The impact of non-stiff fuel injection on the response of a partially premixed pure hydrogen flame

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Introduction

In a partially premixed configuration, both velocity and pressure fluctuations can induce temporal equivalence ratio fluctuations in the vicinity of the fuel injector. Once the pressure oscillation reaches a significant level, the assumption of stiff fuel injection will be compromised, resulting in a fluctuation in fuel mass flow. This study investigates the influence of non-stiff injection on the dynamic response of a jet-stabilized, partially premixed hydrogen flame. This research offers new insights into the dynamic flame response under partially premixed, acoustically non-stiff conditions, and offers valuable insight for the design of future hydrogen-fueled combustion systems.

Experimental Setup

Sketch of a laboratory-scaled micromix burner and the key perturbations.

(a) Time-resolved equivalence ratio measurement system [1]; (b) Time-resolved OH* intensity measurement system.

- Flame tansfer function (FTF):

$$F(\omega) = \frac{\hat{I}(\omega)/\bar{I}}{\hat{u}_r(\omega)/\bar{u}_r}. \quad (1)$$

- The transfer function of ϕ':

$$T_\phi(\omega) = \frac{\hat{\phi}(\omega)/\bar{\phi}}{\hat{u}_r(\omega)/\bar{u}_r}. \quad (2)$$

Model Development

- Mode conversion [2]:

$$\frac{\phi_3'}{\bar{\phi}_3} \approx \frac{\dot{m}_f'}{\bar{\dot{m}}_f} - \frac{\dot{m}_a'}{\bar{\dot{m}}_a} \approx \frac{u_n'}{\bar{u}_n} - \frac{u_2'}{\bar{u}_2}. \quad (3)$$

- Acoustic impedance model for a circular aperture:

$$p_n' - p_2' = i\omega\bar{\rho}_n l_{\text{eff}} u_n' + \bar{\rho}_n C_d \bar{u}_n u_n'. \quad (4)$$

- The resulting equivalence ratio fluctuations:

$$\frac{\phi_3'}{\bar{\phi}_3} = -\frac{1}{JM_2}\frac{p_2'}{\bar{\rho}_2\bar{c}_2\bar{u}_2} - \frac{u_2'}{\bar{u}_2}, \quad (5)$$

where $J = \bar{\rho}_n\bar{u}_n^2/\bar{\rho}_2\bar{u}_2^2$ and $M_2 = \bar{u}_2/\bar{c}_2$.

- The transfer function of ϕ_3':

$$G_\phi = \frac{\phi_3'/\bar{\phi}_3}{u_r'/\bar{u}_r} = g\left(\frac{-Z_r\bar{u}_r}{\bar{\rho}_n\bar{u}_n^2} - 1\right), \quad (6)$$

- The mixing transfer function [3]:

$$H_{\text{mix}} = \frac{\hat{\phi}/\bar{\phi}}{\hat{\phi}_3/\bar{\phi}_3} = \exp\left[\frac{\text{Pe}}{2}\left(1 - \sqrt{1 + i2\pi\text{St}_T\frac{4}{\text{Pe}}}\right)\right]. \quad (7)$$

- The transfer function of ϕ':

$$T_\phi = G_\phi H_{\text{mix}}. \quad (8)$$

The experimental measurement and model prediction of T_ϕ at $\bar{\phi} = 0.66$
Stiff: $\dot{m}_f'/\bar{\dot{m}}_f = 0$; Non-stiff: $\dot{m}_f'/\bar{\dot{m}}_f \neq 0$

Flame Response

- FTFs plotted against Strouhal number St_r, defined using the convective time delay of ϕ', given by $\tau_c = (L_f + L_{\text{inj}})/\bar{u}$.
- Reference velocity: u_r (Left), reconstructed via MMM and controlled at 5%; u_n (Right), estimated using the acoustic impedance model for a circular aperture.

- Evolution of phase-averaged streamwise OH* intensity fluctuation I_x' [4]. Each column illustrates the spatiotemporal distribution of the fluctuations for selected forcing frequencies corresponding to local maxima and minima in the FTF gain.
- Operating condition: $\bar{\phi} = 0.56, 0.66, 0.76$, $\bar{u}_2 = 9.6$ m/s.

Summary

- Pressure oscillations induce additional equivalence ratio fluctuations in non-stiff configurations.
- FTFs show gain modulation due to interference between velocity- and equivalence ratio-driven flame responses [5]. Pressure-induced equivalence ratio fluctuations significantly influence the overall flame response.
- Distinct dynamic behaviors at the top and bottom parts of the flame under the combined modulations in velocity and equivalence ratio.

References

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