Compressibility Effects of Unreacted Propellant on Thermally Choked Ram Accelerator Performance

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Introduction

Successful prediction of the ram accelerator thrust-Mach number relationship for the thermally choked propulsive mode has been accomplished in a straightforward manner that yields the main parameters of the acceleration process. This analysis used one-dimensional modeling of the flow field that propels the projectile (Bruckner et al. 1991) and the quasi-steady conservation equations were applied to a control volume attached to the projectile. Dimensionless parameters were defined: the non-dimensional heat release, non-dimensional thrust, and the pressure and specific volume ratios between the initial and final states, respectively. Performance calculations of thermally choked operation at low fill pressure, i.e., at less than 3 MPa, using the ideal gas equation of state (EOS) for both the unreacted propellant and products were in good agreement with experimental results. In the fill pressure range of 3-8 MPa, however, the products are at such high pressure, i.e., of the order of several tens of MPa, that the ideal gas assumption was no longer valid and a more appropriate EOS was used instead (Bauer et al. 2000).

Discussion

Depending upon the level of fill pressure, several equations of state are available for dense gaseous energetic materials. The virial type of EOS can be more or less sophisticated, depending upon the extent of complexity of the intermolecular modeling, and has been shown to be appropriate for most gaseous explosive mixtures that have been investigated at moderate initial pressures, i.e., less than 10 MPa (Bauer et al. 1994). Accounting for the real gas effects on the combustion products yielded a large increase in the value of the non-dimensional thrust as a function of the freestream Mach number and a corresponding increase in the Chapman-Jouguet (CJ) detonation velocity. For thermally choked performance calculations the Boltzmann EOS has been successfully applied (Bauer et al. 1998). It is based on very simplified molecular interactions, which makes it relatively easy to use in calculations.

In addition to compressibility corrections, the real gas effects on the energetic EOS need to be taken into account. This concerns all the calorimetric coefficients, as well as the thermodynamic parameters, which can no longer be expressed as only a function of temperature. Any thermodynamic property $\tilde{\Psi}$ of the real gas can be expressed in two terms:

$$\tilde{\Psi} = \Psi^0 + \Psi^{ex}$$

where the exponent '0' and 'ex' designate the ideal gas state and excess term respectively. These correction terms may thus be expressed in differential forms (Byers Brown and Amaee 1992). The enthalpy, for instance is expressed in the form:

$$\tilde{h} = c_p T + h^{ex}$$

The set of one-dimensional conservation equations on which this modeling is based requires the knowledge of a series of thermodynamic parameters that can be provided by the classical thermodynamic functions; however, some further numerical and analytical treatment is needed as discussed below.

As the initial pressure increases, the corrections become more sophisticated, but the main relationships that account for real gas effects are basically the same. These include the use of general forms of analytical operators applied to correct the thermodynamic functions and coefficients. Increasing the initial pressure beyond the 8 MPa value, thus yielding combustion products of the order of 100 MPa, may still be sufficiently modeled with a virial-type EOS that includes more severe molecular interaction laws (Heuzé 1986). For instance, the Percus-Yevick EOS was used successfully.

At initial pressures beyond the range of 10 to 12 MPa, a further refinement of the modeling consists of taking into account the real gas corrections for the initial state. It has been shown that the two-constant Redlich-Kwong EOS (Kemp et al. 1975, Morris et al. 1986) is most appropriate for gaseous mixtures at initial pressures in the range of 10 to 50 MPa. It has been successfully used in previous studies dealing with detonation of relatively dense gaseous mixtures and was found to yield a better knowledge of the physical parameters of the initial state (Bauer et al. 1991). This was further validated by thermochemical calculations that allowed a very accurate prediction of the detonation properties of the mixtures. This equation of state is given according to the following form:

$$\frac{pv}{RT} = \sigma(v,T) = \frac{v}{v-b} - \frac{aT^{-1.5}}{R(v+b)}$$

where 'a' and 'b' are physical constants that depend on the critical pressure and temperature of the mixture.

The analytical treatment for incorporating real gas effects of the unreacted propellant into the performance calculations was similar to that used for the combustion products. All thermodynamic properties of the propellant mixture were corrected. This included the caloric imperfection term, namely, $\eta = \frac{\tilde{h}}{c_p T}$ as well as the enthalpy and heat capacities of the unreacted mixture. The general analytical form of the non-dimensional thrust, which has been presented in Bauer et al. (1998), was modified accordingly. Moreover, a calculation of the sound speed was performed involving the real gas corrections based on the Redlich-Kwong EOS. A slightly higher value of the sound speed was obtained, yielding a lower freestream Mach number, which, in turn increases the minimum operating velocity of the thermally choked ram accelerator. The QUATUOR code (Heuzé et al. 1986, 1987) was used in this investigation, especially for determining the thermodynamic parameters in the initial state, as well as for the calculation of the chemical equilibrium composition.

The effects of real gas correction terms on the thermally choked ram accelerator performance show that the non-dimensional thrust-Mach number profiles predicted with the real gas correction to the products increases with increasing fill pressure. However, the inclusion of real gas corrections to the reactants only slightly changes the thrust profile.

The more significant effect of the EOS for the unreacted propellant on ram accelerator operation is the change in sound speed that occurs at elevated fill pressures. A plot of sound speed as a function of fill pressure for $2.6CH_4+2O_2+9.2N_2$ propellant is shown in Figure 1.

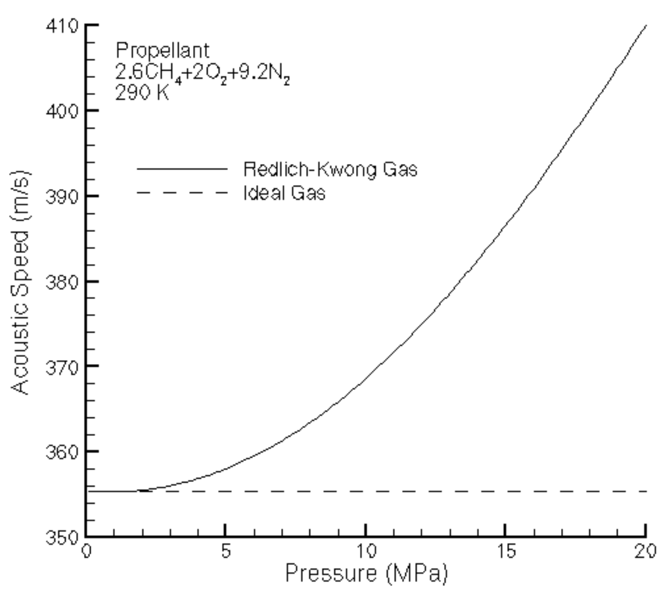

Figure 1: Sound speed of $2.6CH_4+2O_2+9.2N_2$ at 290 K

The sound speed increases by 15% at fill pressures of 20 MPa, which implies that the minimum entrance velocity to initiate ram accelerator operation must be increased by 150 m/s. This effect has indeed been observed in high pressure experiments as reported by Bundy et al. (2000). Another experimental observation that may be accounted for by including the reactant compressibility effects is the increase in the minimum velocity at which a projectile can maintain supersonic flow through its throat (i.e., point of maximum flow occlusion) as presented by Bundy et al. (1999).

Conclusions

The corrections to the conservation equations that were elaborated in this paper are fully generalized and can be applied to any EOS. Ram accelerator thrust in the thermally choked propulsive mode at fill pressures greater than 10 MPa is predicted to be 50% greater than that of an ideal gas. Corrections to the reactants indicate that sound speed is sufficiently altered at elevated fill pressure to affect the minimum entrance velocity and throat starting velocity of the projectile. Details of these analyses and experimental results will be presented.

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