CEMA를 이용한 수소 난류 제트 화염의 동축류 온도에 따른 연소모드 진단

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Diagnostic of combustion modes of turbulent hydrogen jet flames using chemical explosive mode analysis (CEMA)

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ABSTRACT

The flame structure of turbulent lifted hydrogen jet flames with different coflow temperatures (i.e. T_c = 750, 850, and 950 K) is analyzed with chemical explosive mode analysis (CEMA). 3-D direct numerical simulations (DNSs) were performed with 1.28 billion grid points. CEMA identifies local combustion modes, such as auto-ignition, ignition assisted by diffusion and extinction. The local reaction and diffusion source terms are projected to the eigenvector of Jacobian matrix of reaction source term. α (a local combustion mode indicator) defined as ratio of projected diffusion term to reaction term shows local combustion mode of lifted flame.

Key Words : lifted flame, DNS, CEMA, combustion mode

Three direct numerical simulations (DNSs) of turbulent lifted jet flames were performed in a three dimensional slot-burner configuration. Fuel issues from a central jet, which consists of 65% hydrogen and 35% nitrogen by volume at an inlet temperature of T_j = 400 K. Heated co-flow air streams at three different temperatures of T_c = 750 (Case L), 850 (Case M), and 950 K (Case H) surround central fuel jet with atmospheric pressure. The fuel jet and coflow velocities are specified as U_j = 240 m/s and and U_c = 2 m/s, respectively. The fuel jet width, H, is 2 m.

Chemical explosive mode analysis (CEMA) is used to analyze flame structures near the flamebases [1-3].

Reacting flow is governed by following differential equations

$$\frac{\boldsymbol{Dy}}{\boldsymbol{Dt}} = \boldsymbol{g}(\boldsymbol{y}) = \boldsymbol{\omega}(\boldsymbol{y}) + \boldsymbol{s}(\boldsymbol{y})$$

where D/Dt is the material derivative and y represents the solution vector of species concentrations and temperature. $\boldsymbol{\omega}$ and $\boldsymbol{s}$ represent the chemical source non-chemical source terms, respectively.

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The Jacobian of the chemical source term $\boldsymbol{J_\omega}$ and its eigen value ($\boldsymbol{\lambda_e} = \boldsymbol{b_e} \cdot \boldsymbol{J_\omega} \cdot \boldsymbol{a_e}$; $\boldsymbol{a_e}$ and $\boldsymbol{b_e}$ are right and left eigenvectors) is defined as chemical explosive mode (CEM) where $\boldsymbol{\lambda_e}$ is positive and only considered real part. Projected chemical source term ($\boldsymbol{\phi_\omega}$) and non-chemical source (diffusion) term ($\boldsymbol{\phi_s}$) are shown in following equations [3].

$$\boldsymbol{\phi_\omega} = \boldsymbol{b_e} \cdot \boldsymbol{\omega}, \quad \boldsymbol{\phi_s} = \boldsymbol{b_e} \cdot \boldsymbol{s}.$$

The ratio of $\boldsymbol{\phi_s}$ to $\boldsymbol{\phi_\omega}$ is defined as local combustion mode indicator $\boldsymbol{\alpha}$:

$$\boldsymbol{\alpha} = \boldsymbol{\phi_s}/\boldsymbol{\phi_\omega},$$

which describes three different local combustion modes: (1) $\boldsymbol{\alpha > 1}$: the assisted-ignition mode, where diffusion affects significant at this mode. (2) $\boldsymbol{-1 < \alpha < 1}$: the auto-ignition mode, where reaction term is dominant. (3) $\boldsymbol{\alpha < -1}$: the local extinction mode: where the ignition process depressed by large amount of dissipation.

Chemical Damköhler number $\boldsymbol{Da_c} = \boldsymbol{\lambda_e} \cdot \boldsymbol{\chi^{-1}}$ is introduced to elucidate combustion state near the flamebase, $\boldsymbol{\chi}$ is scalar dissipation rate defined by $\boldsymbol{\chi = 2D|\nabla\xi|^2}$ where D is local thermal diffusivity. Here, we explain $\boldsymbol{Da_c}$ briefly. For more details of $\boldsymbol{Da_c}$, readers are referred to a previous study [1]. $\boldsymbol{Da_c}$ is ratio between CEM to $\boldsymbol{\chi}$. $\boldsymbol{\lambda_e}$ represents reciprocal of chemical time scale and $\boldsymbol{\chi}$ represents

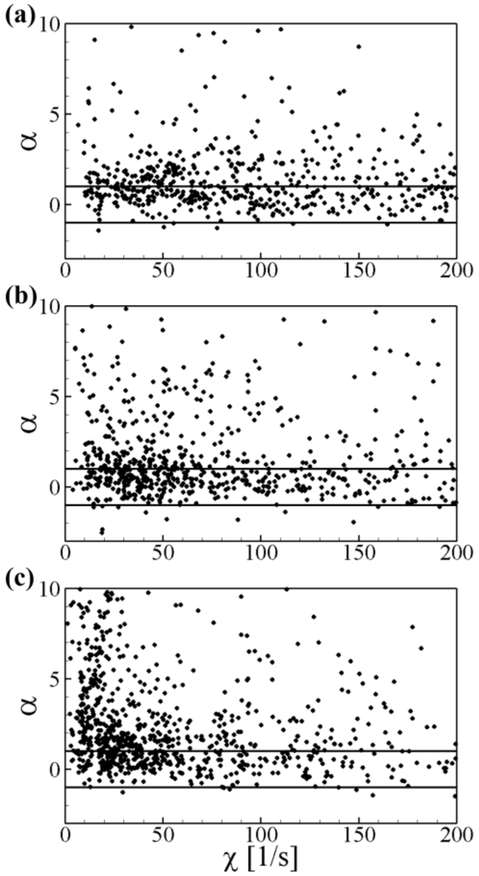

Fig. 1 Scatter plot of combustion mode indicator versus scalar dissipation rate at flamebase; (a) Case H, (b) Case M and (c) Case L. Solid lines indicate α is 1 and -1.

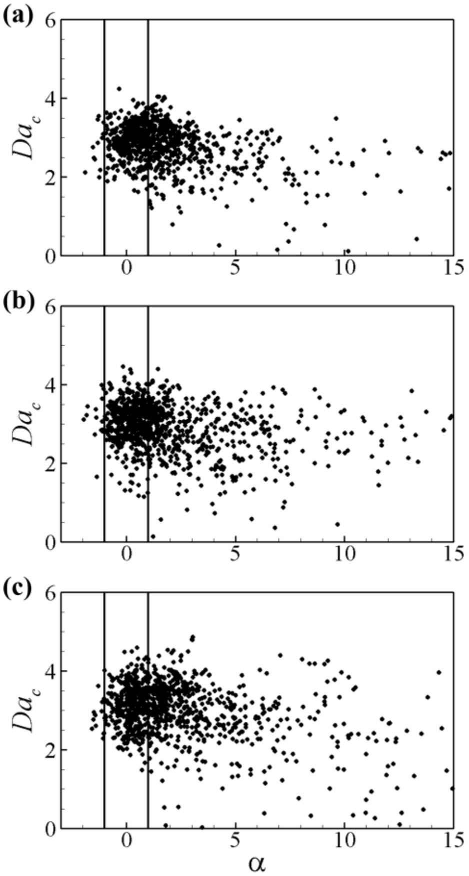

Fig. 2 Scatter plot of $\boldsymbol{Da_c}$ versus combustion mode indicator at flamebase; (a) Case H, (b) Case M and (c) Case L. Solid lines indicate α is 1 and -1.

reciprocal of dissipation time scale. Local mixture that has large positive $\boldsymbol{Da_c}$ means that this mixture would ignite; otherwise ignition would be suppressed by the large dissipation of species or energy.

Flamebase is defined as iso-surface of the mass fraction of OH species Y_{OH} is 0.001 [4]. The steady liftoff heights are 4.8 mm (Case H), 8 mm (Case M) and 10.6 mm (Case L). Figure 1 shows the scatter plot of $\boldsymbol{\alpha}$ versus $\boldsymbol{\chi}$ on the flamebase at certain time.

In case of L, $\boldsymbol{\alpha}$, having large positive values, is distributed low scalar dissipation rate region. Therefore, diffusion-assisted ignition is believed to occur near the flamebase in Case L. As the coflow temperature goes up, diffusion-assisted ignition combustion mode becomes weak.

Figure 2 shows $\boldsymbol{Da_c}$ versus $\boldsymbol{\alpha}$ at the flamebase for 3 different cases. In this figure, $\boldsymbol{Da_c}$ of all three cases indicates that local mixture undergoes ignition process. The case L scatter plot shows that diffusion assisted ignition is relatively strong compared to large coflow temperature cases. In case of L, some points have $\boldsymbol{Da_c} \approx 1$ at high $\boldsymbol{\alpha}$. It means dissipation and reaction balance each other. In case of H, most of points locate whitin auto-ignition zones where $\boldsymbol{\alpha}$ is between 1 and -1. In case of M, the coflow temperature is second explosion limit, and hence, the flamebase is stabilized by a mixed mode between auto-ignition and diffusion-assisted ignition.

In this paper, combustion modes of lifted flames with 3 different coflow temperatures were studied with CEMA. The combustion mode of Case L near the flamebase exhibits auto-ignition which is highly affected by diffusion with low scalar dissipation rates. For Case H, the lifted flamebase has auto-ignition dominated combustion mode. For Case M (850 K), its combustion mode exhibits the mixed characteristics of Cases L and H.

후 기

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