Experimental Study on Quantitative Radiation Properties of Laminar Oxygen-enriched Inverse Diffusion Flames in Gas Turbines* 

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In gas turbines, inverse diffusion flames form when film-cooling air reacts with fuel-rich packets from the combustor. Investigations have focused on the quantitative radiation heat transfer in oxygen-enriched inverse diffusion flames (IDFs) since it plays an important role not only in fundamental combustion research, but also in much research on industry combustion, such as gas-turbine engines. To investigate the quantitative radiation properties of oxygen-enriched IDFs, a mid-infrared thermal camera coupled with two different band-pass filters was selected to acquire the thermal radiation intensity of carbon dioxide and soot. The oxygen mole fraction in the oxidizer was varied from 21% to 100% using a co-flowing inverse flame burner to produce steady flames. The radiation intensities from carbon dioxide are approximately 15 to 20 times stronger than those from soot with different oxygen enrichment in IDFs. Both radiation from carbon dioxide and soot increased as the oxygen index of the oxidizer was increased, and the increase in radiation from carbon dioxide was more drastic than that from soot when the oxidizer was more enriched. However, the growth rate of the maximum radiation emission from carbon dioxide along the flame centerline decreased when the oxygen index of the oxidizer exceeded 80%. Furthermore, a second peak appeared along the flame centerline in the radiation curves from soot when the oxygen index of the oxidizer exceeded 40%. The axial position of the second peak was closer to the burner exit than that of the first peak. Moreover, the values of the second peak presented a steeper growth rate than the first one with greater oxygen enrichment.

Key Words: Gas Turbines, Oxygen Enrichment, Inverse Diffusion Flames, Radiation Intensity, Quantitative Infrared Images

Nomenclature

- λ: wavelength number
- I_b: blackbody spectral intensity
- τ_f: account for transmission loss through filter
- κ_f: spectral absorption coefficient
- s: radiative path length
- Re: Reynolds number of mixed gas
- Re_o: Reynolds number of oxidizer
- φ_overall: stoichiometric equivalence ratio
- H_v: flame height of visible region
- H_b: flame height of blue region
- X_j: mole fraction of component j
- Q_j: volume fraction of component j
- Z_j: compressibility factor of component j
- μ_m: dynamic viscosity of mixed gas
- μ_j: dynamic viscosity of component j
- M_j: mole mass of component j
- Q_m: mass flow rate of mixed gas
- Q_v: volume flow rate of mixed gas
- D: diameter of oxidizer exit
- X: axial height above the burner along the flame centerline

r: radial distance from the flame centerline

1. Introduction

The presence of secondary reaction zones in gas-turbine engines increases the heat load on engine components. This is because inverse diffusion flames form when the film-cooling air reacts with fuel-rich packets from the combustor. There is also the advantage of potentially improving heat transfer, reducing pollutant emissions and reducing the exhaust volume. Accordingly, oxygen-enriched combustion provides benefits for many industrial combustion applications, leading to increased productivity and better product quality for items such as coal gasifiers, gas-turbine engines and industrial stoves. Varying the degree of oxygen enrichment changes the diffusion flame properties in terms of species concentration, structure, temperature, and others, which directly or indirectly affects the radiative characteristics of the flame. The variation in thermal radiation, which includes the continuum and spectral thermal radiation from soot and polyatomic gas, respectively, also contributes to the determination of flame structure, flame temperature and other important parameters. Furthermore, the interaction between thermal radiation and other flame properties becomes more drastic as the ratio of oxygen increases.

Baukal and Gebhart first experimentally studied the relationship between nonluminous flame radiation and oxidizer
composition, and concluded that the flame thermal radiation is dramatically enhanced by removing N\textsubscript{2} from the oxidizer. Wang et al.\textsuperscript{10} measured the radiative loss of turbulent jet flames under an oxygen-enhanced condition with the oxygen index (OI) in the range of 21–100%, and illustrated that radiation loss from flames increased as the ratio of oxygen added increased due to the rise in flame temperature. Numerical and experimental investigations were conducted by Fuentes et al.\textsuperscript{11} to characterize the effects of adding oxygen to the oxidizer stream in terms of radiative heat loss in laminar ethylene diffusion flames. The assumed that the radiative heat flux is enhanced when OI is increased from 17% to 35%, but the rate of increase is substantially reduced when OI is larger than 25%. Hwang and Gore\textsuperscript{12} investigated the spectral radiation of methane/oxygen flames experimentally and demonstrated that the spectral radiation intensity of methane/oxygen flames had a more balanced distribution. Wang et al.\textsuperscript{13} simulated oxygen-enriched turbulent non-premixed flames and demonstrated detailed models for radiation are important, and concluded that soot formation was affected by flame temperature through soot radiation.

The concept of IDF was first introduced by Friend.\textsuperscript{14} Similar to the normal diffusion flame (NDF), the streams of the oxidizer and fuel are separated before combustion, but the arrangement of fuel and air is reversed: the air stream is located in the center of the flame and is surrounded by fuel streams. More stringent requirements for flame stability and NOx emission in most combustors have resulted in IDFs receiving ever-increasing attention in recent years due to their advantage over NDFs because of these flame properties.\textsuperscript{15,16} Wu and Essenhigh\textsuperscript{17} classified inverse diffusion flames through changing the methane and air velocities and identified unstable flames and the emission of more or less soot and six different stable regimes depending on the flow conditions. Kaplan and Kailasanath\textsuperscript{18} simulated NDFs and IDFs with different air and fuel velocities. Blevins et al.\textsuperscript{19} found that the soot structure of IDFs is similar to that of NDFs through acquiring soot specimens and analyzing the morphology.

Although the amount of published literature on IDFs has obviously increased in recent years, only a small number of studies are focused on the radiative heat transfer in IDFs. Demarco et al.\textsuperscript{20} studied the relationship between radiative heat transfer and soot production in IDFs, and demonstrated that radiative heat transfer is one of the important factors in the progress of accurate simulation for soot concentrations and flame temperature. Demarco et al.\textsuperscript{20} studied radiative heat transfer in IDFs numerically using an OI of 21%. The results indicated that the proportion of total heat transfer radiated in NDFs is much higher than that discovered in IDFs, and the ratio of gaseous combustion product to radiative heat transfer is lower than that of soot, Krishnan et al.\textsuperscript{21} researched the radiation properties of various IDFs of C\textsubscript{2}H\textsubscript{6} experimentally, including radiative heat flux distribution, total radiative heat loss and spectral radiation intensities with oxygen mole fractions from 21–100%. There is no denying that the variation of IDFs properties in terms of structure, temperature, species concentration and other parameters are all directly or indirectly affected by the radiation from soot and combustion gases, especially in oxygen-enriched inverse diffusion flames. Therefore, more detailed research regarding the radiative properties of oxygen-enriched IDFs should be conducted in order to obtain an even deeper understanding of the oxygen enrichment effect on the flame structure, temperature and other important parameters.

In the present investigation, quantitative radiation intensity from carbon dioxide (CO\textsubscript{2}) and soot in oxygen-enriched laminar inverse diffusion flames were measured using an infrared camera and varied oxygen enrichment, the oxygen indices varying from 21–100%. In order to have a more conclusive understanding of the influence of oxygen enrichment on the radiative properties of flames, the main difference in the radiation intensity between two wavelengths of interest (i.e., 4.26 µm and 3.6 µm), including the axial positions of peak radiation values, the radiative intensity variation tendency and the proportions of total thermal radiation for 2–5 µm were compared in this research.

### 2. Experimental Methods

The co-annular burner used to produce laminar inverse diffusion flames in this study is similar to the burner used by Blevins et al.\textsuperscript{19} Figure 1 shows the burner has three concentric stainless-steel tubes, and is characterized by an oxidizer inlet diameter of 10 mm (1-mm wall thickness), while the fuel flows in the annulus between the central oxidizer tube and a 36-mm-diameter tube. To prevent secondary flames from forming between the ambient air and fuel, nitrogen was applied with a flow rate of 20 standard liters per minute (slpm), where standard conditions are 293 K and 101 kPa. The volumetric flow rate of the oxidizer (1.0 L/min) and fuel (3.0 L/min) were fixed in all experimental cases. However, the oxygen index was varied with a nitrogen balance to create different oxygen-enhanced conditions. The volumetric fuel flow rate and oxidizer flow rate were measured by rotameters, and had an uncertainty of 5% (95% confidence because of calibration in local ambient conditions).

The thermal radiation intensity of the oxygen-enriched inverse diffusion flames was measured using a mid-infrared camera (FLIR 7700) with an InSb focal plane array

Fig. 1. Schematic diagram of inverse diffusion flame burner.
The infrared images of the thermal radiation intensity acquired covered the entire flame region. The exposure time was changed from 50 µs to 500 µs due to optimizing the detector sensitivity depending on the filter. The sampling frequency was changed from 100 Hz to 132 Hz depending on the infrared camera exposure. For every test condition, the eventual experimental result was defined as the mean value of nearly 3,200 images.

The experimental system is shown in Fig. 2. The axial direction of the flame was defined as X, and the radial direction of the flame was defined as r. In order to acquire radiation intensities from both soot and carbon dioxide (CO₂ + S) (4.26 ± 0.12 µm) and from soot (s) (3.6 ± 0.12 µm) only, two band-pass filters were selected. A high-temperature blackbody furnace was used to calibrate the infrared camera, and the distance between the infrared camera and the blackbody furnace was the same as the distance between the infrared camera and the flame. In the calibration process, the response of the detector and the losses of transmission caused by the lens and filter were included.²²

The narrowband radiation intensity (I) measured along the line-of-sight through the flame as described by the solution to the radiation transfer equation for absorbing-emitting media is²²:

\[
I = \int_{\lambda_1}^{\lambda_2} \alpha_1 I_b(\lambda_0) e^{-\tau_1} d\lambda + \int_{\lambda_1}^{\lambda_2} \alpha_2 I_b(\lambda_2) e^{-\tau_2} d\tau_2 d\lambda
\]

(1)

where \(I_b\) is the blackbody spectral radiant intensity, and \(\lambda_1\) and \(\lambda_2\) are the spectral limits of the filter. The spectral coefficient (\(\alpha\)) included losses of transmission caused by the lens and filter, and the spectral response of the camera focal plane array. The optical thickness (\(\tau\)) is defined as²²:

\[
\tau = \int_0^s \kappa_1 ds
\]

(2)

where \(s\) is the path length and \(\kappa_1\) is the spectral absorption coefficient.

The Reynolds number (Re) in Table 1 is calculated using the following formula:

\[
Re = 0.354 \times \frac{Q_m}{D_{in}} = 0.354 \times \frac{Q_v}{D_v}
\]

(3)

where Re is the Reynolds number of mixed gas, \(Q_m\) is mass flow rate of mixed gas, \(Q_v\) is volume flow rate of mixed gas, and \(D\) is inner diameter of the tube.

\[
\mu_m = \sum_{j=1}^{n} X_j \times \mu_j \times M^{1/2}
\]

\[
\sum_{j=1}^{n} X_j \times M_j^{1/2}
\]

(4)

where \(\mu_m\) is the dynamic viscosity of mixed gas, \(\mu_j\) is dynamic viscosity of component \(j\), and \(M_j\) is mole mass of component \(j\).

\[
X_j = \frac{Q_j}{Z_j(t,p)}
\]

\[
\sum_{j=1}^{N} Q_j
\]

(5)

where \(X_j\) is mole fraction of component \(j\), \(Q_j\) is volume fraction of component \(j\), and \(Z_j\) is the compressibility factor of component \(j\).
3. Results and Discussion

The visible color images of oxygen-enriched CH₄ IDF are shown in Fig. 3. There are two important zones: an inner blue chemical reaction region and an outer visible yellow downstream region. The axial position at the beginning of the yellow luminous flame zone moves upstream (i.e., toward the exit of the oxidizer) as the O₂ mole fraction increases. The blue fuel-rich edge of the reaction gets blurrier because the blue inner reaction zone becomes increasingly luminous.16)

As shown in Fig. 3, the blue edge of the flame was chosen as the characteristic of reaction zone flame height for these inverse diffusion flames.23) Figure 4(a) depicts the increasing tendency of flame heights in different zones as the oxygen index increases. The blue reaction height shows a more gradual growth trend compared to the yellow downstream flame height. The oxidizer mass flow rate, which is the main influential factor on the blue reaction zone height in IDF as the role of fuel mass flow rate in normal diffusion flames, was fixed at 1.0L/min under all test conditions. The measurement results of the flame temperature, along with the flame centerline under different experimental conditions, are shown in Fig. 4(b). This was obtained using the temperature measurement module of the infrared camera, and an obvious increase in flame temperature can be seen in Fig. 4(b). Meanwhile, the distance between adjacent peak values of flame temperature along the centerline became larger as the mole fraction in the oxidizer increased. This may be due to the increase in the velocity of heat generation resulting from the participation of more oxygen atoms in the combustion chemical reaction. Increasing oxygen enrichment contributed directly to generating more heat in the blue reaction zone. Meanwhile, the temperature in the yellow downstream zone (i.e., fuel-rich side) rose due to more heat being imported into this zone—toward downstream—by convection, conduction and radiative heat transfer. The most active radicals in combustion systems are H, OH and O. The reaction rate for the formation of these radicals increases as the result of increasing the flame temperature at the time of oxygen enrichment. In the study on the effects of oxygen enrichment on methane-air flames,24) the researchers found that the peak mole fraction increased approximately twofold above radicals even if 10% oxygen enhancement was added to the flame. Therefore, in a high-temperature environment, increasing these radicals will accelerate a series of soot formation processes, including hydrocarbon pyrolysis, surface deposition, aggregation and carbonization, and excluding oxidation on the...
fuel-rich side. More and more soot will form in the yellow downstream zone as more O$_2$ is added in the oxidizer, resulting in a significant increase in the height of the yellow downstream zone.

3.1. Total quantitative imaging of radiation at 2–5μm

The time-averaged radiation intensities of different oxygen-enriched IDF's are presented in Fig. 5. An intense radiation region was observed near the burner exit, corresponding to the blue reaction zone in Fig. 3. As the ratio of oxygen increased, the planar area of the intense radiation intensity region became larger. Meanwhile, the radiation intensity in this region obviously increased; especially when the oxygen mole fraction in the oxidizer exceeded 60%. The increase in radiation intensity, as described above, may be a combined effect of higher temperature and more radiative medium, which can be enhanced by adding oxygen directly to the oxidizer. However, compared to the significant increase in radiation intensity in the reaction zone, no significant increase in radiation intensity was found in the luminous reforming zone. The significantly different tendency of radiation intensity increasing between the two zones in IDF’s proved that the effect of oxygen enhancement in the oxidizer mainly influenced the blue reaction zone of IDF’s.

Figure 6 shows the time-averaged radiation intensity along the flame centerline with O$_2$ added to the oxidizer, wavelengths of 2–5 μm. The peak radiation intensity along the flame centerline increased significantly as the oxygen index increased. Meanwhile, the axial positions of the peak radiative intensity for the IDF’s. The 2–5 μm wavelengths also shifted upstream, which is similar to the variation tendency of peak OH values reported in previous research. Moreover, the infrared radiative intensities decrease both upstream and downstream. As described above, the effect of oxygen enrichment mainly influenced the blue reaction zone of IDF’s, so the radiation intensity had a steeper rise from the exit of the burner to the position of maximum total radiative intensity. Furthermore, the steepness became more drastic as the ratio of oxygen increased.

It is known that an oxygen-enriched flame will increase the partial pressure of CO$_2$ and H$_2$O. Meanwhile, the flame temperature also increases, resulting in H$_2$O and CO$_2$ receiving more heat through different heat transfer methods, such as conduction, convection and radiation. Accordingly, there will be a significant increase in gas thermal radiation in IDF’s. Additionally, there will be a large amount of soot in the fuel-rich zones of the oxygen-enhanced flames, which promotes continuous radiation from the flames. Therefore, the combined effect of high temperature and a high concentration of radiative medium, including CO$_2$, H$_2$O and soot, promotes the variation of radiative properties in oxygen-enriched IDF’s. However, in order to acquire a more comprehensive and deeper understanding of this issue, more detailed research is required.

3.2. Quantitative imaging of radiation from CO$_2$ and soot

The radiation intensities of IDF’s in a narrow band (4.26 ± 0.12 μm) are presented in Fig. 7. An intense radiation region was captured in the quantitative time-averaged images of infrared radiation intensity. The planar area of high infrared radiation intensity and the value of radiation intensity in this region both rose significantly as the ratio of oxygen increased, similar to that shown in Fig. 5. As is well known, almost all of the radiation energy in the 4.26 ± 0.12 μm wavelength came from CO$_2$, only a small amount came from the soot. Therefore, the radiation intensity in the 4.26 ± 0.12 μm wavelength reflects the concentration of CO$_2$ to some extent.

As shown in Fig. 8, methane converted to methyl (CH$_3$) indicates the beginning of methane pyrolysis. The three most important chemical reactions related to methane combustion include R11 (CH$_4$ + O ⇔ CH$_3$ + OH), R53 (CH$_4$ + H ⇔ CH$_3$ + H$_2$), and R98 (CH$_4$ + OH ⇔ H$_2$O + CH$_3$). In the GRI 3.0 kinetic scheme, the most important radicals that contribute to methane pyrolysis are O, OH and H. However, when oxygen was added, the main influence of oxygen enhancement on the oxidation pathways was the pyrolysis of CH$_3$, rather than creating methyl through the methane pyrolysis process.

There is a clear difference in the pyrolysis of CH$_3$ and CH$_4$. CH$_3$ is converted into CH$_2$, CH$_2$O, C$_2$H$_6$ and CO.

\begin{align*}
\text{CH}_3 & \rightarrow \text{CH}_2\text{O} & \text{R10:} & \text{CH}_3 + \text{O} \rightleftharpoons \text{CH}_2\text{O} + \text{H}; \\
\text{CH}_3 & \rightarrow \text{CH}_2\text{O} & \text{R119:} & \text{H}_2\text{O} + \text{CH}_3 \rightleftharpoons \text{OH} + \text{CH}_3\text{O}; \\
\text{CH}_3 & \rightarrow \text{CO} & \text{R284:} & \text{O} + \text{CH}_3 \rightleftharpoons \text{H} + \text{H}_2 + \text{CO};
\end{align*}
Although important radicals such as H, OH and O exist, their contribution to methane pyrolysis was almost unchanged at the time of oxygen enhancement. The total amounts of the three radicals all obviously increased, such as the principal route of radical production including O and OH for accelerating the chemical reaction R38 ($O_2 + H \rightarrow OH + O$), while the main reaction of H radical production was R10 ($CH_3 + O \leftrightarrow CH_2O + H$) and R84 ($H_2 + OH \leftrightarrow H_2O + H$). The progress rates of the three reactions listed above all increased significantly even if an enrichment of only 10% was added. There was a rise of approximately 2.5 times, 3.5 times and 4 times in the reaction progress rates of R10, R38 and R84, respectively. Then the results described above directly accelerated the rate of methane oxidation reaction. The reaction progress rate of R11, R53 and R98 were approximately 3.5 times, 4 times and 4 times faster, respectively. These changes in the chemical reaction progress of methane pyrolysis resulted in larger amounts of CH$_3$ taking part in the chemical reactions.
In the pyrolysis process of CH₃, some CH₃ was synthesized into C₂H₆; however, most of the CH₃ was converted into CH₂O, CH₂O, CO and CH₂(s) through the chemical reactions related to OH, H, and O. When more oxygen atoms participated in the combustion chemical reaction, the synthesis rate of C₂H₆ dropped significantly. Numerical simulation results demonstrated that 20% enhancement decreases the conversion rate of C₂H₆ from about 20% to approximately 5–10%. Moreover, the formation of more CH₂O would result in decreasing the formation of CH₃O, while CH₃Oi→CH₂O. This indicates that increasing CH₂O reduced the reaction rate of R10 significantly, and another high radiation intensity region appeared near the burner exit. Additionally, the decrease in the concentration of CO₂ acquiring a significant increase through R99 (CO + OH ↔ H + CO₂) in the blue reaction zone of IDFs.

Figure 11 depicts the time-averaged radiation intensity along the flame centerline with the addition of various amounts of O₂ to the oxidizer in the 3.6 ± 0.12 μm wavelength. The peak value of soot radiation intensity continuously rose as the ratio of oxygen was increased in the oxidizer, which is different from the NDFs. Due to the inverted positions of the oxidizer and fuel between IDF and NDF, the hydrocarbon fuel stream was not surrounded by the oxidizer stream. The chemical reaction heat was imported from the blue reaction region to the rich-fuel region as more and more hydrocarbon molecules underwent reactions such as decomposition, aggregation and carbonation in a high-temperature environment, thereby accelerating the process of soot formation.

Furthermore, with the continual increase of the oxygen mole fraction in the oxidizer, another high radiation intensity region appeared near the burner exit. Additionally, the distance between the axial position of the second high radiation intensity and burner exit decreased when the ratio of oxygen was higher in the oxidizer. This corresponds to the description in research about the influence of oxygen enhancement on incipient soot particles in IDFs, Jung et al. They found that the position at the beginning of the yellow flame moves upstream (i.e., toward the burner tip) when the oxidizer was more enhanced.

Another characteristic of the soot radiation intensity along the flame centerline is also shown in Fig. 11; the style of the curve change from one peak to two peaks when the ratio of oxygen in the oxidizer has been increased. The second peak value of the soot radiation intensity occurs when the...
oxygen index exceeds 40\%, and the position of the second peak is closer to the burner exit than the position of the first peak. With more oxygen being added in the oxidizer, compared to the rate of increase of the first peak value, the second peak value shows a more rapid increase. The difference in the increasing rate between the two peak values may have resulted from different rates of rising temperature and the formation rate of the soot in the blue reaction zone and yellow luminous reforming zone. Apparently, as described in previous discussions, the reaction zone where the second peak value occurs, experienced a more rapid rise in temperature and a faster formation rate for the soot when compared to the luminous reforming zone. Therefore, the second peak value surpasses the first peak value when the ratio of oxygen in the oxidizer is gradually increased.

The variation of the peak radiation intensity and oxygen mole fraction at different wavelengths is presented in Fig. 12. It can be seen that the peak radiation intensity always increases as the oxygen mole fraction increases, and the rate of increase in peak radiation intensity is much lower.
in the 3.6 ± 0.12-µm wavelength than the other two, which may be the result of different formation rates of soot and CO₂ as the oxygen fraction increases. A particular characteristic can only be found in the curve of the 4.26 ± 0.12-µm wavelength: when the oxygen mole fraction in the oxidizer exceeds 80%, the curve becomes more smooth, which demonstrates that the rate of increase in peak radiation intensity for the 4.26 ± 0.12-µm wavelength slows down compared to the test conditions when there is a lower ratio of oxygen.

As discussed in previous sections, increasing the amount of oxygen can accelerate the formation rate of CO₂ through the main reaction route, R99 (CO + OH ⇌ H + CO₂). However, the reverse reaction of R99 and reaction R153 (CH₃(s) + CO₂ ⇌ CO + H₂O) would both be enhanced when the concentration of CO₂ reaches a relatively high level, which results in a rise in CO₂ consumption and CO production, and eventually reduces the radiation intensity in the 4.26 ± 0.12-µm wavelength to some extent. Furthermore, no obvious decrease can be found in the rate of increase in the peak radiation intensity of the 3.6 ± 0.12-µm wavelength. In other words, the increase in peak radiation intensity when the ratio of oxygen in the oxidizer is higher is almost a fixed rate for the 3.6 ± 0.12-µm wavelength. This proves that no soot oxidation reaction occurs on the fuel-rich side in IDFs when the ratio of oxygen is increased.

Moreover, the main contribution to the infrared radiation of IDFs in the range of 2-5 µm can be determined through comparing the radiation intensities of the 4.26 ± 0.12 µm and 3.6 ± 0.12 µm wavelengths. As shown in Fig. 12, the maximum intensity of 4.26 ± 0.12-µm wavelength radiation along the flame centerline is approximately 15–20 times that of the 3.6 ± 0.12-µm wavelength. Therefore, the vast majority of radiative energy comes from the 4.26 ± 0.12-µm
wavelength, and the radiative proportion of the 4.26 ± 0.12-µm wavelength in the range of 2–5 µm rises continuously as the ratio of oxygen increases.

4. Summary and Conclusion

Quantitative images of infrared radiation intensity in the range of 2–5 µm obtained through the laminar oxygen enrichment of methane inverse diffusion flames were presented, interpreted and analyzed in this investigation. The main conclusions are as follows:

1. The time-averaged images demonstrate the qualitative and quantitative differences in radiation from CO2 (4.26 ± 0.12 µm) and soot (3.6 ± 0.12 µm). The infrared images show the maximum radiation intensities from CO2 and soot both appeared in the blue reaction zones near the burner exit.

2. The radiation intensities from CO2 are approximately 15–20 times stronger than those from soot at different levels of oxygen enrichment in IDFIs. The radiative properties of oxygen-enriched IDFIs are almost dominated by the radiation from CO2, and the radiative proportion of CO2 in the range of 2–5 µm rises continuously as the ratio of oxygen is increased.

3. The axial positions of maximum radiative intensity in the 4.26 ± 0.12-µm wavelength and in the range of 2–5 µm both shifted upstream to the burner exit as the oxygen index increased, which is consistent with past inverse diffusion flame structure measurements. However, the rate of increase for the maximum radiation emission from CO2 along the flame centerline decreased when the oxygen mole fraction in the oxidizer exceeded 80%. Furthermore, the second peak appeared in the curves of radiation from soot along the flame centerline when the oxygen mole fraction in the oxidizer exceeded 40%. The axial position of the second peak was closer to the burner exit than that of the first peak. Moreover, the values of the second peak presented a faster rate of growth than the first peak when the ratio of oxygen was increased.

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