Detonationless Supersonic Flame Spread

Elaine S. Oran, Vadim N. Gamezo, and Alexei M. Khokhlov

Laboratory for Computational Physics and Fluid Dynamics

US Naval Research Laboratory

Washington, DC 20375

The purpose of this paper is to bring to your attention a powerful regime of combustion that has been seen in experiments and recently explained by computations. This regime is characterized by the spread of a supersonic flame in a medium that will *not necessarily* undergo transition to detonation.

This regime is quite different from classical flames or detonations in that it involves truly multi-dimensional transient phenomena. Nonetheless, it can exist long enough to have important applications in propulsion, particularly *micro* propulsion, and applications to safety of highly energetic materials. The potential application to propulsion is attractive because it is efficient in spreading the flame, it increases the surface area of the flame, it accelerates the burning to supersonic speeds, and when it does not lead to detonation, avoids excessive pressure loading characteristic of detonations.

The key elements of this flame are:

– At least partially premixed fuel and oxidizer. We probably need enough mixed to propagate a laminar flame initially. It is possible that inhomogeneities are an asset.

– A gradient in velocity, such as that provided by the presence of either a boundary layer or a wake. The presence of vortices in the boundary layer is an asset.

– A shock. This can be quite weak, depending on the energy content and reactivity of the fuel.

– At least partial confinement or the presence of obstacles in the flow.

The plan of this presentation is to describe the detonationless supersonic combustion and its history, to describe ways this phenomenon has appeared in experiments and numerical simulations, and then to discuss its use for propulsion and micropropulsion.

Detonationless Supersonic Flame Spread: One Example

Detonationless supersonic flames can arise when shocks, flames, and boundary layers are present together in a chamber. Even when a simple planar shock, a laminar flame, and a laminar boundary layer interact, the result is an extremely nonuniform flow with multiple shocks, weak pressure fluctuations, vortices, slip lines, funnels of reacted and unreacted material protruding into one another, and pockets of unburned material surrounded by very convoluted flame surfaces. This is exacerbated with higher Mach-number shocks, low ratios of specific heats γ (as occurs in hydrocarbon fuels), or if there is turbulence or vortical structures in the flow.

Consider a shock that propagates down a tube from left to right. Behind the shock, a boundary layer is formed along the wall. The result is a slightly curved shock, for which the exent of the curvature depends on the properties of the materials in the channel and of the the bounding wall. This shock reaches and reflects from the right vertical wall. Now consider the times series of frames shown in Figure 1, which occurred after such reflection [1]. The now-reflected shock moves back through the channel, through previously shock material and the boundary layer created by the incident shock. As it interacts with the boundary layer, it bifurcates, producing the classical lambda structure that may grow quickly as the structure moves back through the channel. The bifurcation is well-documented in the literature and fairly well understood [2]. Remaining questions involve the effects of three dimensions and particularly of the corners, and how, if, and when the size of the structure self-limits.

Now complicate this picture with the presence of a flame at a location in the channel where the flame can interact with the lambda structure. One possible result is shown in Figure 2 [1]. The large vortex in the lambda structure interacts with the flame and essentially acts as a flame holder. As this vortex moves down the channel at supersonic speeds, it drags the flame with it. The flame is stretched, it's surface area increases, and more energy is released. This accelerates the flame. Thus there is a transient flame-vortex-shock complex that is formed and, for a significant amount of time, stays attached to each other. This complex many or may not lead to a situation in which there is a transition to detonation.

Some Comments on the Shock-Flame-Vortex Complex

The first point to make is that the detonationless supersonic flame is much easier to form than it was in the example shown in Figure 2. The flame may appear even during the incident-shock phase of the problem, and it can occur in situations for which there is spontaneous combustion. For example, it appeared in the incident-shock stage for the case of a narrow tube, where there are weak shocks generated by shock-flame interactions, or where the flame has actually reached the bounding surface [3]. It can occur as a result of spontaneous ignition behind a shock wave. It can occur behind a shock wave generated as a flame accelerates.

A second point to make is that the detonationless supersonic flame has been seen in experiments. It was reported it in schlieren pictures, where it appears as flame moving at supersonic speeds [4]. Understanding the origin of this complex resolved what had been something of a mystery. A supersonic flame has been noted in pulse-detonation experiments [5].

The detonationless supersonic flame is stable enough to last a while. It should last long enough to be of use in micropropulsion devices. As yet, it is not determined whether it could be self-limiting in velocity and strength.

The presence of boundary layers or wakes is important. These create velocity gradients. This use and influence of wakes has been explored to some extent by computations [6] and seen in experiments [7]. The development of appropriate boundary layers and their role in accelerating flame has been noted by [8].

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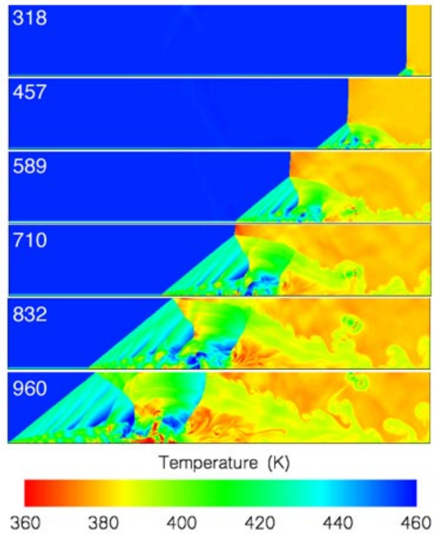

Figure 1. Computations showing a sequence of temperature fields showing the development of the inert bifurcated structure behind the reflected shock in an ethylene-air mixture for incident shock strength $M_s = 1.9$ [1]. Time (μs) is shown in the upper left corner.

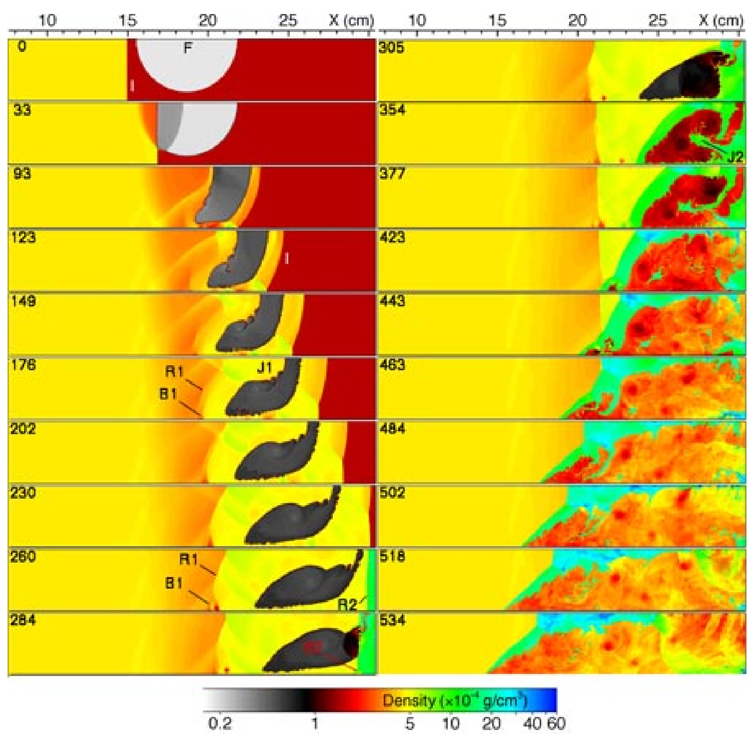

Figure 2. Computations of density fields showing the overall flow development of a supersonic flame in an ethylene-air mixture. The supersonic flame has developed by 450 μs. The incident shock has strength $M_s = 1.8$. Time (μs) is noted on the upper left of each frame. The letters indicate the incident shock (**I**), the flame (**F**), reflected shocks (**R1, R2**), funnels of unreacted material (**J1, J2**), and bifurcated structures (**B1, B2**).