Flame Acceleration and Detonation Transition in Narrow Tubes

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Introduction

The work described here arose from the confluence of two studies: one on micropropulsion for microgravity environments and another on fundamental mechanisms of deflagration-to-detonation transition (DDT). Here we present selected results of numerical simulations of flame acceleration in narrow tubes from the micropropulsion point of view, and then show how an accelerating laminar flame can lead to a detonation in a narrow channel.

We solve the unsteady, compressible, Navier-Stokes equations, including a simplified model for chemical reactions and energy release in a low-pressure acetylene-air system. Adaptive mesh refinement is applied to capture the wide range of scales over which the physical phenomena occur. Essentially the same computer code was used previously to study DDT in shock tubes (e.g., [1,2]). Complete descriptions of the equations, solution method, and input parameters used here are given in [1].

Flame Acceleration in Narrow Channels

A laminar flame propagating towards the open end of a channel filled with a gaseous combustible mixture can behave in a number of ways, depending on the reactive material and the properties of the channel itself. The flame front can, for example, oscillate, be quenched, form interesting shapes (such as tulip flames) and patterns (such as cellular flames), or even become unstable and undergo a transition to a turbulent flame. Here we consider relatively narrow channels (channel width of the order of the flame thickness) with adiabatic walls. In this case, the laminar flame continuously accelerates as it moves down the channel, also accelerating the mass of unburned material ahead of it [3]. Acceleration is measured relative to the laboratory coordinate system, and the laminar flame speed remains essentially unchanged. This process it is being considered for micropropulsion because it can, in theory, produce substantial thrust at the outflow boundary [4].

Figures 1–3 summarize the problem and provide background information. The flame acceleration is caused by the interaction of the flame with the velocity gradient in the boundary layer that forms ahead of the flame. Figure 1 is a schematic that shows the two-dimensional (2D) computational domain, the boundary conditions, and the way in which the flame becomes distorted. Figure 2, taken from [3], shows that the flame accelerates for adiabatic walls, and the flame velocity oscillates around the laminar one-dimensional speed for constant temperature walls.

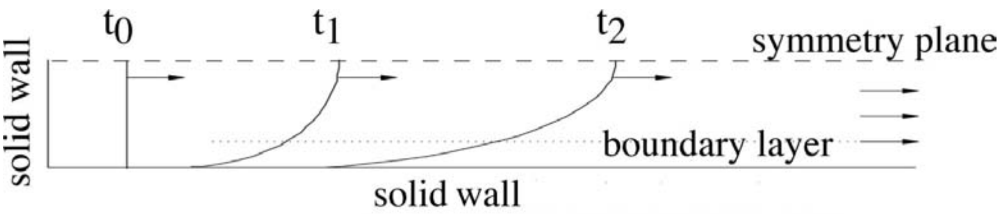

Figure 1. Schematic of the problem geometry used to describe a laminar flame accelerated by a boundary-layer effect. The flame front is shown at the initial time t_0, and at later times t_1 and t_2.

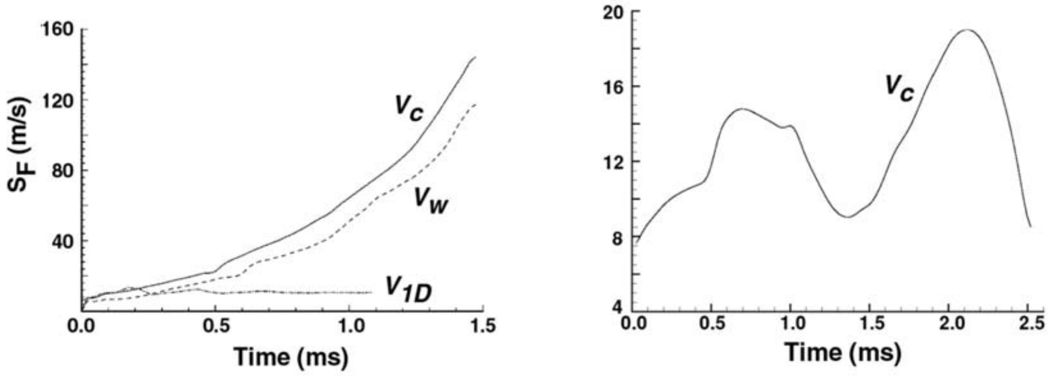

Figure 2. Computed flame velocities in laboratory coordinates for the ethylene-air flame in a narrow (0.25 cm) tube: V_C, centerline, V_W, near the wall; V_{1D}, one-dimensional flame.

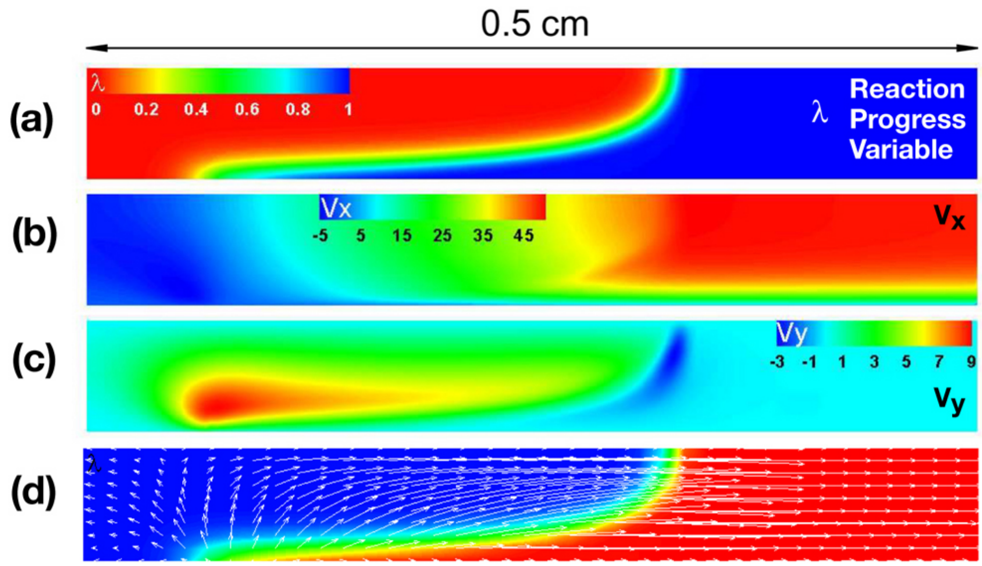

Figure 3. Computed flame structure for an ethylene-air flame in a narrow tube (0.064 cm), at 3.1×10^{-4} s. (a) Reaction progress variable. (b) Vertical velocity, V_x. (c) Longitudinal velocity V_y. (d) Velocity vectors.

The flame acceleration for adiabatic walls can be attributed to several factors. First, the flame surface increases as the flame propagates through the nonuniform flow created by the boundary. Second, the effective tube area decreases as the flame moves down the tube because of the growth of the boundary layer. In addition, the material burned in the boundary layer jets upwards and turns, thus further accelerating the flame, as shown in Fig. 3. The flame acceleration and the thrust created at the open end of a three-dimensional (3D) square channel is a factor of two greater than in a 2D channel [4].

Direct Laminar Flame to Detonation Transition

If the channel is long enough, compression waves generated by the energy release converge to form a shock. The required channel length for this to happen depends on the energetics of the specific reactive system considered. We show this for 8.192 cm long and 0.064 cm wide 2D channel filled with a reactive system that is 2.6 times more energetic that the stoichiometric acetylene-air mixture. The pressure profiles in Fig. 4 show that a shock forms early, and then gradually increases in strength as it propagates in the channel. The temperature of the unreacted material between the shock and the flame also increases, and eventually reaches the point of self-ignition in the boundary layer near the wall. The result is a spontaneous reaction wave that propagates through the temperature gradient along the wall. This spontaneous wave can evolve into a detonation, as shown by the temperature profiles in Fig. 4c.

The evolution of the spontaneous wave and transition to a detonation are also shown by the time sequence of the density fields in Fig. 5. The spontaneous wave develops in the boundary layer, and generates a compression wave that propagates along the boundary layer and triggers the energy release in the hot material. The compression wave quickly evolves into a shock, and the shock-reaction complex eventually becomes a self-sustained detonation wave that spreads from the boundary layer to the bulk flow in the middle of the channel. The problem we consider here is similar in form to that studied by Kagan and Sivashinsky [5], but in our case the way in which the transition to detonation occurs appears different.

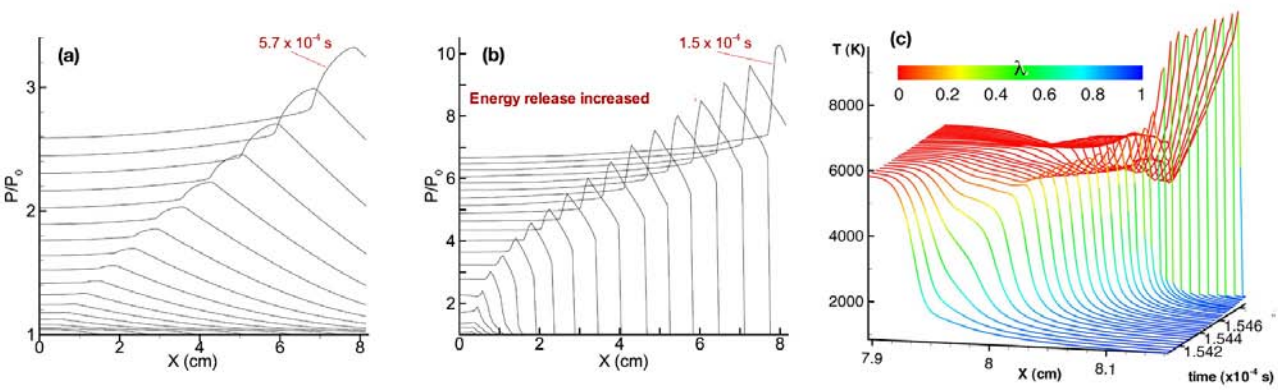

Figure 4. Evolution to a detonation. (a) Pressure waves generated for the original system. (b) Pressure waves generated for the more energetic system, showing the development of a shock wave. (c) Temperature profiles near the channel wall for the more energetic system, with the unburned mass fraction, λ, superimposed in color.

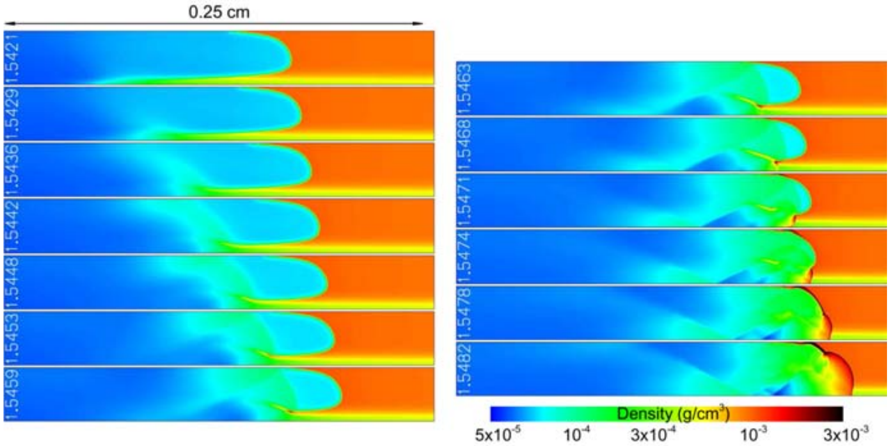

Figure 5. Density profiles showing the evolution of the laminar flame interacting with a boundary layer, and a transition to a detonation. Note that the spontaneous wave emerges at the bottom wall, in the boundary layer. It evolves into a shock-reaction complex that propagates through the boundary layer and emerges finally as an overdriven detonation.

Summary

Oscillating flames propagating in channels have been the subject of experiments and theory for many decades. Accelerating flames have also been seen and studied (see, for example, [6]), but to a lesser extent. In this work, we consider laminar flame propagating in narrow channels, where flows are dominated by boundary-layer effects. We show that in this case the flame and the flow can be accelerated to high velocities and provide a substantial thrust. When the channels were long enough to allow a shock to develop, a transition to detonation was observed in the boundary layer.

Acknowledgments

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