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ABSTRACT

An experimental and numerical investigation is presented of a lifted turbulent H₂/N₂ jet flame in a coflow of hot, vitiated gases. The vitiated coflow burner emulates the coupling of turbulent mixing and chemical kinetics exemplary of the reacting flow in the recirculation region of advanced combustors. It also simplifies numerical investigation of this coupled problem by removing the complexity of recirculating flow. Scalar measurements are reported for a lifted turbulent jet flame of H₂/N₂ (Re=23,600, $H/d=10$) in a coflow of hot combustion products from a lean H₂/Air flame ($\phi=0.25$, T=1,045K). The combination of Rayleigh scattering, Raman scattering, and laser-induced fluorescence is used to obtain simultaneous measurements of temperature and concentrations of the major species, OH, and NO. The data attest to the success of the experimental design in providing a uniform vitiated coflow throughout the entire test region. Two combustion models (PDF: joint scalar Probability Density Function and EDC: Eddy Dissipation Concept) are used in conjunction with various turbulence models to predict the lift-off height ($H_{PDF}/d=7$, $H_{EDC}/d=8.5$). Kalghatgi's classic phenomenological theory, which is based on scaling arguments, yields a reasonably accurate prediction ($H_K/d=11.4$) of the lift-off height for the present flame. The vitiated coflow admits the possibility of auto-ignition of mixed fluid, and the success of the present parabolic implementation of the PDF model in predicting a stable lifted flame is attributable to such ignition. The measurements indicate a thickened turbulent reaction zone at the flame base. Experimental results and numerical investigations support the plausibility of turbulent premixed flame propagation by small scale (on the order of the flame thickness) recirculation and mixing of hot products into reactants and subsequent rapid ignition of the mixture.

INTRODUCTION

Clear understanding of turbulent flame stabilization in an environment of hot combustion products will aid the advancement of combustion technology. Practical combustor designs employ the recirculation of hot combustion products to achieve flame stabilization in their intensely turbulent flows. Numerical investigations of these flows are difficult to execute because of the detailed, fully coupled, turbulent fluid mechanics and chemical kinetics. A challenge for combustion researchers is to design experiments that address flame stabilization in combustion products, while decoupling the chemical kinetics from the complex recirculating flow.

The simplified flow of the vitiated coflow burner provides experimental and numerical access to fundamental combustion features of recirculation burners. The design (Fig. 1) consists of a jet flame in a coaxial flow of hot combustion products from a lean premixed flame (vitiating coflow). The reacting flow associated with the central jet exhibits similar chemical kinetics, heat transfer, and molecular transport as recirculation burners without the recirculating fluid mechanics. The well-defined, uniform boundary conditions and simplified flow associated with the coaxial jet design are attractive features for numerical modeling. Additionally, the open design facilitates the use of optical diagnostics.

The vitiated coflow burner enables investigation of stabilization mechanisms for lifted turbulent jet flames in environments that are relevant to combustion applications but have not been studied systematically. Typically, lifted turbulent jet flame experiments are conducted on fuel jets in cool air, where the air is either quiescent or a low velocity coflow. The range of flows that can be studied is limited because a relatively small increase in air coflow velocity can result in flame blow-off. In turbulent jet flame research, this limitation of flame stability is often circumvented with the use of pilots [1,2], which introduce the complexity of a third stream (jet, pilot, and coflow) and non-uniformity of fluid entrained by the jet. The vitiated coflow is a large pilot that provides a uniform environment for the investigation of highly turbulent jet flames with low Damköhler numbers. Such turbulent flow characteristics are exemplary of practical combustors.

Lifted turbulent jet flames have received significant attention in the combustion literature, and competing theories of flame stabilization have been proposed [e.g., 3-5]. A recent review in the text by Peters [6] presents the view that stabilization of a lifted flame involves the propagation of a turbulent partially premixed flame at a speed that balances the local streamwise convective velocity. This description consolidates ideas involving turbulent premixed flame propagation and triple flame (or edge flame) propagation, and computations based upon this concept

have yielded successful predictions of liftoff height [7]. It has also been proposed [8,9] that hot, product containing eddies rotate upstream, entrain preheated reactants, and facilitate reaction. Recent studies using scalar field imaging [10] and PIV [11] showed evidence of the importance of such recirculation at the stabilization region.

In the present study, multiscale laser diagnostics and numerical models are used to investigate a lifted turbulent H₂/N₂ jet flame in a coflow of lean H₂/air combustion products. This lifted flame has some features consistent with the theory of stabilization by propagation of a turbulent partially premixed flame. However, the conditions of the vitiated coflow admit the interesting possibility that mixtures can autoignite as they convect downstream. In addition, there are features in the laser measurements that suggest the reaction zone in the stabilization region is thickened (thicker than the smallest estimated scales of turbulence) or may include localized ignition events. Experimental and computational results are discussed in the context of these novel conditions.

EXPERIMENTAL METHODS

Experiments were conducted on a lifted turbulent H₂/N₂ jet flame in a vitiated coflow (Table 1). The combustor consists of a central H₂/N₂ turbulent jet with a coaxial flow of hot combustion products from a lean premixed H₂/Air flame (Fig. 1). The design is an adaptation of the design by Chen et al. [2]. The central jet exit diameter is $d=4.57$ mm and the coflow flame is stabilized on a perforated disk with 87% blockage and an outer diameter of 210 mm. The central jet extends 70 mm above the surface of the perforated disk. For the conditions listed in Table 1, the observed lift-off height was $H/d\cong 10$, and the total flame length was $H_f/d=30$.

Simultaneous, temporally and spatially resolved measurements of temperature and species mass fractions were obtained using laser diagnostic systems of the Turbulent Diffusion Flame laboratory at the Combustion Research Facility of Sandia National Laboratories. Details of the experimental setup and calibration techniques have been previously presented [12-15]. Spontaneous Raman scattering and Rayleigh scattering, using two frequency-doubled Nd:YAG lasers, were combined to measure temperature and the concentrations of N₂, O₂, H₂O, and H₂. Concentrations of OH and NO were measured using laser-induced fluorescence (LIF). The LIF systems were operated in the linear fluorescence regime, and corrections were applied on a shot-to-shot basis to account for local variation in Boltzmann fraction and collisional quenching rates for OH and NO. These multiscale measurements were virtually simultaneous, with delays of about 100ns between the different laser pulses. The spatial resolution of the system is 750 μ m. NO concentrations were consistently very low in this flame ($Y_{NO}<3$ ppm), and they will not be presented here.

The precision and accuracy of the Raman-Rayleigh-LIF system is determined from calibration flame measurements [15]. The precision of single-shot measurements of an H₂ flame with no fluorescence interferences is limited by the photoelectron shot noise [16], and it is indicated by the standard deviations (RMS) of the flat (Hencken) flame measurements: temperature 1.2%, N₂ 3.2%, H₂O 5.4%, OH 12% and NO 10%. Experimental uncertainties in averaged scalar values were estimated from the repeatability of calibration results and uncertainties in reference quantities. Representative uncertainties for the present results are: temperature 3%, N₂ 3%, H₂O 4%, and OH 10%. Uncertainty in the O₂ is best represented as an absolute error in mass fraction of about ±0.005, regardless of the local value of Y_{O₂}.

NUMERICAL METHODS

Presented are two turbulent combustion models, the Eddy Dissipation Concept (EDC) and the Probability Density Function (PDF). These models are coupled with either the standard *k-ε* or Reynolds stress fluid dynamic model for turbulent flow.

Eddy Dissipation Concept (EDC) Numerical Method

The general-purpose CFD code *Spider* [17] with EDC was developed at the Norwegian University of Science and Technology division of Thermodynamics in Trondheim. The turbulent reacting flow is modeled by the density-weighted Reynolds-averaged conservation equations for momentum components, energy, and mass fractions of species. Turbulence was modeled either by the standard *k-ε* model or by two versions of Reynolds-stress models by Launder, Reese and Rodi (LRR) [18] or by Jones and Musong (JM) [19,20]. In the present calculations *Spider* employs a 2-D axisymmetric geometry.

The mean reaction rate of chemical species *j* is modeled by EDC [21,22] as

$$\bar{R}_j = -\frac{\bar{\rho}\gamma^*\dot{m}^*}{(\gamma^*)^{1/3}}(Y_j^0 - Y_j^*),$$

where γ^* is the mass fraction of turbulence in fine structures and \dot{m}^* is the reciprocal of the fine-structure residence time ($\tau^* = 1/\dot{m}^*$). These two quantities are expressed as functions of the turbulence energy and the turbulence energy dissipation rate [21,23]. Specifically, the fine-structure residence time is assumed proportional to the Kolmogorov time scale. Y_j^0 and Y_j^* are the mass fractions of species *j* in the surrounding fluid state and the

fine structure state. The fine structure is regarded as a perfectly stirred reactor and the mass balance for species j in the reactor is modeled as

$$\frac{dY_j^*}{dt} = \frac{R_j^*}{\rho^*} + \frac{1}{\tau^*} (Y_j^0 - Y_j^*)$$

These species mass balances, together with equations for energy and momentum, are integrated in time until steady state is reached. A detailed H_2 mechanism taken from GRI-Mech 2.11 [24] is used (carbon species and reactions excluded).

Probability Density Function (PDF) Numerical Method

The model utilizes the joint scalar PDF for composition only and the k - ε turbulence model for a parabolic flow [25]. The turbulent flux and scalar dissipative terms appearing in the PDF transport equation are modeled by a gradient diffusion model and the Curl mixing model [26], respectively. Monte Carlo simulation is used to compute the transport equation for the PDF [27]. Four hundred stochastic particles per grid are used. A 7-step reduced chemistry (6 steps for combustion and 1 for NO formation) is integrated directly in time for each particle. The reduced chemistry model has been thoroughly tested and performs well in calculations of laminar opposed-flow nonpremixed flames, laminar premixed flames, perfectly stirred reactors, and ignition. Therefore, we expect satisfactory performance here.

RESULTS AND DISCUSSION

The structure of the lifted turbulent H_2/N_2 jet flame is investigated by examining the measured temperature and species concentrations profiles. Centerline measurements were taken from $z/d=1$ to 34 downstream of the nozzle exit. Radial profiles were obtained at several axial locations ($z/d=1, 8, 9, 10, 11, 14$ and 26). The radial domain covered by these profiles was -3mm to 50mm with spacing typically between 1 and 3mm. The single-shot data was processed and the Favre averages and RMS fluctuations were generated. The following formulation, modified for the current H_2/N_2 system, determines the mixture fraction [28].

$$f = \frac{(1/2M_H)(Y_H - Y_{H,2}) - (1/M_O)(Y_O - Y_{O,2})}{(1/2M_H)(Y_{H,1} - Y_{H,2}) - (1/M_O)(Y_{O,1} - Y_{O,2})}$$

The stoichiometric mixture fraction for the present fuel composition is $f_s=0.474$.

Inlet and Far-Field Boundary Conditions

Radial profiles of Favre averaged temperature at $z/d=1, 14$ and 26 are plotted in Fig 2. The measured mean temperature in the coflow at $z/d=1$ is uniform (2% RMS), indicating a well-mixed mixture. Also, the far-field (coflow) measurements of temperature do not change with axial distance. Thus, the integrity of the coflow is maintained in the entire test region. The same well-defined boundary conditions are observed for the species measurements. These results demonstrate that the flame can be modeled as a jet flame issuing into an infinite hot coflow, and they attest to the success of the experimental design.

Flame Structure and Lift-Off Height

The OH mass fraction, Y_{OH} , is used as a marker of the average flame lift-off height in both measured and modeled results. Fig. 3a shows a contour map generated using an aggregate of the point measurements (white dots). Several points were taken in the flame stabilization region to provide adequate resolution for determination of the lift-off height, $H/d \cong 10$, which was taken to be the location where the Favre average Y_{OH} reaches 600 ppm.

The numerical models each predict a lifted flame structure, which is a significant result in itself, regardless of the accuracy of the predicted lift-off height. It is was not obvious, *a priori*, that the PDF model would predict a lifted flame because the present calculation proceeds in a downstream marching solution and includes no mechanism for propagation of a turbulent premixed or partially premixed flame into the convecting flow. However, it is apparent from Fig. 3b that there is reaction progress for some fraction of the PDF particles well upstream of the flame stabilization location at the $Y_{OH}=600$ ppm contour. This result is associated with auto-ignition of mixed fluid, a process that would not occur with a cold air coflow. There were no visually obvious auto-ignition events well below the lift-off height; perhaps they would have been revealed by radial profiles taken at intermediate locations ($1 < z/d < 8$). However, the flame does spontaneously ignite in the laboratory, starting at a far downstream location, when the coflow is operating and jet flow is turned on. This possibility for auto-ignition leading to flame stabilization in the vitiated burner and the PDF calculation are worthy of further exploration.

Results from three numerical simulations are shown. Fig. 3b shows the OH contours from the PDF combustion model and the standard $k-\varepsilon$ model, which yields a lift-off height of $H_{PDF}/d=7$. Using the same $k-\varepsilon$ model, the EDC model predicts $H_{EDC}/d=8.5$, as shown in Fig. 3c. The standard $k-\varepsilon$ model is known to over-estimate the turbulent diffusivity and, consequently, over predict the spreading rate of round jets. This may account for the wide flame predictions in these two calculations (Figs. 3b and 3c) relative to the experimental results (Fig. 3a). The

third simulation, using the EDC model and the LRR Reynolds stress model, predicted a shorter lift-off height of $H_{LRR}/d=5$ (Fig. 3d). The overall flame shape is narrower than that predicted by the standard $k-\varepsilon$ model and in better agreement with the measured flame width, even though the lift-off height is under predicted.

Using the present EDC model, a parametric study was conducted to explore the sensitivity of the predicted lift-off height to boundary conditions, turbulence models, and grid resolution. The base case employed the standard $k-\varepsilon$ model, and the boundary conditions consisted of a fully developed turbulent pipe flow ($\bar{u}_j=107\text{m/s}$) for the jet and a uniform flow field ($\bar{u}_c=3.5\text{m/s}$) for the coflow. The inlet coflow turbulence variables k and ε were determined using rough estimates of the integral length scale and turbulence intensity ($\lambda_o=1\text{mm}$ and $u'/u_c=5\%$). Most cases were calculated with a mesh of 60×55 (axial \times radial) with grids clustered near the jet exit. The predicted lift-off height was found to be insensitive to changes in the coflow turbulence parameters (increased to $\lambda_o=3\text{mm}$ and $u'/u_c=10\%$) and unaffected by the use of detailed modeling of the nozzle wall turbulence. Increases in the jet velocity to $\bar{u}_j=120\text{m/s}$ and the coflow velocity to $\bar{u}_c=10\text{m/s}$ caused the predicted lift-off height to increase by roughly 25% and 50%, respectively. Refinement of the grid revealed a sensitivity of the calculated lift-off height to grid resolution, confirming that fine grids in the near field region are needed for adequate accuracy. The mesh was refined to 150×55 , while keeping the computational domain for all EDC simulations fixed ($z/d=40 \times r/d=12$). However, further increases in grid resolution (beyond 150×55) produce insignificant changes in model results. The fine grid resolution was also used for the computational domain of Reynolds stress models. The results in Figs. 3 and 4 were calculated using the fine grid. Predictions of lift-off height by the Reynolds stress turbulence models were consistently lower than those by the $k-\varepsilon$ model.

Figure 4 compares centerline profiles of mixture fraction and oxygen mass fraction and shows the sensitivity of predicted mixing rates to the turbulence model. The peak in oxygen seen near $z/d \approx 14$ (Fig 4b) illustrates the upstream penetration (increased with lift-off height) and subsequent consumption of oxygen by the flame. By presenting an entrainment rate profile similar to the Y_{O_2} centerline profile, Han and Mungal [29] observed a similar correlation between mixing and lift-off height. Since the standard $k-\varepsilon$ model over-predicts turbulent diffusion for round jets, the predicted oxygen penetration is higher than the data, as evident by the early (PDF) or high (EDC) centerline Y_{O_2} peaks and the rapid decay in mixture fraction. While the lift-off height predicted by the EDC with the Reynolds stress model is low, both predicted centerline profiles agree well with the data.

Combustion Statistics at Flame Stabilization

Scatter data of temperature vs. mixture fraction are shown in Fig. 5. Approximately 4,000 point measurements from different radial positions were grouped together to form a probability density map for three axial positions ($z/d=8,11,14$). There is a clear progression from a predominantly mixing condition ($z/d=8$) to vigorous flame burning ($z/d=14$) that corresponds to the transition from mixing only to mixing combined with ignition and flame stabilization. Since the flame is not attached to the nozzle, the central fuel jet entrains hot oxidizer from the coflow, evolving into a partially premixed flow with fluid temperatures corresponding to the mixing line between the jet and coflow boundary conditions in Fig. 5c. Beyond the potential core of the jet there is progressive dilution of the richest samples, such that the fuel-rich boundary condition for combustion at $z/d=14$ has decreased from $f=1.0$ to values between $f\sim 0.9$ and $f\sim 0.6$. Also plotted in Fig. 5a are the results from a series of laminar opposed flow flame calculations with equal molecular and thermal diffusivities. Corresponding calculations with full transport (i.e. with differential diffusion included) poorly matched the data, suggesting that turbulent stirring is more important than differential molecular diffusion in determining the relative mass fractions of major species in the measured flame. The fuel side boundary condition for the laminar flame calculations was set at $f=0.8$, to represent this measured departure from the pure jet composition.

The range of scalar dissipation rates in the turbulent flame above the stabilization region can be estimated by determining the strain rates whose corresponding opposed flow laminar flame solutions match the upper and lower bounds of the laser shot measurements [30], particularly on the fuel-lean side. In Fig. 5a, the laser shot data is approximately bounded by solutions with strain rates of 100s^{-1} and $5,000\text{s}^{-1}$. The computed strain rate prior to laminar flame extinction was $13,000\text{s}^{-1}$, and a number of data points are below the $5,000\text{s}^{-1}$ solution. It should be noted that the low strain rate calculation adequately describes the lean side results as expected, since these results correspond to the hot co-flow where low strain should prevail and where viscosity is still relatively high. The rich-side experimental results cannot be adequately represented by this limited set of laminar flame calculations because of the broad range of fuel-side boundary conditions produced by mixing upstream of the reaction zone.

Perhaps the most interesting condition can be seen in Fig. 5b, where the data is scattered throughout the zone between the mixing (lower) and fast chemistry (upper) limits on temperature. This axial position ($z/d=11$) is one diameter above the observed lift-off height. The behavior of the scatter data in Fig. 5b is qualitatively different from that reported for lifted H_2 jet flames in air [31,32], where there is clear bimodality between unreacted and

reacted samples in the region of flame stabilization. Results for the present burner suggest the existence of a thickened turbulent flame in the stabilization region. A laminar premixed flame simulation predicts an unstrained flame thickness of $\delta_L=2.5\text{mm}$, while the turbulence models suggest a Kolmogorov scale of roughly 50-500 microns in the stabilization region. Therefore, it may be argued that there are turbulent eddies of order 1mm within a thickened reaction zone. The observed scatter could also result from a process of small-scale mixing and ignition at the flame base, as outlined below.

Flame Stabilization

The experimental and numerical results present an opportunity to discuss possible flame stabilization mechanisms for the vitiated coflow burner. The presented EDC and $k-\varepsilon$ model results (Fig. 3c) indicate an average flow velocity of 10m/s at the flame base, while the maximum laminar premixed flame speed was calculated to be $S_L=3\text{m/s}$ for reactants at $f=0.4$ along the mixing line. A factor of 3 increase in velocity for a propagating turbulent premixed or partially premixed flame is plausible [6,33,34]. Interestingly, the correlation by Kalghatgi [4], which is based upon scaling arguments:

$$H_K = 50 \left(\frac{v_{\text{jet}} U_{\text{jet}}}{S_{L,\text{max}}^2} \right) \left(\frac{T_{\text{coflow}} M_{\text{jet}}}{T_{\text{jet}} M_{\text{coflow}}} \right)^{1.5},$$

yields a relatively accurately prediction of our measured lift-off height. For the present flame the jet mixture viscosity is $v_{\text{jet}}=2 \times 10^{-5} \text{ m}^2/\text{s}$, and molar mass of the jet and coflow mixtures are $M_{\text{jet}}=21.5$ and $M_{\text{coflow}}=27.6$. For the given conditions, this engineering correlation predicts a lift-off height of $H_K/d=11.4$, indicating the robustness of the correlation and suggesting that stabilization of the present flame may be controlled by the same mechanisms that control lifted flames in cold air. However, the potential for auto-ignition of mixed fluid and the behavior of the temperature scatter data noted above both allow for speculation on variations or additional mechanisms that may contribute to stabilization of the present flame.

It is possible that auto-ignition of mixed fluid is only important for the transient startup of the laboratory flame and that, once ignited, a propagating partially premixed flame advances upstream to a lift-off height for which convective times from the nozzle are shorter than ignition delay times for any fluid sample along the mixing line. It is also possible that auto-ignition in the stabilization region serves to augment or anchor the propagating flame. A specific mode of ignition-enhanced turbulent flame propagation is illustrated in Figs. 5d,e and is based on the observation that the ignition delay for mixtures of products and reactants can be short compared to the timescale of

small eddies in the stabilization region. The illustration shows mixing of product and reactant samples (Fig. 5d), each at $f=0.4$. Such mixing could occur around an auto-ignition kernel or by eddy turnover in the thickened partially premixed flame. After rapid ignition of the mixed fluid, a reaction front propagates through neighboring mixtures (Fig. 5e). This sort of mixing/ignition/propagation mechanism would be consistent with the measured distribution of temperature scatter data in Fig. 5b. However, multiscale imaging measurements would be needed to detect such events.

CONCLUSIONS

1. The vitiated coflow burner provides a simplified flow with well-defined boundary conditions. Measurements confirm that the coflow properties are uniform throughout the test region. The configuration enables the examination of turbulent mixing and chemical kinetics relevant to the modeling of advanced combustors without the complex recirculating fluid mechanics.
2. Simultaneous multiscale measurements of a lifted H_2/N_2 jet ($H/d \cong 10$) were presented and compared to a series of numerical simulations with various combustion and turbulence models. Numerical results from a PDF and an EDC combustion model reasonably predict the lift-off height ($H_{PDF}/d=7$, $H_{EDC}/d=8.5$).
3. Features of the instantaneous scalar measurements in the stabilization region, together with information on laminar flame thickness and turbulence quantities from calculations, suggest that a thickened turbulent partially premixed flame exists at the flame stabilization location.
4. The vitiated coflow admits the possibility of auto-ignition of mixed samples. Such ignition is the only possible stabilization mechanism in the PDF calculation, which proceeds by a parabolic marching solution. While there is no clear experimental evidence of auto-ignition events below the lift-off height, it is plausible that auto-ignition or turbulent mixing of products and reactants in the stabilization, followed by rapid ignition, may augment the stability of the present flame.

REFERENCES

1. Masri, A. R., Dibble, R. W., and Barlow, R. S., *Prog. Energy Combust. Sci.* 22:307 (1996).
2. Chen, Y.G., Peters, N., Schneemann, G.A., Wruck, N., Renz, U., & Mansour, M.S., *Combust. Flame* 107:223 (1996).
3. Vanquickenborne, L. & Van Tiggelen, A., *Combust. Flame* 10:59 (1966).
4. Kalghatgi, G.T., *Comb. Sci. Tech.* 41:17 (1984).
5. Pitts, W.M., *Proc. Comb. Inst.* 22:809 (1988).
6. Peters, N., *Turbulent Combustion*, Cambridge University Press, 2000 p.237-261.
7. Chen, M., Herrmann, M., and Peters, N., *Proc. Comb. Inst.* 28:167 (2000).
8. Broadwell, J.E., Dahm W.J.A., & Mungal, M.G., *Proc. Comb. Inst.* 20:303 (1984).
9. Dahm, W.J.A., & Dibble, R.W., *Proc. Comb. Inst.* 22:801 (1988).
10. Tacke, M.M., Geyer, D., Hassel, E.P., & Janicka J., *Proc. Comb. Inst.* 27:1157 (1998).
11. Upatnieks, A. Driscoll, J. F., Ceccio, S. L., *Proc. Comb. Inst.* 29:?? (2002).
12. Nooren, P. A., Versluis, M., van der Meer, T. H., Barlow, R. S., and Frank, J. H., *Appl. Phys. B* 71:95 (2000).
13. Barlow, R.S., Karpetis, A.N., Frank, J.H. & Chen, J.Y., *Combust. Flame* 127:2102 (2001).
14. Nguyen, Q.V., Dibble, R.W., Carter, C.D., Fiechtner, G.J., & Barlow, R.S., *Combust. Flame* 105:499 (1996).
15. Barlow, R.S., Fiechtner, G.J., Carter, C.D., & Chen, J.-Y., *Combust. Flame* 120:549 (2000).
16. Dibble, R.W., Masri, A.R., & Bilger, R.W., *Combust. Flame* 67:167 (1987).
17. Melaaen, M.C., Ph.D. Dissertation, University in Trondheim, 1990.
18. Launder, B. E., Reece, G. J., & Rodi, W., *J. Fluid. Mech.* 68(3):537 (1975).
19. Jones, W. P., *Turbulent Reacting Flows*, Academic Press Ltd., 1994 p.171-189.
20. Jones, W. P., Musonge, P., *Phys. Fluids* 31(12):3589 (1988).
21. Ertesvåg, I. S., *Turbulent Flow & Combustion* (in Norwegian), Tapir Academic Publisher, 2000 p.309-372.
22. Gran, I. R., Magnussen B. F., *Comb. Sci. Tech.* 119:191 (1996).
23. Ertesvåg, I. S., Magnussen, B. F., *Comb. Sci. Tech.* 159:213 (2000).
24. Bowman, C.T., Hanson R. K., Davidson, D. F., Gardiner Jr., W. C., Lissianski V., Smith, G. P., Golden, D. M., Goldenberg, M., Frenklach, M., *Gri-Mech* 2.11, http://www/me.berkeley.edu/gri_mech/ (1999).
25. Smith, N.S.A., Bilger, R.W., Carter, C.D., Barlow R.S., & Chen, J.Y., *Comb. Sci. Tech.* 105:357 (1995).

26. Pope, S.B., *Proc. Comb. Inst.* 23:591 (1990).
27. Chen, J.-Y. & Kollmann W., *Proc. Comb. Inst.* 22:645 (1988).
28. Bilger, R.W., Stårner, S.H., & Kee, R.J., *Combust. Flame* 80:135 (1990).
29. Han, D.H. & Mungal, M.G., *Combust. Flame* 124:370 (2001).
30. Warnatz, J., Maas, U., & Dibble, R.W., *Combustion, Physical & Chemical Fundamentals, Modeling & Simulation, Experiments, Pollutant Formation*, 3rd Edition, Springer-Verlag, 2000 p.195.
31. Cheng, T. S., Wehrmeyer, J. A., and Pitz, R. W., *Combust. Flame* 91:323 (1992).
32. Brockhinke, A., Andresen, P., Kohse-Höinghaus, K., *Appl. Phys. B* 61:533 (1995).
33. Liñán, A., & Williams, F.A., *Fundamental Aspects of Combustion*, Oxford University Press, 1993 p.120.
34. Ruetsch, G.R., Vervisch, L., & Liñán, A., *Phys. Fluids* 7:1447 (1995).

Table 1 Flame and flow conditions.

Central Jet		Coflow	
Q_{H_2} (slm)	25	Q_{H_2} (slm)	225
Q_{N_2} (slm)	75	Q_{AIR} (slm)	2,100
T_{JET} (K)	305	T_{COFLOW} (K)	1,045
V_{JET} (m/s)	107	V_{COFLOW} (m/s)	3.5
Re_{JET}	23,600	Re_{COFLOW}	18,600
d_{JET} (mm)	4.57	D_{COFLOW} (mm)	210
		ϕ	0.25
X_{H_2}	0.2537	X_{O_2}	0.1474
X_{N_2}	0.7427	X_{H_2O}	0.0989
		X_{N_2}	0.7534

Q: volumetric flow rate; X: mole fraction; Re: Reynolds number; d and D: diameter.
 ϕ : equivalence ratio.

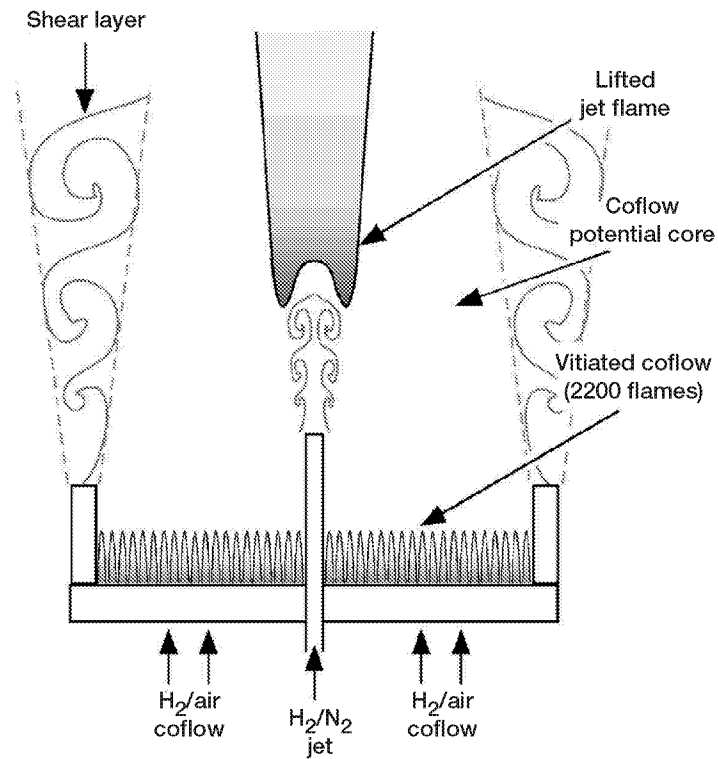


Figure 1.—Vitated coflow burner: a lifted H₂/N₂ jet flame in a coflow of hot combustion products from a lean premixed H₂/air flame.

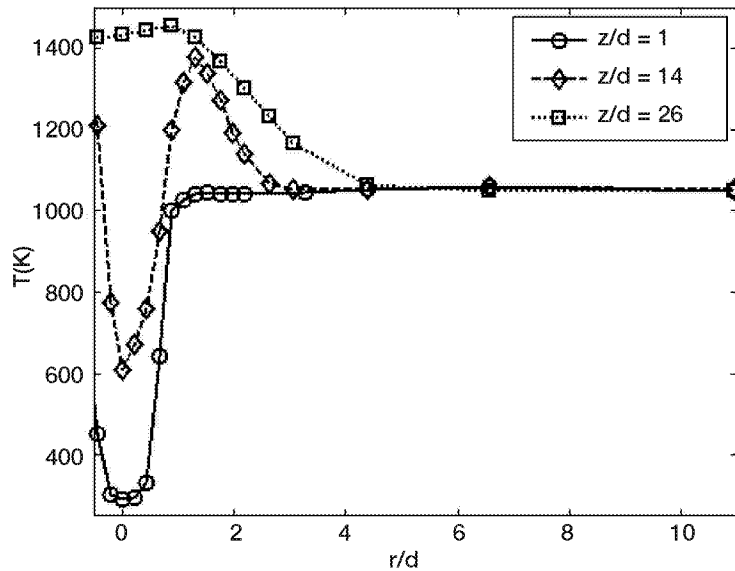


Figure 2.—Radial profile of Favre averages for temperature at axial locations $z/d = 1, 14, 26$. Well-defined boundary conditions are shown by the $z/d = 1$ profile and the matching far-field measurements.

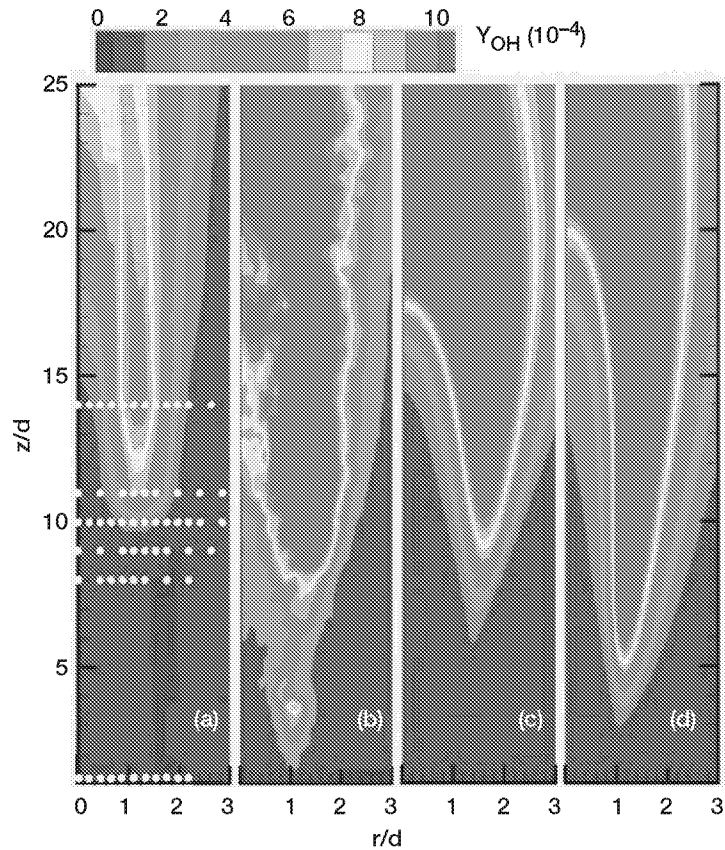


Figure 3.—The flame structure is represented by the averaged OH mass fraction fields. Presented are experimental results (a), PDF combustion with standard $k-\epsilon$ turbulence model (b), EDC combustion with $k-\epsilon$ turbulence model (c) and EDC combustion with LRR Reynolds stress model (d). The white dots in plot (a) denote the locations of the laser based multiscalar measurements.

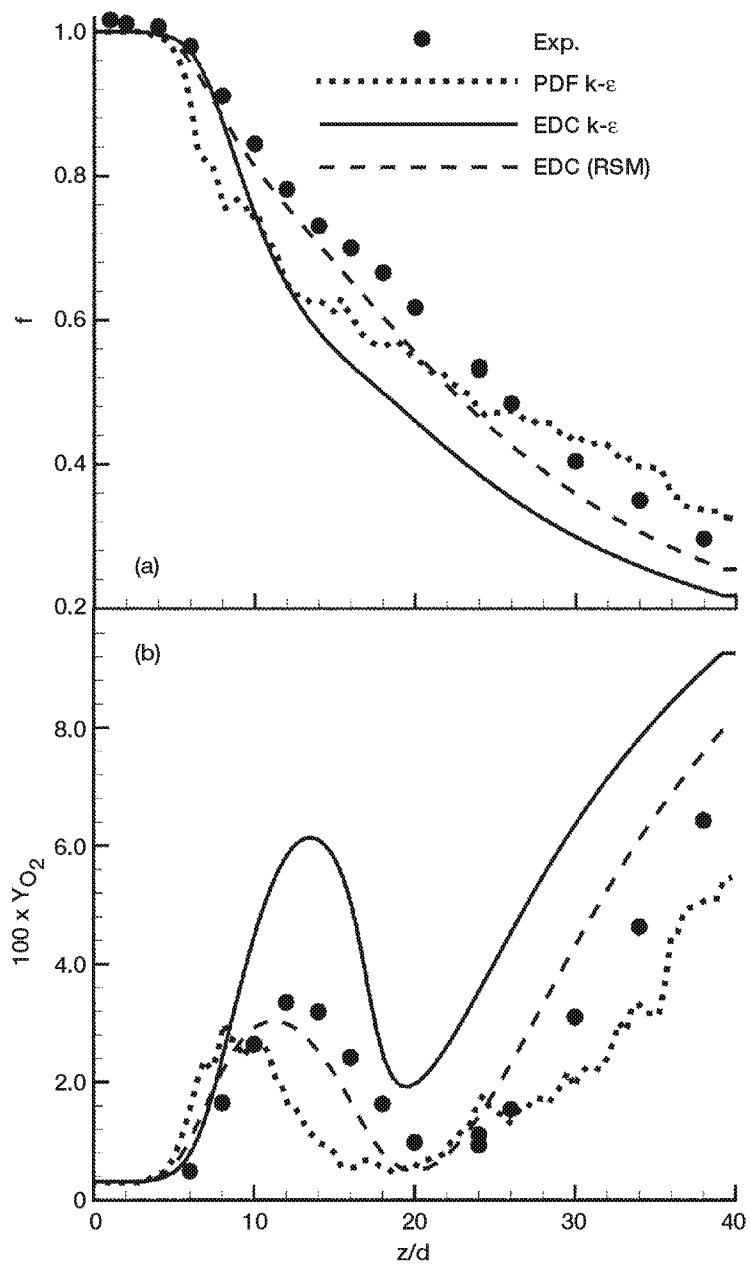


Figure 4.—Axial profiles of the mixture fraction (a) and oxygen mass fraction (b). Presented are experimental results (solid circles), PDF combustion with $k-\epsilon$ turbulence model (dotted line), EDC combustion with $k-\epsilon$ turbulence model (solid line), and EDC combustion with LRR Reynolds stress model (dashed line).

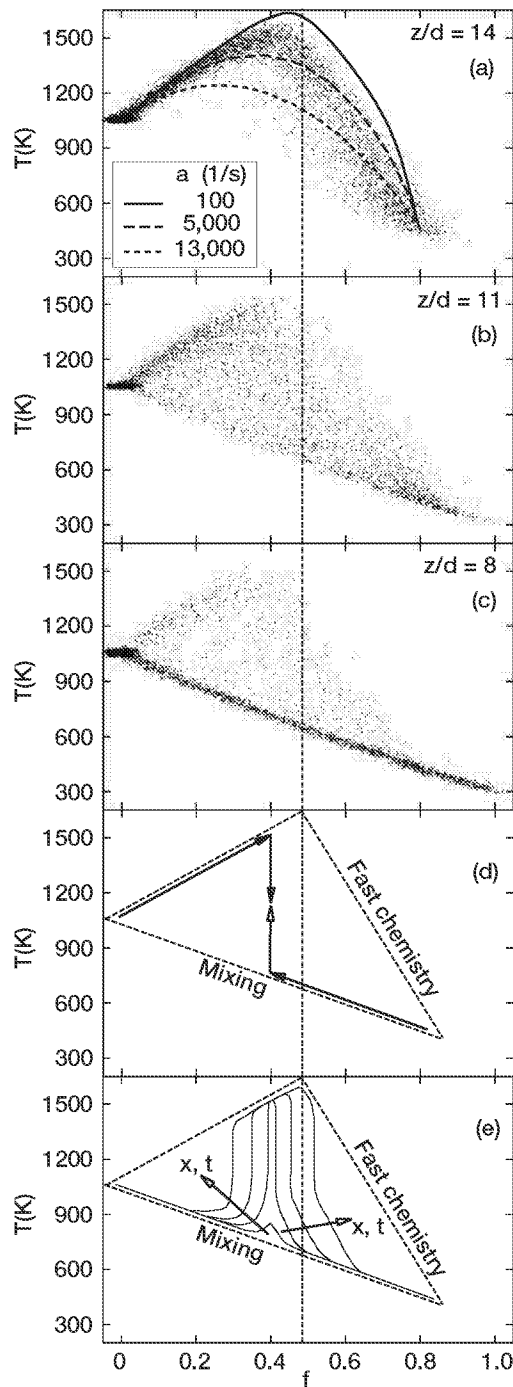


Figure 5.—Scatter plots of temperature vs. mixture fraction from three axial positions ($z/d = 14, 11, 8$) showing the progress from mixing (c) to fully burning (a). Data from complete radial profiles were grouped together to form each plot. Lines in (a) show the results of steady strained opposed-flow nonpremixed laminar flame calculations with equal species and thermal diffusivities. Schematic of the fastest possible auto-ignition ($f = 0.4$) and flame-holding (d). Schematic of the classic ignition scenario [6, p. 219], starting at $f = 0.4$ and propagating in time and space (e).

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13. ABSTRACT (Maximum 200 words) An experiment and numerical investigation is presented of a lifted turbulent H ₂ /N ₂ jet flame in a coflow of hot, vitiated gases. The vitiated coflow burner emulates the coupling of turbulent mixing and chemical kinetics exemplary of the reacting flow in the recirculation region of advanced combustors. It also simplifies numerical investigation of this coupled problem by removing the complexity of recirculating flow. Scalar measurements are reported for a lifted turbulent jet flame of H ₂ /N ₂ (Re = 23,600, H/d = 10) in a coflow of hot combustion products from a lean H ₂ /Air flame (φ = 0.25, T = 1,045 K). The combination of Rayleigh scattering, Raman scattering, and laser-induced fluorescence is used to obtain simultaneous measurements of temperature and concentrations of the major species, OH, and NO. The data attest to the success of the experimental design in providing a uniform vitiated coflow throughout the entire test region. Two combustion models (PDF: joint scalar Probability Density Function and EDC: Eddy Dissipation Concept) are used in conjunction with various turbulence models to predict the lift-off height (H _{PDF} /d = 7, H _{EDC} /d = 8.5). Kalghatgi's classic phenomenological theory, which is based on scaling arguments, yields a reasonably accurate prediction (H _K /d = 11.4) of the lift-off height for the present flame. The vitiated coflow admits the possibility of auto-ignition of mixed fluid, and the success of the present parabolic implementation of the PDF model in predicting a stable lifted flame is attributable to such ignition. The measurements indicate a thickened turbulent reaction zone at the flame base. Experimental results and numerical investigations support the plausibility of turbulent premixed flame propagation by small scale (on the order of the flame thickness) recirculation and mixing of hot products into reactants and subsequent rapid ignition of the mixture.				
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