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OXYHYDROGEN OBLIQUE DETONATION SUPPORTED BY TWO-DIMENSIONAL WEDGE

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Abstract

A numerical analysis is performed on the possibility of generating a standing oblique detonation (SOD) around a two-dimensional blunted wedge. The incoming hypersonic flow consists of a uniformly-premixed stoichiometric oxyhydrogen mixture diluted by 70% Argon of a Mach number higher than its Chapman-Jouguet value 4.8.

Varied parameters are the nose radius, wedge angle, and the Mach number and temperature of the incoming flow. Based on the Euler equations and realistic oxyhydrogen elementary reactions, the 2nd-order-accurate explicit or implicit TVD upwind scheme of Yee-Harten gives the following different modes in SOD; (i) steady oblique coupled detonations, (ii) steady oblique decoupled detonations, (iii) oscillating but standing oblique coupled/ decoupled detonations, and (iv) run-away detonations which are unable to stand in front of a wedge.

1. Introduction

As a start of a real SCRAMJET engine, where combustion would be performed probably in a mixed mode of highly-turbulent diffusion flames and a number of shock wave interactions, exothermic chemical reactions occurring behind a leading shock wave in a hypersonic premixed gas mixture are interesting and useful. This mode of combustion, i.e. a detonation steadily maintained in front of a blunt "detonation holder" like an oblique shock wave, has not been studied widely. The authors group[1-5], a NASA Ames group[6] and Pratt[7] have recently been active in exploring the fundamental properties of a standing oblique detonation (SOD) from numerical and theoretical point of view.

There is a fundamental problem in the concept of standing oblique detonation: Can a detonation steadily be stabilized in front of a two-dimensional wedge or a three-dimensional cone-cylinder, without causing decoupling between the oblique bow shock wave and subsequent chemical reaction zone in a realistic gas mixture like oxyhydrogen?

This paper is to find out the conditions necessary to establish a standing oblique detonation over a two-dimensional wedge; changed parameters are (i) wedge angle, (ii) incident Mach number, (iii) temperature of incident gas mixture, and (iv) radius of the blunted tip portion of wedge. Other than these parameters, there could be an additional one like exothermicity by changing the mixing ratio among oxygen, hydrogen and diluent; in the present calculation, however, the mixture has been fixed at $2H_2 + O_2 + 7Ar$.

Another problem is whether the well-known triple shock structure always existing in a Chapman-Jouguet detonation persists in a standing oblique detonation. A number of slip surfaces behind multiple Mach reflections, curved shock waves and shock wave interactions, along with their nonsteady characters, can enhance mixing between (i) burnt and unburnt gases, and (ii) locally rich and lean mixtures. Therefore, even if the incoming flow is insufficiently mixed between oxidizer (air) and fuel (hydrogen), still the triple-shock/multiple-Mach-reflection structure can play an important role of mixing enhancement: The existence of such an unsteady triple-shock structure is already found out by Wang and Fujiwara[1].

2. Formulation of Problem

Fundamental equations are the Euler equations containing source terms arising from chemical reactions, that are expressed in a vectorized conservation-law form in the Cartesian coordinate system (x,y,t). The 11 unknowns are ρ_i (i = H_2, O_2, OH, H, O, HO_2, H_2O and Ar), ρu, ρv and the total energy e which is given by

$$e=\sum_{i=1}^{N}\rho_i h_i+\frac{1}{2}\rho(u^2+v^2)-p, \tag{1}$$

where p denotes the pressure, u and v the velocity, ρ the mass density, $h_i = h_i\,(T)$ the enthalpy of i-th species given in JANAF Table, N = total number of existing chemical species = 8. Temperature T, the most important physical quantity in a chemically reacting flow, is decoded from the solution e, h_i and the equation of state $p = \rho RT$ where the gas constant R is defined as

$$R=\frac{R_0}{\rho}\sum_{i=1}^{N}\frac{\rho_i}{M_i}. \tag{2}$$

Here R_0 = the universal gas constant and M_i = the molecular weight of i-th species. Thus the gas under study is a mixture of real gases governed by a set of the following elementary chemical reactions between molecular hydrogen and oxygen:

$$H_2+O_2=2OH,$$

$$H+O_2=OH+O,$$

$$OH+H_2=H_2O+H,$$

$$O+H_2=OH+H,$$

$$OH+OH=H_2O+O, \tag{3}$$

$$H+OH+M=H_2O+M,$$

$$H+H+M=H_2+M,$$

$$H+O_2+M=HO_2+M,$$

$$HO_2+OH=H_2O+O_2.$$

The chemical constants, i.e. the frequency factor, the power index of temperature and the activation energy in each forward reaction rate expressed in a modified Arrhenius form, are taken from Ref. 8). The rate constants of each backward reaction are given from the temperature dependence of the pressure equilibrium constant of a chemical species easily found in JANAF Thermodynamic Tables. The law of mass action can provide the source terms of the Euler equations using only ρ_i and T, thereby giving the Euler equations in a closed form.

The physical quantities are non-dimensionalized in the following way: The coordinate x and y by the radius of curvarture L^* of a two-dimensional wedge, the velocity u and v by the sound speed a_∞ of incoming uniform hypersonic flow, the density ρ by the density ρ_∞ of incoming flow, the pressure p and the total energy e by $\rho_\infty a_\infty^2$, the temperature T and the enthalpy h by a_∞^2, the time t by $\tau = L^*/a_\infty$, and the rate of mass production w by $\rho_\infty a_\infty/L^*$.

Due to a number of elementary chemical reactions in the present phenomenon, there are several characteristic times τ_i, along with the fluid dynamic characteristic time τ; this can make the entire equations stiff and essentially difficult to solve. Such stiffness can be solved by introducing spatially sufficient resolution into a utilized grid system and by making the grid adaptive to the resolution of highly-exothermic and strong-gradient regions in a flow.

3. Numerical Procedures

The fundamental equations are transformed into a general coordinate system (ξ,η), which is typically shown in Fig. 1. A technique of locally adaptive grids is utilized to

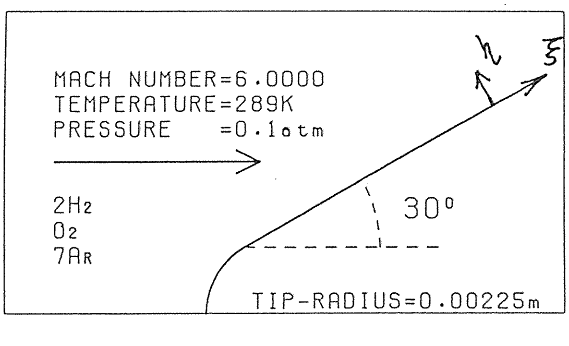

Fig. 1. Geometry of 2-D blunted wedge.

capture a leading bow shock wave and to resolve rapid chemical reaction immediately behind the shock wave. In other words, the Rankine-Hugoniot relations have to hold across the bow shock where chemical reactions are supposed to be frozen due to insufficient residence time within the shock profile. The solution to a non-reacting perfect-gas/real-gas flow under the same incident Mach number is used as the initial condition to a reacting flow problem. In reacting flows the utilized grid points are 51 or 86 in ξ direction and 51 in η direction. With the evolution of calculation from an initial condition toward the final steady/stationary-oscillating solution, the position of the bow shock is gradually stabilized, and the line $\xi = 37$ is adjusted to fit the position of the bow shock, while maintaining the ξ = constant lines intact. Namely the shape of η = const lines are adaptively altered several times to fit the bow shock, thereby reducing the number of grid lines and yet holding high resolution in the reacting region near the shock wave. A perfect ZND detonation profile is obtained even on the stagnation streamline in the shock layer where the most rapid chemical reaction is expected to occur; chemical reaction is completely separated from the shock wave.

As numerical scheme of integration, an implicit TVD upwind technique by Yee-Harten is used; note here that the source terms are treated explicitly. Without resorting to a fully implicit technique, we are able to reach convergent/non-divergent solutions.

Since the enthalpy h_i of each species is a complicated function of temperature fabricated from JANAF Thermodynamic Tables, decoding of temperature T from the total energy e requires the following process: (i) An approximate solution from the sign change of r.h.s. and (ii) the exact solution by Newton-Raphson method starting from the approximate solution.

4. Results and Discussions

Calculations are performed in the following parameter range:

(i) Incident Mach number $M_\infty = 6$ and 10, while the Chapman-Jouguet Mach number $M_{CJ} = 4.8$.

(ii) Wedge tip radius of curvature $L^* = 2.25$, 3, 4 and 6 mm.

(iii) Wedge half angle $\theta = 30$, 35, 37 and 40 degree.

(iv) Incident temperature $T_\infty = 298$ and 600 K, while maintaining the incident velocity U at a constant value; the sound speed and as a result the incident Mach number M_∞ are changed.

(v) Incident pressure is kept unchanged at $p_\infty = 0.1$ atm.

First, the parameters are selected as $M_\infty = 6$, $L^* = 2.25$ mm, $\theta = 30$ degree and $T_\infty = 298$ K. As seen in Figs. 2 (a), (b) and (c), the leading bow shock decoupled with the reaction zone toward the downstream part of

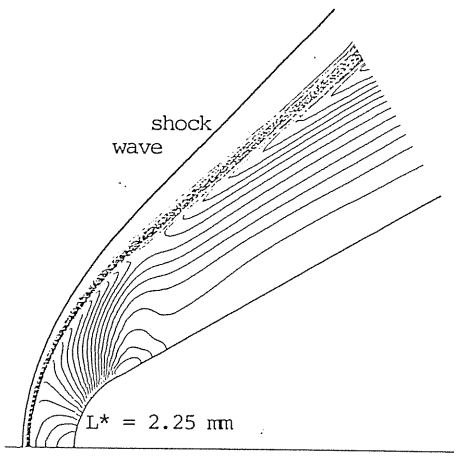

Fig. 2 (a) Contours of H_2O density for $L^* = 2.25$ mm, $M_\infty = 6$ and $\theta = 30$ degree.

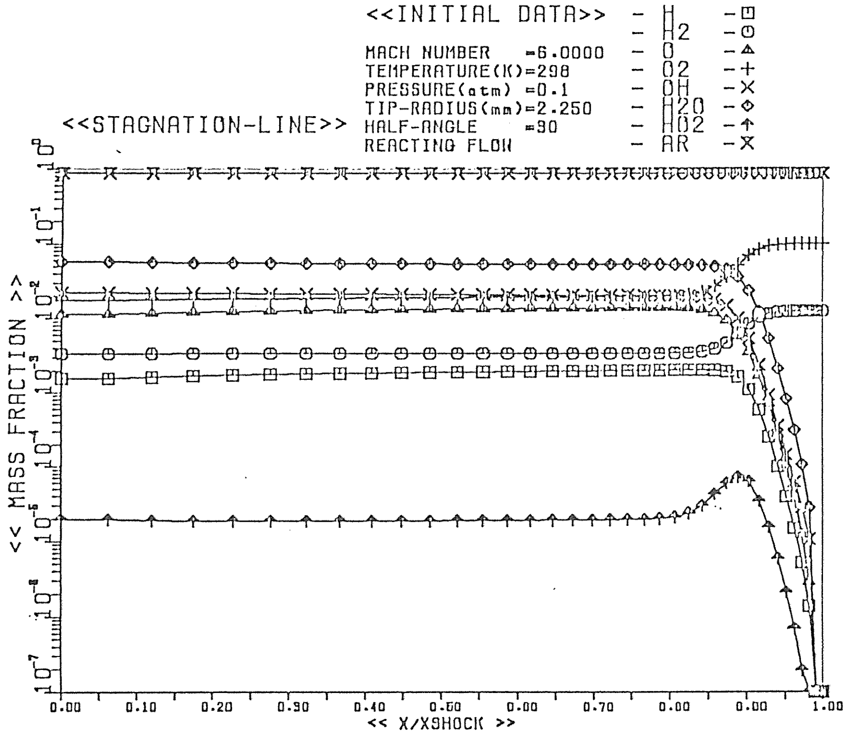

Fig. 2 (b) The distribution of mass fraction of i-th chemical species along the stagnation streamline between the bow shock wave ($x/x_{shock} = 1.0$) and the body surface ($x/x_{shock} = 0$).

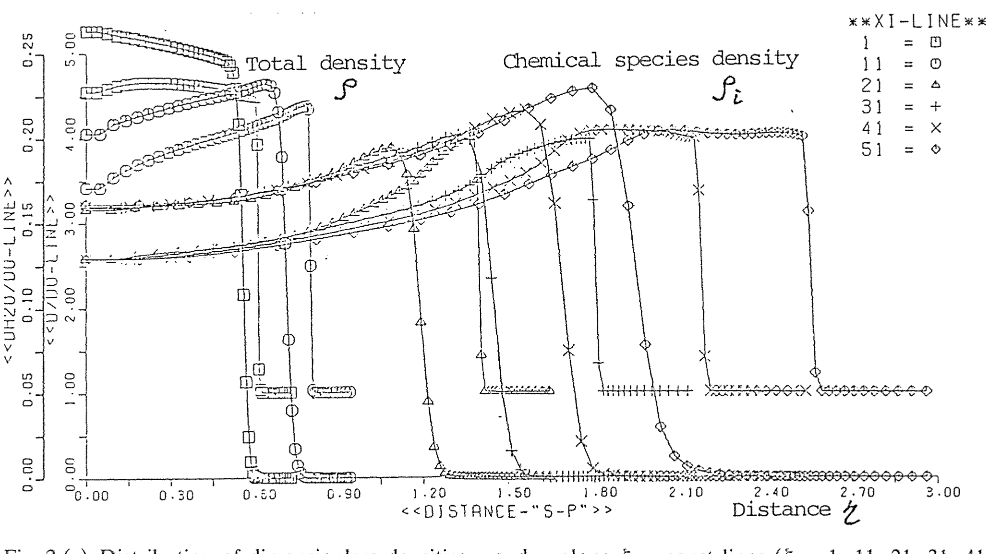

Fig. 2 (c) Distribution of dimensionless densities ρ and ρ_i along ξ = const lines (ξ = 1, 11, 21, 31, 41 and 51). The bow shock is captured almost as a discontinuity which completely separates from subsequent chemical reactions.

the shock. Fig. 2 (b), showing the mass fraction ρ_i/ρ of each species along the stagnation streamline, indicates that H_2 and O_2 show no jump across the shock and start decreasing when the other species start increasing; complete separation between shock and reaction. Fig. 2 (c) shows the distribution of the density ρ and ρ_{H_2O} along several ξ = const lines (ξ = 1, 11, 21, 31, 41, and 51). The jump in ρ corresponds to the location of the bow shock, while the jump in ρ_{H_2O} indicates the region of chemical reaction; note that both are clearly separated and, in addition, only one or two grid points are necessary to describe a shock wave profile.

There are basically two characteristic length scales in the present problem; the tip radius L^* and the chemical induction distance L. L^* mainly controls the gasdynamic aspect like shock standoff distance. When the tip radius is increased to $L^* = 4$ mm, the first striking result to note is that, as shown in Fig. 3, the reaction zone has ceased to decouple with the bow shock, maintaining a nearly constant distance between the two even in the downstream. This situation is not altered for an increased tip radius $L^* = 6$ mm. Thus $L^* = 4$ mm seems to be a critical size as a holder of coupled standing oblique detonations.

When the wedge angle is increased, the subsonic flow domain limited in the frontal shock layer for $\theta = 30$ degree (Fig. 4 (a)) is extended to the downstream throughout the wedge surface (Fig. 4 (b)); however, most of the flow is still supersonic. For a higher wedge angle $\theta = 40$ degree, the flow behind the bow shock gradually becomes subsonic throughout the flowfield during the calculation evolution, and then the bow shock proceeds forward never to give a standing position. After several attempts the critical wedge angle is found to be $\theta = 37–40$ degree; this type of criterion suggested by Pratt[7] is shown in Fig. 5, where existence of solution can not be explained easily without performing numerical calculation.

Finally, a higher incoming temperature $T_\infty = 600$ K, while the incoming velocity kept unaltered, generates a weaker bow shock due to a lower incoming Mach number, and as a result the temperature immediately behind the bow shock is lower. Thus the long chemical induction time is not enough to provide a coupled standing oblique detonation.

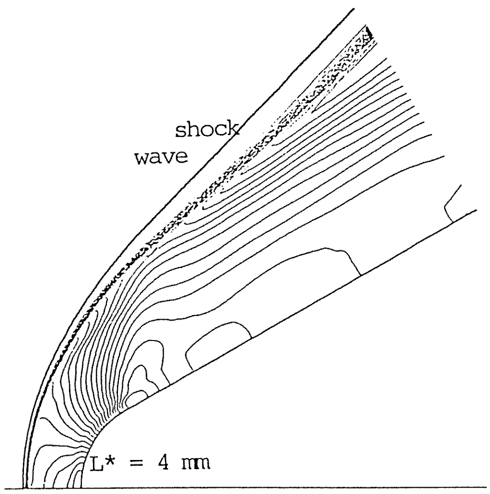

Fig. 3. Contours of H_2O density for $L^* = 4.0$ mm, $M_\infty = 6$ and $\theta = 30$ degree.

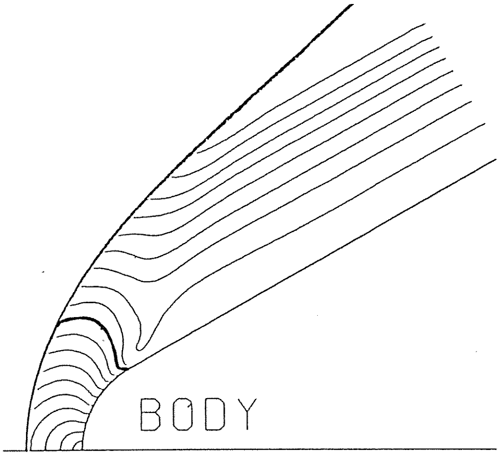

Fig. 4 (a) Sonic locus in shock layer for θ = 30 degrees.

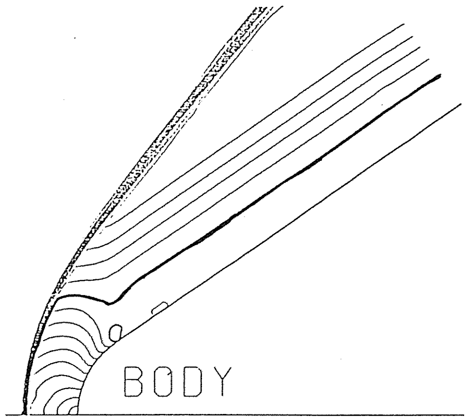

Fig. 4 (b) Sonic locus for θ = 35 degrees.

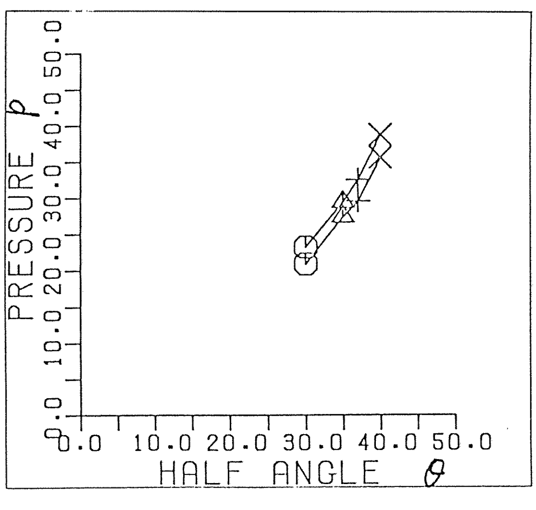

Fig. 5. A polar curve p-θ relation to SOD for M_∞ = 6 and L^* = 3 mm.

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