Three-dimensional SRM propellant flames

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Abstract

This is one of a sequence of elementary flame studies designed to provide an understanding of the complex combustion field that is generated by burning a heterogeneous solid propellant of the kind used in high-performance rockets. Here, for the first time, we examine periodic three-dimensional flames supported by a periodic array of spherical AP particles imbedded in a fuel binder. A strategy for dealing with a wide range of AP particle sizes is proposed, and some preliminary calculations of flame configurations are presented.

Introduction

We are concerned with heterogeneous propellants formed when AP particles are imbedded in a fuel binder. In our model the propellant surface is assumed to be flat, and regresses uniformly to generate an assigned mass flux of reactants. We are concerned, not with a full coupling of the combustion field, fluid flow, and thermal field in the solid, but with the effects of propellant geometry on the nature of the flames. To this end we use model equations similar in some respects to those used in the classical Burke-Schumann problem, viz.

$$L(X,Y,T) = (-1,-1,1)\delta XYe^{-\vartheta/T}, L \equiv \frac{\partial}{\partial z} - \frac{1}{Pe}\nabla^2. \tag{1}$$

The mass fractions (X oxidizer, Y fuel) have been scaled with the stoichiometric coefficients α_X and α_Y which appear in formulas below, and Pe is the Peclet number. Our treatment differs from that of Burke and Schumann in a number of ways: we account for finite chemistry effects; we use flux conditions at the propellant boundary rather than Dirichlet data; and we retain streamwise diffusion. However, like Burke and Schumann we use the constant density model, assigning the flow field, a uniform one with mass flux M, the latter absorbed into the Peclet number. In earlier work we examined two-dimensional flames supported by sandwich propellants and by one-dimensional periodic propellants, [1], [2]. Here we are concerned with two-dimensional periodic propellants that support three-dimensional flames.

Typical propellant geometry that we consider is shown in Figure 1. AP spheres of radius 1 are stacked periodically as shown. Smaller spheres of radii 0.35, not shown, are placed in a regular fashion in the interstices between the large spheres. To account for smaller AP particles, necessary for stoichiometric purposes (most of the propellant must be AP) we assume that the binder and these smaller particles can be modeled as a homogeneous component, a fraction α of which is oxidizer. Thus the flux conditions at the propellant surface $x = 0$ are:

$$\begin{aligned} X - \frac{1}{Pe}\frac{\partial X}{\partial z} &= \frac{1}{\alpha_X} \text{ or } \frac{\alpha}{\alpha_X}, \\ Y - \frac{1}{Pe}\frac{\partial Y}{\partial z} &= 0 \text{ or } \frac{(1-\alpha)}{\alpha_Y}, \end{aligned} \tag{2}$$

where the choices depend on whether the surface is oxidizer or the binder combination.

At any instant the total flux of oxidizer is

$$\frac{A_{AP}}{\alpha_X} + \frac{\alpha}{\alpha_X}A_B, \tag{3}$$

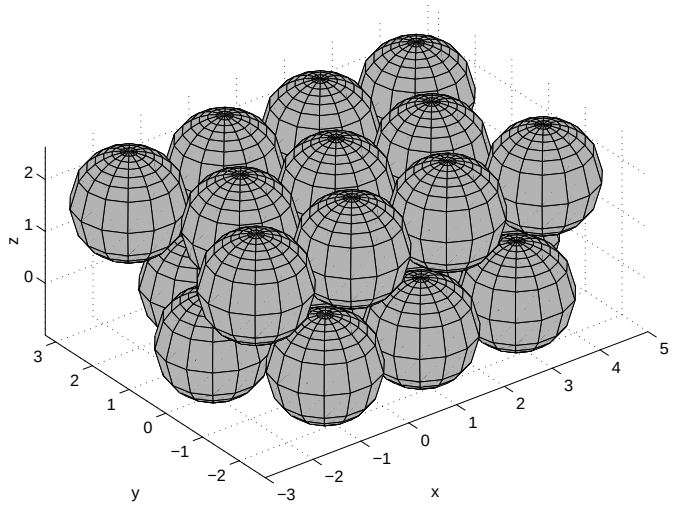

Figure 1: Array of AP particles imbedded in modified binder, see text.

and the total flux of fuel is

$$\frac{(1-\alpha)}{\alpha_Y} A_B, \tag{4}$$

where A_{AP} is the exposed area of AP, and A_B is the exposed area of the binder combination.

If we integrate these fluxes over the burn time, the total volume of oxidizer that is consumed is

$$\frac{1}{\alpha_X} V_{AP} + \frac{\alpha}{\alpha_X} V_B, \tag{5}$$

and the total volume of fuel that is consumed is

$$\frac{(1-\alpha)}{\alpha_Y} V_B \tag{6}$$

where V_{AP} is the volume of the explicitly defined AP particles, and V_B is the volume of the remainder of the propellant.

For a stoichiometrically apportioned propellant, these volumes must be equal, whence

$$1 = \frac{\alpha_X}{\alpha_Y} \frac{(1-\alpha)}{V_{AP}/V_B + \alpha}. \tag{7}$$

Since V_{AP}/V_B is fixed by the geometry, cf. Figure 1, and α_X/α_Y is fixed by the gas-phase stoichiometry (we have chosen the value 7 for this ratio in the earlier 2-dimensional work (loc.cit.)), Equation (7) determines α.

Results

We have solved Equations (1) by adding time derivatives, and using the method of lines, as in the earlier work, loc.cit. For the 3-dimensional calculations, the code is parallelized. Figure 2 shows a portion of the propellant surface at $z = 0$, and we show here flame configurations within a comuputational domain defined by these boundaries and with z varying from zero to some sufficiently large value, where Neumann data may be applied. Periodic boundary conditions are used in the $x - y$ plane. Slices through the combustion field at different values of x are shown in Figure 3. The contour values were assigned values 20, 15, 10, 5, 1, .5, .2, and the plotting routine plots all those that are relevant. Thus if only two contours are shown ($x = .5$), they carry values .2 and .5, and the reaction rate does not exceed 1. Reaction, and therefore heat production, is weak for the middle 3 panels ($x = .38, .5, .62$), an order of magnitude smaller than for the other panels. The local maxima arise because of mixing ahead of the nominal diffusion flames supported by the oxidizer/binder reaction, and where these maxima are large there will be intense local heating of the propellant surface. This heating (edge-flame heating) together with that from the AP decomposition flame (not part of our model at this stage), is what causes regression of the propellant. A preliminary conclusion, consistent with the two-dimensional results in reference [2], is that the edge-flame heating provides heat primarily to the binder.

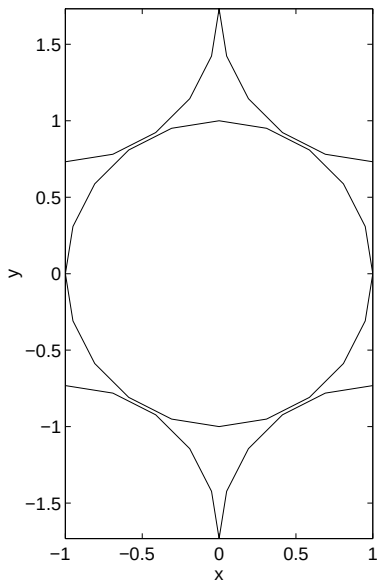

Figure 2: Intersection of the computational domain with the propellant surface.

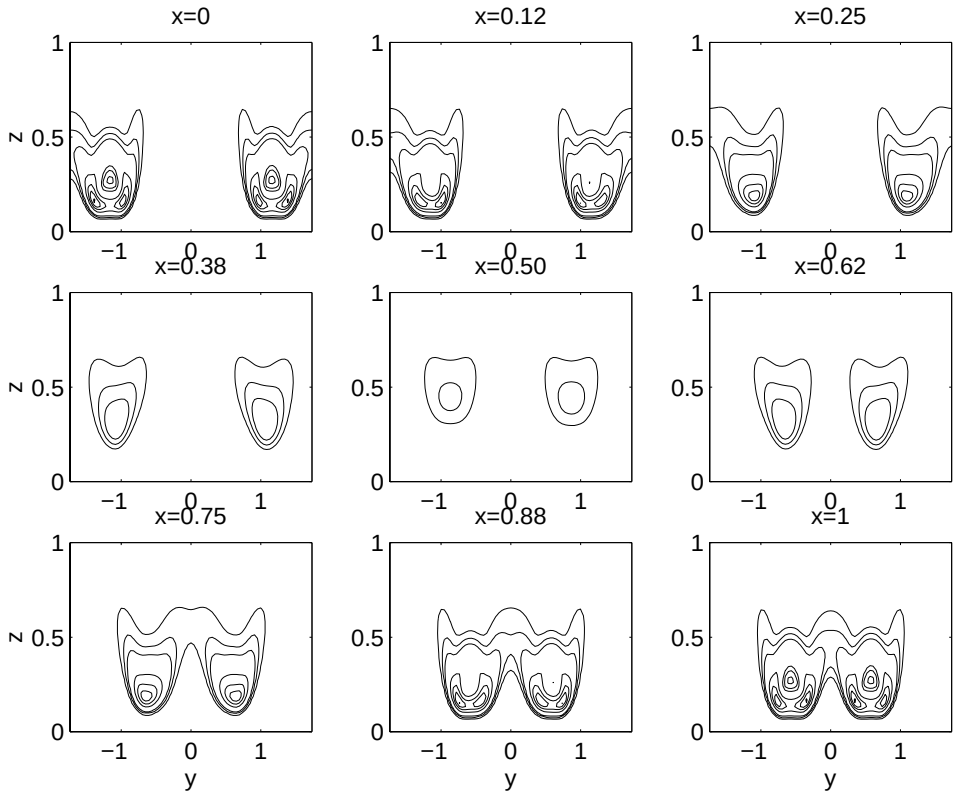

Figure 3: Reaction-rate contours in the $y-z$ plane, for various values of x; $Pe = 5$, $\delta = .005 \times e^{20}$. The contour values are 20, 15, 10, 5, 1, .5, .2 with the higher values omitted if there are fewer than 7 contours.

Acknowledgement

The work of JB is supported by AFOSR, by BMDO/ONR under a MURI grant to the University of Illinois, grant No. N00014-95-1-1339, and by the U.S. Department of Energy through the University of California under Subcontract number B341494. TLJ is supported by the latter agency.

References

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