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SPECTRAL AND TOTAL RADIATION PROPERTIES OF TURBULENT CARBON MONOXIDE/AIR DIFFUSION FLAMES

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Abstract

A study of the structure and radiation properties of round turbulent carbon monoxide/air diffusion flames is described. Measurements of mean and fluctuating streamwise velocity and mean temperatures, spectral radiation intensities and radiant heat fluxes were made. The measurements were used to evaluate predictions based on the laminar flamelet concept and narrow band radiation models both ignoring (using mean properties) and considering (using a stochastic method) effects of turbulence/radiation interactions. State relationships were found by correlating auxiliary measurements in laminar flames. Structure and radiation predictions were reasonably good for present test conditions. Effects of turbulence/radiation interactions were small for these reactants (increasing spectal intensities ca. 10%) since radiation properties vary slowly with mixture fraction near stoichiometric conditions.

Nomenclature

a	acceleration of gravity
d	burner exit diameter
f	mixture fraction
g	square of mixture fraction fluctuations
k	turbulent kinetic energy
$\dot{m}_o$	burner mass flow rate
P(f)	probability density function of f
$\dot{Q}$	heat release rate
$\dot{Q}_{rad}$	radiative heat loss from flame
$\dot{q}''$	radiative heat flux
r	radial distance
Re	burner Reynolds number
Ri	burner Richardson number
T	temperature
u	streamwise velocity
v	radial velocity
x	height above burner
Y_i	mass fraction of species i
ε	rate of dissipation of turbulence kinetic energy
υ	kinematic viscosity
ρ	density

Subscripts

c	centerline quantity
o	burner exit condition
∞	ambient condition

Superscripts

$(\bar{\ })$, $(\ )'$	time-averaged mean and fluctuating quantity
$(\tilde{\ })$, $(\ )''$	Favre-averaged mean and fluctuating quantity

Introduction

This study is an extension of earlier work on the structure and radiation properties of turbulent methane/air and propane/air diffusion flames.[1-5] The present investigation considers turbulent carbon monoxide/air diffusion flames both theoretically and experimentally. These reactants yield a nonluminous flame having relatively simple chemistry and radiation properties, which simplifies interpretation of results. The objective of the study was to complete new measurements of the structure and radiation properties of turbulent carbon monoxide/air diffusion flames. Analysis was used to help interpret the measurements and to initiate evaluation of models of the process. An aspect of particular interest was the effect of turbulent fluctuations on flame radiation properties, i.e., to examine potential errors when radiation predictions are based on mean properties, which is common practice. The following discussion is brief, additional details and a complete tabulation of data are provided by Gore et al.[6] and Jeng et al.[7]

We recently reviewed past work on the radiative properties of turbulent flames and this discussion will not be repeated.[8] It was concluded that additional data were needed to support development of analysis -- particularly, results for well-defined experimental conditions having information on both structure and radiation properties. Another important issue for turbulent flames is the effect of turbulent fluctuations on flame radiation. Current practice generally ignores this interaction and mean scalar properties are used to predict radiation intensities and heat fluxes.[8,9] Yet Cox[10] and Kabashnikov and Kmit,[11] using simplified analysis, find that turbulent fluctuations appreciably increase (up to 2-3:1) radiative heat fluxes in flames, in comparison to values based on mean properties.

The present study is an extension of work by Jeng and coworkers,[1-5] who examined these same issues for methane/air and propane/air diffusion flames. Measurements of flame structure and radiation properties were used to evaluate models of these phenomena. Structure was analyzed using a Favre--averaged k-ε-g turbulence model, which incorporates the conserved-scalar formalism, similar to the approach described by Bilger.[12] A central element of this model is the use of the laminar flamelet approximation to relate scalar properties to mixture fraction. This

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approximation is based on observations by Bilger[13] and Liew et al.[14] that scalar properties in laminar diffusion flames can be correlated as universal functions of mixture fraction for a wide range of flame stretch rates, only showing departure from universality near extinction limits. Use of these ideas yielded reasonably good predictions of the scalar structure of turbulent methane and propane/air diffusion flames.[3,4]

Structure predictions were subsequently used to evaluate methods for predicting the spectral radiation intensities and radiant heat fluxes of turbulent methane/air diffusion flames.[2,5] Spectral radiation intensities were predicted using a narrow-band model described by Ludwig et al,[9] but with extensions to include the gas bands due to methane and carbon monoxide. Computations were made both using mean properties along a path, and using a stochastic method to allow for turbulence radiation interactions. The stochastic method employed random-sampling techniques adapted from Shuen et al.[15] The comparison between predictions and measurements was encouraging. Differences between mean property and stochastic predictions suggested only modest effects of turbulence/radiation interactions, e.g., stochastic predictions were generally only 20-30% higher than mean property predictions. Such differences are on the order of uncertainties in the narrow-band model and the structure model. Summing spectral radiation intensity predictions over both wavelengths and radiation paths covering all portions of the flame seen by the detector, using the discrete-transfer method described by Lockwood and Shah,[16] also yielded reasonably good predictions of radiative heat fluxes.

The objective of the present investigation was to further test these ideas by completing new measurements for turbulent carbon monoxide/air diffusion flames. Mean and fluctuating velocities, and mean temperatures, spectral radiation intensities, and radiative heat fluxes were measured for two turbulent carbon monoxide/air diffusion flames. These results, along with recent structure measurements by Razdan and Stevens[17] for the reactants, were used to evaluate predictions. Structure measurements in laminar carbon monoxide/air diffusion flames were also completed, to develop state relationships needed by the analysis.

The paper begins with discussion of experimental and theoretical methods. Results concerning the state relationship measurements and the structure of the turbulent diffusion flames are then described. The paper concludes with descriptions of predicted and measured spectral radiation intensities and radiative heat fluxes.

Experimental Methods

Test Arrangement

Experimental methods were generally similar to past work and will only be discussed briefly.[1-5] The turbulent diffusion flames involved vertical injection of carbon monoxide from a water-cooled burner into still air. The burner had a screened plenum followed by a 25:1 contraction which terminated in a 5mm diameter exit passage. The flames were attached at the burner exit using a small coflow of hydrogen from a slot just below the exit in the burner passage. The burner was housed in a screened enclosure to reduce room disturbances. The burner could be traversed in three directions, to accommodate rigidly-mounted optical instrumentation.

An uncooled concentric-tube burner was used for the laminar flame measurements. The carbon monoxide flowed from a central tube (14.3mm in diameter) with a coflow of air from a concentric port having an inside diameter of 102mm. The burner flows were smoothed using a bed of stainless-steel balls and honeycomb (1mm hexagonal cells x 25mm long) which was flush with the burner exit. The flames were shielded from drafts with a concentric cylindrical quartz tube (115mm inside diameter) which extended 10mm beyond each measuring plane. Fine-mesh screen was used to shield the upper portions of the flame.

Instrumentation

Velocities. Mean and fluctuating velocities were measured using a single-channel laser Doppler anemometer (LDA). The LDA used a 50mW HeNe laser and was operated in the dual-beam forward-scatter mode. Frequency shifting was used to eliminate directional bias and ambiquity. Seeding levels were high; therefore, the analog output of the burst-counter signal processor was integrated directly to yield time averages without velocity bias. The measuring volume had a diameter of 0.24mm and a length of 0.72mm. Analysis indicated that gradient broadening effects were small, except near the downstream end of the potential core. Uncertainties (95% confidence) of mean and fluctuating velocities were less than 5 percent.

Temperatures. Mean temperatures were measured using a butt-welded thermocouple constructed out of 0.075mm diameter Pt/Pt-10% Rh wires. The region of the junction was somewhat enlarged, having a diameter of rougly 0.2mm. The junction wires were mounted on heavier lead wires, spaced 12mm apart to provide a traversable probe. The thermocouple output was recorded with an integrating digital voltmeter. Temperature measurements were not corrected for radiative heat losses and are estimated to be 100-200K too low in the hottest parts of the flames.

Species Concentrations. Composition was only measured during the laminar flame experiments. A quartz sampling probe, operated choked, was used with a sampling orifice of 0.1-0.2mm diameter and a rounded probe tip having a radius of 0.75mm. Samples were analyzed using a gas chromatograph having a hot-wire detector. The gas chromatograph was calibrated with known gas mixtures. Uncertainties in composition measurements are estimated to be less than 15%.

Spectral Radiation Intensities. Spectral radiation intensities were measured for radial paths through the flames using a 250mm grating monochromator with a pyroelectric detector (Oriel Corp., models 7240 and 7084). The field of view was roughly 10mm in diameter with a 1.2° field angle. A water-cooled aperture between the flame and the monochromator prevented overheating of the instrument. Various gratings and order-sorting filters were used to cover the wavelength range 2.4-6.0μm, which includes the 2.7 and 4.3 μm bands of carbon dioxide and the 4.7μm band of carbon monoxide. The system function of the monochromator was calibrated using a blackbody source heated by a furnace. Higher-order harmonics of known wavelengths from a mercury arc and a HeNe laser were used to calibrate the wavelength readout. Uncertainties in these measurements were less than 20%.

Radiative Heat Fluxes. Total radiative heat flux distributions were measured along the base and the axis of the turbulent flames using a gas-purged, water-cooled sensor (Medtherm, Type 64F-10-22, with a 150° viewing angle). The sensor was positioned so that the flame boundaries were entirely within its viewing angle, except for points far from the burner exit, which contribute very little to the radiative flux in any event. Uncertainties of these measurements were less than 10%.

Test Conditions

Test conditions for the turbulent flames are summarized in Table 1. Both the present flames and the flame considered by Razdan and Stevens[17] are shown, since the latter flame was also used to evaluate structure predictions. Relatively high burner exit Reynolds numbers were used, to assure turbulent flow. Initial Richardson numbers were relatively low; nevertheless, effects of buoyancy were still appreciable, particularly near the end of the visible flame zone for the lowest Reynolds number flame.

Table 1. Summary of Turbulent Flame Test Conditions[a]

Reynolds Number[b]	13140	7470	11400
Source	Present Study	Present Study	Razdan & Stevens[17]
Richardson Number[c]	$2.3x10^{-5}$	$7.9x10^{-5}$	$3.9x10^{-5}$
Measured u_o(m/s)	51.5	24.8	35.5
$k_o^{1/2}/u_o$	0.051	0.058	---
$\dot{Q}$(kW)	8.9	5.3	7.6
$\dot{Q}_{rad}/\dot{Q}$(%)	8.4	11.4	----
Flow Rates (mg/s):			
Fuel	895	531	760
Hydrogen	19.2	4.8	1.7

[a] Flow directed vertically upward from a 5mm diameter passage, in still air at NTP (except for the Razdan and Steven[17] flame where there was a 0.13m/s coflow of air). Commercial Grade carbon monoxide, Linde Division of Union Carbide, containing 1.12% hydrogen by volume.

[b] $Re = u_o d/\upsilon$ based on fuel-gas properties at exit

[c] $Ri = ad/u_o^2$

Initial conditions for the present flames were defined by measuring $\bar{u}$, $\overline{u'}$ and $\overline{v'}$ at x/d = 2, which was the position nearest the exit which was accessable to the LDA. The initial turbulence kinetic energy distribution was estimated from these measurements, assuming that radial and tangential velocity fluctuations were equal. Initial values of ε were estimated from the rate of decay of velocity fluctuations in the potential core.

Theoretical Methods

Flame Structure

Theoretical methods were similar to past practice and will only be described briefly.[2-5] The conserved-scalar method was used to estimate flame structure, assuming: (1) boundary layer approximations for an axisymmetric flame with no swirl, (2) negligible mean kinetic energy, (3) equal exchange coefficients for all species and heat, (4) negligible radiative energy exchange within the flames, and (5) buoyancy only affects the mean flow. Assumptions 1 and 2 represent conditions of the experiments. Assumption 3 is widely adopted for analysis of turbulent mixing in gases and is reasonably satisfactory at high Reynolds numbers. Assumption 4 is justified by the relatively small radiative heat loss fractions of present flames, cf., Table 1. Assumption 5 has been shown to provide reasonably good predictions of mean properties in turbulent diffusion flames having similar initial conditions.[3,4] The Favre-averaged formulation of Bilger[12] was adopted (although details differ) which involves solving governing equations for mean conservation of mass, momentum and mixture fraction and modeled governing equations for k, ε and g. All model constants were fixed by measurements in constant-and variable-density noncombusting jets.[3]

Scalar properties were found from the probability density function of mixture fraction in conjunction with the laminar flamelet state relationships which provide scalar properties as a function of mixture fraction. A clipped Gaussian Favre probability density function was used, similar to past work.[3,4] The laminar flamelet state relationships were only used for the mass fractions of major species. Temperatures and densities were computed as a function of mixture fraction, for the measured compositions, assuming that the flame lost the measured fraction of its chemical energy release by radiation. The calculations for temperature and density used the Gordon and McBride[19] Chemical Equilibrium Algorithm.

Spectral Radiation Intensities

The equation of radiative transfer was solved for various paths through the flame, ignoring scattering using the narrow-band analysis of Ludwig et al.[9] The analysis considered all gas bands in the region of interest, e.g., the 2.7 and 4.3μm bands of carbon dioxide and the 4.7μm band of carbon monoxide, using the Goody statistical narrow-band model in conjunction with the Curtis-Godson approximation for an inhomogeneous gas path. A slightly-modified version of the computer algorithm RADCAL, developed by Grosshandler,[18] was used for the computations.

Spectral intensity computations are straight- forward when turbulence/radiation interactions are ignored. The structure analysis provides both time- and Favre-averaged mean scalar properties along the radiation path. Properties needed for the calculations are taken to be time-averages.

The stochastic analysis was used to gain insight concerning turbulence/radiation interactions. This involves dividing the gas path into eddies, having lengths equal to the local dissipation length scale. Each eddy is assumed to have uniform properties. The properties of each eddy are found by randomly sampling its time-averaged probability density function for mixture fraction and obtaining scalar properties for this mixture fraction from the state relationships. Once all eddy properties are specified along the gas path, spectral intensities are calculated similar to the mean property method. Random sampling continues in this manner, until sufficient realizations have been computed to obtain statistically-significant results.

Radiative Heat Fluxes

Computations of radiative heat fluxes are a straight-forward extension of the spectral radiation intensity computations when the discrete transfer method of Lockwood and Shah[16] is used. This involves determining the spectral intensity for various wavelengths and paths passing through the point in question (120 paths to the sensor location in this instance, allowing for symmetry) and then summing over both wavelengths and paths to find the total radiative heat flux. Paths are chosen to cover the region viewed by the detector with the contribution of each weighted according to the solid angle it intercepts and the angle of the path normal to the detector surface. The present calculations were based on mean property predictions to shorten calculations, since turbulence/radiation interactions were not found to be large for carbon monoxide/air diffusion flames.

Results and Discussion

State Relationships

Measurements of species concentrations and temperatures in the laminar carbon monoxide/air diffusion flames are illustrated in Figs. 1 and 2. The

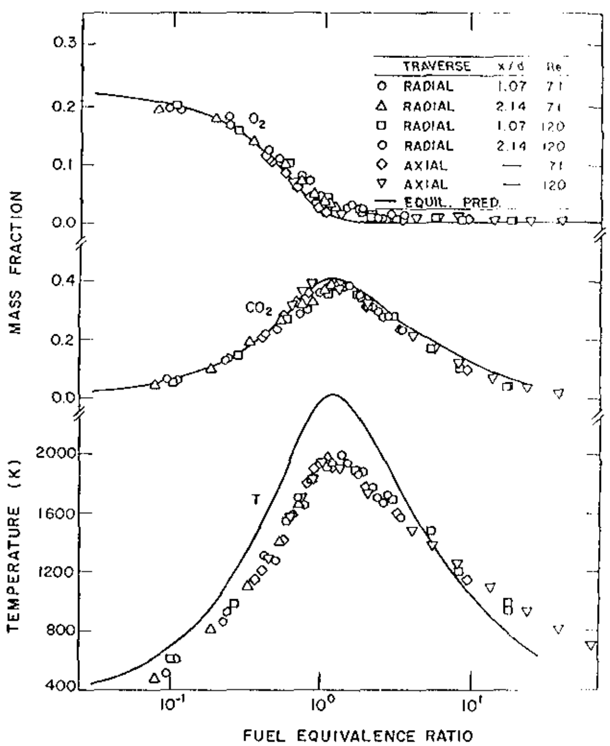

Fig. 1. Carbon monoxide/air state relationships.

measurements are plotted as a function of fuel equivalence ratio; however, mixture fraction is a single-valued function of this variable. Fuel equivalence ratio was found from the measured carbon and oxygen concentrations in the sample. Measurements are identified by the type of traverse from which they were obtained (radial at various heights or along the axis) and by the burner Reynolds number (based on the fuel flow). Specific positions for each value can be obtained from the data tabulation.[7] Equilibrium predictions for an adiabatic flame, from the Gordon and McBride[19] code, are also plotted in the figures.

It is evident that the measurements correlate as a function of fuel equivalence ratio, supporting the laminar flamelet concept for these test conditions. Aside from temperature (where radiative and convective heat losses from the flame and radiation errors of the thermocouple are factors), the

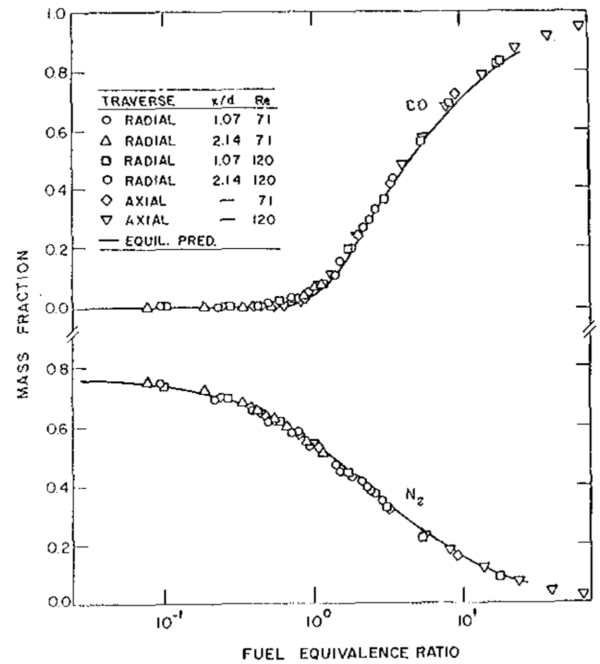

Fig. 2. Carbon monoxide/air state relationships (continued).

correlations are in excellent agreement with predictions of local thermodynamic equilibrium. This behavior is not usually observed for carbon dioxide and carbon monoxide in fuel-rich regions of hydrocarbon flames, where oxidation of carbon monoxide to carbon dioxide does not proceed very rapidly in the presence of fuel molecules.[20] In the present case, the capability of the system to approach thermodynamic equilibrium provides a physical justification for the flamelet concept. Figures 1 and 2 represent the state relationships used during subsequent structure and radiation computations.

Flame Structure

Structure results for the present two turbulent flames were similar; therefore, only results for the Re = 7470 flame will be presented due to space limit- ations. The measurements of Razdan and Stevens[17] provide supplemental information on species concentrations and will be considered as well.

Measurements and predictions of mean and fluctuating streamwise velocities along the axis, for Re = 7470, are illustrated in Fig. 3. Recall that time- averages were measured while the analysis predicts Favre averages. The difference between the two for mean velocities is typically not large in flames, in comparison to experimental uncertainties, ca. 10%.[21,22] However, Favre-averaged velocity fluctuations along the axis are on the order of 20% lower than time-averages, and can be as much as 40% lower in high-temperature portions of the flow.[21,22] The analysis only yields k; therefore, $\tilde{u}'$ has been estimated for plotting in Fig. 3, assuming isotropic turbulence ($\widetilde{u''^2} = 2k/3$) which is consistent with other model assumptions. If the usual level of anisotropy in jets is assumed ($\widetilde{u''^2}$=k), predictions would be roughly 20% higher.

Results in Fig. 3 show that mean velocities along the axis are predicted reasonably well, except near the end of the potential core where gradient biasing tends to reduce measured mean velocities. Similar difficulties are encountered near the end of the potential core for velocity fluctuations. The predicted values of $\tilde{u}'_c$ are generally lower than the measured values of $\overline{u'_c}$. However, this is consistent with expected lower values of Favre averages and the usual levels of anisotropy of velocity fluctuations in jet-like flows, as noted earlier.

Predicted and measured mean temperatures along the axis, for the same flame, are illustrated in Fig. 4. The theory provides both Favre-and time averages;

therefore, both estimates are shown since the degree of density weighting of the thermocouple measurements is unknown.[21] As noted earlier, the temperature measurements were not corrected for radiative heat losses and are 100-200K too low in the highest temperature regions of the flow. Considering effects of radiation and uncertainties in the type of average actually measured, the comparison between predictions and measurements is reasonably good.

Predicted and measured centerline mean temperatures and compositions for the flame considered by Razdan and Stevens,[17] are illustrated in Fig. 5. Favre-averaged predictions of mean composition are illustrated while the measurements have indeterminant levels of density weighting.

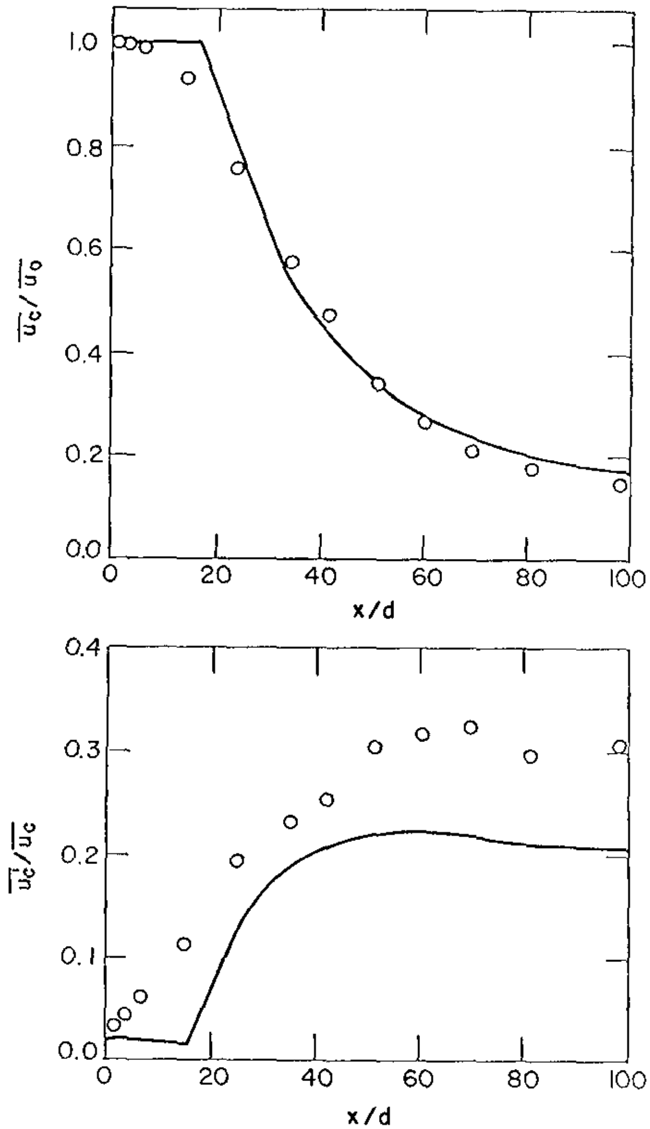

Fig. 3. Variation of mean and fluctuating streamwise velocities along the axis, Re = 7470.

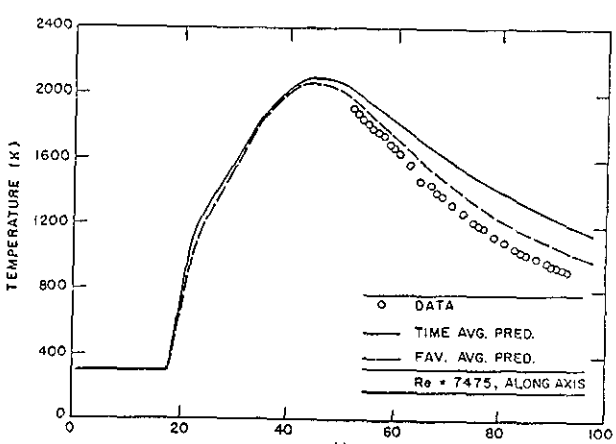

Fig. 4. Variation of mean temperatures along the axis, Re = 7470.

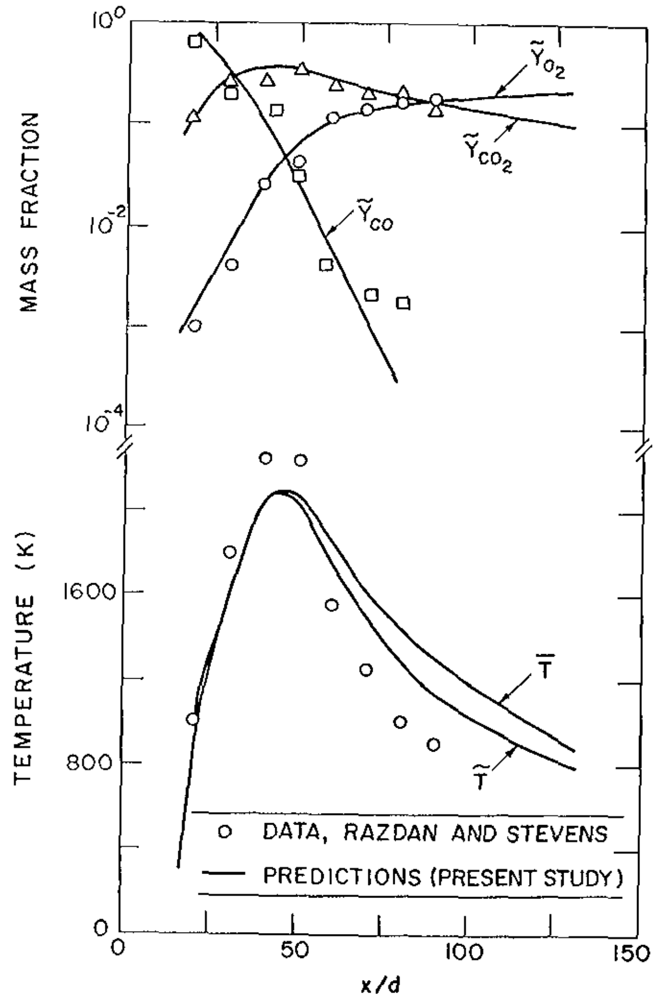

Fig. 5. Mean species mass fractions and temperatures along the axis, Re = 11400.

Differences between Favre- and time-averaged concentrations are generally less than 10% along the axis, except near the flame tip where Favre averages are roughly 50% lower than time averages. Based on these considerations, predictions of mean concentrations are reasonably good. Predictions for both Favre and time averages underestimate measured mean temperatures near the flame tip.

Spectral Radiation Intensities

The structure evaluation suggests that the present model provides reasonable predictions of mean properties in the present flames; therefore, we turn to consideration of radiation properties. Measurements and predictions of spectral radiation intensities for the present two flames are illustrated in Figs. 6-8. Measurements were undertaken for horizontal radial radiation paths through the flames at x/d = 50 and 90, the former position being very close to the flame tip. Both mean property and stochastic predictions are illustrated in the figures.

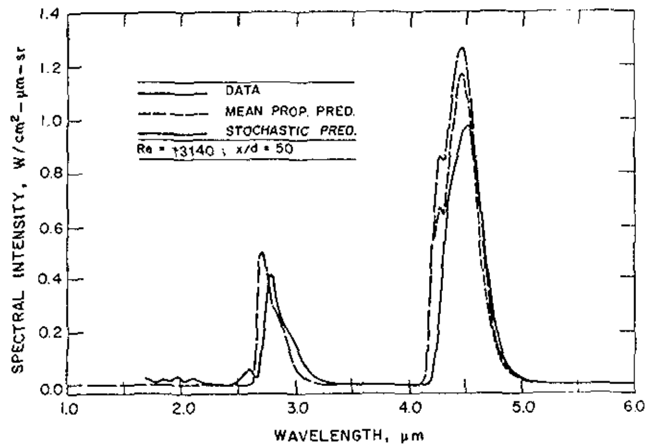

Fig. 6. Spectral radiation intensities at x/d = 50, Re = 13140.

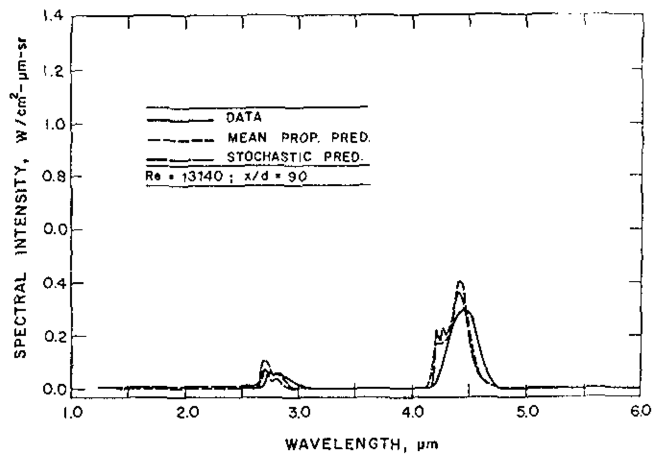

Fig. 7. Spectral radiation intensities at x/d = 90, Re = 13140.

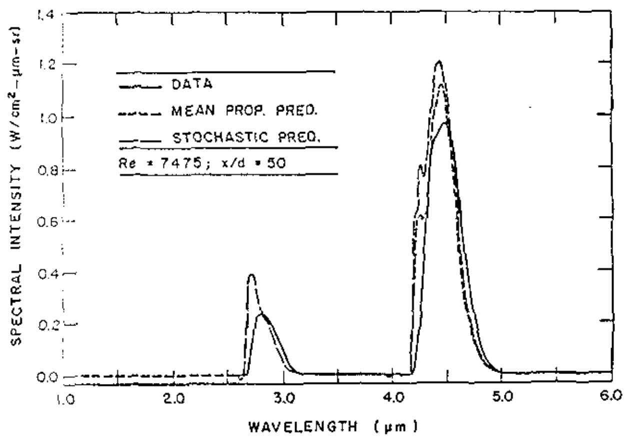

Fig. 8. Spectral radiation intensities at x/d = 50, Re = 7475.

Results in Figs. 6-8 show that spectral radiation intensities are dominated by the 2.7 and 4.3µm bands of carbon dioxide, although the 2.7µm band is not very apparent at x/d = 90. Concentrations of carbon monoxide are small at the positions considered, similar to Fig. 5; therefore, the 4.7µm band of carbon monoxide is not observed. Spectral radiation intensities are highest near the flame tip, e.g., x/d = 50, where temperatures and concentrations of carbon dioxide are both high cf., Fig. 5. The comparison between predictions and measurements is encouraging, particularly since predictions depend on estimates of both structure and radiation properties. Effects of turbulence/radiation interactions are not large for these flames, with stochastic predictions only about 10% higher than mean property predictions. In contrast, turbulence/radiation interactions caused stochastic predictions to be 20-30% higher than mean property predictions for turbulent methane/air diffusion flames.[2] This is due to the relatively slow variation of radiation properties (viz., temperature and carbon dioxide concentration) with mixture fraction for this reactant combination. This behavior follows since the stoichiometric mixture fraction of carbon monoxide/air diffusion flames is substantially higher than hydrocarbon fuels (0.29 instead of 0.06).

Radiative Heat Fluxes

Measurements and predictions of total radiative heat fluxes to points surrounding the present turbulent flames are illustrated in Figs. 9 and 10. Figure 9 is an illustration of results for the detector facing the flame axis and traversing in the vertical direction at a distance of 300mm from the axis. The radiative heat flux is highest near the flame tip, ca. x/d = 45 and 50 for the low and high Reynolds number flames. Figure 10 is an illustration of results for a detector facing vertically upward in the plane of the burner exit and traversing radially outward. In this case, the radiative heat flux decreases monotonically with increasing radial distance. Although peak mean temperatures and compositions are the same for both flames, radiative heat fluxes are lower for the lower Reynolds number flame due to its smaller dimensions, e.g., buoyancy causes the flames to be shorter and narrower at lower Reynolds numbers for the present test range. This effect would disappear at higher Reynolds numbers, where flame structure is relatively independent of Reynolds number. Predictions are in reasonably good agreement with measurements, e.g., discrepancies are on the order of 10%.

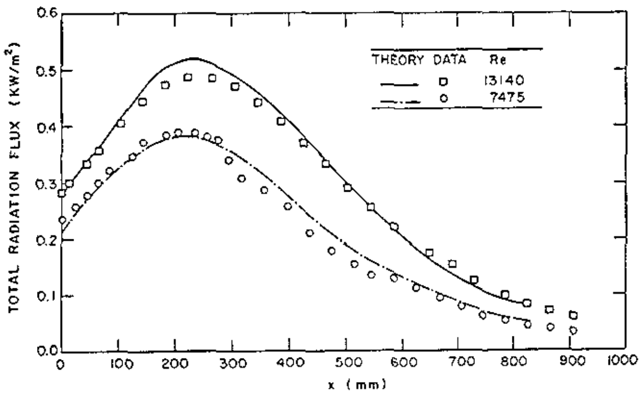

Fig. 9. Total radiative heat fluxes along the axis.

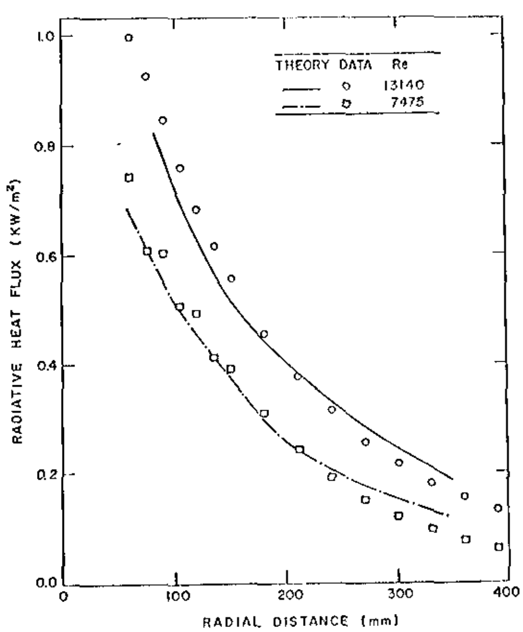

Fig. 10. Total radiative heat fluxes in the plane of the burner exit.

Conclusions

The major conclusions of the study are as follows:

1. For the range of conditions examined here, state relationships of carbon monoxide/air diffusion flames are nearly universal, and very close to predictions based on local thermodynamic equilibrium, supporting the laminar flamelet concept.

2. The present conserved-scalar k-ε-g analysis for structure was in reasonably good agreement with measurements, using measured initial conditions with all empirical constants fixed by results for noncombusting jets.

3. The present radiation analysis achieved reasonably good predictions of spectral radiation intensities and radiative heat fluxes, similar to past experience for turbulent methane/air diffusion flames.[2,5] Effects of turbulence/radiation interactions are small for the carbon monoxide/air flames only increasing spectral radiation intensities on the order of 10%, due to the relatively slow variation of radiative properties with mixture fraction for this flame system.

Comparable studies are currently in progress to evaluate present methods for nonluminous hydrogen/air diffusion flames as well as soot-containing luminous diffusion flames.

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