PROPAGATION SPEED CALCULATIONS FOR A MODEL RAM ACCELERATOR

Joseph M. Powers* and Matthew J. Grisman†
Department of Aerospace and Mechanical Engineering,
University of Notre Dame,
Notre Dame, Indiana 46556-5637.

Summary

This paper presents results of a numerical analysis to determine steady propagation speeds of a projectile fired into a gaseous mixture of fuel and oxidizer. For tractability, the steady supersonic flow of an inviscid calorically perfect ideal reacting gas over a symmetric double wedge, unconfined by a cowl, is considered. Propagation speeds are found which give rise to shocks of sufficient strength to induce a reaction zone to be in a region which allows the combustion-induced thrust to balance the wave drag. For a fixed heat release greater than a critical value, two steady propagation speeds are predicted. The solution at the higher Mach number is statically stable while the solution at the lower Mach number is statically unstable. This methodology can be applied to analyze devices which have more complex geometries such as the ram accelerator or oblique detonation wave engine.

This study is an extension of a previous study [1] which gave qualitative results, but lacked sufficient numerical resolution to accurately capture the lead shock. To remedy this, we have written a new code, based on the Roe method, to analyze the problem. The results show a significant improvement in that the lead shock is captured well. Furthermore, the results indicate that conclusions of Ref. [1] were qualitatively correct. Further calculations are planned to better resolve the reaction zone which presently occurs over three to four grid cells. Reference [1] also reviews the relevance of this study to the ram accelerator and oblique detonation wave engine. Additonally, it gives a full description of the methodology used to select steady propagation speeds.

In this paper we briefly describe the problem considered in Ref. [1] and show some sample results from the new code. We also give an extensive list of recent ram accelerator literature along with some recent related studies in detonation theory, Refs. [2-40]. A review of more early literature is given in [31] and [33].

Geometry and Flow Features

We consider the geometry shown in Fig. 1, a symmetric double wedge with half angle θ and length L. The depth of the double wedge and cowl is taken to be infinite and the flow

*Assistant Professor

†Research Graduate Assistant, Ph.D. Candidate

This project was supported by the University of Notre Dame.
Presented at the First International Workshop on Ram Accelerator, Saint-Louis, France, September 7-10, 1993.

is assumed to have no variation in this direction. The Cartesian coordinate system, with its origin at the leading edge and with the x axis aligned with the incoming flow is also indicated. The character of a typical reactive flowfield is given in Fig. 1. For an incoming supersonic freestream, an oblique shock is attached to the leading edge. The oblique shock triggers a small amount of chemical reaction. The reaction releases enough heat to prevent freezing as a fluid particle passes through a centered rarefaction attached to the apex. Downstream of the apex, a significant amount of heat is released such that a pressure rise is induced to counter the wave drag. An oblique shock is attached to the trailing edge to turn the flow to the x direction.

Model

The model equations are taken to be the unsteady Euler equations and species evolution equation for a reactive calorically perfect ideal gas with one-step, irreversible, Arrhenius kinetics. The nomenclature and assumptions are standard and similar to those used in [1] and [31].

$$\frac{d\rho}{dt} + \rho \frac{\partial v_i}{\partial x_i} = 0, \tag{1}$$

$$\frac{dv_i}{dt} + \frac{1}{\rho}\frac{\partial P}{\partial x_i} = 0, \tag{2}$$

$$\frac{dP}{dt} - \gamma \frac{P}{\rho}\frac{d\rho}{dt} = (\gamma - 1)\rho\kappa q(1-\lambda)\exp\left(\frac{-E}{RT}\right), \tag{3}$$

$$\frac{d\lambda}{dt} = \kappa\,(1-\lambda)\exp\left(\frac{-E}{RT}\right), \tag{4}$$

$$e = \frac{1}{\gamma - 1}\frac{P}{\rho} - \lambda q, \tag{5}$$

$$P = \rho RT. \tag{6}$$

Numerical Analysis

A numerical analysis of Eqs. (1–6) was performed using a new code [41] based on the Roe method. In brief, the code uses an explicit Roe scheme [42] and fractional stepping to integrate the equations in a generalized, curvilinear coordinate system. The integration has second-order spatial accuracy and first-order temporal accuracy. In the implementation of the Roe scheme, all eigenvalues and eigenvectors of the generalized flux Jacobian matrices were obtained analytically, resulting in an efficient yet robust code. The code has been benchmarked against one-dimensional unstable detonation cases described in Ref. [4] and the two-dimensional steady results of Ref. [31]. The second-order spatial accuracy was obtained using a modified version of the higher-order TVD schemes for Roe averaging suggested by Osher and Chakravarthy [43]. A common 199 x 99 fixed grid was used. All cases were run on an IBM RS/6000 POWERstation 350 with a speed of 18.6 Mflops and 64 Mb RAM.

Convergence to steady-state was typically achieved in about 5000 time iterations which required about three hours of computing time.

Results

The following conditions were modeled with the new code: ambient pressure of 1 bar, ambient density of 1.225 kg/m^3, activation energy of 1.019 MJ/kg, rate constant of 2.64×10^7 s^{-1}, molecular weight of 28 $kg/kgmol$, specific heat ratio of 7/5, wedge length of 0.1 m, and wedge half-angle 5°. A search was conducted at various values of heat release to find Mach numbers which gave rise to a force balance on the projectile. Such balances were found for freestream Mach numbers in the range of 5.5 to 8.5 and for heat releases from 0.9919 to 1.12 MJ/kg.

Figure 2 shows the pressure along the grid line following the wedge surface. Three curves are plotted for $M_0 = 8.2$: 1) the analytic solution for an inert flow, 2) the numerical solution for the same inert flow, and 3) the numerical solution for the heat release which gives rise to an approximately zero drag flow, $q = 0.996$ MJ/kg. Also indicated are the respective drag forces per unit depth for each case. By comparing numerical and analytic results in the inert case, it is seen that the numerical solution captures the proper magnitude of the pressure changes, with slight discrepancies at the discontinuities. The computed drag forces of 1941 and 1926 N/m are very close for both cases. Introduction of reaction with heat release significantly alters the pressure distribution, consequently resulting in a force equilibrium and therefore approximately 0 N/m drag.

The resolution of these results represents a significant improvement over those previously reported (see figure 13, [1]) in which artificial viscosity was used for shock capturing. Figures 3 and 4 show pressure and product mass fraction contours, respectively, for the zero drag reactive case of Fig. 2 and indicate that most reaction occurs near the wedge apex. The pressure increase induced by the reaction counters the decrease caused by the rarefaction so as to maintain the aft-body pressure at an elevated magnitude, leading to a force balance. Figures 5 and 6 show pressure and product mass fraction contours for $M_0 = 7.0$ and $q = 1.014$ MJ/kg. Again, a force balance exists. However, here the reaction takes place primarily on the aftbody.

A series of calculations was then performed to find the variation of Mach number which gives rise to a force balance as a function of heat release. Results are plotted in Fig. 7. Below a critical value of heat release there is no Mach number for steady projectile propagation. Above this critical value, two speeds are predicted. Speeds on the upper branch are statically stable while those on the lower branch are statically unstable. On the stable branch, a positive perturbation in Mach number increases the post-shock temperature, thus decreasing the induction zone length and moving the reaction to the projectile forebody. This then increases the drag which tends to restore the projectile to its equilibrium speed. Similarly a negative perturbation of Mach number moves the reaction zone onto the aftbody, increasing the thrust and again restoring equilibrium. On the unstable branch, the heat release is concentrated downstream on the aftbody. A positive perturbation in Mach number increases the region of high pressure on the aftbody, increasing the thrust, thus pushing the projectile away from its equilibrium. The results indicate that on the statically stable branch, an increase in heat release gives rise to an increase in steady speed of propagation.

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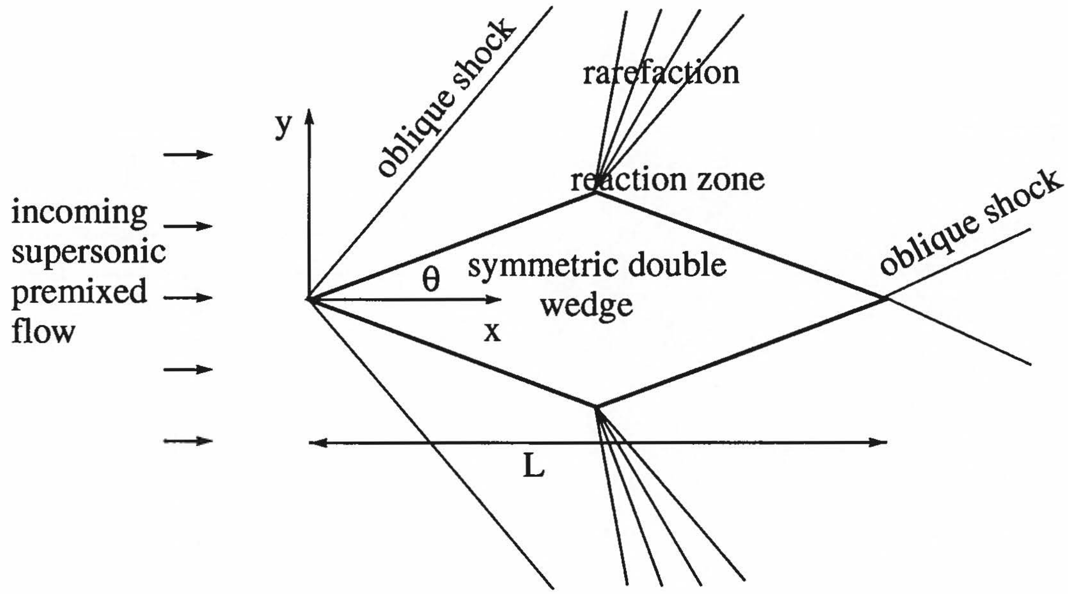

Figure 1: Schematic of geometry and flow features

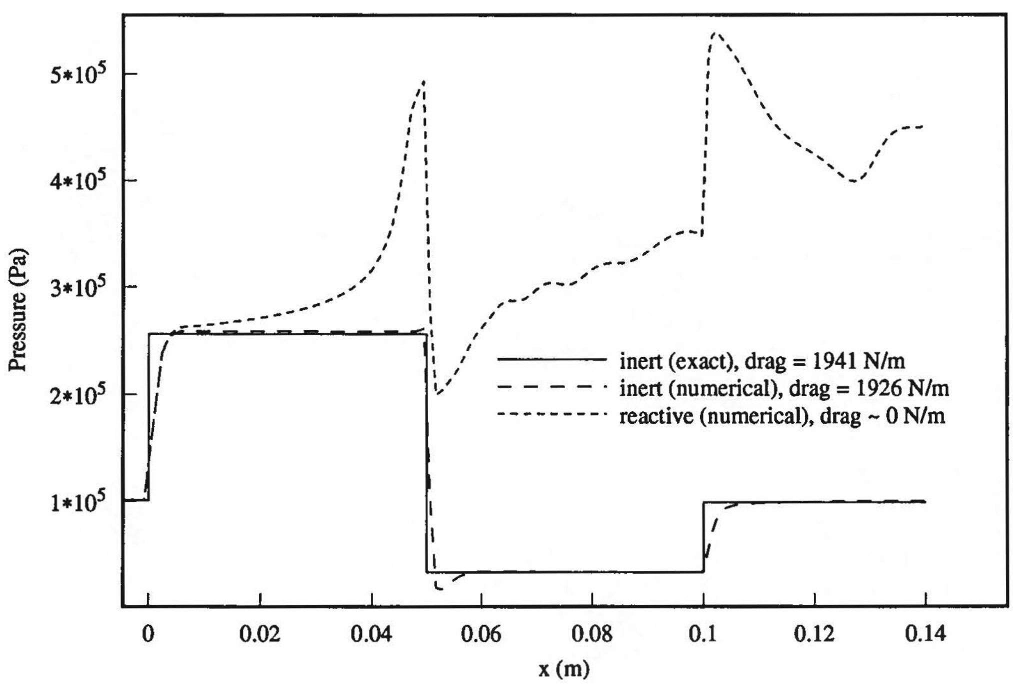

Figure 2: Wedge surface pressures for exact and numerical inert solutions, and an approximately zero drag numerical solution with reaction ($M_0 = 8.2$, $q = 0.996\ MJ/kg$).

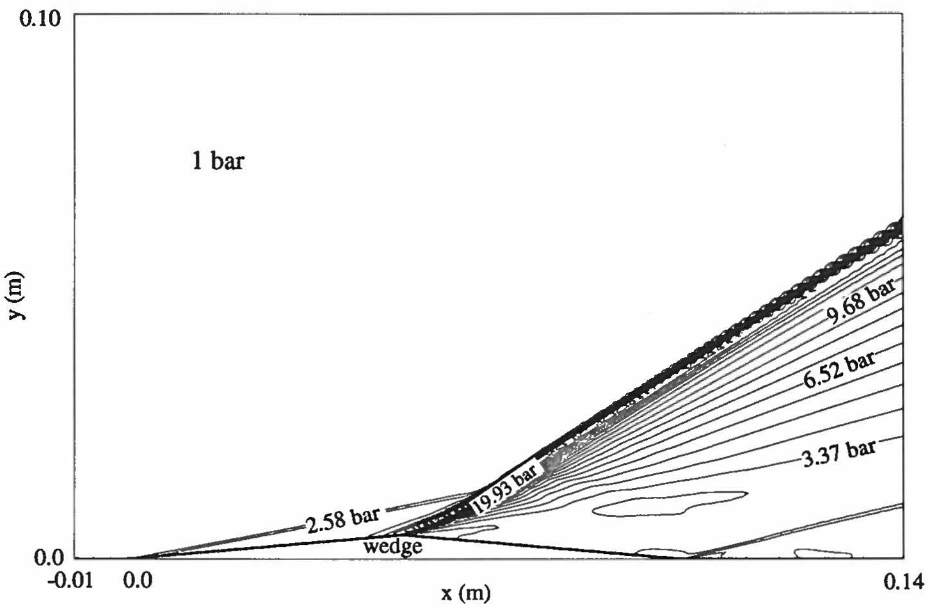

Figure 3: Pressure contours for statically stable case ($M_0 = 8.2$, $q = 0.996\ MJ/kg$).

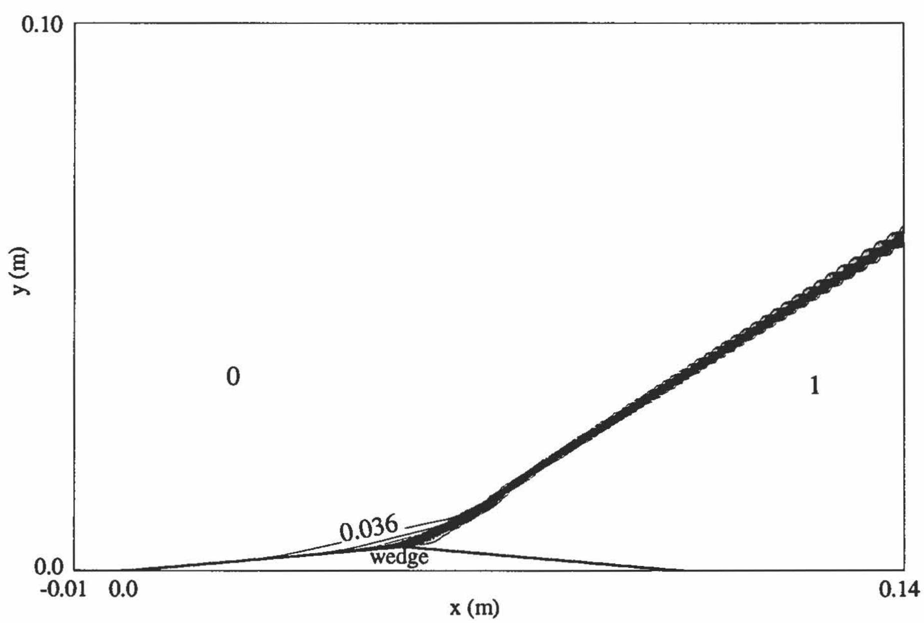

Figure 4: Product mass fraction contours for statically stable case ($M_0 = 8.2$, $q = 0.996\ MJ/kg$).

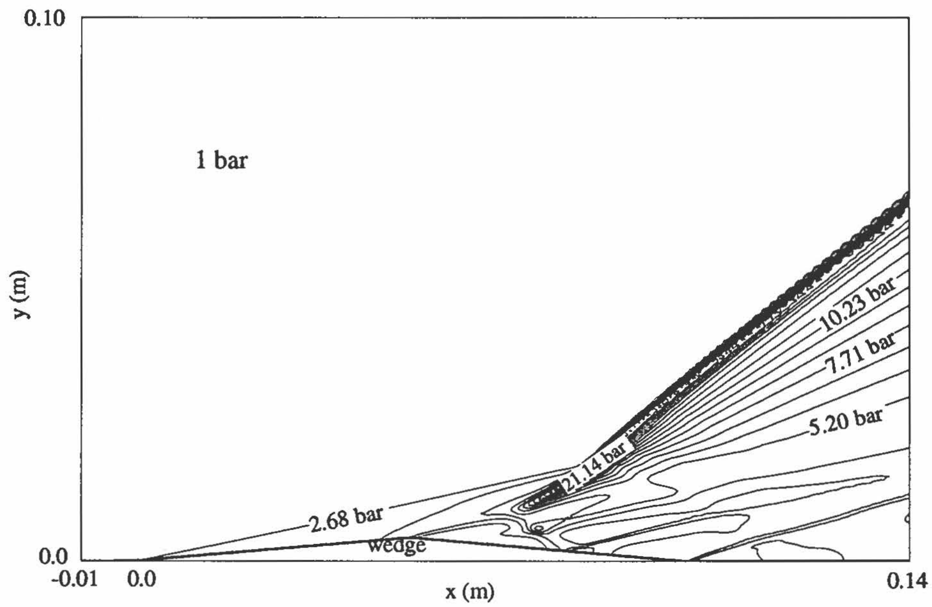

Figure 5: Pressure contours for statically unstable case ($M_0 = 7.0$, $q = 1.014\ MJ/kg$).

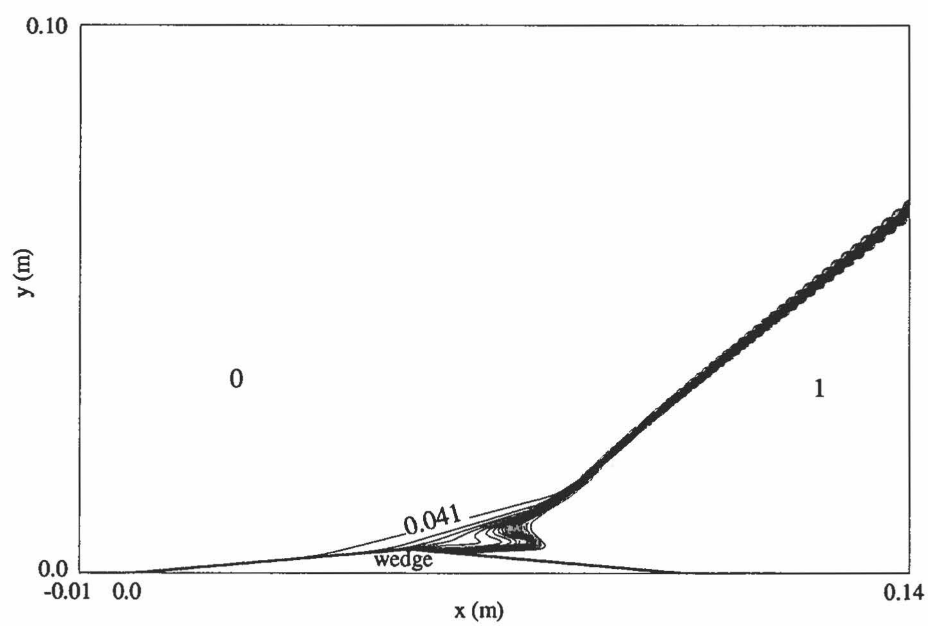

Figure 6: Product mass fraction contours for statically unstable case ($M_0 = 7.0$, $q = 1.014\ MJ/kg$).

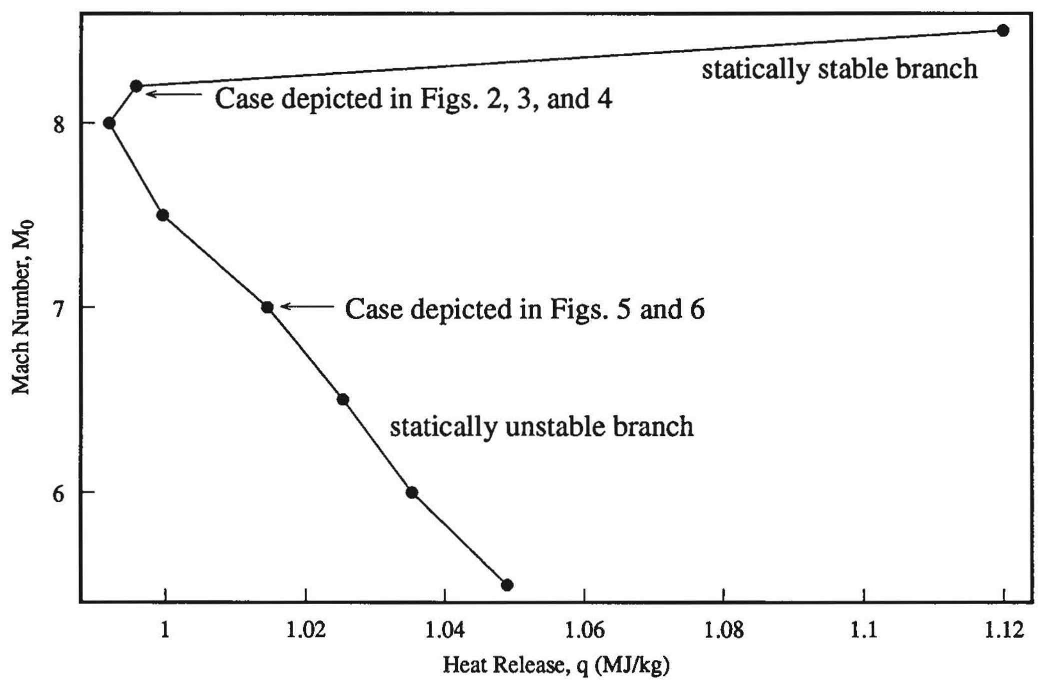

Figure 7: Zero drag flight Mach numbers for fixed geometry and variable heat release.