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Premixed flame stability and transition to detonation in a supersonic combustor

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ABSTRACT

Simulations of a supersonic, reacting, premixed flow in a channel were performed to investigate the effect of flow speed on ignition, flame stability, and transition to detonation. The configuration studied was a rectangular channel with a supersonic inflow of stoichiometric ethylene–oxygen, a transmissive outflow boundary, and no-slip adiabatic walls. The compressible reactive Navier–Stokes equations were solved by a high-order numerical algorithm on an adapting mesh for inflow Mach numbers, M_∞, of 3 to 10. For $M_\infty = 3$, the fuel-oxidizer mixture does not reach a sufficient temperature for autoignition. Boundary layers that form on the top and bottom walls deflect the incoming flow, resulting in the formation of an oblique shock train. For $M_\infty \geq 5$, the fuel-oxidizer mixture ignites in the boundary layers and the flame front expands into the channel. The flame front becomes unstable and turbulent with time due to a Rayleigh–Taylor (RT) instability at the interface between the low-density burned gas and high-density unburned gas. Detonation is initiated in several locations at the flame front and in the unburned gas through an energy-focusing mechanism. As M_∞ increases, the time scales for growth of the RT instability at the flame front and eventual detonation increase significantly. Despite the difference in time scales, the flame evolution process is qualitatively independent of M_∞: ignition in the boundary layer, laminar flame expansion, growth of an RT instability at the flame front, turbulent flame expansion, and deflagration-to-detonation transition.

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1. Introduction

A comprehensive understanding of combustion in high-speed flows is required for the development of robust hypersonic vehicles. Airbreathing engines that operate at high supersonic and hypersonic flight speeds will enable more economical space access and the next generation of extended-range, rapid response missile systems due to significant gains in efficiency over traditional rocket engines [1,2]. Achieving flame stability across a wide range of inflow conditions in the engine of an airbreathing hypersonic vehicle is a challenge [3,4] due to the small timescales for mixing, ignition, and complete combustion. The fundamental physics underlying ignition and combustion in high-speed flows is complex due to the chemical reactions, shocks, boundary layers, and turbulence present in these systems. Computational and experimental studies exploring the interaction of these phenomena will enable the design of higher-performing and more reliable hypersonic engines.

Combustion of premixed fuels and the effect of high-speed turbulence on flame development has been studied computationally [5–7], finding that under certain regimes of system size and turbulence intensity, premixed flames are inherently unstable [8]. Detonation waves can be used instead of a flame or deflagration as a propulsion mechanism in a supersonic engine [9–11]. Detonation engines have been studied experimentally [12–14] and computationally [15–18] to characterize performance and detonation wave stability under a range of conditions. Prior work has examined the mechanisms for the deflagration-to-detonation transition (DDT) [19–21], which is required for ignition in rotating and pulse-detonation engines. Hypersonic combustor test facilities are used to study the stabilization of detonation waves in high-speed premixed flows [22,23].

The purpose of this work is to characterize the effect of high supersonic and hypersonic flow speeds on premixed flames and identify the conditions that lead to flame instability and DDT. This paper presents a series of simulations performed to investigate the effect of varying inflow Mach number, M_∞, of an initially homogeneous fuel-oxidizer mixture into a constant-area combustor on ignition, flame growth, formation of fluid instabilities, and DDT. $M_\infty = 3$ to 10 are considered here.

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2. Background

Experimental and computational study of the fundamental physics underlying combustion, flame stability and acceleration, turbulence, and DDT has been substantial due to the need to understand these phenomena and their complex interactions as they are present in physical systems, ranging from aircraft engines to supernovae. Recent emphasis on achieving economical and reliable hypersonic flight for defense and space access has directed significant research effort into these subjects. A brief overview of some of the previous work in these areas is provided here to contextualize the work discussed in this paper.

Turbulence plays a key role in flame instability and, as such, turbulence-flame interaction is one of the most intensively studied phenomenon in combustion. Poludnenko et al. observed that turbulence resulted in unstable burning, which created pressure build-up around the flame and the formation of shocks [8]. Coupling of pressure gradients with density gradients across the flame led to amplification of turbulence within the flame, flame acceleration, and, in some cases, detonations. The response of premixed flames to oscillatory pressure waves was investigated by Teerling et al. [24]. They determined that pressure waves magnify wrinkling in the flame surface due to a RT instability, which increases the overall burning rate of the flame. The effect of pressure waves on premixed flame stability in channels was studied by Xiao et al. [25]. The acoustic properties of the channels into which the premixed flames propagated played an important role in the formation of the pressure waves that affected flame evolution. They observed that the wrinkling and perturbations to the flame shape were due to the growth of a RT instability at the flame surface. The interaction of pressure waves with curved flame fronts was found to have a destabilizing effect that triggered the RT instability, resulting in deformation of a smooth, laminar flame to a distorted tulip flame [26].

In supersonic flow, shocks generated by deflection of the flow or by flame expansion have a significant effect on flame evolution. Shock-flame interactions were studied experimentally by Thomas et al. [27]. They found that perturbation of an initially laminar flame by shocks induced turbulence in the flame causing it to accelerate and often couple closely to the shock. If the shock increased local gas pressure and temperature sufficiently, transition to detonation occurred in the immediate vicinity of the reaction front. Similar results were observed computationally [28] in the collisions of shocks and expanding flame fronts. The shock-flame interaction, primarily through the Richtmyer–Meshkov fluid instability, created a highly turbulent flame brush as funnels of unburned gas propagated into the burned gas. Repeated shock-flame interactions, and coalescence of shocks in the unburned gas, resulted in the development of high-speed shocks that moved in and out of the turbulent flame, creating conditions under which DDT might occur. Interaction of the flame with strong shocks also generated high levels of vorticity in the flame brush, which can lead to direct initiation of a detonation [29].

The process for flame acceleration and the mechanism of DDT in smooth and obstructed channels has been studied experimentally. Much of this work is summarized by Ciccarelli et al. [30]. Acceleration of the flame compresses, heats, and induces turbulence in the unburned reactants and creates conditions for the initiation of a detonation. Detonation initiation occurs through a variety of processes, such as shock focusing, instability near the flame front, flame interactions with pressure waves, or pressure and temperature fluctuations in the boundary layer. Numerical simulations have also been used to investigate the mechanisms for DDT [19]. Shock-flame interactions were found to be important in creating the conditions in which DDT can occur. As shocks passed through turbulent flames, the shock strength was enhanced and the shock-flame collision drove the turbulence in the flame. The intense pressure fluctuations caused by passing shocks in the region of the turbulent flame brush created hot spots, or localized ignition centers, in the unburned gas. The hot spot produced a detonation through an ignition-gradient mechanism [31,32] if the gradient of reactivity was sufficient to support propagation of the spontaneous reaction wave. If the gradient could not support the propagation of a detonation wave, a decoupled shock and flame front would form. Gamezo et al. observed DDT through the ignition-gradient mechanism in obstructed channels when the reflection of Mach stems against obstacles ignited hot spots that transitioned to spontaneous waves and detonations [33].

More recent computations have shown that, when the blockage ratio in an obstructed channel was reduced, detonations occurred through an energy-focusing mechanism [20,34]. The collision of shocks deposited significant energy into the turbulent unburned gas at a time scale smaller than the acoustic time scale of the gas, resulting in the direct initiation of a detonation. The passage of a strong shock through a turbulent flame was also observed to increase energy release at the flame front and, in some cases, caused it to transition to a detonation. When the channel was unobstructed, the detonation initiated in the boundary layer of unburned gas formed against the wall, between the leading shock and the expanding flame [35]. Preheating by the leading shock and viscous dissipation in the boundary layer ignited the unburned gas, producing a spontaneous wave that transitioned to detonation. Regardless of blockage ratio or channel geometry, flame stability and the processes of flame growth and detonation initiation are primarily dependent upon the complex interactions between the flame, shocks, boundary layers, and turbulence. This paper explores the interplay between these phenomena in the context of high-Mach flow of a fuel-oxidizer mixture through an unobstructed combustor of uniform cross-sectional area.

3. Numerical and physical model

The numerical model solves the full set of Navier–Stokes equations for an unsteady, fully compressible, chemically reacting gas,

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{U}) = 0 \tag{1}$$

$$\frac{\partial (\rho \mathbf{U})}{\partial t} + \nabla \cdot (\rho \mathbf{U}\mathbf{U}) + \nabla P = \nabla \cdot \hat{\tau} \tag{2}$$

$$\frac{\partial E}{\partial t} + \nabla \cdot ((E+P)\mathbf{U}) = \nabla \cdot (\mathbf{U} \cdot \hat{\tau}) + \nabla \cdot (K \nabla T) - \rho q \dot{w} \tag{3}$$

$$\frac{\partial (\rho Y)}{\partial t} + \nabla \cdot (\rho Y \mathbf{U}) + \nabla \cdot (\rho D \nabla Y) - \rho \dot{w} = 0 \tag{4}$$

$$P = \frac{\rho R T}{M} \tag{5}$$

where ρ is the mass density, $\mathbf{U}$ is the velocity, E is the energy density, P is the pressure, T is the temperature, Y is the mass fraction of reactant, $\dot{w}$ is the reaction rate, q is the total chemical energy release, K is the thermal conduction coefficient, D is the mass diffusion coefficient, R is the universal gas constant, and M is the molecular weight. The reaction of a stoichiometric mixture of ethylene and oxygen is modeled using a simplified, calibrated chemical-diffusive model,

$$dY/dt \equiv \dot{w} = -A \rho Y \exp(-E_a/RT) \tag{6}$$

where A is the pre-exponential factor and E_a is the activation energy. The effects of viscosity, diffusion, and heat conduction are dependent upon temperature and density,

$$\nu = \nu_0 \frac{T^n}{\rho}, D = D_0 \frac{T^n}{\rho}, \frac{K}{\rho C_p} = \kappa_0 \frac{T^n}{\rho}, \tag{7}$$