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The acoustic response of Burke–Schumann counterflow flames

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ABSTRACT

The acoustic response of strained nonpremixed flames is investigated using as a canonical model problem the planar counterflow configuration subject to small harmonic fluctuations of the stagnation-point pressure and strain rate. To focus on effects of modified transport rates the analysis employs the limit of infinitely fast reaction for a general non-unity Lewis number of the fuel, including values of interest in hydrogen-oxygen and hydrocarbon-oxygen systems. For both acoustic-pressure and acoustic-velocity response, differential–diffusion effects are shown to promote the fluctuations of the flame location and reactant consumption rates (while in the pressure response, distinct behaviors of the flame temperature were observed depending on stoichiometry). The results are used, together with the Rayleigh criterion, to investigate the frequency dependence of the amplification/attenuation rate relevant in computations of acoustic instabilities. The analysis predicts acoustic amplification for all frequencies in the pressure response, whereas a critical crossover frequency is identified in the strain response demarcating the transition from attenuation to amplification of acoustic energy.

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1. Introduction

Acoustic combustion instabilities, characterized by the amplification of pressure oscillations corresponding to the acoustic eigenmodes of the combustion chamber, mainly through interactions with the exothermic combustion reactions, have been a significant concern in the development of liquid-propellant rocket engines from the beginning [1]. In an effort to minimize the potential physical manifestations of these instabilities – including excessive vibration, thermo-mechanical failure, and reduced performance – there has been considerable incentive for scientific studies that provide valuable insight into this unwanted phenomena [2]. Associated concerns about instabilities continue in recent years [3–8]

Difficulty in predicting acoustic instabilities is intrinsically linked to the complex nature of the turbulent multi-phase conditions throughout the combustor, so that in the absence of a general theory for describing such flows, insufficient knowledge of unsteady high-pressure phenomena limits predictive capabilities of acoustic instabilities. Despite this, significant progress has been made with use of flamelet-modeling approaches, in which the turbulent flame is modeled as an ensemble of laminar flamelets that are strained and distorted by the turbulent flow [9,10]. Computations of liquid-propellant rocket-engine instabilities using flamelet modeling require not only knowledge of the statistics regarding distributions of elementary laminar flamelets throughout the chamber but also their response functions to acoustic excitation [11]. The present paper addresses the last aspect of this challenging problem by investigating the acoustic response of planar counterflow nonpremixed flames.

The counterflow diffusion flame has been utilized in the past as a canonical problem to investigate the interplay of the pressure oscillations with the oscillations of rates of heat release by chemical reactions, which are modified as the acoustic perturbations propagate through the diffusion layers of the flames. In the linear limit, the analysis may be greatly simplified by noting that the acoustic pressure nodes and velocity antinodes coincide [12] so that the flame response to pressure perturbations and velocity perturbations may be studied independently by regarding the flamelet to be located at the appropriate node. The analysis here will be concerned with the Burke–Schumann (B–S) limit of infinitely fast reaction, a limit previously considered in the analysis of droplet burning [13] and fuel plates [14]. Unlike these early analyses, our computations account for differential diffusion effects associated with fuel Lewis numbers different from unity.

The solutions obtained here pertain to a flame sheet separating two unsteady regions in chemical equilibrium. This not only provides the basic structure for future studies accounting for finite-rate effects but also quantifies one of the two contributions that arise of finite-rate cases, namely, the direct transport-region contribution. In these respects, it is worth pointing out that some of the previous finite-rate analyses of flame acoustic response

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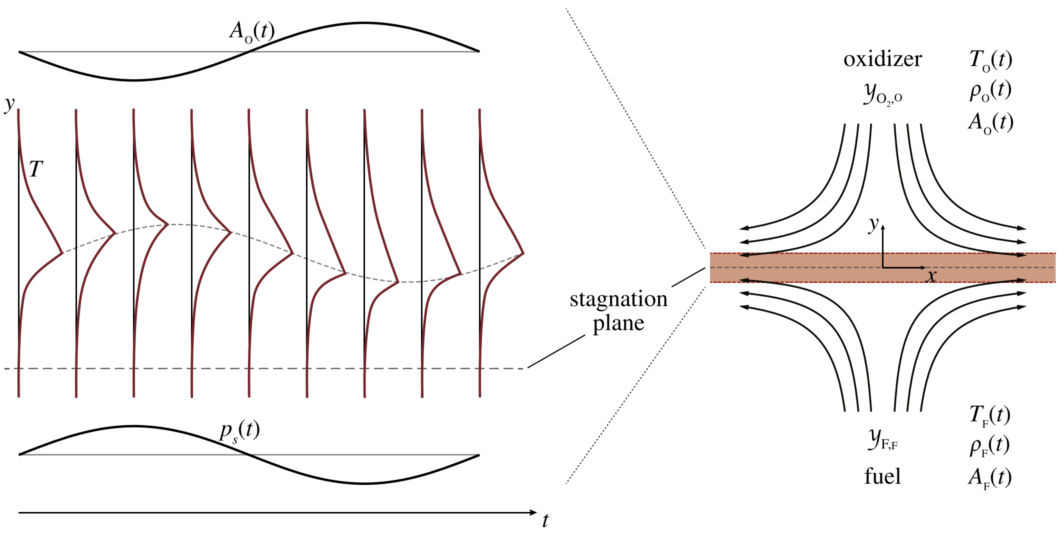

Fig. 1. A schematic view of the planar counterflow system studied here along with a detailed view of the characteristic time evolution of the temperature profile and associated flame location over an acoustic cycle.

[15,16] have investigated the so-called premixed-flame regime [17], including fuel leakage of order unity into the oxidizer side, which is chemically frozen rather than in chemical equilibrium. This basic structure, fundamentally different from the B-S structure, is favored when the stoichiometric mixture fraction Z_S is sufficiently small, as occurs in hydrocarbon-air systems, for which $Z_S \simeq 1/16$. Much larger values $Z_S \simeq 1/5$ are found when the oxidizer is oxygen, which is much more relevant for liquid-propellant rocket-engine applications, in which burning is likely to occur predominantly in the diffusion-flame regime [17], which, at leading order, reduces to the B-S limit investigated here. This fact underscores the need to quantify accurately the response of B–S flames as a necessary step in future efforts to account for effects of realistic chemistry descriptions.

As shown recently [18], the description of stagnation-point mixing layers subject to large variations in density and transport properties resulting from chemical heat release can be facilitated by introducing a thermal-conductivity-weighted coordinate, which is adopted here in formulating the problem in Section 2. The limit of infinitely fast reaction and the perturbation strategy for its description are discussed in Sections 3 and 4, respectively. The acoustic pressure response is discussed in Section 5. The acoustic velocity or strain response is examined in Section 6. A discussion of implications to acoustic instabilities is given in Section 7, which is followed by concluding remarks in Section 8.

2. Problem formulation

We consider a locally planar strained mixing layer situated in the stagnation-point flow generated by counterflowing streams of fuel and oxidizer. At moderately large Reynolds numbers the thin mixing layer separates two effectively inviscid and isentropic streams whose structure provides appropriate boundary conditions for the analysis of the unsteady chemically active mixing region [19]. A reference system moving with the dividing streamline is employed in the description, with cartesian coordinates (x, y) and the oxidizer approaching from $y = +\infty$, as indicated in Fig. 1. Subscripts O and F are used to denote properties in the oxidizer and fuel streams, respectively. In the outer inviscid streams the velocity field is given by the potential solutions $(v_x, v_y) = A^*_O(x, -y)$ and $(v_x, v_y) = A^*_F(x, -y)$ in terms of the time-dependent strain rates $A^*_O(t)$ and $A^*_F(t)$, an asterisk identifying original dimensional variables throughout. The problem is formulated for low-Mach number flow and acoustic wavelengths large compared with the characteristic dimension of the stagnation-point region. Under those conditions, the pressure differences from the time-dependent stagnation-point value $p^*_s(t)$ are small and can be correspondingly neglected when writing the equation of state $p^*_s = \rho^*(R/M)T^*$ involving the density ρ^*, temperature T^*, and mean molecular weight M, with R denoting the universal gas constant.

The analysis specifically considers small fluctuations of the pressure $p^*_s(t)$ and of the strain rates $A^*_O(t)$ and $A^*_F(t)$. Mixing of the two streams is confined to a thin layer of characteristic thickness $\delta_m = [\bar{\lambda}^*_O/(\bar{\rho}^*_O c^*_p \bar{A}^*_O)]^{1/2}$, small compared with the natural length scale used in defining the relevant Reynolds number. Here c^*_p is the specific heat at constant pressure, and $\bar{\lambda}^*_O$, $\bar{\rho}^*_O$, and $\bar{A}^*_O$ are the mean values of the thermal conductivity, density, and strain rate in the oxidizer stream. Within this slender layer, the solution takes a self-similar form, with the time t and the distance y to the stagnation plane entering as the only independent variables [20]. In the description, the streamwise component of the velocity $v_x = xA^*(y, t)$, linearly proportional to the streamwise distance x, is conveniently described in terms of the strain rate $A^*(y, t)$, whose variation across the mixing layer is determined from momentum conservation. This mixing-layer region exhibits large transverse changes of the density and transport properties, mainly associated with the temperature increase caused by the heat release at the flame. While these changes have often been handled in the past through introduction of a density-weighted transverse coordinate, recent work [18] suggests that weighting the coordinate with the inverse of the thermal conductivity is beneficial, especially from the viewpoint of providing a compact transport operator, as will be seen below. To this end, the problem is formulated with use made of an inverse-thermal-conductivity-weighted coordinate

$$\eta(y, t) = (\bar{\lambda}^*_O/\delta_m) \int_0^y \frac{\mathrm{d}y}{\lambda^*(y, t)}, \tag{1}$$

and a modified nondimensional transverse mass flux

$$F = -\frac{\rho^* v_y + \rho^* \lambda^* \int_0^y \frac{\partial}{\partial t}\left(\frac{1}{\lambda^*}\right)\mathrm{d}y}{\bar{\rho}^*_O \delta_m \bar{A}^*_O}, \tag{2}$$

replacing the streamwise velocity in the integration.

In addition, the mean properties of the oxidizer stream are used to define scaled variables $\tau = \bar{A}^*_O t$, $A(\eta, \tau) = A^*/\bar{A}^*_O$, $p_s(\tau) = p^*_s/\bar{p}^*_s$, $T(\eta, \tau) = T/\bar{T}^*_O$, $\rho(\eta, \tau) = \rho^*/\bar{\rho}^*_O$, and $\lambda(\eta, \tau) = \lambda^*/\bar{\lambda}^*_O$. In

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