OH-Planar Laser-Induced Fluorescence Measurements in Laminar Diffusion Flames of n-Heptane with Coflow Air Diluted by N₂ and CO₂

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ABSTRACT: The distribution of hydroxyl (OH) radicals in the laminar diffusion flame of n-heptane was studied by planar laser-induced fluorescence (PLIF). The influences of nitrogen (N₂) and carbon dioxide (CO₂) dilution on the formation and distribution of OH radicals were analyzed. The corresponding dilution ratios (volume fractions) of both N₂ and CO₂ vary from 0 to 5%. The results show that for the n-heptane flame, the OH radical is mainly concentrated in the two wings of the flame, presenting a radially approximate symmetrical distribution. Both N₂ and CO₂ dilutions decrease the intensity of the maximum OH radical fluorescence and the total OH radical fluorescence. Moreover, the flame temperature decreases more significantly with the CO₂ dilution ratio due to the combination of the dilution effect and thermal effect.

1. INTRODUCTION

In the process of fuel combustion, there will be severe exhaust emissions, such as soot, nitrogen oxide (NOₓ), and polycyclic aromatic hydrocarbons. With more concerns about climate change and air pollution, exploring clean and efficient combustion technologies has become one of the most urgent goals of the combustion research in recent years. Planar laser-induced fluorescence (PLIF) technique has the advantages of obtaining non-contact measurements and high sensitivity, high spatial resolution, and high temporal resolution in combustion measurements, and PLIF for the OH radical (OH-PLIF) is widely used in the combustion research. As a fundamental radical in the flame, the OH radical is an intermediate component produced in most combustion processes, and the distribution of OH radicals can characterize the spatial distribution of the flame front and the concentration level of the OH radical can represent the combustion intensity.

Previous studies have ranged from focusing on the OH-PLIF measurement of gaseous fuels to obtaining related information of the flame propagation velocity and flame structure. Law et al. studied the effect of flame stretch on Bunsen flame and the laminar combustion velocity based on OH-PLIF. The results showed that the flame stretching interfered with the combustion intensity and affected the distribution of OH radicals in the reaction zone, and the flame propagation velocity was significantly affected by the stretching effect. Daniele et al. revealed the structure and the flame propagation velocity of the turbulent flame of a synthetic gas under high-temperature and high-pressure conditions. Moreover, Lee et al. examined the combustion instability of the H₂/CO/CH₄ premixed flame using the 12.5 kHz high-speed OH-PLIF technology and calculated the flame length using the obtained PLIF images. They indicated that the shorter mixing time and the larger flame length were the root causes of the syngas flame instability. The distribution of OH radical fluorescence signals in syngas/air Bunsen flame with different H₂ contents, different equivalent ratios, and different Reynolds numbers was studied by OH-PLIF. Additionally, Strakey investigated the effect of the H₂ content on the flame structure of lean premixed methane under different pressure conditions using the OH-PLIF technology. The experimental results demonstrated that the increase of pressure made the thickness of the OH radical region become thinner, while the increase of the H₂ content significantly enhanced the OH radical formation in the flame. Furthermore, Sadanandan investigated the effect of pressure on the characteristics of the flame by employing OH-PLIF. The research showed that the syngas flame exhibited the structure of double flame front under all experimental conditions, one of which was located in the shear layer and the other was located between the fuel inlet and the oxidant nozzle.

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On the other hand, dilute oxy-fuel combustion is one of the most valuable technologies for reducing CO₂ and NOₓ emissions during the combustion process.¹²⁻¹⁴ The effects of a diluent on the flame combustion characteristics were also studied based on OH-PLIF. Yang et al.¹⁵ explored the effects of N₂, CO₂, and H₂O dilution on the two-dimensional temperature and concentration fields of OH in the methane premixed flame by utilizing PLIF thermometry and bidirectional PLIF. They demonstrated that the temperature field of the methane Bunsen flame with different diluents presented an uneven and symmetrical structure. In comparison with the N₂ and H₂O diluents, CO₂ dilution has a better effect in reducing the flame temperature. Ge et al.¹⁶ measured the flame characteristics of the H₂/CO/CO₂ non-premixed flame using OH-PLIF and discussed the flame structure changes with N₂ dilution. It was found that the structure of the double flame front appears at the root of the non-premixed syngas flame, and the change in the CO/H₂ ratio enabled the position of the flame root to move and compress the thickness of the reaction zone. However, when N₂ was diluted in syngas flame, the whole flame structure changed, and the two-fire front structure merged into a single-front structure. Moreover, Han et al.¹⁷ studied the turbulent premixed flame (methane/air) mixed with CO₂ using high-speed PLIF. The results presented that the flame length was extended by CO₂ addition with an enhancement of unburned pocket formation in the downstream portion of the flame. The apparent size and the consumption speed of the fine-scale unburned reactant pockets were similar among flames with varying CO₂ additions. The global consumption speed of flames with CO₂ addition was reduced predominantly by a reduction in the laminar flame speed. Also, some experiments were conducted to evaluate the inhibition efficiency of CO₂ on methane/air coflow diffusion flames.¹⁶ The addition of CO₂ diluted the reactive mixture and resulted in a flame temperature drop, and the peak OH concentration decreased with the CO₂ addition.

Since the cetane number of n-heptane is close to that of conventional diesel, n-heptane is frequently used for flame measurement as a surrogate of diesel. Compared with lighter gas fuels such as methane and hydrogen, vaporized n-heptane exhibits different combustion characteristics. n-Heptane exhibits a lower laminar combustion rate compared to hydrogen at the same stretch rate.¹⁹ Daca et al.²⁰ reported that the maximum soot volume fraction values of n-heptane are larger than those of methane at the same pressure. In addition, Liu et al.²¹ showed that the addition of n-heptane can effectively reduce the volume fraction of soot produced by the combustion of butanol isomers in laminar diffusion flames.

In addition, it should be noted that since the PLIF concentration measurement requires calibration of parameters, such as angle, detector response, collision quenching, and energy transfer,²²,²³ this will affect the measurement accuracy.²⁴ Therefore, it is difficult to directly correlate the OH-PLIF signal intensity to the OH radical concentration with high precision.

### Table 1. Experimental Settings

| f₇-heptane (g/h) | fN₂-carrier (L/min) | fN₂-dilution (L/min) | fL₂-air (L/min) | φN₂ - dilution (%) | φCO₂ - dilution (%) |
|-----------------|---------------------|----------------------|-----------------|-------------------|-------------------|
| 4.0             | 0.1                 | 0                    | 10.0            | 0                 | 0                 |
| 0.1             | 9.9                 | 1                    | 1               | 1                 | 1                 |
| 0.2             | 9.8                 | 2                    | 2               | 2                 | 2                 |
| 0.3             | 9.7                 | 3                    | 3               | 3                 | 3                 |
| 0.4             | 9.6                 | 4                    | 4               | 4                 | 4                 |
| 0.5             | 9.5                 | 5                    | 5               | 5                 | 5                 |
| 4.5             | 0.1                 | 0                    | 10.0            | 0                 | 0                 |
| 0.1             | 9.9                 | 1                    | 1               | 1                 | 1                 |
| 0.2             | 9.8                 | 2                    | 2               | 2                 | 2                 |
| 0.3             | 9.7                 | 3                    | 3               | 3                 | 3                 |
| 0.4             | 9.6                 | 4                    | 4               | 4                 | 4                 |
| 0.5             | 9.5                 | 5                    | 5               | 5                 | 5                 |
| 5.0             | 0.1                 | 0                    | 10.0            | 0                 | 0                 |
| 0.1             | 9.9                 | 1                    | 1               | 1                 | 1                 |
| 0.2             | 9.8                 | 2                    | 2               | 2                 | 2                 |
| 0.3             | 9.7                 | 3                    | 3               | 3                 | 3                 |
| 0.4             | 9.6                 | 4                    | 4               | 4                 | 4                 |
| 0.5             | 9.5                 | 5                    | 5               | 5                 | 5                 |

Figure 1. Burner and liquid fuel vaporization system.
In summary, a certain number of research studies have been carried out on the flame characteristics by OH-PLIF; however, the focus of these studies was mainly on the gaseous fuels. Consequently, in this study, the OH radical formation in coflow laminar diffusion flames of n-heptane was investigated using a pressurized liquid fuel vaporization system and by employing the OH-PLIF technique. Then, the effects of N₂ and CO₂ diluents on the formation and distribution of n-heptane laminar diffusion flame OH radicals were investigated.

2. MATERIALS AND METHODS

2.1. Fuel and Flame Setup. In this study, a coflow burner was applied to produce a laminar diffusion flame of n-heptane. Air was chosen as the coflow gas in the combustion process. As mentioned above, the dilution of coflow air has an impact on the combustion characteristics of laminar flame. The OH radical formation with the coflow air diluted by N₂ and CO₂ was further studied in the current study. Table 1 shows the experimental...
settings for dilution of N₂ and CO₂ including the fuel mass flow rates, the carrier gas volume flow rates, the co-flow air volume flow rates, and the volume flow rates of the fluid from the nozzle.

2.2. High-Pressure Burner and Fueling System. The experiments were performed using a high-pressure combustion system, mainly consisting of a high-pressure chamber, a fuel evaporator, and a coflow burner and a dilution system.
composed of N₂ and CO₂ was added to study the effect of dilution on OH radicals, as shown in Figure 1.

It is noted that all fuel pipes are wound with resistance wires and heated to 160 °C and wrapped with insulation asbestos to ensure that the temperature of the heating pipe is higher than the boiling point of n-heptane (98.5 °C). The layout of the liquid fuel vaporization system is shown in Figure 1, where the liquid fuel in the fuel accumulator is pressurized with N₂. The pressurized liquid flow is measured using a liquid mass flow controller, and the amount of liquid entering the burner is adjusted by controlled evaporation and using a controlled evaporator mixer (Bronkhorst, High-Tech CEM System, W-102A). The flow rate of the carries gas N₂ is controlled using a mass flow controller (MFC, Seven Star, D07-7). All carrier gas and air fuel pipes are stainless steel pipes with a diameter of 6.35 mm. Further details regarding the burner setup can be found in our previous study. In this study, CO₂ or N₂ diluent is mixed with coflow air in a certain proportion, and the dilution rate refers to the molar fraction of the diluent. Each gas pipeline is equipped with an MFC (Seven Star, D07-7) to control the gas flow rate. The diluent and air are evenly mixed in the buffer as an oxidant and made to enter the burner for combustion. The pressure at which all experiments are carried out is atmospheric conditions.

2.3. OH-PLIF Diagnostic System and Data Process. The PLIF measurement system mainly includes an Nd:YAG laser (Quanta-Ray), a dye laser (Sirah Lasertechnik GmbH), a frequency multiplier (generates laser with a specific frequency to the excitation medium), an ICCD camera, and a computer control system as shown in Figure 2.

A tunable dye laser is pumped at 532 nm using an Nd:YAG laser, delivering pulses at a repetition rate of 10 Hz. The laser beam of the dye laser is then doubled in frequency using a frequency doubling crystal. For fluorescence measurements, the laser wavelength is tuned according to the Q₁(8) line of the A²Σ−X²Π(1,0) band of OH at 283.533 nm. A laser power of 435 mJ was used as the light source of PLIF in order to work on the linear regime of fluorescence of OH, and the beam energy per pulse was reduced to 20 mJ after the laser beam passed through the dye laser.

The laser beam can be converted to a laser sheet with a height of 48 mm and a thickness of 1 mm by a sheet-forming optical device and then passed through the flame centerline. Since scattering from soot particles and fluorescence from aromatic molecules might have been collected as well, the laser sheet passing through the flame was collected by the beam dump and a OH bandpass filter (Δλ = 20 nm) was centered at 308 nm (see Figure 3) to isolate the OH emission.

An intensified CCD camera with a spatial resolution of 1024 × 1024 (ICCD, Princeton, PI-MAX4) was mounted in a direction perpendicular to the laser sheet to capture the OH-PLIF signals with a gain of 55%, a gate time of 400 ns, and a delay of 385 ns.

The OH radical fluorescence signal images recorded by the ICCD camera can be transmitted to the computer for data processing. The OH radical fluorescence signal undergoes a process of continuous simultaneous excitation and quenching, so three shots were taken for each condition (50 photos were collected in each shot and stored in one dimension to minimize the impact of flame instability). Figure 4a shows the OH-PLIF image recorded in a single time. The average signal image (i.e., Figure 4b) can be obtained by averaging each group of 50 pieces of data. However, the ICCD camera also collects some information on the surrounding interference signals, such as the radiation signal of the flame itself and the radiation signal of the incandescent lamp. As shown in eq 1, the image after average processing needs to be subtracted from the background signal, which gives the OH-PLIF signal images required from the experiment.
where $A_i$ is the OH fluorescence signal of a single image, $A_{\text{background}}$ is the background signal, and $A_{\text{PLIF}}$ is the final OH-PLIF image signal required from the experiment.

After the signal image was obtained, the fluorescence intensity of each pixel in the image can be obtained. This study mainly calculated the signal intensity of the maximum OH radical fluorescence intensity and the total OH radical intensity under each working condition to explore the formation and distribution of OH radicals in laminar flame. Here, $I_{\text{max}}$ represents the maximum OH radical fluorescence signal intensity, and $I_{\text{total}}$ represents the total OH radical intensity, which is expressed as eq 2.

$$I_{\text{total}} = \sum_{i=1}^{n} I_i$$

where $n$ is the number of pixels whose intensity is higher than 5% of the maximum OH radical fluorescence signal, and $I_i$ is the intensity of a single pixel’s OH radical fluorescence signal.

For the convenience of description, the fluorescence region signal is divided into an inner region and an outer region as shown in Figure S. The outer region is defined as the area within the boundary being 5% of the maximum PLIF intensity, while the inner region is the area surrounded by the outer region and the nozzle. In addition, the OH signal area is also defined, which is the area enclosed by the inner and outer regions along the boundary. The flame height is defined as the distance from the burner to the position on the centerline without diluent addition.

### 3. RESULTS AND DISCUSSION

#### 3.1. Effect of N$_2$ Dilution on the OH Radical Formation

Figure 6 shows the OH-PLIF signals generated by the n-heptane flame when the N$_2$ dilution ratio is 0−5 vol %. It can be observed that with the increase of the N$_2$ dilution ratio, the height of the outer region changes slightly with the maximum variance of 0.26 mm for the three experimental sets of n-heptane flow rates. Nevertheless, the height of the inner region gradually increases with the dilution ratio, and the maximum increase was 3 mm at n-heptane flow rates of 4.5 g/h (see Figure 6g−l). The fluorescence intensity gradually decreases with the dilution ratio. When the n-heptane flow rates are 4.5 and 5.0 g/h, the increase of the dilution ratio increases the lifting distance between the flame and the nozzle, and the breach appears at the tip of the flame in the inner region as the dilution ratio increases to 5%.

According to the Burke−Schumann theory, the reaction sheet exists under the condition of $Z = Z_c$. Here, $Z$ and $Z_c$ are the stoichiometric mixture fraction and the real mixture fraction, respectively, and the real mixture fraction is expressed as eq 3.

$$Z = 1 - e^{-m/D\rho r}$$

where $m$ is the mass flow rate of fuel; $\rho$ is gas density; $D$ is mass diffusivity; and $r$ is the radial co-ordinate.

The stoichiometric mixture fraction is expressed as eq 4.

$$Z_c = \left(1 + \nu_{\infty}/\nu_{g0}\right)^{-1}$$
where $Y_F$ is the mass fraction of fuel in the fuel stream; $Y_O$ is the oxygen mass fraction in the oxidizer stream, and $v$ is the mass of oxygen consumed per unit mass of fuel. According to eqs 3 and 4, the calculated stoichiometric mixture fraction and real mixture fraction are listed in Table 2.

From Table 2, it is observed that the stoichiometric mixture fraction gradually decreases while the real mixture fraction gradually increases with the $n$-heptane mass flow rate. For a certain case, the stoichiometric mixture fraction is smaller than the real mixture fraction, which indicates that rich combustion becomes dominated with the fuel flow rate. As a result, the appearance of the breach of the flames might be owing to the fact that shortage of oxygen is strengthened with the dilution.

Figure 7 plots the curve of the maximum OH radical fluorescence intensity variation with $N_2$ dilution. With the increase of the $N_2$ dilution ratio, the maximum OH radical signal intensity decreases. The concave or convex fitting curves of $n$-heptane with different flow rates shown in Figure 7 might be caused by measurement uncertainties. Although $N_2$ does not directly participate in combustion, the oxygen content carried by the air will decrease accordingly, reducing the concentration of reagents per unit volume and thus reducing the chemical reaction rate. Moreover, the addition of the $N_2$ diluent could change the specific heat mixture, flame temperature, diffusion efficiency, and thermal conductivity. In particular, the flame temperature becomes lower and the combustion intensity declines, which leads to less OH radical formation. As shown in Figure 8, the total OH radical intensity along with the increase of the $N_2$ diluent also presents a downward trend.

Figure 9 shows the OH signal area enclosed by the inner and outer regions along the boundary at different $N_2$ dilution ratios. The OH signal area changes slightly with the dilution ratio, which indicates that the $N_2$ dilution ratio has a limited effect on the flame shape. In addition, the average OH signal shows a downward trend as the nitrogen dilution ratio increases, which is mainly attributed to the decrease in the total fluorescence intensity (Figure 8), which the OH signal areas almost keep constant as shown in Figure 9.

Figure 10 shows the images of the OH radical fluorescence signal of the $n$-heptane flame at different $CO_2$ dilution ratios. The height of the internal region and the outer region gradually rises, and the fluorescence intensity gradually decreases with the dilution ratio increase. When the $CO_2$ dilution ratio is above the critical value of 3%, the distance between the flame and the baseline (at the tip of the nozzle) increases as the dilution ratio increases. This is attributed to the dilution effect which has the most significant impact on the liftoff of a diffusion flame followed by the thermal effect. Moreover, it is found that when the dilution ratio is 10%, the flame rises higher and swings severely from side to side, which eventually makes the flame to go off. With the increase of the $CO_2$ dilution.
ratio, the mass fraction of the oxidant decreases, which increases the liftoff height of the \textit{n}-heptane flame by approximately 8 mm. The results observed in this experiment are consistent with those observed by Oldenhof et al.\textsuperscript{31,32} In the study of CO\textsubscript{2} dilution, the flame becomes more stable than in the addition of N\textsubscript{2} because of the coupled effects of hydrodynamic and thermal-diffusive instabilities on the flame.\textsuperscript{30,33,34} In addition, compared with nitrogen dilution, the specific heat capacity of CO\textsubscript{2} is about 1.6 times that of N\textsubscript{2} at a representative flame temperature, so the OH fluorescence intensity caused by the N\textsubscript{2} thermal effect is more significant.

Figures 11 and 12 show the influence of CO\textsubscript{2} dilution on the maximum OH radical fluorescence signal intensity and the total OH radical intensity of \textit{n}-heptane flame, respectively. With the...
increase of CO₂ dilution, the maximum OH radical fluorescence signal intensity and the total value show a downward trend. The fitting curve of n-heptane for different flow rates shown in Figure 12 shows a concave downward trend with the CO₂ dilution ratio, while the fitting curve for the N₂ diluent shown in Figure 8 is convex. Figure 13 shows that as the CO₂ dilution rate increases, the OH signal area decreases slightly, while the average OH signal decreases. Similar to the effect of the N₂ diluent, first, the addition of the CO₂ diluent reduces the concentration of reactants per unit volume and reduces the rates of chemical reactions. Second, CO₂ has a high specific heat value, which will absorb the heat released by n-heptane combustion and reduce the temperature and thus reduce the volumetric combustion intensity. As a result, the OH fluorescence intensity decreases because for a given n-heptane flow rate and outer flow composition, the lowered temperature flame can reach a local equilibrium state, which makes the lower temperature to lead to a lower OH fluorescence intensity. In addition, CO₂ directly participates in the chemical reaction process \( \text{OH} + \text{CO} = \text{H} + \text{CO}_2 \) and inhibits the n-heptane combustion process by competing for the H radical between the reactions \( \text{H} + \text{CO}_2 = \text{OH} + \text{CO} \) and \( \text{H} + \text{O}_2 = \text{O} + \text{OH} \), which reduces the concentration of the H radical.33 This effect is more pronounced at a higher dilution ratio of CO₂ (5%). In addition, the addition of CO₂ generates a large number of OH radicals, and excessive OH radicals cause more oxidation and hence inhibit the formation of the soot precursor, thus in turn affecting the formation and distribution of OH radicals.35 Moreover, the quenching rate coefficients of N₂ and CO₂ are different in the n-heptane flame. Marinelli et al.36 believed that the fluorescence quenching rate coefficient of CO₂ is larger than that of N₂. However, considering the impact of CO₂ itself on OH radicals, the quantitative evaluation of the effect of quenching efficiency on the fluorescence emission of excited OH still needs further study.

### 3.3. Comparison of the Effects of N₂ and CO₂ Dilution on the Formation of the OH Radical

Figure 14 shows the effect of N₂ and CO₂ dilution on OH radical formation. It can be seen that the total fluorescence intensity of the flame with N₂ dilution is lower than that with CO₂ from the general trend. Meanwhile, according to the error bar (standard deviation), the flame stability is lower when CO₂ participated.

Figures 15 and 16 show the radial and axial OH signal profiles for N₂ and CO₂ diluents under different n-heptane mass flow rates, respectively. The profile of the radial fluorescence intensity shown in Figure 15 is obtained at a flame height of 16 mm, which typically represents the variation of the OH signal with the dilution of different diluents. It is also seen that in Figure 15, under the same n-heptane flow rate, the OH signal intensity diluted by CO₂ is lower than that by N₂, which is caused by the CO₂ lift-off effect.

For the convenience of description and representativeness, the flame centerline was chosen to observe the change in the OH signal with the radial distance. Figure 16 shows that the axial distance at the peak position corresponding to the OH signal intensity with the CO₂ diluent does not coincide, while that of the N₂ signal intensity profile is relatively concentrated within a certain distance, which is mainly because the lift-off effect of CO₂ becomes more significant with the dilution ratio. By comparing Figures 6 and 10, for the diluent at the same ratio, the flame lift-off height caused by CO₂ is about 6.32 mm higher than that by N₂. When the n-heptane flow rate is 4.5 g/h and the dilution ratio is 5%, the corresponding lift-off height of N₂ and CO₂ is about 2 and 8 mm, respectively. This indicates that the flame stability of n-heptane with the CO₂ diluent is better than that with N₂. Actually, CO₂ will participate in the chemical reaction \( \text{CO}_2 + \text{H} \leftrightarrow \text{CO} + \text{OH} \). The addition of the CO₂ diluent decreases the content of OH, O, and H radical formation by reducing the chemical reaction rate in the fuel combustion process.29,37 As a result, the total fluorescence intensity decreases as the CO₂ dilution ratio increases. Moreover, the specific heat capacity of CO₂ is higher than that of N₂, so the absorption of combustion heat by CO₂ is larger than that of N₂. On the other hand, CO₂ is a third-body molecule, and CO₂ dilution will increase the tri-body reaction rate for n-heptane. Davis et al.38 pointed out in their study that the tri-body effect of CO₂ is 2.4 times higher than that of N₂. Therefore, in the process of the chemical reaction \( \text{CO}_2 + \text{H} \leftrightarrow \text{CO} + \text{OH} \), the competition for the H radical increases, which might decrease the chemical reaction rate and lower the flame stability. In addition, the molar masses of N₂ and CO₂ are 28 and 44 g/mol, respectively, so for the same dilution ratio, the flame lift-off for the CO₂ dilution appearing in advance can be attributed to its higher momentum.

### 4. CONCLUSIONS

This study investigated the OH radical formation in the flames of n-heptane by OH-PLIF, and the effects of N₂ and CO₂ dilution on the formation of OH radicals were analyzed. The major conclusions are as follows:

1. Both N₂ and CO₂ dilutions can reduce the maximum OH radical fluorescence signal intensity and the total OH radical fluorescence signal intensity of the n-heptane flame. Moreover, N₂ dilution has a more significant impact on the formation of the OH radical;

2. When the dilution ratio increases to a certain value, the flame fluorescence region will be lifted. The stoichiometric mixture fraction gradually decreases, while the real mixture fraction gradually increases with the n-heptane mass flow rate. For a certain case, the stoichiometric mixture fraction is smaller than the real mixture fraction.

3. Compared with N₂ dilution, CO₂ is more significant in reducing the flame temperature, and the flame lift-off height shows an increasing trend as the dilution ratio increases.

Further research on the concentration of OH radicals in n-heptane laminar diffusion flames at elevated pressures will be the focus of our future study.

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Notes
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NOMENCLATURE

- \( f_{\text{hept}} \): mass flow rate of n-heptane (g/h)
- \( f_{\text{N}_2}\text{-carrier} \): volume flow rate of carrier gas (L/min)
- \( f_{\text{Air}} \): volume flow rate of air (L/min)
- \( f_{\text{N}_2}\text{-dilution} \): volume flow rate of \( \text{N}_2 \) dilution (L/min)
- \( f_{\text{CO}_2}\text{-dilution} \): volume flow rate of \( \text{CO}_2 \) dilution (L/min)
- \( A_{\text{OHbackground}} \): OH radical fluorescence signal of the single image background image
- \( I_{\text{OH}} \): maximum OH radical fluorescence signal intensity (a.u)
- \( I_{\text{OHmix}} \): total OH radical fluorescence signal intensity (a.u)
- \( Z \): stoichiometric mixture fraction
- \( Y_{\text{FD}} \): mass fraction of fuel in the fuel stream
- \( Y_{\text{OD}} \): oxygen mass fraction in the oxidizer stream
- \( \rho \): gas density
- \( D \): mass diffusivity
- \( r \): radial co-ordinate

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