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Numerical Implementation of Flame Propagation and Flameholding

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Abstract

The level surface approach for following flame front propagating in a premixed medium is adapted to incorporate the flameholding scheme. This allows one to follow the motion of an N-1 dimensional surface in N space dimensions. The flame speed may be an arbitrary function of flame geometry and the front is passively advected by an underlying flowfield. This algorithm provides an accurate calculation of the flame curvature which may be needed for the flame propagation computation and thereby the estimation of curvature-dependent flame speeds. A numerical demonstration of this methodology is applied to simulate the excursion of an anchored V-flame and locate the final equilibrium position.

Key Words : Flame Propagation, Flameholding, Premixed Flame

1. Introduction

The world wide energy crisis and the ensuing need for more efficient use of the finite energy resources makes an understanding of combustion processes at a fundamental level imperative. In particular, the propagation of premixed flames has been investigated due to their use in industrial, military and automotive applications. Much progress has been made in the past decade in the numerical modeling as well as in the experimental observation. Nevertheless, the coupling of the exothermic chemical reaction with the hydrodynamic flowfield is a difficult problem to solve and so more studies on a fundamental level are still needed. Since the premixed flame is charaterized by its intrinsic propagation speed, an accurate description of flame motion within a flowfield is essential to a better understanding of the combustion process.

The laminar flamelet concept[1] is based on the idea that the flowfield consists of a collection of flame elements embedded in a flowfield. The structure of these flamelets is analyzed separately from the flow so that the complicated chemistry is decoupled from the simulation of the flow-

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field. In many practical situations, the flame thickness is much smaller than the smallest length scale and so the flamelet descriptions are relevant[2]. If one goes one step further beyond the flamelet model, a flame sheet model is employed by taking the zero limit for the flame thickness and thereby solving only for the flame front geometry[3]. In this case, the flame front acts as an infinitely thin hydrodynamic discontinuity which separates two regions of constant densities and propagates into the fresh mixture at a prescribed flame speed. The speed may be a function of the local curvature of the flame front, which avoids hydrodynamic instability[4]. Fluid elements at the flame front undergo a thermal expansion as they burn, creating a jump in the normal component of velocity across the flame front.

Typically there have been two types of numerical methods for tracking interfaces such as crystal growth and flame propagation. One is to follow the surface of the interface parametrized by marker points[5]. The positions of marker points are updated in time according to the equations of motion. This can be effective in an attempt to follow the motions of small perturbations. But an artificial regridding procedure is required for large, complex motions when marker particles merge together and so the curvature of the propagating front builds up. But this regridding procedure resembles diffusion and overshadows the real effects of interface motions. The other is to track the motion of the interior region separated by the interfaces[6]. The interior is discretized by employing a grid on the computational domain and assigning to each cell a volume fraction corresponding to the amount of interior fluid located in that cell. An advantage is that no new computational elements are needed in the calculation unlike the parametrization procedure. Also complicated topological interfaces are easily handled, but it is difficult to accurately represent the interface movements.

In this study, the level surface approach[7] for following flame front propagating in a premixed medium is adapted to the case of a rod-stabilized premixed V-flame. This flame configuration chosen is of both practical and fundamental significance. Premixed fuel and air flows vertically around a circular cylinder or a bar, held perpendicular to the mean flow direction. A V-shaped flame can be stabilized by the hot products which recirculate in the wake of a bar and so come into contact with the cold reactants. The reactant gases are ignited by contact with the hot products and two oblique flame sheets form, one on each side of the body. The study of flame stabilization on bluff bodies is also a subject of ongoing practical concern since it has application in the vast majority of industrial devices, ranging from jet-engine afterburners to practical combuation systems. These power-production devices require that flames be retained in the system. Gas velocities usually exceed the flame speed and hence the flames must be stabilized against the blowout, a condition at which flames are transported out of the burner and the combustion ceases. In order for a flame front to be stationary, the local condition for stabilization of the flame should be realized in such a way that the normal velocity of the unburnt gas and the normal flame speed must be equal at the flame front. This can be achieved by the presence of a flameholder or retention point, line or region.

The main objective in this work is to numerically incorporate the above flame stabilization idea into the level surface approach. The test problem is the simple case of rod-stabilized premixed flame, a configuration which has been investigated extensively both experimentally and theoretically. A numerical demonstration is presented describing the evolution of an anchored V-flame and the final equilibrium location of the interface after a sufficient time.

2. Physical Model

The main assumptions of our model for flame propagation and its response to the accompanying flowfield are:

a) the flowfield is two-dimensional and inviscid,

b) the Mach number is small enough to consider the flowfield as incompressible,

c) the flame acts as an interface which separates two regions of different but constant density and propagates into the unburnt region at a prescribed flame speed S_u.

It is convenient to formulate the flame propagation problem in terms of an equation for a scalar field. Following Osher & Sethian[8], we define a continuous initial distance

function such that $\Psi > 0$ in the unburnt region, $\Psi < 0$ in the burnt region and the $\Psi = 0$ represents the flame front as depicted in Fig. 1.

In order to find an equation for the evolution of a scalar field Ψ which corresponds to the propagating flame, the motion of some level surface $\Psi = C$ is considered. Let $(x(t), y(t))$ be the trajectory of a particle located on this level surface, so

$$\Psi = (x(t),\ y(t),\ t) = C. \tag{1}$$

The particle speed $\frac{\partial x}{\partial t}$, in the direction $-\boldsymbol{n}$ normal to the flame, is given by the flame speed S_u. Thus, with the convention adopted here that the normal vector $\boldsymbol{n}$ points in the direction of the burnt gas

$$-\boldsymbol{n} \cdot \frac{\partial x}{\partial t} = S_u \tag{2}$$

where $\boldsymbol{n}$ is given by $\boldsymbol{n} = -\nabla\Psi/|\nabla\Psi|$. When the chain rule is applied to Eq. (1),

$$\Psi_t + \frac{\partial x}{\partial t} \cdot \nabla\Psi = 0 \tag{3}$$

is obtained. A substitution of $\boldsymbol{n}$ to Eq. (2) converts Eq. (3) to

$$\Psi_t + S_u|\nabla\Psi| = 0 \tag{4}$$

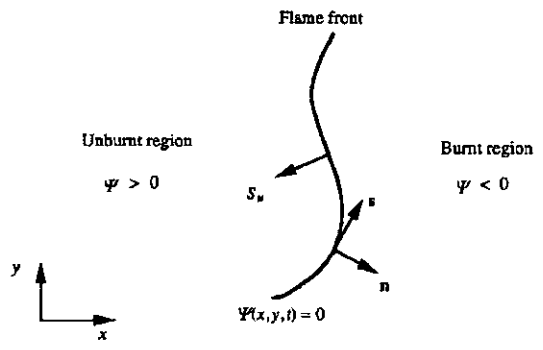


Fig. 1 Flame front configuration.

A flame propagates with its own burning speed relative to the accompanying flowfield. The flowfield influences the flame location by advection. Hence, there exists a mutual interaction between the flame and flowfield. In this case, the scalar field equation with propagation and advection becomes

$$\Psi_t + S_u|\nabla\Psi| + U \cdot \nabla\Psi = 0 \tag{5}$$

The second term represents propagation and the third term denotes advection of the scalar field. The velocity vector $\boldsymbol{U}$ is the convection velocity of the unburnt fluid just upstream of the flame front.

3. Numerical methods

We present the numerical details for an approximation to Eq. (5) of the flame motion. The algorithm uses the method of fractional steps to decompose the flame motion into propagation and advection. First, we propagate the flame as a result of burning. Then the flame is advected by the incoming velocity field. A flame-anchoring algorithm for the flameholder of the V-flame is developed to stabilize the flame against the blowout.

3.1 Flame propagation with advection

We discretize the Eq. (5) with the initial condition $\Psi(x,y,0)=0$. The scalar field Ψ is initialized by taking $\Psi(x,y,0) = \pm d(x,y)$, where d is the distance from the point (x,y) to the initial surface and the plus/minus sign is chosen if the point (x,y) is inside the unburnt/burnt region of the computational domain. Following the argument of Osher and Sethian, Eq. (4) for $S_u=1$ can be written as

$$\Psi_t + H(u,\ v) = 0 \tag{6}$$

where $H(u,\ v) = f(u^2,\ v^2)$ with $u = \Psi_x,\ v = \Psi_y$, and f is a non-decreasing function in both variables. A upwind monotone scheme for this case yields the following numerical flux,

$$g = f[(\max(D_-^x\Psi_{jk}^n,\ 0))^2 + (\min(D_+^x\Psi_{jk}^n,\ 0))^2,$$
$$(\max(D_-^y\Psi_{jk}^n,\ 0))^2 + (\min(D_+^y\Psi_{jk}^n,\ 0))^2] \quad (7)$$

where the difference operators in Eq. (7) are defined by

$$D_-^x\Psi_{jk}^n = \Psi_{j,k}^n - \Psi_{j-1,k}^n,$$
$$D_+^x\Psi_{jk}^n = \Psi_{j+1,k}^n - \Psi_{j1,k}^n,$$
$$D_-^y\Psi_{jk}^n = \Psi_{j,k}^n - \Psi_{j,k-1}^n,$$
$$D_+^y\Psi_{jk}^n = \Psi_{j,k+1}^n - \Psi_{j,k}^n.$$

This is fully upwind in that, if $H_1 = \frac{\partial H}{\partial u} < 0$ and $H_2 = \frac{\partial H}{\partial v} < 0$, then the scheme looks in the proper direction. The scheme is monotone if the Courant condition, $\frac{\Delta t}{\Delta x}|H_1| + \frac{\Delta t}{\Delta y}|H_2| \le \frac{1}{2}$, is satisfied.

A first order upwind scheme is used for the advection part as follows:

$$U \cdot \nabla\Psi \approx U_-^+ D_-^x\Psi_{ij} + U_i^- D_+^x\Psi_{ij} + V_j^+ D_-^y\Psi_{ij} + V_j^- D_+^y\Psi_{ij}.$$

We note that the Courant condition for the Eq. (5) yields

$$(|S_u| + |U|_{\max})\frac{\Delta t}{\Delta x}(|H_1| + |H_2|) \le \frac{1}{2}.$$

3.2 Flame anchoring

Since unburnt gas velocities in combustors usually exceed the flame speed in order to achieve high power densities, we need to devise ways against blowout. This can be enforced by the presence of a so-called retention point (or line) or small retention region which ensures that a flame is held back and stabilized. The ignition impulse is transmitted from the retention point to neighboring portions of an unburnt mixture.

We now design an implementation of the above idea of flame stabilization into the level surface scheme[9]. Flames are attached to a flameholder by laying down an initial ignition field Ψ_{th} on an Eulerian grid and letting Ψ_{th} acts as a source of an ignition impulse from the location of a circular flameholder, as is shown in Fig. 2. As flames propagate

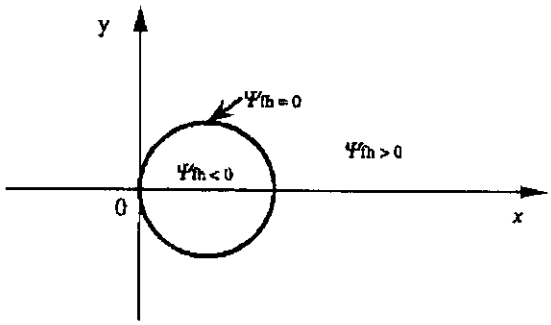


Fig. 2 Scalar field for flameholder, Ψ_{th}.

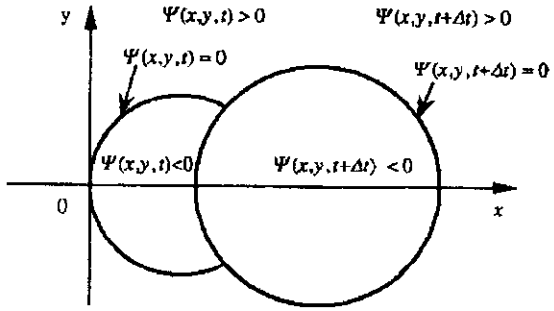


Fig. 3 Scalar field at time t, $\Psi(x, y, t)$, and at time $t + \Delta t$, $\Psi(x, y, t + \Delta t)$, after propagation and advection.

with their own speeds and are advected with accompanying flowfields, they are held back on the location of a flameholder by superimposing Ψ_{th} onto the propagating scalar field Ψ. This flame anchoring algorithm is used to ensure that flames always remain within the computational domain and begin at the retention point (or region) irrespective of their initial shapes.

As an example, consider a two-dimensional case of flameholding. We want to hold the flame by a circular flameholder shown in Fig. 2. There is an incoming flow from the negative x to positive x and flame is propagating to the radial direction. Suppose we have a flame located on a small circle which is a zero-level surface at a initial time t, as is depicted in Fig. 3. We have new flame location on a larger circle at a later time $t + \Delta t$ due to propagation and advection. We impose the scalar field Ψ_{th} for flameholder

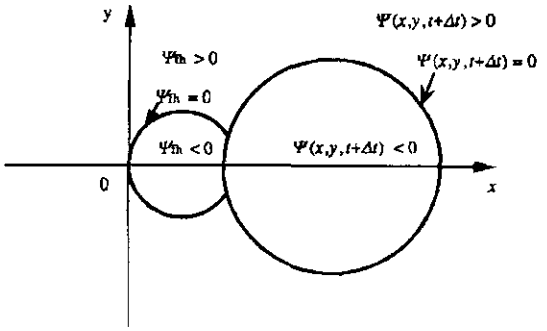


Fig. 4 Combining of Ψ_{th} and $\Psi(x, y, t + \Delta t)$

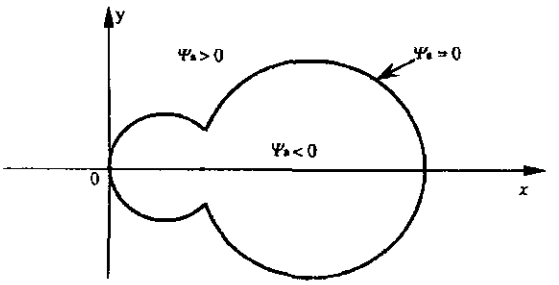


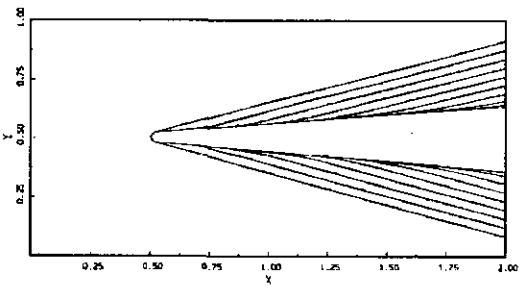
Fig. 5 Anchored scalar field Ψ_a which is the minimum of Ψ th and $\Psi(x, y, t + \Delta t)$ and the anchored flame position as a level surface of $\Psi_a = 0$.

in Fig. 2 to the scalar field at $t + \Delta t$ in Fig. 3. At each time step, we take the minimum of Ψ_{th} and the scalar field by propagation and advection, as is shown in Fig. 4, to get an anchored scalar field Ψ_a. The level surface equal to $\Psi_a = 0$ gives the flame position in Fig. 5 which is anchored by the circular flameholder.

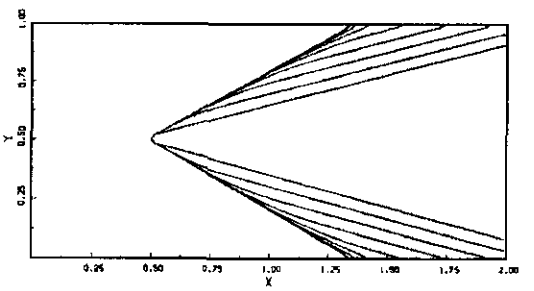
4. Numerical examples

The numerical method is applied to the kinematic behavior of a V-shaped premixed flame, a flameholder placed between two walls. Although we are simulating an open flame, numerical work requires a finite computational domain. Hence, the solution domain is truncated to a rectangle of axial (x) length equal to 2 and transverse (y) width equal to 1. Incoming fresh mixture enters the computational domain at $x = 0$ with a velocity equal to 1. All velocities and lengths are scaled with the incoming free-stream velocity and the transverse width, respectively. The combination of the two gives a time scale. The flameholder is located at (x, y) = (0.5, 0.5). Non-dimensional flame speed is given as an input. The grid size is equal to 0.02 and the time step is 0.004 in order to satisfy the Courant condition. At the inlet, we choose a fixed boundary condition: the periodic reinitialization of the level surface function Ψ ensures that these upstream boundary conditions do not affect the downstream computation. The downstream boundary conditions for Ψ are outflow conditions, and the upward differencing precludes the use of boundary conditions along the exit. On the solid walls, the boundary conditions for Ψ are mirror conditions.

In this case the V-flame simply adjusts kinematically to the incoming flow. The sine of the angle between the flame and the centerline is equal to the flame speed divided by the free stream velocity. Since the incoming flow is not disturbed by the presence of the flame, the equilibrium shape



(a) $S_u / U = 0.08$



(b) $S_u / U = 0.5$

Fig. 6 Flame response as the flame speed varies.

of the flame should be planar. Fig. 6(a) and (b) show the response of the flame as the flame speed varies: (a) $S_u / U = 0.08$ and (b) $S_u / U = 0.5$. At time $t = 0$, the flame is initialized at an arbirary chosen angle, the same in both cases. In case (a) the flame closes up at each successive equal time intervals until the equilibrium condition is met, the opposite is true for case (b).

5. Conclusions

The level suface algorithm, originally developed for handling a topological merging and breaking of a complex interface motion, is adapted to account for the flame stabilization by adding the flameholding scheme. The resulting flame anchoring algorithm is shown to simulate the kinematic adjustment of an anchored V-flame to the incoming flowfield accurately. Some of the important features of this study are as follows.

(a) The flame anchoring algorithm is successfully developed by combining the flame propagation scheme with the flameholding scheme.
(b) The equilibrium angle between the flame and the centerline is reached as predicted from flame kinematics.
(c) This algorithm does not require the interface to remain a function, and the first order scheme used here is simple to program.

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