spray is monodispersed, the SMD continually decreases with distance from the burner. Predictions from both dispersion models are almost identical. Agreement is good for the initially larger drop size. For the initially smaller drop size, however, the length of the two-phase flow region is greatly underestimated as previously noted.

Predictions for the SMD radial profiles at $x/d_n = 50$ and 100 are given in Fig. 5. Again, both theoretical models provide very similar results. Discrepancies with experimental data are presumably associated with the predicted vaporization rates. This difficulty appears equally troubling to both models—especially near the high gradient flame region.

Conclusion

Based on our evaluation, the proposed SDWT turbulent spray model may be easily extended to dilute combusting sprays with satisfactory results. Global spray structure predictions are as good as for the SSF method with significant improvement in computational efficiency. Model agreement with experimental measurements was good in most cases. Discrepancies between theory and experiment involve underestimation of the length and width of the two-phase flow region and overestimation of drop transport rates near the flame zone for small drops. These difficulties are attributed to the discrete droplet vaporization model rather than the dispersion model. They should not be associated with a neglect of fluctuating scalar properties since results from a previous study[4,5] accounting for such fluctuations yielded similar behavior.

Although the basic results of the evaluation are favorable with regard to the SDWT method, there are special considerations that should be addressed in using the technique. For instance, the possibility of the pdf widths becoming too large in high gradient regions may pose problems in certain cases. There is also the question of treating flows with recirculation. It seems intuitively reasonable to apply the SDWT model as long as the characteristic pdf width is much smaller than the characteristic width of the recirculation region, but a definitive criterion is lacking. From the promising results obtained thus far, however, it does appear that the technique can eventually be developed to make practical spray combustion computations at reduced computational costs.

Acknowledgments

This work was conducted as part of an ongoing spray combustion stability project supported by the University of Tennessee-Calspan Center for Space Transportation and Applied Research, the University of Tennessee Space Institute, Tullahoma, TN, under NASA Grant NAGW-1195, and was supported in part by Rocketdyne Division, Rockwell International, Canoga Park, CA.

References

[1]Litchford, R. J., and Jeng, S.-M., "Efficient Statistical Transport Model for Turbulent Particle Dispersion in Sprays," *AIAA Journal,* Vol. 29, No. 9, 1991, pp. 1443–1451.

[2]Litchford, R. J., and Jeng, S.-M., "Efficiency of a Statistical Transport Model for Turbulent Particle Dispersion," *AIAA Journal,* Vol. 30, No. 5, 1992, pp. 1434–1438.

[3]Litchford, R. J., and Jeng, S.-M., "Probability Density Function Shape Sensitivity in the Statistical Modeling of Turbulent Particle Dispersion," *AIAA Journal,* Vol. 30, No. 10, 1992, pp. 2546–2549.

[4]Shuen, J.-S., Solomon, A. S. P., and Faeth, G. M., "Drop-Turbulence Interactions in a Diffusion Flame," *AIAA Journal,* Vol. 24, No. 1, 1986, pp. 101–108.

[5]Shuen, J.-S., Solomon, A. S. P., and Faeth, G. M., "The Structure of Dilute Combusting Sprays," NASA CR-174838, Jan. 1985.

[6]Jeng, S.-M., and Faeth, G. M., "Species Concentrations and Turbulence Properties in Buoyant Methane Diffusion Flames," *Journal of Heat Transfer,* Vol. 106, Nov. 1984, pp. 721–727.

[7]Bilger, R. W., "Turbulent Jet Diffusion Flames," *Progress in Energy and Combustion Science,* Vol. 1, Pergamon Press, New York, 1976, pp. 87–109.

[8]Lockwood, F. C., and Naguib, A. S., "The Prediction of the Fluctuations in the Properties of Free, Round-Jet, Turbulent, Diffusion Flames," *Combustion and Flame,* Vol. 24, No. 1, 1975, pp. 109–124.

[9]Bilger, R. W., "Reaction Rates in Diffusion Flames," *Combustion and Flame,* Vol. 30, No. 3, 1977, pp. 277–284.

[10]Liew, S. K., Bray, K. N. C., and Moss, J. B., "A Flamelet Model of Turbulent Non-Premixed Combustion," *Combustion Science and Technology,* Vol. 27, Dec. 1981, pp. 69–73.

Interaction Between Chemical Reaction and Turbulence in Supersonic Nonpremixed H_2-Air Combustion

R. Villasenor*
Vanderbilt University, Nashville, Tennessee 37235
J.-Y. Chen†
University of California, Berkeley, Berkeley, California 94720
and
R. W. Pitz‡
Vanderbilt University, Nashville, Tennessee 37235

Introduction

In the last decade a number of numerical schemes capable of solving the complete two-dimensional Navier-Stokes equations coupled with chemical reaction have been developed for both confined and unconfined compressible flows. These efforts have focused more on improving numerical efficiency than on developing new physical models for turbulent combustion. Recent studies[1,2] have shown that the lower-upper successive overrelaxation scheme (LU-SSOR) is computationally efficient for reacting supersonic flows.

In many applications of the aforementioned codes to supersonic turbulent combustion, the mean chemical reaction rates are evaluated simply based on Arrhenius expressions with the mean values of temperature and species concentration. Therefore, the potential impact of turbulent fluctuations in temperature and species on chemical reactions has not been considered, and we will refer to such an approach as the *laminar chemistry* model. It has been well known that, in subsonic turbulent combustion, the neglect of the fluctuation effects on the mean chemical reaction rates can lead to erroneous predictions of chemical processes, giving incorrect ignition point or species concentrations. However, modeling the effects of turbulence on chemical kinetics remains unresolved, and it is still an area of intense research efforts.[3] To evaluate the potential impact of turbulence on various chemical processes in supersonic turbulent reacting flows, an approximation is developed to account for the influence of temperature and species fluctuations in the limit of weak turbulence. This approach seems especially appropriate for supersonic nonpremixed turbulent flames where the turbulent mixing is less vigorous than its counterpart in subsonic flows; however, the method only permits qualitative features to be studied. With this approximation, we will concentrate this study on the level of radial concentrations and the point of ignition in supersonic turbulent nonpremixed hydrogen jet flames.

Influence of Turbulence on Chemical Reaction

The effect of small fluctuations in temperature and species concentration can be incorporated into numerical predictions by modifying the Arrhenius chemical source terms as

$$\tilde{w}_A = -\rho^2 M_A \tilde{K}_f \frac{\tilde{Y}_A \tilde{Y}_B}{M_A M_B} (1 - \alpha_{AB})$$

Received Aug. 22, 1991; revision received March 27, 1992; accepted for publication March 30, 1992.

*Graduate Student, Department of Mechanical Engineering.
†Assistant Professor.
‡Assistant Professor, Department of Mechanical Engineering.

where α_{AB} is the segregation parameter[4] and $\tilde{K}_f = K_f(\tilde{T})\theta_f^*$ is a modified rate constant taking into account the temperature fluctuations through the parameter θ_f^*. The segregation parameter is defined as $\alpha_{ij} = -\overline{Y_i'' Y_j''}/\tilde{Y}_i\tilde{Y}_j$, which describes the degree of mixing of two species i and j at the molecular level. If two species are fully mixed at the molecular level, the segregation parameter is simply zero as $\overline{Y_i'' Y_j''} = 0$. For small temperature fluctuations, the probability density function (pdf) of temperature is assumed to have a normal distribution. Note that, strictly speaking, temperature is a bounded scalar and a bounded pdf shape would be more appropriate. Because of the strong nonlinear temperature dependence of rate constants, θ_f^* is always larger than one for small fluctuations with a normal distribution. In the laminar chemistry model mentioned earlier, α_{ij} is set to zero and θ_f^* is set to unity.

The modified reaction rates with the preceding approximated turbulence effects are incorporated into a modified version of the LU-SSOR scheme for axisymmetric jet flames. The Favre-averaged transport equations for mass, momentum, energy, and species can be found in Ref. 3. For simplicity, the turbulence transport is modeled by the Eggers[5] algebraic mixing length model. Details of the numerical scheme, the H_2-air kinetic mechanism, and the procedure used in the evaluation of the laminar thermodynamic and transport properties are described in Ref. 1.

Results and Discussions

We investigate the potential interactions between turbulence and chemistry in the supersonic axisymmetric hydrogen jet flames in the experiment of Beach reported by Evans et al.[6] The individual effects of temperature and species fluctuations are explored by comparing results from three numerical simulations using different chemistry source terms. In case 1, calculations are carried out with the laminar chemistry model, i.e., without the influence of turbulent fluctuations. In case 2, the magnitude of all segregation parameters is set to 30% but zero temperature fluctuations. In case 3, a 5% level of temperature fluctuations is considered with no concentration fluctuations.

To evaluate the overall model performance, a comparison of calculated and measured mass fractions of major species at 8.26 diameters downstream is presented in Fig. 1 for case 2. Results from cases 1 and 3 (not shown) are only slightly different from case 2 because of the low level of turbulence fluctuations considered here. As can be seen from Fig. 1, the predictions are in satisfactory agreement with the experimental data in regions near the jet centerline. However, significant disagreement between the predictions and the experimental data are noticed for radial locations greater than $r/d = 0.60$, where the predicted O_2 and water concentrations are substantially different from the data. By comparison with our previous numerical calculations of the same jet flames using a k-ϵ model,[7] we conclude that the crude mixing length model of Eggers is responsible for the discrepancies noted earlier.

To appreciate the effects of turbulence on combustion, the corresponding minor species at the axial location $x/d = 8.26$

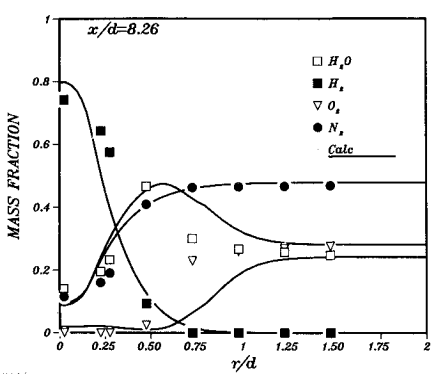

Fig. 1 Calculated and measured mass fractions of major species at location $x/d = 8.26$ for case 2.

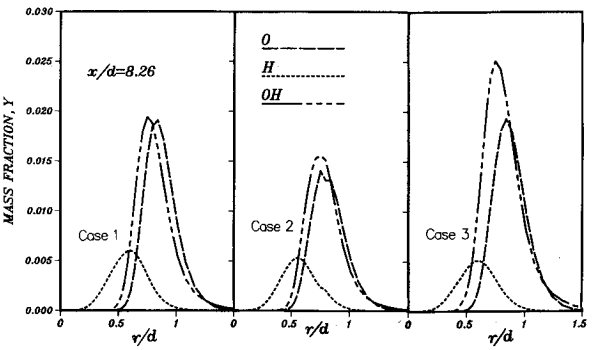

Fig. 2 Minor species concentration distributions at location $x/d = 8.26$ for cases 1, 2, and 3.

are presented in Fig. 2, for cases 1, 2, and 3, respectively. It is worth noting that, by including fluctuations (either temperature or species), the OH concentration is enhanced relative to the O or H atom concentrations, but 5% temperature fluctuations lead to larger OH. This can be explained by the fact that the most temperature-dependent step $H + O_2 \rightleftharpoons OH + O$ is greatly enhanced in the forward direction by the temperature fluctuation.

An interesting feature of case 2 is that the minor species profiles are lower than those obtained with laminar chemistry. This can be best understood in a bimolecular reacting system where the segregation parameter is always positive. Hence, the mean consumption rate reaches its maximum value only when the segregation parameter approaches zero. Consequently, any unmixed fluids tend to decrease the mean chemical reaction rate. However, in multicomponent reacting systems, the segregation parameters can be positive, negative, or zero.[4] Despite the complexity of our present chemical reaction mechanism, the overall contribution of these correlations on the species fluctuation terms tends to reduce the reaction rates, a similar trend that is well understood in a simple bimolecular system.

The impact of turbulence fluctuations on the predicted ignition locations has been examined. We found that temperature fluctuations tend to promote combustion, and hence the ignition point is moved closer to the nozzle exit when a 5% temperature variance is included in the calculation. However, inclusion of species fluctuations delays the initiation of combustion and hence the ignition point is moved slightly downstream.

Conclusions

The effects of species and temperature fluctuations on chemical processes have been independently explored for a supersonic turbulent reacting jet under weak turbulence. The numerical code used here is the first of its kind to use the LU-SSOR scheme for axisymmetric flows with nonpremixed combustion. Numerical studies of a supersonic H_2 jet flame into a supersonic coflowing airstream are conducted.

The results indicate that species fluctuations decrease the absolute levels of radicals whereas temperature fluctuations increase radical levels. Flame ignition is promoted when temperature fluctuations are considered, based on both computed radical concentrations and reduced penetration of oxidizer into the fuel jet. Furthermore, the ignition delay region for the flame studied in this work agrees well with that reported by Beach[8] (2.4 diameters) in a similar experiment.

Acknowledgments

The authors are grateful for the financial support provided by the National Science Foundation (through Presidential Young Investigator Grant CTS-8657130) and by Sandia National Laboratories at Livermore, CA.

References

[1]Shuen, J. S., and Yoon, S., "Numerical Study of Chemically Reacting Flows Using an LU Scheme," AIAA Paper 88-0436, Jan.

1988.

[2] Tsai, Y. L., and Hsieh, K. C., "Comparative Study of Computational Efficiency of Two LU Schemes for Non-Equilibrium Reacting Flows," AIAA Paper 90-0396, Jan. 1990.

[3]Bilger, R. W., "Turbulent Flows with Non-Premixed Reactants," *Turbulent Reacting Flows,* edited by P. A. Libby and F. A. Williams, Springer-Verlag, New York, 1981, pp. 65–113.

[4]Chen, J.-Y., and Kollmann, W., "Segregation Parameters and Pair-Exchange Mixing Models for Turbulent Nonpremixed Flames," *Twenty-Third Symposium (International) on Combustion,* Combustion Inst., Pittsburgh, PA, 1990, pp. 751–757.

[5]Eggers, J. M., "Turbulent Mixing of Coaxial Compressible Hydrogen-Air Jets," NASA TN D-6487, Sept. 1971.

[6]Evans, J. S., Schexnayder, C. J., and Beach, H. L., "Application of a Two-Dimensional Parabolic Computer Program to Prediction of Turbulent Reacting Flows," NASA TP-1169, March 1978.

[7]Villasenor, R., Chen, J.-Y., and Pitz, R. W., "Modeling Ideally Expanded Supersonic Turbulent Jet Flows with Nonpremixed H_2 -Air Combustion," *AIAA Journal,* Vol. 30, No. 2, 1992, pp. 395–402.

[8]Beach, H. L., "Supersonic Mixing and Combustion of a Hydrogen Jet in a Coaxial High-Temperature Test Gas,"AIAA Paper 72-1179, Nov. 1972.

Dynamical Scaling of a Model Unsteady Separating Flow

Mukund Acharya* and Anwar Ramiz†
Illinois Institute of Technology, Chicago, Illinois 60616

Introduction

MODEL experiments have proven to be of considerable value in understanding the physical mechanisms that control the unsteady separation process and the evolution of the vorticity field over surfaces. Francis et al.,[1] for example, studied the flow produced over a symmetric airfoil by an oscillating fence-like spoiler located at midchord on the suction surface. They documented the presence of a dynamically evolving vortical structure that had many of the characteristics of the dynamic stall vortex that is associated with an airfoil in pitching motion. They observed that, for the range of Reynolds numbers and frequencies tested, the vortical structure remained attached to the spoiler during the upstroke and that it grew mainly in the streamwise direction, with the growth rate of the vortex proportional to the square root of the reduced frequency k of spoiler oscillation.

In another model experiment that exhibits some characteristics of the leading-edge separation over unsteady airfoils, Ramiz and Acharya[2] and Ramiz[3] formulated techniques for the nonintrusive detection of flow state that show promise for use in the active control of unsteady separated flows. The experiment documented the unsteady separating flowfield generated by the deployment at constant pitch rate of a spoiler-like flap, with height $h = 4$ cm and a 60-cm span, into the initially attached flow over a flat plate, 60 cm wide and 3.1 m long. The flap, located at $x_0 = 137$ cm from the plate leading edge, had a single ramp-up motion from 0 to 90 deg over a rise time T_0. The resulting unsteady flow was studied for a Reynolds number range $1.5 \times 10^5 < Re_{x_0} < 2.6 \times 10^6$ and rise times T_0 between 0.06 and 2 s (corresponding to a dimensionless pitch rate $0.001 < a^+ < 0.35$). The formation and growth of the separated region were examined by using a combination of unsteady wall static pressure and flow-direction measurements at several locations downstream of the flap. A proper understanding of the development of an unsteady flow such as this requires a perspective based on vorticity dynamics. The results of the present experiments are consistent with the suggestion of Reynolds and Carr[4] that the growth of the separation region is controlled by two different mechanisms that set a balance between the vorticity input and output to the separated region.

Received June 4, 1991; revision received Feb. 19, 1992; accepted for publication Feb. 21, 1992.

*Associate Professor, Fluid Dynamics Research Center. Member AIAA.

†Graduate Research Assistant, Fluid Dynamics Research Center.

Results and Discussion

Nature of the Unsteady Flow

References 2 and 3 provide a detailed description of the measurement techniques and their validity, as well as the results. A sample data set is described here to provide the requisite background for the discussion of dynamical scaling in the following section. Figure 1, reproduced from Ref. 2, shows typical flow-direction data at $x/h = 2$ for five transverse locations ranging between $0.1 < y/h < 4.0$. A zero c_p line for each trace in this figure aids in determining the flow direction at each location; a positive value indicates forward flow. The wall static pressure at this location has also been shown for reference. Several features of the unsteady flow are apparent. Prominent among these is the signature of the initial vortex as it is released from the flap and is convected downstream. This correlation between the occurrence of a suction peak and the vortex passage has been observed in other unsteady flows as well.[1,5,6] Flow reversal is seen only in the traces recorded at $y/h < 1$. The flow reverses direction first nearest to the wall, with delays occurring in this reversal as y/h increases. Recirculating flow in the separated region forming behind the flap results in reversed flow in the near-wall part of this region. Thus, the existence of reversed flow near the wall at any streamwise location is an indication that the separated region has grown in extent up to this location. Measurements of the direction of flow in the near-wall region along the plate can thus be used to obtain a measure of the streamwise extent of the separated region.

Dynamical Scaling

Data such as those presented in Fig. 1, recorded over a range of T_0 and approach flow velocities, showed that the length and time scales of the separation process depend on T_0 and flow velocity. It was found that the behavior of the flow was determined by the relative magnitudes of two time scales: the rise time of the flap and the time available for the vorticity generated at the flap to accumulate in the separated region developing behind the flap. The growth of the separated region beyond a given streamwise location downstream of the flap was preceded by the convection of the initial vortex past that location. In addition, the time of arrival of the vortex at this location was given by the first instant of flow reversal in the near-wall region. This time instant t_d, when flow reversal was first detected in the near-wall region during a flap-rise

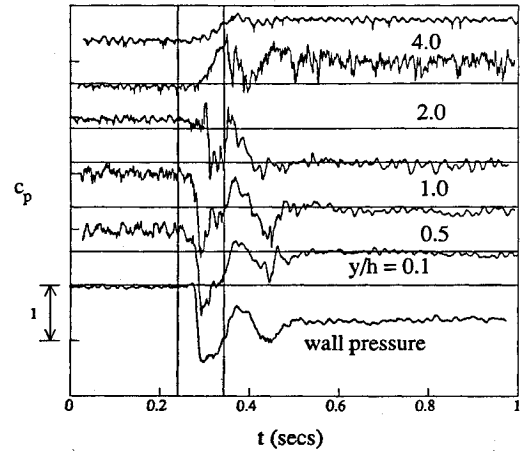

Fig. 1 Typical flow-direction data; $T_0 = 0.1$ s, $Re_{x_0} = 9 \times 10^5$, $x/h = 2$.