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ON THE EXISTENCE OF REAL STANDING DETONATIONS IN SCRAMJETS

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ABSTRACT

Some decades ago the idea that standing detonations accounted for combustion in scramjets gained widespread popularity and continues in occasional use, despite the marked changes in our current understanding of detonations. Thus, the original concept of the wave was a unidimensional phenomenon, with the leading shock, produced by interactions of the unburnt flows with each other and the walls of the chamber, switching on exothermic reactions in a plane a fixed distance behind it. On account of the profound influence of the temperature of the unburnt mixture on the reaction steps initiating the release of heat, such a system, were it initially to be produced, would rapidly be transformed into a real multidimensional detonation by any small perturbation in the flow of unburnt mixture.

We outline the conditions of mixing, flow velocities, temperatures and pressures required for a real detonation to exist in a supersonic combustor. Since these appear to be achievable over a wide range of properties of the mixture, we examine the probable effects of the characteristic dimension of the combustor.

INTRODUCTION

The idea that stationary detonation waves can exist in scramjets is not new. Thus Nicholls et al (1959, 1962 and 1963) postulated an ideal front resulting from the expansion of a jet of hydrogen in a hot supersonic flow of air in a convergent-divergent nozzle. Their concept involved very fast mixing, unaffected by the presence of the reaction zone which was triggered by the injection shock. Then, the hypothesis of a non-structured detonation was tenable. Presently, it is accepted (Nettleton, 1987) that at least one shock propagating across the consequently non-planar lead front is required, with reaction zones in gas heated by a combination of the attenuating portion of the lead front and transverse wave and by the Mach stem. Thus it is timely to examine the consequences of these findings on the role of detonations in scramjets.

Consider mixing and combustion requirements of a standing front. Although the composition of the mixture need not be uniform across the duct, it must be within the limits of flammability but remain unburnt until engulfed by the front. Since the air stream supplies momentum, molecularly mixed regions are likely to be so fuel-lean that a single-headed front of considerably larger area than that of duct results.

Section 2 presents theoretical detonation velocities for mixtures likely to be encountered in scramjets in order to assess whether, when enhanced by the area ratio of wave to duct, standing fronts are feasible. Section 3 considers lifetimes of molecularly-mixed regions in analogous fashion based on historical values of ignition delays, τ, recommended by Momtchiloff et al (1963).

Standing waves are possible on both scores, so Section 3 deals with a more acceptable criterion, involving the relationship between spacing of transverse waves, λ, and characteristic dimension of the duct,d. The sparse experimental data (Bull et al, 1982 and Tieszen et al, 1986 and 1991) on the effects of initial temperature, pressure and composition are presented. We have supplemented these using a well-established but empirical relationship between ignition distance, L, derived from τ, determined from recent kinetic data, and λ, rather than taking Barthel's (1974) more basic approach. The rigour of the latter is weakened by the observed irregularities in λ in oxyhydrogen mixtures not diluted by a noble gas. Despite the resultant uncertainties, it appears that the effects of initial pressure and temperature on the occurrence of standing fronts should be analogous to the well-known peninsular of deflagrations.

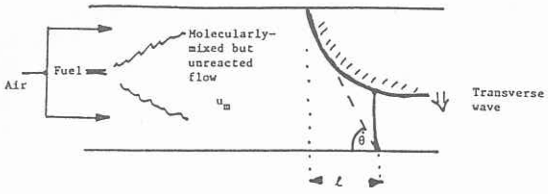
CHAPMAN-JOUGUET VELOCITIES IN HYDROGEN-AIR MIXTURES

Fig. 1 is a sketch of s single-headed front found in marginally detonable media. Its average velocity, D_{CJ}, is described by unidimensional theory

$$D_{CJ} = \left[2q\left(\gamma_2^2 - 1\right)\right]^{0.5}$$

where q is the energy released per unit mass of mixture in forming products at equilibrium behind the lead wave and γ_2 is their ratio of specific heats. For single-headed waves the velocity of the Mach stem, D_M, is $D_M = 1.3\ D_{CJ}$ and of the most attenuated portion, D_a, $D_a = 0.6D_{CJ}$.

FIGURE 1

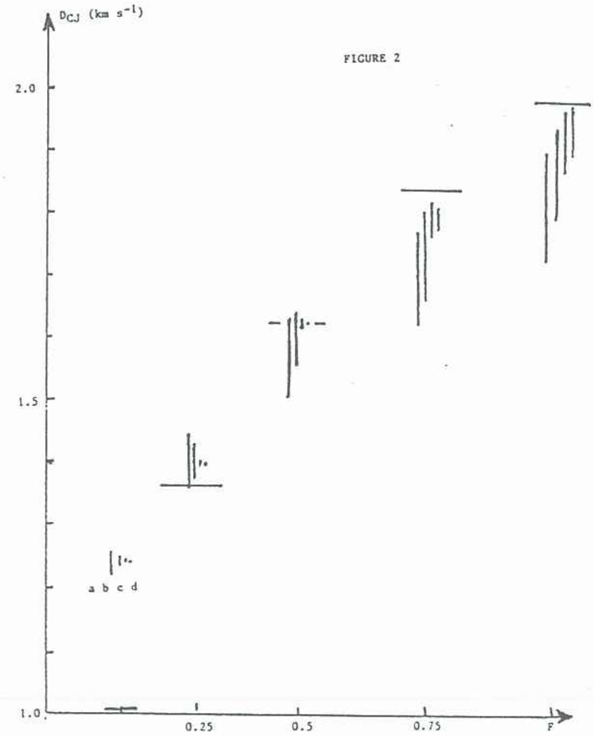


Stationary real detonation when

(i) $D_{CJ} = u_m \sin\theta$

(ii) $\tau_{ig} = \ell / u_m$

Temperatures, pressures and compositions in scramjets and models thereof vary over wide ranges. We have chosen a temperature of 200 K for the fuel jet (> 200 K for flight conditions with skin cooling), air temperatures from 800 to 2000 K, pressures from 10 to 300 kPa and compositions $F \leq 1.0$.



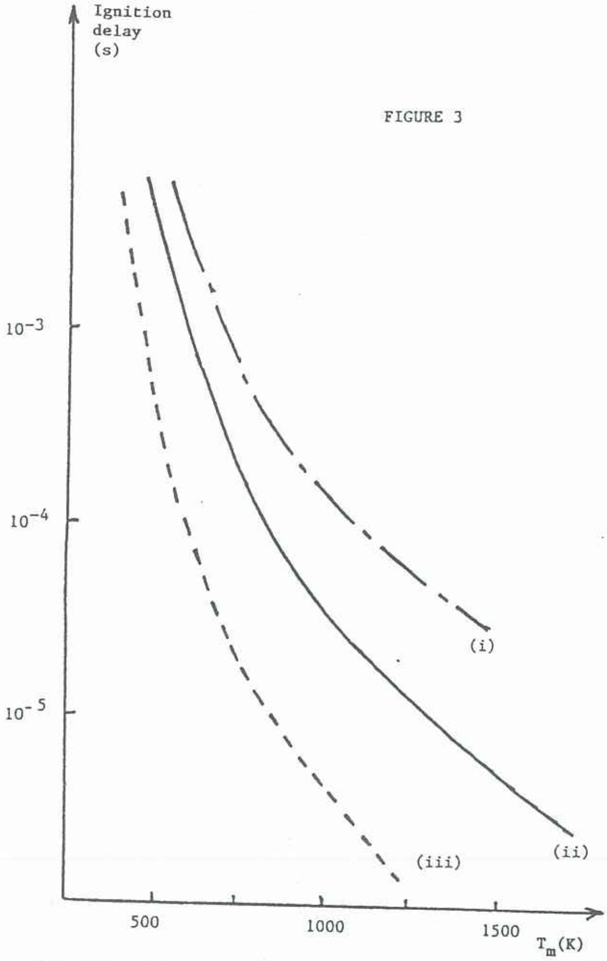
Effect of composition on Chapman-Jouguet velocity of hot hydrogen-air mixtures; a,b,c & d, T_a = 2000, 1500, 1000 & 800 K respectively; maximum D_{CJ}, P_o = 300 kPa and minimum D_{CJ}, p = 10 kPa; — D_{CJ} for mixture at ambient temperature and pressure

Fig. 2 shows the computed results. Quenching via losses to the walls occurs for $D_{CJ} < 1.5$ km s^{-1}. suggesting a lower limit of $F \sim 0.3$. Standard values for 298 K and 100 kPa are denoted by bars. Note that the effect of increasing dissociation of products with increasing air temperature is still manifest at a pressure of 1 Ma.

Referring to Fig. 1 with the skewed front at an effective angle to the wall, θ, a standing front can exist when $D_{CJ} = U_m \sin\theta$, where U_m is the axial velocity of the mixture. Observed distances between head and tail of the lead wave, l, can be approach d, so that standing detonations should be possible over the range of flight velocities, v_f, of practical interest $1.5 \leq v_f \leq 7.0$ km s^{-1}.

HISTORICAL VALUES OF τ IN HYDROGEN-AIR MIXTURES

In chain-branching processes τ is associated with the build up of a pool of radical and atomic species via a limited degree of highly endothermic dissociative reaction and a preponderance of thermally neutral branching steps, resulting in only a limited change in temperature. This occurs later during the highly exothermic, 3 body recombination steps. Thus τ depends most strongly on the initial temperature, less strongly on pressure and only weakly on composition of the mixture.



Ignition delays for stoichiometric mixtures of hydrogen with air: (i) kPa, (ii) 100 kPa and (iii) 1 MPa

Fig. 3 shows historical values recommended from a combination of experimental and computed results for stoichiometric mixtures of hydrogen and air. The data exhibit the expected trends with changing initial conditions. The suggested increase in τ for mixtures departing from F = 1 is ≤ 2.

The structure of the front can only be preserved when the time of passage into the trailing edge t > τ. With ℓ = 30 mm, typical of confinements d ≤ 0.1 m and U_m = 2 km s^{-1}, t = 15 μs, within the range τ Fig. 3 indicates as appropriate to an operational scramjet.

DETONATIONS IN SCRAMJETS

Whilst recognising there are alternative ways of predicting pressure, temperature and composition limits (Gelfand et al, 1991), we have preferred that involving matching λ with d. With lower-limit quenching as λ approaches d, the distance between lead wave and completion of reaction increases, resulting in enhanced losses to the wall, so that alternative theories involving losses from an ideal wave converge with the present approach.

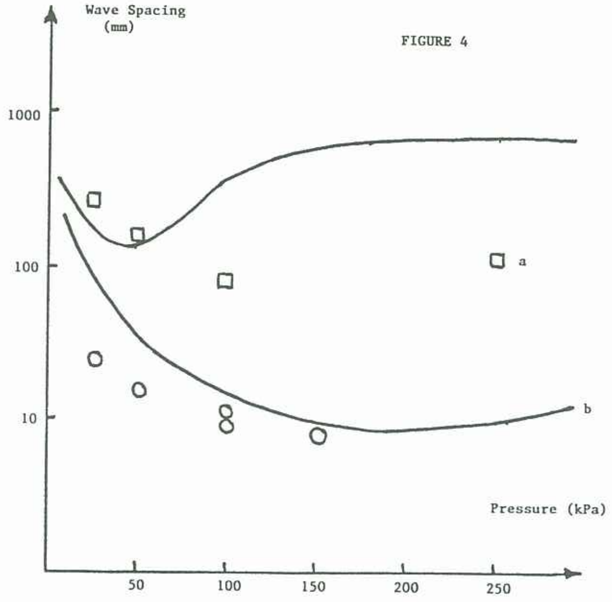


FIGURE 4

Influence of initial pressure and composition on spacing of transverse waves;

□ & a F = 0.5 o & b F=1.0

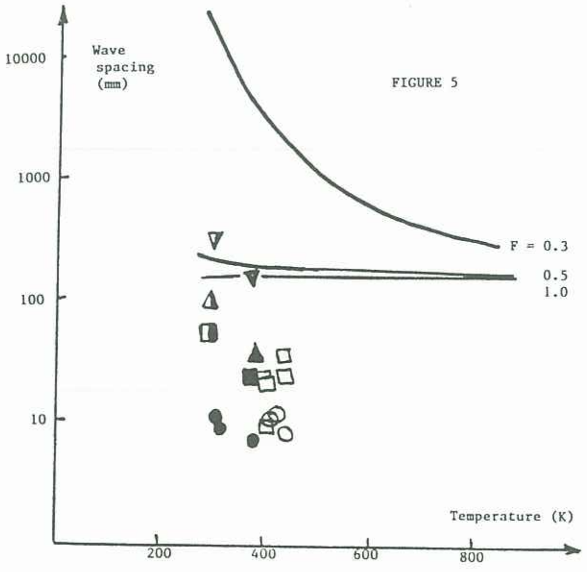


FIGURE 5

Effect of temperature on spacing; F=0.43 F=0.6, 0 F=1.0 and , F=3.0

Fig. 4 shows experimental results on the effects of initial pressure and composition on λ and Fig. 5 the sparse results on influence of temperature and composition. The full lines come from a kinetic analysis, using recently recommended rate constants, of induction length, defined as that at which dT/dx is a maximum (Shepherd, 1990), and the well established but empirical relationship λ = nL where 10 < n < 100 (Nettleton, 1987). We have taken n = 70, producing reasonable accord with the experimental results and suggesting initial temperatures in a typical scramjet should have little effect on λ, providing F > 0.3.

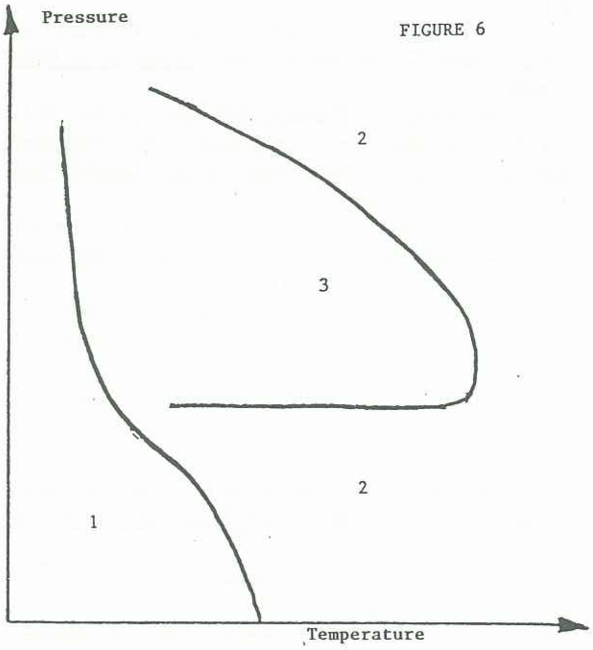


FIGURE 6

National detonation peninsula for mixtures of fixed composition: 1 no ignition, 2 deflagration and 3 standing detonation.

On this basis Fig. 6 presents the likely effects of pressure and temperature on combustion regimes in a scramjet. In region 1 low temperatures and pressure result in large values of τ and at higher temperatures but low pressures recombination reactions are too slow for a flame. Region 2 involves such low values of τ that ignition follows almost immediately on molecular mixing, as would occur with atomic oxygen present in the free stream. Region 3, that of standing detonations is bounded at low pressures by the requirement λ < d.

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