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FLAMELET MODELING OF LIFTED TURBULENT METHANE/AIR AND PROPANE/AIR JET DIFFUSION FLAMES

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The stabilization mechanism of lifted turbulent jet diffusion flames is a test problem for models of partially premixed turbulent combustion. In these flames, combustion processes occur in both the non-premixed and the premixed mode. For the flame stabilization process, however, flame propagation of the premixed branches seems to play a crucial role. In this paper, a flamelet model for partially premixed turbulent combustion is presented that combines flamelet models for non-premixed and premixed combustion. A new model for the turbulent burning velocity in partially premixed flows is proposed. It is based on a formulation for a conditional turbulent burning velocity which depends on mixture fraction. The effect of partially premixing is taken into account by using the presumed probability density function (pdf) approach in terms of the mixture fraction. Mean scalar quantities on both sides of the premixed flame front are calculated in the same way. From a computational point of view, the model has the advantage that the calculation of the chemical processes can be decoupled from the flow calculation, allowing for simulations of realistic configurations, yet retaining detailed chemistry. The model is used to simulate the stabilization process of turbulent methane/air and propane/air jet diffusion flames. The calculated lift-off heights compare favorably with experimental data from various authors.

Introduction

Research on lifted jet diffusion flames has been conducted for more than 50 years [1]. Despite this long-time effort, the physical mechanisms of turbulent flame stabilization are still not well understood [2]. Theories for the flame stabilization mechanism may be divided into three categories: (1) premixed flame propagation [3,4], (2) flamelet quenching [5], and (3) flame extinction due to large-scale turbulent structures [6].

The underlying assumptions for the premixed flame propagation approach are that fuel and oxidizer are fully premixed at the base of a lifted diffusion flame and that stabilization occurs at the position where the mean flow velocity at the contour of mean stoichiometric mixture is equal to the burning velocity of a stoichiometric premixed turbulent flame [3,4]. In contrast, Peters and Williams [5] proposed that diffusion flamelet extinction is responsible for flame stabilization. They argue that there is insufficient residence time below the flame base to achieve spatial and temporal uniformity of the mixture. Although there is little doubt that diffusion flame quenching is responsible for the lift-off of an initially attached flame, detailed experimental analyses conducted over the last 15 years do not confirm the flamelet quenching hypothesis for flame stabilization [7]. Finally, Broadwell et al. [6] proposed that hot combustion products are carried by large-scale turbulent structures to the edge of the jet, where they re-enter the jet and ignite the combustible mixture. In their view, both lift-off and blow-out occur when the re-entrained products are mixed so rapidly with the unburned jet fluid that there is insufficient time to initiate the reaction before the temperature and the radical concentration drop below some critical value. In his review of these different approaches, Pitts [2] came to the conclusion that none of these theories can satisfactorily predict lift-off and blow-out behavior.

In recent years, triple flames have attracted much interest, because it is believed that they may play a crucial role in many partially premixed combustion situations including the stabilization mechanisms of turbulent jet flames. Liñán [8] and Kioni et al. [9] have shown theoretically that in laminar flows, lifted flames are stabilized by a triple-flame configuration. Veynante et al. [10] and Favier and Vervisch [11] have demonstrated that triple flames are able to survive strong interactions with vortices by adjusting their structure to a new transient environment, thus being more robust than pure diffusion flames.

In this paper, we propose a flamelet model for partially premixed turbulent combustion that is based on the premixed flame propagation mechanism, but that will take the triple-flame structure as a key element of the partially premixed situation into account. Flamelet models [12–14] have been very useful in combining turbulence and non-equilibrium chemistry. The advantage of the flamelet concept is the fact that it allows the decoupling of the chemistry

calculation from the calculation of the turbulent flow field.

The Flamelet Model for Partially Premixed Turbulent Combustion

At the base of the lifted turbulent diffusion flame, fuel and oxidizer are partially premixed. The instantaneous surface of stoichiometric mixture separates lean and rich regions. When a flame propagates through the inhomogeneous fluctuating mixture of fuel and oxidizer, an instantaneous flame front separates burned and unburned gases. Thus, a formulation for both premixed and non-premixed combustion has to be used. For this purpose, the flamelet model of non-premixed combustion [15] is combined with the flamelet model for premixed combustion [16].

The mixing of fuel and oxidizer in the turbulent flow field is described by the transport equation of the mean mixture fraction, $\tilde{Z}$, and the variance, $\widetilde{Z''^2}$

$$\frac{\partial(\bar{\rho}\tilde{Z})}{\partial t} + \nabla\cdot(\bar{\rho}\tilde{\mathbf{v}}\tilde{Z}) = \nabla\cdot\left[\frac{\mu_t}{Sc_{\tilde{Z}}}\nabla\tilde{Z}\right] \quad (1)$$

$$\frac{\partial(\bar{\rho}\widetilde{Z''^2})}{\partial t} + \nabla\cdot(\bar{\rho}\tilde{\mathbf{v}}\widetilde{Z''^2}) = \nabla\cdot\left[\frac{\mu_t}{Sc_{\widetilde{Z''^2}}}\nabla\widetilde{Z''^2}\right] + \frac{2\mu_t}{Sc_{\widetilde{Z''^2}}}(\nabla\tilde{Z})^2 - \bar{\rho}\tilde{\chi} \quad (2)$$

where the Schmidt numbers $Sc_{\tilde{Z}}$ and $Sc_{\widetilde{Z''^2}}$ are chosen as 0.7, and the scalar dissipation rate $\tilde{\chi}$ is modeled as

$$\tilde{\chi} = c_\chi\frac{\tilde{\varepsilon}}{\tilde{k}}\widetilde{Z''^2} \quad \text{and} \quad c_\chi = 2.0 \quad (3)$$

Here, $\tilde{k}$ is the turbulent kinetic energy, and $\tilde{\varepsilon}$ is its dissipation rate.

In order to describe premixed combustion, the level set approach based on the G-equation is introduced [17]. The scalar G is equal to the constant G_0 at the location of the instantaneous premixed flame front. Thus, the surface $G(\mathbf{x},t) = G_0$ divides the flow field into the regions of burned gas where $G(\mathbf{x}, t) > G_0$, and unburned gas where $G(\mathbf{x}, t) < G_0$. The equation for the mean location of the turbulent flame front then reads [16]

$$\frac{\partial(\bar{\rho}\tilde{G})}{\partial t} + \nabla\cdot(\bar{\rho}\tilde{\mathbf{v}}\tilde{G}) = \bar{\rho}s_{T,p}|\nabla\tilde{G}| - \bar{\rho}D_t\tilde{\kappa}|\nabla\tilde{G}| \quad (4)$$

where $\tilde{\kappa}$ is the curvature of the mean flame front and D_t is the turbulent diffusivity, which can be determined from the integral length scale, ℓ, and the fluctuation velocity, v',

$$D_t = a_4\ell v', \qquad a_4 = 0.78 \quad (5)$$

In addition, the turbulent flame brush thickness, $l_{F,t}$, can be determined from the variance of G by the simple relation

$$l_{F,t} = \left.\frac{(\widetilde{G''^2})^{1/2}}{|\nabla\tilde{G}|}\right|_{\tilde{G}=G_0} \quad (6)$$

evaluated at the location of the mean premixed flame front $\tilde{G} = G_0$. The equation for the variance of G is [16]

$$\frac{\partial(\bar{\rho}\widetilde{G''^2})}{\partial t} + \nabla\cdot(\bar{\rho}\tilde{\mathbf{v}}\widetilde{G''^2}) = \nabla_\parallel\cdot(\bar{\rho}D_t\nabla_\parallel\widetilde{G''^2}) + 2\bar{\rho}D_t(\nabla\tilde{G})^2 - c_s\bar{\rho}\frac{\tilde{\varepsilon}}{\tilde{k}}\widetilde{G''^2} \quad (7)$$

where $\nabla_\parallel$ denotes differentiation only tangential to the mean flame front. Using equations 6 and 7, it is shown in Ref. [7] that for large times the turbulent flame brush thickness, $l_{F,t}$, of a one-dimensional unsteady flame is proportional to the integral length scale

$$l_{F,t} = b_2\ell, \qquad b_2 = 1.78 \quad (8)$$

What remains is the determination of the turbulent partially premixed burning velocity, $s_{T,p}$, in equation 4. In order to model this quantity, we follow in essence the assumption that fuel and oxidizer are locally premixed, such that the partially premixed flame propagates through a stratified, though locally premixed environment. For premixed turbulent combustion, the turbulent burning velocity, s_T, can be determined from [16]

$$\frac{s_T - s_L}{v'} = -\frac{a_4b_3^2}{2b_1}Da + \left[\left(\frac{a_4b_3^2}{2b_1}Da\right)^2 + a_4b_3^2Da\right]^{1/2} \quad (9)$$

where s_L is the laminar burning velocity of a plane flame, $Da = s_L\ell(v'l_F)$ is the Damköhler number, ℓ and l_F are the integral length scale and the laminar flame thickness, v' is the turbulence intensity, and $a_4 = 0.78$, $b_1 = 2.0$, and $b_3 = 1.0$ are constants derived from turbulence modeling.

Let us, for illustration purposes, consider a stationary laminar triple flame in a constant velocity field. The leading edge of such a flame, called the triple point, propagates along a surface that is in the vicinity of the stoichiometric mixture. On the lean side of that surface, there is a lean premixed branch, and on the rich side there is a rich premixed branch, both propagating with a lower burning velocity. Behind the triple point, a diffusion flame develops into which unburned intermediates such as H_2 and CO diffuse from the rich premixed flame branch, and the left-over oxygen diffuses from the lean premixed flame branch. The premixed branches are inclined

in such a way that, while the normal burning velocity decreases as one moves downstream on the lean and on the rich branch, its projection onto the oncoming flow direction has to be equal to the oncoming flow velocity. This indicates that each part of a triple flame, parameterized in terms of the mixture fraction, contributes to the propagation velocity of the whole structure in a similar way. Therefore the parts can be considered separately. A conditional turbulent Damköhler number, $Da(Z)$, can then be introduced into equation 9 to determine the conditional burning velocity, $s_T(Z)$, as

$$s_T(Z) = s_L(Z) + v'f\{Da(Z)\} \quad (10)$$

where $f\{\ \}$ represents the right-hand side of equation 9, and $Da(Z)$ is defined as

$$Da(Z) = \frac{s_L(Z)\ell}{v'l_F(Z)} = \frac{s_L^2(Z)\ell}{v'D} \quad (11)$$

In the second part of equation 11, the laminar flame thickness, $l_F(Z)$, has been replaced by $l_F(Z) = D/s_L(Z)$, where the laminar diffusivity, D, has been assumed to be mixture fraction independent. Using a presumed probability density function (pdf) approach, the mean turbulent burning velocity of a partially premixed flame, $s_{T,p}$, can then be determined from

$$(\bar{\rho}s_{T,p}) = \int_0^1 \rho(Z)s_T(Z)P(Z)dZ \quad (12)$$

where $P(Z)$ is chosen to be a beta-pdf. If $s_T(Z)$ is defined with respect to the unburned mixture, $\rho(Z)$ is to be evaluated there. If it is assumed that turbulent partially premixed flame propagation proceeds by an ensemble of laminar triple flamelets, the laminar burning velocity, $s_L(Z)$, should be the velocity normal to the premixed flame surface of a laminar triple flame. Plessing et al. [18] compared these local values of $s_L(Z)$ found in laminar triple flames to those of planar premixed flames at different mixture fraction levels. They found the two to be in qualitative good agreement. For simplicity, we will therefore use the laminar burning velocity, $s_L(Z)$, taken from a planar premixed flame in a homogeneous mixture with mixture fraction Z.

The set of equations 1, 2, 4, and 8 represents the flamelet model for partially premixed turbulent combustion used in this paper, while equations 10 and 12 model the turbulent partially premixed burning velocity needed in equation 4, and equation 6 together with equation 8 defines the variance of G.

Numerical Method

In order to simulate turbulent partially premixed combustion, the flamelet model described above has been implemented into the FLUENT code [19]. In addition to the conservation equations of mass and momentum, an equation for the mean total enthalpy, $\tilde{h}$, is solved

$$\frac{\partial(\bar{\rho}\tilde{h})}{\partial t} + \nabla\cdot(\bar{\rho}\tilde{\mathbf{v}}\tilde{h}) = \frac{d\bar{p}}{dt} + \nabla\cdot\left(\frac{\bar{\rho}\nu_t}{\mathrm{Pr}_t}\nabla\tilde{h}\right) \quad (13)$$

replacing the original energy equation of the FLUENT code. Here Pr_t is the turbulent Prandtl number, which is chosen as 0.7.

To avoid numerical difficulties, the scalar function $\tilde{G}$ is calculated as a distance function, meaning that away from the mean flame front, a re-initialization procedure of the $\tilde{G}$ field using $|\nabla\tilde{G}| = 1$ has to be performed. This is achieved using an algorithm proposed by Sussman et al. [20]. The turbulence is described by a standard $\tilde{k}$-$\tilde{\varepsilon}$ model, which includes buoyancy effects and a round jet correction.

In order to describe the scalar fields, a flame sheet model is adopted. This model does not resolve the laminar premixed flame structure, but rather replaces it with a jump. The dependence of the scalar field on the mixture fraction, however, is taken into account by calculating the diffusion flamelet structure. Thus, there are two possible states for the diffusion flamelet, either burning (for $G > G_0$) or nonburning (for $G < G_0$). 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

$$\tilde{Y}_{i,b}(\tilde{Z}, \widetilde{Z''^2}, \tilde{\chi}_{st}) = \int_0^1 Y_i(Z, \chi_{st})P(Z)dZ \quad (14)$$

Here, $Y_i(Z, \chi_{st})$ is determined from a library of burning diffusion flamelets, setting the conditional scalar dissipation rate, χ_{st}, of the flamelets equal to the conditional mean scalar dissipation rate, $\tilde{\chi}_{st}$, both defined at stoichiometric mixture. The latter can be calculated from

$$\tilde{\chi}_{st} = \frac{\tilde{\chi}f(Z_{st})}{\int_0^1 f(Z)P(Z)dZ} \quad \text{and}$$

$$f(Z) = \exp(-2[\mathrm{erfc}^{-1}(2Z)]^2) \quad (15)$$

where the mean value $\tilde{\chi}$ is determined by equation 3. The boundary conditions for these flamelets are those of pure air and fuel. A beta-function pdf is used in equations 14 and 15. In the unburned gas, all mass fractions are zero except those of fuel and oxidizer. These mass fractions, being linear in mixture fraction, are evaluated from

$$\tilde{Y}_{F,u} = Y_{F,1}\tilde{Z} \text{ and } \tilde{Y}_{Ox,u} = Y_{Ox,2}(1 - \tilde{Z}) \quad (16)$$

Within the turbulent flame brush, the average mass fractions are determined from the weighted sum

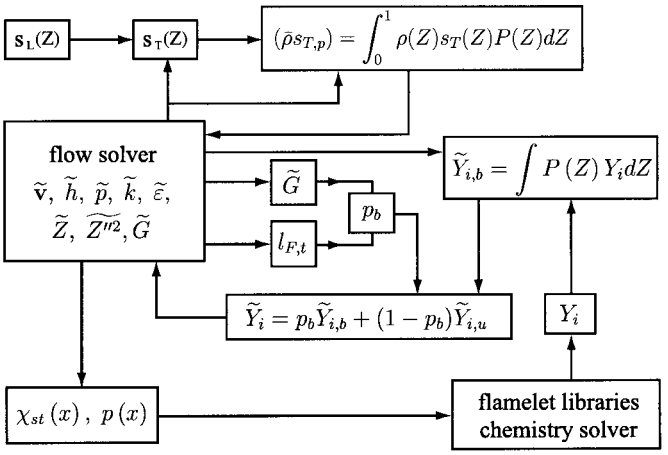

FIG. 1. The code structure for the flamelet model of partially premixed turbulent combustion.

$$\tilde{Y}_i = p_b\tilde{Y}_{i,b} + (1 - p_b)\tilde{Y}_{i,u} \quad (17)$$

Here, p_b denotes the probability of finding burned gas

$$p_b = p_b(G > G_0) = \int_{G=G_0}^{\infty} \frac{1}{\sqrt{2\pi\widetilde{G''^2}}} \exp\left(-\frac{(G - \tilde{G})^2}{2\widetilde{G''^2}}\right)dG, \quad (18)$$

where a Gaussian distribution is assumed for the pdf of G. The mean temperature, $\tilde{T}$, can then be calculated from equations 13 and 17 using

$$\sum_{i=1}^{n} \tilde{Y}_i h_i(\tilde{T}) = \tilde{h} \quad (19)$$

where the specific enthalpies, h_i are taken from NASA polynomials. Fig. 1 summarizes the computational steps in the simulation of partially premixed turbulent combustion using the proposed flamelet approach.

Results

The model presented above was used to calculate methane/air and propane/air turbulent jet flames for a wide variety of fuel nozzle exit velocities and different fuel nozzle diameters. The results were compared to experimental data of Kalghatgi [21], Miake-Lye and Hammer [22], Donnerhack and Peters [23], and Røkke [24].

Turbulent Methane/Air Jet Flames

In the experiments to be considered, a fuel stream of pure methane was injected into ambient air through a nozzle with a diameter $D = 4$ mm or $D = 8$ mm. In the calculated cases with a nozzle diameter of 8 mm, the mean fuel exit velocity, $\tilde{u}_0$, was varied from 40 m/s to 100 m/s, whereas it was varied from 20 m/s to 50 m/s for the cases with a nozzle diameter of 4 mm. The fuel exit velocity profile was assumed to follow the 1/7 power law, the turbulent intensity was set equal to 10% of the inlet flow velocity, and the integral length scale of the turbulent inflow was set equal to the nozzle diameter. Fuel and air temperatures were both 298 K, and the ambient pressure was 1 bar.

For the cases with a nozzle diameter of 8 mm, the simulations were performed for a domain of 1000 mm × 400 mm axial × radial length, with 191 × 77 non-equidistant computational grid cells. For the case with the nozzle diameter of 4 mm, the domain size was 440 mm × 190 mm axial × radial length, with the same number of grid cells.

The mass fractions, Y_i, of the laminar diffusion flamelets were determined by using a steady flamelet library with the scalar dissipation rate, χ_{st}, as the parameter. The flamelet library was produced by the RIF code [25], in which the chemistry of methane/air diffusion flames was described by a detailed chemical mechanism involving 354 chemical reactions among 30 chemical species assuming equal diffusivity for all species. For the methane/air flame, the stoichiometric mixture fraction was $Z_{st} = 0.055$.

In order to initialize the simulation, the cold flow was calculated at first for the different fuel exit velocities, using equation 16 to determine the mean chemical mass fractions. Then the mixture was ignited at a downstream location by initialization of the G-field in such a way that $\tilde{G} = G_0 \pm |\mathbf{x} - \mathbf{x}_0|$. After ignition, the flame front propagated until it finally reached a steady state, stabilizing at the lift-off height, H. Since the mean curvature term in equation 4 was found to be small, it was neglected in the following. In Fig. 2, the laminar burning velocity $s_L(Z)$ for equation 10, taken from Refs. [18,26], the

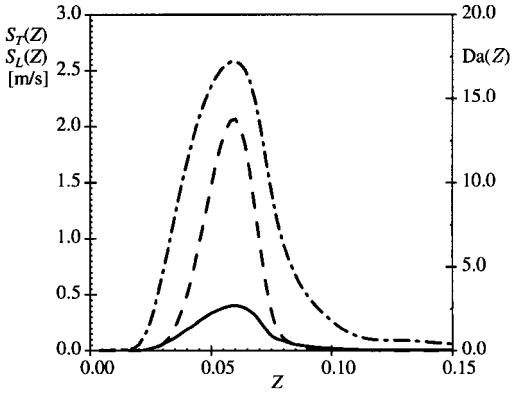

FIG. 2. Quantities at the lift-off height. The laminar burning velocity (——), the conditional Damköhler number (- - - -), and the conditional turbulent burning velocity (–·–·–·–·–), evaluated for $v' = 1.4$ m/s and $\ell = 8.5$ mm as a function of the mixture fraction.

conditional turbulent burning velocity, $s_T(Z)$, from equation 10 and the Damköhler number $Da(Z)$ are shown as a function of the mixture fraction, Z, evaluated for $\ell = 8.48 \times 10^{-3}$ m and $v' = 1.41$ m/s. These quantities were calculated at the lift-off height of the jet flame with a fuel exit velocity of $\tilde{u}_0 = 80$ m/s and a fuel nozzle diameter of $D = 8$ mm. Fig. 3 shows the mean flame fronts $\tilde{G} = G_0$ for different fuel exit velocities with a fuel nozzle diameter of 4 mm after stabilization has been reached. The mean shape of the lifted diffusion flame is similar to that of a laminar triple flame. The stabilization points are located on the lean side and, in the case of low fuel exit velocities, near the isoline of stoichiometric mixture. Fig. 4 shows enlargements of the stabilization region for an exit velocity of $u_0 = 40$ m/s and an exit diameter of $D = 8$ mm. In the left picture, thin lines denote isocontours of mixture fraction and the thick line represents the mean flame front contour. The expansion at the flame front deflects the stream lines and, thereby, the mixture fraction isolines at the flame base. Stabilization occurs in this case slightly on the lean side, at $\tilde{Z} = 0.05$. The middle picture shows the mean OH distribution, and the mean temperature distribution is shown on the right. The location of the maximum OH concentration indicates the location of the trailing mean diffusion flame. The discernible local minimum of OH is due to locally slightly higher values of the mixture fraction variance.

The calculated non-dimensional lift-off heights, H/D, are shown as a function of the fuel exit velocity, $\tilde{u}_0$, in Fig. 5. The predicted lift-off heights are in good agreement with the experimental data of Kalghatgi [21], Miake-Lye and Hammer [22], and Donnerhack and Peters [23].

Turbulent Propane/Air Jet Flames

The simulations were carried out according to the configuration and experimental conditions given by Røkke [24]. Pure propane was injected into the ambient air through a nozzle with a diameter of $D = 6$ mm. In the calculated cases, the mean fuel exit velocity, $\tilde{u}_0$, was varied from 20 m/s to 120 m/s. The turbulent intensity was assumed to be 10% of the inlet flow velocity, and the integral length scale of the turbulent inflow was assumed to be equal to the nozzle diameter. Fuel and air temperatures were both 293 K, and ambient pressure was 1 bar. The simulations were performed for a domain of 440 mm $\times$ 190 mm axial $\times$ radial length, with 191 $\times$ 77 non-equidistant computational grid cells. The laminar diffusion flamelets were calculated by the RIF code, in which the chemistry of propane/air diffusion flames was described by a detailed chemical mechanism involving 36 chemical species [25]. The mixture fraction at stoichiometric mixture was $Z_{st} = 0.0601$. The laminar burning velocity, $s_L(Z)$, of the unstretched premixed propane/air flame was obtained from Ref. [27].

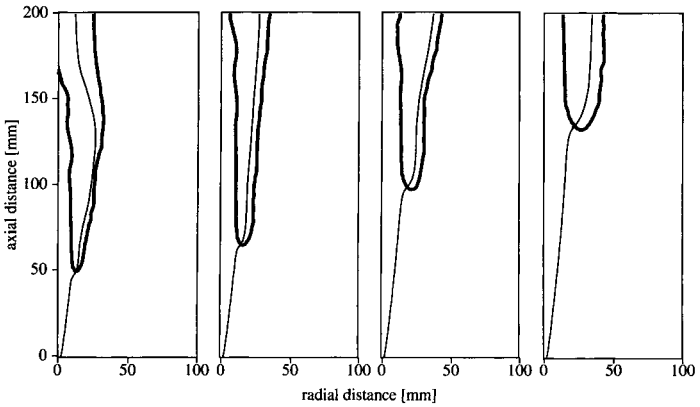

FIG. 3. The mean shape of the turbulent flame front (thick line) for methane/air jet flames at fuel nozzle exit velocities of $u_0 = 20$, 30, 40, and 50 m/s (from left to right) for a fuel nozzle diameter of $D = 4$ mm. Thin lines are isolines of the mean mixture fraction at stoichiometric mixture.

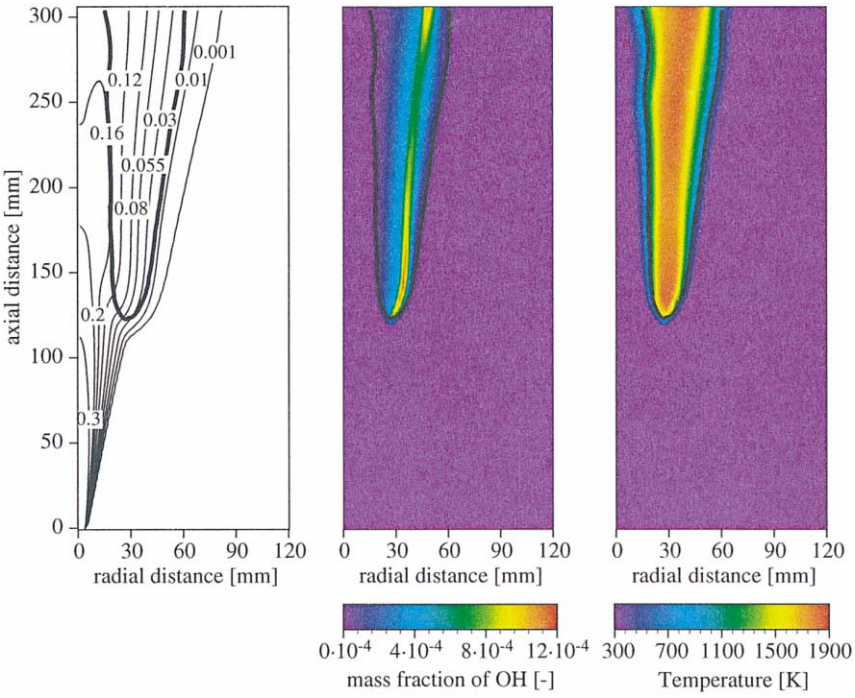

FIG. 4. Results for the methane/air jet flame with a fuel nozzle exit velocity of $u_0 = 40$ m/s and $D = 8$ mm. The left picture shows isolines of the mixture fraction (thin lines) and the shape of the mean turbulent flame front (thick line), the middle picture shows the mean OH mass fraction, and the right picture shows the mean temperature distribution.

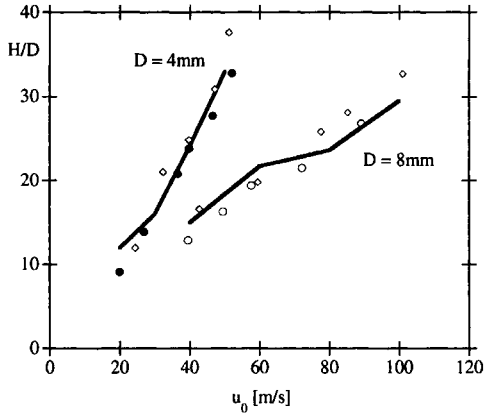

FIG. 5. Normalized lift-off heights, H/D, of methane/air jet diffusion flames for $D = 4$ mm and $D = 8$ mm. Comparison of flamelet model (——) with experimental data by Kalghatgi (○) [21], Miake-Lye and Hammer (●) [22], and Donnerhack and Peters (◇) [23].

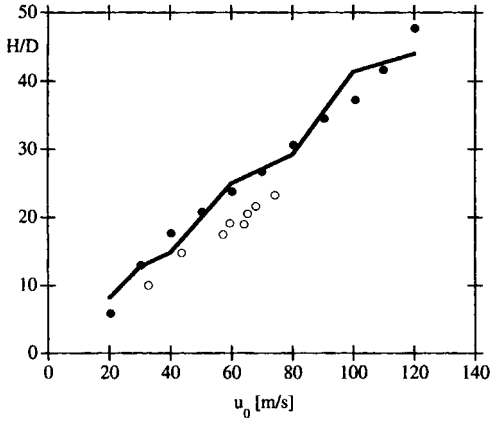

FIG. 6. Normalized lift-off heights, H/D, of propane/air jet diffusion flames for $D = 6$ mm. Comparison of flamelet model (——) with experimental data by Røkke (●) [24] and Kalghatgi (○) [21].

Figure 6 shows the calculated values of H/D compared to the measured data given by Røkke [24] and Kalghatgi [21]. It can be seen that the calculated lift-off heights are in good agreement with the experimental data of Røkke [24], whereas there is a slight discrepancy with the data of Kalghatgi [21].

Conclusions

In this paper, a flamelet formulation for partially premixed turbulent combustion has been presented. It combines the flamelet models for turbulent premixed and non-premixed combustion in order to describe turbulent flame propagation in inhomogeneous mixtures of fuel and oxidizer. A level set approach was applied to calculate the location and geometry of the partially premixed flame front, while mixing was described using the mixture fraction. A new model for the turbulent partially premixed burning velocity is presented; it is based upon turbulent premixed flame propagation but takes the partial premixing via a conditional turbulent burning velocity into account.

The presented flamelet model has been used to simulate lifted turbulent methane/air and propane/air jet flames for a variety of fuel exit velocities and nozzle diameters. The simulation results show that the mean structure of the lifted turbulent diffusion flame is similar to that of a laminar triple flame. The stabilization points are found to be located on the lean side and, in the case of low fuel exit velocities, near the isoline of stoichiometric mixture. The predicted lift-off heights are in good agreement with experimental data.

The results of this work show that the mechanisms of stabilization can be explained by the partially premixed flame propagation approach, where the mixture ahead of the stabilization point is assumed to be locally premixed.

It is remarkable that the approximation of equation 9 for the turbulent burning velocity (that was validated for homogeneous premixtures only [16]) can be used without modifications or additional constants for the prediction of flame stabilization at the lift-off height in turbulent jet diffusion flames. Flame stabilization in lifted turbulent jet flames is probably the most severe test for any model for partially premixed combustion, because turbulence is very intense as a result of the relatively high shear in a jet.

Acknowledgments

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COMMENTS

F. C. Gouldin, Cornell University, USA. Your model results are very encouraging. They show good agreement with flame lift-off height measurements. Since mixing of jet fluid with surrounding air before combustion is an important aspect of your model, I would expect that inflow boundary conditions would be important and would influence lift-off height. For your calculations, what were the boundary conditions? Are these conditions consistent with the experiments you modeled? Finally, have you varied these conditions to determine their effect on lift-off height?

Author's Reply. The numerical boundary conditions were consistent with the experiments. In the experimental setups, the fuel nozzle lengths were such that fully developed turbulent pipe flows were achieved. Miake-Lye and Hammer (Ref. [22] in paper) measured the fuel nozzle velocity profiles and found them to be in reasonable agreement with the power law of Nikuradse (Ref. [28] in paper) $u/u_0 = (1 - r/R)^{1/n}$, which we used with $n = 7$ for all cases. Fuel concentration and temperature were always kept at the measured values. Turbulence intensity and the integral length scale were not reported in any of the experimental work considered here; therefore a turbulent intensity of Tu = 10% and an integral length scale of $\ell = D$ were assumed. We believe that these choices do not have a major effect on the resulting lift-off height, however, a detailed analysis of the influence of Tu and ℓ on the lift-off height remains to be done.