Nonlinear Acoustic-Pressure Response in Laminar Counterflow Diffusion Flames of Hydrogen and Air

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Introduction

Transient flamelet responses to external perturbation such as flow velocity or pressure oscillation have been investigated recently for better understanding of turbulent flames in combustion systems. These are in the category of flame or combustion dynamics and especially, acoustic-pressure responses of diffusion flames are closely related to combustion instabilities in systems such as solid and liquid propellant rocket motors, ramjets, utility boilers, and furnaces, where flames may be subject to intensely fluctuating pressure waves. Among combustion instabilities, acoustic instability is a phenomenon that pressure oscillations are amplified through in-phase heat addition/extraction from combustion. Acoustic instabilities may arise from any nonlinear processes present in propulsion systems, such as atomization, turbulent mixing and combustion. Combustion is of particular interest because it is the fundamental source of thermal energy that can be fed to amplify and sustain acoustic oscillations, however, most of works [1–4] are limited to linear analysis having infinitesimal amplitude of oscillation.

The present study is to focus on the acoustic responses of counterflow diffusion flames under stagnation pressure oscillation by adopting a detailed hydrogen/air chemistry. The nonlinear responses of flames to pressure oscillation with finite amplitude are numerically investigated.

Model

Numerical analysis is carried out in an axisymmetric counterflow configuration in which oxidizer(air) is injected from the boundary located at ∞ while fuel(hydrogen) is injected from the other boundary at $-\infty$. The governing equations of the continuity, momentum, species and energy in the boundary layer formation for the counterflow can be found in the literature [5]. The external pressure perturbation is simulated in the form of

$$P_s(t)/P_{s,m} = 1 + A\sin(2\pi\omega t) \tag{1}$$

where P_s is the stagnation-point pressure, A is the relative amplitude, ω is the frequency, t is the time, and subscript m denotes the mean value. This process can be considered as isentropic and the temperatures of the fuel and oxidizer streams, T_F and T_O, will be considered to vary with time because of the compression work associated with the variable stagnation-point pressure $P_s(t)$. The detailed kinetic mechanism for hydrogen oxidation [6] is employed in this study. Thermodynamic and transport properties

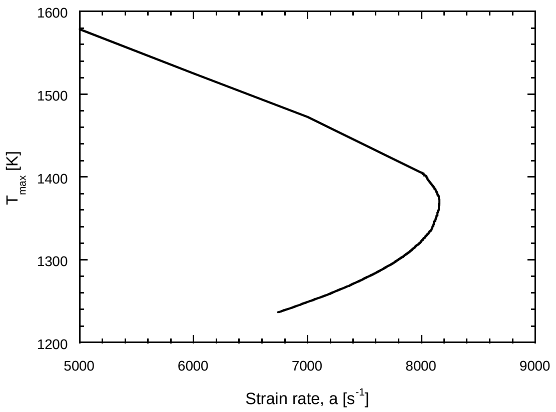

Figure 1: Variations of maximum temperature as a function of strain rate at the mean pressure $P_{s,m} =$ 1 atm.

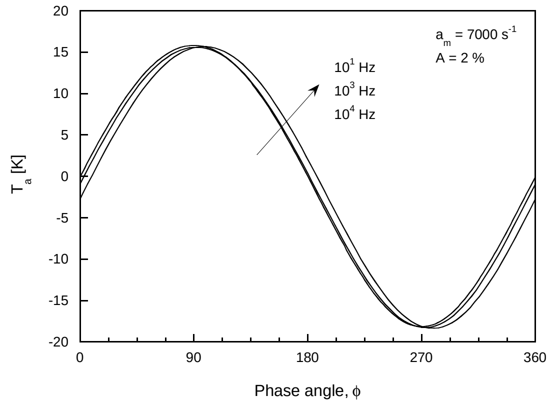

Figure 2: Responses of maximum temperature fluctuation of near-extinction flame to slow, medium and fast pressure oscillations.

are calculated from CHEMKIN-II [7] and TRANSPORT PACKAGE [8], respectively. The acoustic response is monitored by calculating the instantaneous maximum flame temperature from transient flame structures. Details on solution methods can be found elsewhere [4, 9].

Results and Discussion

Prior to analyzing the acoustic response of strained hydrogen/air counterflow diffusion flames to pressure oscillations, steady-state flame structures are first examined. The overall steady-state behavior of hydrogen/air counterflow diffusion flames is shown in Fig. 1, where variation in the maximum flame temperature with strain rates at $T_F = 300$ K, $T_O = 300$ K, and $P_{s,m} = 1$ atm is plotted. Previous studies [2, 3] showed that flame responses to external perturbation are quite sensitive near extinction condition, which is also demonstrated in this figure, and thereby the response of flame in near-extinction regime ($a_m = 7000\ s^{-1}$) is focused here.

Contribution of counterflow diffusion flames to acoustic instability can be judged by the Rayleigh criterion [10]. It states that acoustic amplification occurs if, on the average, heat is added in phase with pressure oscillation. With the imposed harmonic pressure variation given in Eq. (1), the acoustic responses of near-extinction flame ($a_m = 7000\ \mathrm{s}^{-1}$) to various oscillations, namely fast oscillation (10^4 Hz), intermediate oscillation (10^2 Hz), and slow oscillation (10^0 Hz), are shown in Fig. 2 as a function of phase angle, ϕ. Note that T_a indirectly represents the fluctuation of heat release rate. Heat release rate and pressure oscillate in phase with each other, on the average, at any frequency. These results imply that the flame is capable of responding immediately to pressure oscillations and follows the quasi-steady response since the effect of finite-rate chemistry is more dominant than that of flow field at any realistic frequencies. Accordingly, responses to these pressure oscillations do not show any significant phase lag and the almost identical response is exhibited among them. This indicates that near-extinction flames always contribute to acoustic amplification.

Nonlinear acoustic responses to the imposed pressure oscillation with finite amplitude, A, are shown

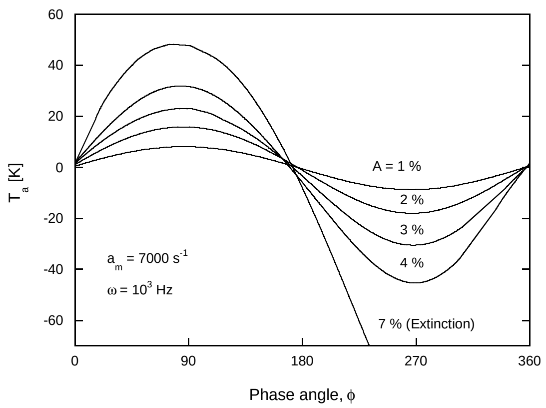

Figure 3: Variations of maximum temperature fluctuation for various amplitude of pressure oscillation($a_m = 7000$ s^{-1}, $\omega = 10^3$ Hz and $P_{s,m} = 1$ atm).

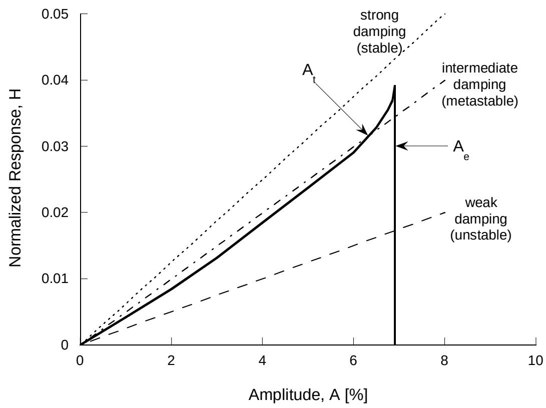

Figure 4: Variations of normalized maximum temperature response as a function of acoustic-pressure amplitude for $a_m = 7000$ s^{-1}, $\omega = 10^3$ Hz and $P_{s,m} = 1$ atm.

in Fig. 3 for $\omega = 10^3$ Hz, $a_m = 7000$ s^{-1}, and $P_{s,m} = 1$ atm. When the pressure oscillations pass their minimum values, the flames are close to extinction condition. As a result, the fluctuation of maximum temperature, T_a, is much greater near the phase angle of $\phi = 270°$ compared to that near $\phi = 90°$. Especially, it is appreciable as A increases. In addition, the response to pressure oscillation with $A = 7$ % shows that flame can be extinguished if A is greater than a certain critical amplitude. The intensity of chemical reaction, especially in the near-extinction regime, is very sensitive to pressure variation. Thus, an excessive decrease of pressure leads to flame extinction.

In order to evaluate the overall amplification contribution of flames throughout one complete oscillation cycle, the maximum temperature fluctuation is normalized by acoustic amplitude A as

$$H = \int_0^{\tau} [T_a/T_m] \sin(2\pi\omega t)\, dt \tag{2}$$

The variation of H is shown in Fig. 4 for the same condition corresponding to Fig. 3. The characteristics of the temperature response are seen to be quite nonlinear in that the increase of H with increasing A becomes greater as A becomes larger. The value of H is expected to become zero beyond the critical value of acoustic pressure amplitude $A = A_e$. Such response behavior can also be deduced from the steady flame structure, *i.e.*, enhanced nonlinear response occurs when the instantaneous pressure passes near its minimum. As the acoustic amplitude increases, flame condition becomes closer to extinction during the passage of the minimum pressure, so that the increase of H becomes greater. If A is greater than a critical value, which is 7 % in this calculation, then the chemical reaction during the passage of the minimum pressure is too weak to support the flame. Therefore, flame is extinguished and the flame response vanishes.

The present results of nonlinear flame response can be viewed as a possible mechanism to produce the threshold phenomena discussed in the work of Clavin et al. [11], in which acoustic instabilities can be triggered only by acoustic perturbations with amplitudes greater than a certain threshold amplitude. To show this possibility, three different damping response lines, each corresponding to strong, weak, and intermediate damping, are indicated in Fig. 4 by the dotted line, dashed line, and chain dotted line, respectively. First, consider the case of strong damping which is marked stable in Fig. 4. The only intersection between the amplification and damping rates occurs at $A=0$. This implies that any acoustic perturbation is attenuated and the system is stable. For the case of weak damping, there are intersections at $A=0$ and at $A=A_e$, and only the intersection at $A=A_e$ is stable. Therefore, all acoustic disturbance will eventually converge to $A=A_e$, and the system is always unstable. The third case corresponds to the intermediate damping, in which two stable intersections at $A=0$ and $A=A_e$ are separated by an unstable one at $A=A_t$. If the initial amplitude of a disturbance is greater than A_t, the acoustic amplitude converges to A_e. Otherwise, the disturbances are attenuated. Consequently, the system is metastable and could exhibit the threshold behavior.

Summary

The structures and nonlinear acoustic-pressure responses of hydrogen/air counterflow diffusion flames have been numerically studied by employing a detailed hydrogen/air chemistry. The nonlinear responses are examined by imposing harmonic pressure perturbations with various amplitudes on counterflow diffusion flames. Near-extinction flames always respond to pressure oscillations without noticeable delay, leading to acoustic amplification and large flame responses occur during the passage of minimum pressure because flames near extinction are more sensitive to pressure fluctuations. Consequently, the flame response, normalized during one complete oscillation cycle, increases with much faster rate than the rate of increase in the amplitude of pressure oscillation. This nonlinear response behavior can be interpreted as a possible mechanism in generating the threshold phenomena observed during engine tests in propulsion systems.

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