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Numerical Studies on Structure and Stabilization Mechanism of Turbulent Nonpremixed Lifted Methane/Air Jet Flames

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The flame liftoff characteristics considerably influences the flame stabilization and pollutant formation in practical combustion devices and largely depends on flow configurations, fuel type, heat losses and mixing conditions etc. The lifted non-premixed turbulent jet flames involve many fundamental mechanisms, which involve ignition, local extinction, re-ignition, and flame propagation. Since these physical phenomena are strongly coupled and highly nonlinear, explanations of the stabilization mechanism have been quite controversal.

This study is mainly motivated to numerically analyze the detailed flame structure and stabilization mechanism in the lifted non-premixed turbulent jet flames. The present study adopts two different turbulent combustion models based on the strained laminar premixed flamelets[1], which use two parameters such as mixture fraction and reaction progress variable and level set approach[2], in order to get closure of turbulence-chemistry interaction. In the strained laminar premixed flamelet model, the laminar heat release rate is obtained at each mixture fraction and reaction progress variable and turbulent mean heat release rate in energy equation is calculated by using the joint PDF of mixture fraction and reaction progress variable. For simplicity, the mixture fraction and reaction progress variable are assumed to be statistically independent each other, the joint PDF is equal to the product of each PDF. The commonly used PDFs for mixture fraction and reaction progress variable is beta function distribution. In order to account the flame straining effect, the distribution of flame straining is assumed to be a quasi-Gaussian PDF [3]. The laminar heat release rate is calculated using one dimensional premix code with chemical kinetics of GRI-Mech 2.11. In the level set approach, the G-equation is introduced to describe premixed combustion. The scalar G is equal to the constant G_0 at the location of the instantaneous premixed flame front. Thus, the surface $G(x,t) = G_0$ divides the flow field into the regions of burned gas where $G(x,t) > G_0$, and unburned gas where $G(x,t) < G_0$. Since G is the non-reacting scalar, it avoids complications associated with counter-gradient diffusion and there is no need for a source term closure.

This approach also uses the other scalar of mixture fraction to express the mixing state in the reacting flow field. There are two possible states for the diffusion flamelet, either burning ($G>G_0$) or non-burning ($G<G_0$). For the burning flamelets, the mass fractions of the chemical species are determined by using a steady-state flamelet library with the conditional scalar dissipation rate χ_{st} as a parameter. In the burned gas, the mean mass fractions are calculated using a presumed PDF approach. In the unburned gas, all mass fractions are zero except those of fuel and oxidizer. These mass fractions are to be linear in mixture fraction. Within the turbulent flame brush, the average mass fractions are determined from the weighted sum of mass fractions of burned and unburned gas.

The validation case includes the measurement of Muniz and Mungal [4] which has the detailed experimental data of liftoff height and velocity fields near flame base for various co-flow air conditions. In their experiment, the fuel of methane (99.0% purity) is injected through the nozzle of 4.8mm diameter and the co-flow velocity ranges from 0 to 1.85m/s. Figure 1 shows that the comparison of liftoff height as a function of jet exit velocity for two different co-flow conditions. The predicted liftoff heights are defined by the onset of heat release rate. Except the jet exit velocity of 16m/s, the predicted liftoff heights reasonably well agree with the experimental data. Figure 2 and Figure 3 present the mean temperature fields for various flow inlet conditions. By increasing the jet exit velocity, the stabilization point is progressively apart from inlet and centerline. Numerical results indicate that the present approach has the predicative capability to realistically represent the essential features of the lifted turbulent jet flames in terms of flame liftoff height and mean flow patterns near flame stabilization point. Figure 4 shows the mean flame fronts, $\tilde{G} = G_0$, and the stoichiometric mixture fraction lines for different fuel exit velocities with the co-flow air velocity of 0.34 m/s after stabilization has been reached. The stabilization points are located the slightly lean side and is increasing the distance from the nozzle exit and centerline by increasing the fuel jet velocity. Figure 5 represents the iso-lines of mean mixture fraction, temperature field, turbulent flame speed, and distribution of OH mass fraction with a co-flow air velocity of 0.34 m/s and a fuel jet velocity of 16m/s. The expansion at the flame front deflects the streamlines and mixture fraction iso-lines. The turbulent flame speed has high value near flame stabilization point. Since the net convective flux of G is equal to the production of G due to the turbulent flame speed near the flame base, the stabilization of lifted flame is accomplished. The location of the maximum OH concentration indicates the location of the trailing mean diffusion flame between two premixed flame front expressed by

G_0 surface. In Figure 6, the liftoff heights predicted by the present level set approach are compared with experimental data for three different jet exit velocities and two co-flow conditions. The predicted liftoff heights are defined as the distance between nozzle exit and the lowest axial location of G_0. Compared to results of the strained premixed laminar flamelet model, the liftoff heights predicted by the level set approach are favorably agreed with experimental data for all cases.

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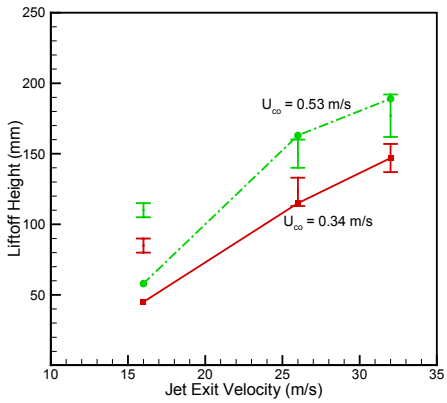

Figure 1 Comparisons of liftoff height for methane lifted jet flame are plotted as a function of jet exit velocity (symbol : prediction, error bar : experiment)

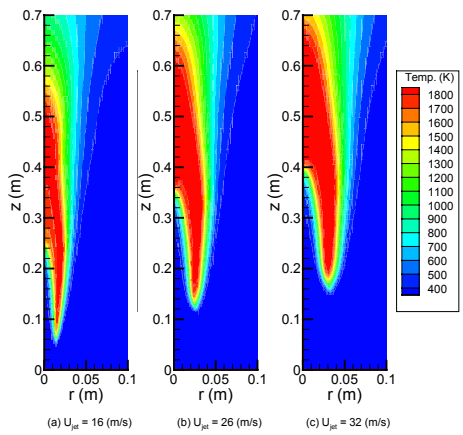

Figure 2 Temperature distributions for various jet exit velocity at co flow air velocity = 0.34 m/s.

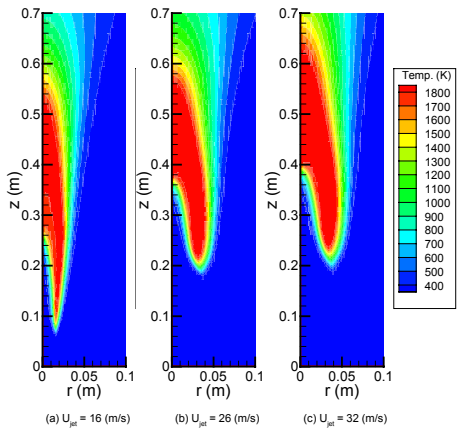

Figure 3 Temperature distributions for various jet exit velocity at co flow air velocity = 0.53 m/s.

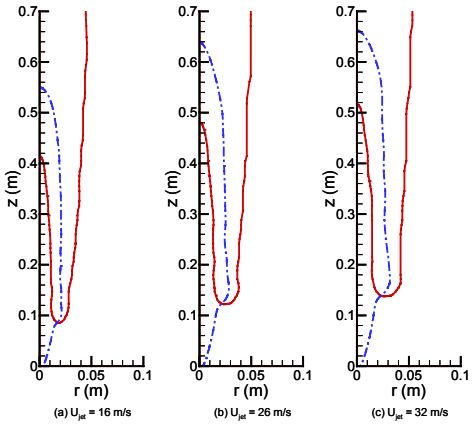

Figure 4 The mean shape of the turbulent flame front (solid line) for methane/air jet flames at fuel nozzle exit velocities of (a) 16m/s, (b) 26m/s and (c) 32m/s and co-flow air velocity of 0.34m/s using Level-Set approach. The dashdot lines denote the mean stoichiometric lines.

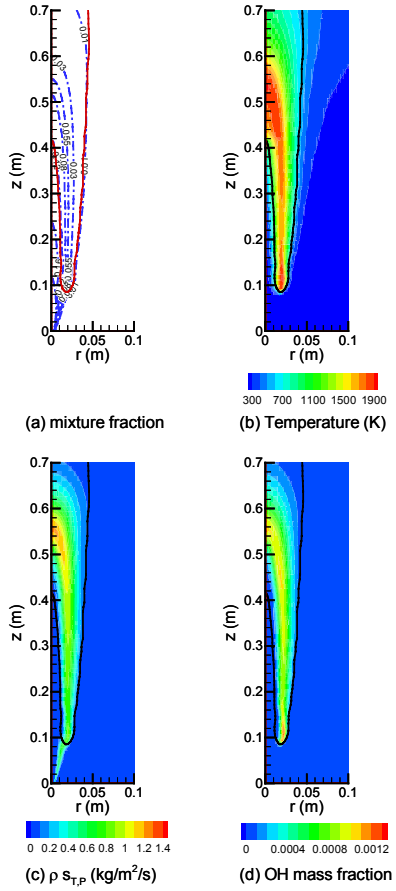

Figure 5 Results of Level-Set approach for the methane/air jet flame with a fuel nozzle exit velocity of 16m/s and co-flow air velocity of 0.34m/s; (a) iso-lines of mean mixture fraction, (b) mean temperature, (c) turbulent flame speed, and (d) OH mass fraction. Solid lines denote the flame fronts.

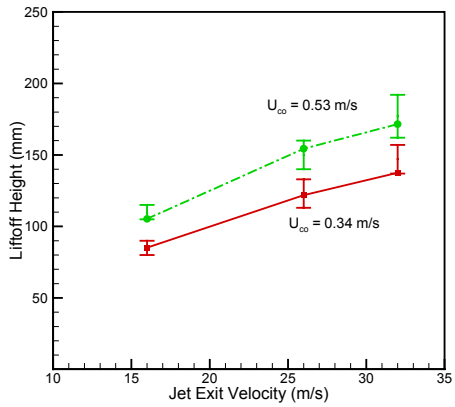

Figure 6 The comparison of liftoff height as a function of jet exit velocity (Error bars represent the experimental data, solid line denotes cases for co-flow velocity of 0.34m/s)