beyond the upper concentration (σ =5000g/m^3). For particles of "intermediate" size (10µm), augmentation of σ results, in a first time, in decreasing D. The minimum value of D is obtained for σ of the order of magnitude of 2000 g/m^3. Then, the detonation velocity increases with σ and reaches the value 1642 m/s at 5000 g/m^3. For "large" particles (d=20µm), the detonation velocity decreases monotonously when σ increases, and drops to 1501m/s when σ = 5000 g/m^3.

For mixture B, a monotonous augmentation of D with σ is obtained only for 2µm particles. With 5 µm particles, augmentation of D is obtained only for $\sigma \leq$ 3000 g/m^3.

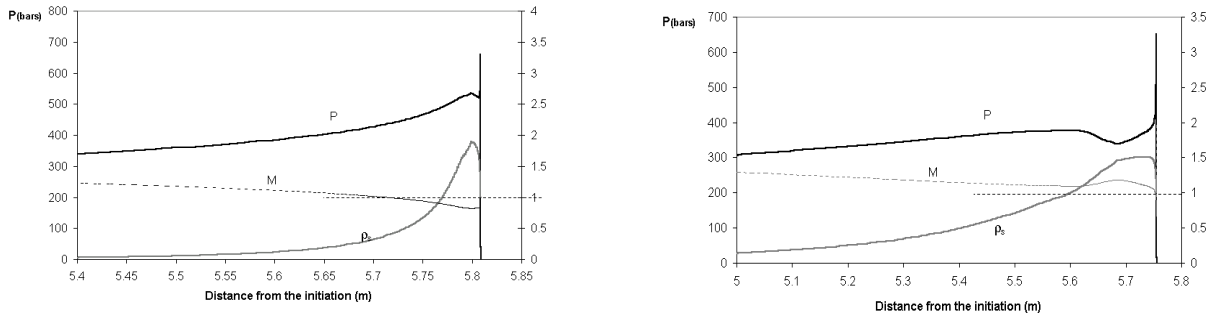
Beyond, addition of particles results in a decrease of D. For larger particles, increase of particle concentration results in a monotonous decrease of the detonation velocity.



(mixture A) (mixture B)

Figure 2 - Influence of the diameter of particles on the variation of the detonation velocity as function of the mass particle concentration of magnesium, at the end of propagation in the Ramac tube (6m). Calculations with the UKV code.

Further information on the influence of particle size may be obtained from the comparison of pressure, Mach number and particle density evolution. Typical examples are shown in Fig.3 for 5 µm and 10 µm particles with concentration σ = 1000 g/m^3, at the end of propagation in the tube (6m). For fine 5µm diameter particles (see Fig.3a), ignition occurs very early behind the detonation front and most of the magnesium is burnt in the subsonic zone (M=(D-u)/c<1, in coordinates relative to the leading front) behind the detonation front.



(a) 5µm (b) 10µm

Figure 3 - Pressure (P), Mach number (M) and particle density (ρ_s) profiles in the terminal part of the Ramac tube. Mass concentration σ= 1000 g/m^3 ; mixture A.

This subsonic zone is widened (0.06m) due to particle burning and the detonation structure is of the SFD type (Single Front Detonation), according to classification of detonation regimes in hybrid two-phase mixtures described previously by Veyssiere and Khasainov [6]: Additional heat release supplied by the burning of particles contributes to the augmentation of the detonation velocity. The complete combustion of magnesium is achieved 0.27m behind

the detonation front. On the opposite, in the case of 10µm particles, the detonation structure is different (Fig.3b). The subsonic zone is very thin (less than 0.002m) and no combustion of magnesium occurs inside it. This situation is typical of a PGD type detonation (Pseudo-Gas Detonation) as described in [6]. Evolution of pressure and particle density behind the front is due to relaxation of particles in the supersonic unsteady flow. Ignition of magnesium particles is discerned 0.07m behind the detonation front and generates important changes in the evolution of flow parameters: pressure re-increases and the particle density drops more rapidly. But, the heat release due to particle burning occurs too far in the flowfield to support the propagation of the leading front and the flow remains supersonic (in coordinates relative to the leading front). As a result, the detonation velocity is smaller than that of the mixture without particles as indicated in Fig.2.

In mixture A, for 10 µm particles, the detonation structure changes at concentrations greater than 2000 g/m^3 and becomes again of SFD type. This explains the re-augmentation of detonation velocity for high values of particle concentration. Results show that a large amount of magnesium is burnt before the CJ point like for finer particles, but the length of the subsonic zone is very extended, 0.31m, that is more than five times larger than for 2µm particles. Hence, the detonation velocity is augmented, but less than with fine particles.

Consequences on the performances of Ramaccelerators

Experiments of Henner [3] displayed that in the subdetonative mode, the terminal velocity of the projectile with the propellant mixture A could reach 1730 m/s, that is substantially higher than the CJ detonation velocity of the gaseous reactive mixture (1547 m/s). Analysis of the results of Fig.2 shows that under certain conditions, this velocity can be reached with the help of an additional heat release supplied by the combustion of magnesium particles (ablated from the projectile) with the gaseous products. Though thermodynamic equilibrium calculations indicate that theoretically this value could be obtained, in mixture A, for magnesium concentrations greater than about 1900 g/m^3, gasdynamic calculations show (see Fig.2) that this possibility strongly depends on particle size: for 2µm diameter particles, a minimum concentration of about 2100 g/m^3 is necessary, but for 5 µm diameter particles it requires more than 4200 g/m^3, and this velocity cannot be reached with 10µm or 20µm particles. Moreover, values of the detonation velocity plotted in Fig.2 indicate that the expectable highest performances correspond to a velocity of 1900 m/s at 5000 g/m^3. It can be noticed also that a limited but significant improvement of performances can be obtained with particles of intermediate size (10µm) provided their mass concentration in the mixture be sufficiently high, that is greater than 4000 g/m^3. At 5000 g/m^3, a gain of about 100m/s is yet possible with this size of particles.

Mixture B is more energetic, thus the detonation velocity of the pure gaseous mixture, D=1786 m/s, is higher than for mixture A. However, addition of magnesium particles is less efficient, since only very small particles (2 µm) are able to provide a substantial gain of the detonation velocity. For 5 µm particles the gain is limited and the particle concentration should be less than 3000 g/m^3.

As the problem of projectile acceleration is essentially a non stationary process, we have performed further calculations to exhibit in which conditions the steady detonation could be reached in the 6m tube. The evolution of detonation velocity along the tube as

function of the initiation energy is shown in Fig.4. Whatever be the initiation energy, the front velocity is the same after 2 m of propagation and is quasi constant at the end of the tube.

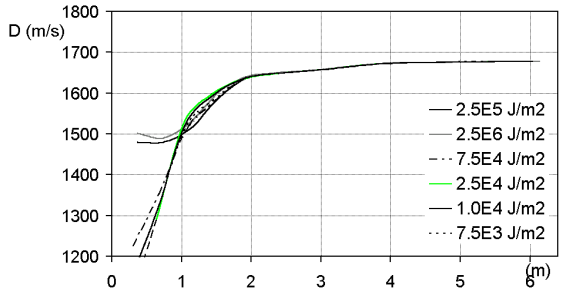


Figure 4 - Evolution of the detonation velocity along the tube as function of the initiation energy. Particle diameter 5 μm; concentration σ = 3000 g/m^3.

In conclusion, experimental observations of Henner [3] can be explained satisfactorily by the potential contribution of the magnesium ablated from the projectile to an augmentation of effective heat release in the propelling mixture (in addition to projectile weight loss). Therefore, a substantial gain of the terminal velocity of an inert projectile can be obtained by adding magnesium particles to the gaseous reactive mixtures: The efficiency will depend on the composition of reactive mixture and on particle characteristics: sufficiently fine particles and adequate mass concentration are required. It is worthy to note that present calculations were made assuming a uniform distribution of particles inside the tube. Considering particle concentration gradients inside the tube would be of great interest. However, experimental validation of present predictions in a real experimental Ramac tube is necessary.

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