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Effects of H_2 enrichment on combustion characteristics in inverse swirl diffusion flames of H_2 -doped jet fuel using OH, CH_2O , fuel and temperature imaging

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ABSTRACT

Hydrogen (H₂) and jet fuel co-firing is regarded as a promising transition strategy of decarbonization in aviation industry. Considering the simplicity and safety during highly hydrogen enrichment conditions, the inverse swirl diffusion (ISD) combustion holds research value. Given the current lack of understanding for the flame properties of H2-enriched pre-evaporative jet fuel ISD co-combustion, in this work, the simultaneous planar laser-induced fluorescence (PLIF) of hydroxyl (OH), formaldehyde (CH₂O), and fuel, as well as the non-linear excitation regime two-line atomic fluorescence (NTLAF) thermography imaging, are used to study the effects of hydrogen enrichment on ISD flame intricate structure and temperature field. The results show the positive effects of H₂ enrichment. The ISD flames display a blue hue and the increase in doping hydrogen helps the flames stabilize under global-lean conditions with almost no CO emission and low CO₂ emission at the chamber exit. And the H₂ enrichment contributes to inhibiting the CH₂O formation upstream, reducing the generation of isolated reaction islands and promoting the strength of the flame wings, favoring the suppression of flame instability. In contrast, when at low H_2 enrichment rate, the shift of the heat release zone and high-temperature zone, and the enlargement of the cold zone, are found in flame upstream. The analysis of the probability distribution functions (PDF) of temperatures confirms the effective effects of hydrogen on inhibiting the local flame fluctuations. Although the increase in the overall temperature level due to the hydrogen addition would lead to a promotion in NO_x generation, the discussion on the structural analysis and flame propagation stability of ISD flames demonstrates the significance of H₂ enrichment for the achievement of leaner low-NO_x combustion of ultra-H₂enriched jet fuel in the future.

1. Introduction

In aviation industry, the way of mitigating CO₂ emissions through enhanced combustion efficiency of aero-engines or the use of novel fossil fuels may hit a bottleneck in the future. The imperative to curtail fossil fuel usage and escalate the adoption of zero-carbon fuels has emerged as a focal point of research, aiming to mitigate the greenhouse effectinduced escalation in global warming. Within this context, as a clean, zero-carbon energy source, hydrogen has garnered increasing attention in the co-combustion with jet fuel in aero-engines, which is served as a promising transition strategy of emission reduction in aviation industry. The simulation for a jet engine was carried out by Alabaş et al. [1] to study the effect of the hydrogen/kerosene blend on the combustion characteristics and pollutant emissions, suggesting the great reductions of CO and CO₂ emissions with higher H₂ addition while the promotions of flame temperature and NO_x at the same time. But low oxygen content would help to inhibit NO_x emissions as well. A numerical work of Ilbas et al. [2] also had similar conclusions. Frenillot et al. [3] and Burguburu et al. [4] performed some experimental studies on several hydrogenenriched kerosene swirling flames in large gas turbines with high power output, revealing the positive effects of hydrogen enrichment on promoting flame stability and inhibiting pollutant emissions. In addition, the promoting effects of H₂ addition on basic combustion characteristics such as the laminar flame speeds, flame reactivity and decarbon kinetic mechanisms for the co-combustion of hydrogen and jet fuel were also reported in many basic scientific studies [5–9].

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However, considering the addition of ultra-rich hydrogen into practical aviation combustion systems, traditional premixed combustion presents serious safety concerns. The high reactivity of hydrogen poses grave challenges in avoiding flame holding and flashback [7], thereby escalating the safety issues of premixed equipment structure. This is also one of the reasons why current experimental literature of hydrogendoped kerosene turbulent flames rarely involve a higher hydrogen enrichment rate (above 30 % by total heating value). Thus, partiallypremixed and diffusive combustion styles hold great importance, such as micro-mixed combustion [10] or colorless distributed diffusive combustion [1] used for hydrocarbons and hydrogen co-firing. However, considering the simplicity, affordability, and safety, inverse swirl diffusion (ISD) combustion [11-13] undoubtedly has substantial benefits during highly-hydrogen-enrichment conditions. Firstly, the annular fuel outlet and air outlet of the ISD burner are entirely separated, effectively resolving internal safety issues of the burner when in richhydrogen-doping conditions. Secondly, the component structure of an ISD burner is relatively uncomplicated and compact, favoring easy implementation of jet fuel pre-evaporation and inherent costeffectiveness. At the same time, by relying on the adjustable and potent central air swirl, the high flame height and incomplete combustion drawbacks of diffusion flame can be suppressed. Therefore, the preevaporative ISD combustion of highly-hydrogen-enriched jet fuel is of practical significance.

Research related to inverse swirl diffusion (ISD) combustion has been discussed extensively in the literature [11-18]. Detailed structural research was conducted by Elbaz and Roberts [11,12], where they elucidated the intricate interactions between flame and flow inherent in ISD flames by employing high-velocity OH-PLIF/PIV. They found that the inception of the inner shear layer (ISL), triggered by the internal recirculation zone (IRZ) and inflow jet in IDS flames, could enhance fuel-air intermixing. Furthermore, the recirculation of heated exhaust gas played a crucial role in stabilizing the flame root. In past studies, the heat release zone, one of the most active combustion regions, important for studying the flame stability and flame front distribution, is usually analyzed using OH* chemiluminescence imaging or single shot OH-PLIF [11]. However, the results of these methods are rough estimates of the heat release zone. More accurate methods, such as simultaneous OH \times CH₂O [19,20], demand further attention. In addition, temperature imaging is important in explaining flame fluctuations and pollutant generation in turbulent combustion fields. Unfortunately, analyses of IDS flame temperature distributions still rely on single-point temperatures measured by thermocouples [13,16,21].

Although reports on the ISD combustion of hydrogen-enriched jet fuel are currently scarce, some studies on hydrogen-enriched methane swirl flames may provide some insights. Many studies [22-26] have demonstrated that the addition of hydrogen prompts methane swirl flames to shift upstream towards the nozzle, leading to a more compact heat release rate distribution and shorter length due to a significant increase in laminar flame speed. Meanwhile, an excessively high hydrogen blending ratio would lead to the transition of flame topology and flow-flame interactions in methane flames [24,27,28]. These phenomena corroborate the substantial influence of hydrogen on the transition of heat release region and flame structure in swirl flames. Since the fuel-air arrangement of ISD combustion varies from the premixed or partially-premixed flames, and the physicochemical properties of preevaporative jet fuel also differ from simple methane, the impact of a high proportion of doping-hydrogen on the ISD flame structure and flame stability remains unknown. Additionally, in many methane turbulent flames [21,23], the addition of hydrogen leads to an increased flame temperature level, causing fluctuations in local flame temperature and displacement of high-temperature regions, which affects NO_x emissions in the hydrogen-enriched flames. As for ISD combustion, whether hydrogen enrichment influences the ISD temperature field requires further support from instantaneous data. Given the current lack of understanding of the ISD flame's intricate structure and the importance

of experimental methods for validating numerical simulations, experimental methods especially laser-based diagnostic, are necessary for the analyses of highly-hydrogen-enriched jet fuel ISD flames.

In this work, a typical ISD burner equipped with a fuel-mixing preevaporation system was built up, and a series of ISD flames of H_2 enriched jet fuel were generated for investigation. The simultaneous planar laser-induced fluorescence (PLIF) of hydroxyl (OH), formaldehyde (CH₂O), and fuel were used for capturing the instantaneous distributions of combustion products, and the non-linear excitation regime two-line atomic fluorescence (NTLAF) thermography imaging [29–33] was used for instantaneous temperature recording. In-depth analyses of the effects of hydrogen enrichment on the ISD flame structure and flame stability were presented in conjunction with a variety of laser-based experimental data. This work is to provide some in-depth discussions into ISD combustion of H₂-enriched jet fuel, hoping to promote the cocombustion applications of large-scale hydrogen-doped jet fuel.

2. Experimental setup

2.1. Burner configuration

Fig. 1 (a) presents the inverse swirl diffusion (ISD) burner used in this work, similar to the burner setup used in [11]. The steady central swirl in the burner was maintained by the interaction between the tangent flow and axial flow. The geometrical swirl number could be derived by the tangent and axial flow rate [34] which was set at 22.8 L/min and 20.7 L/min, respectively. To guarantee flame stability, the geometrical swirl number [34] based on the airflow was kept at 2.89, maintaining an adequate swirl intensity. The annular slot of the fuel exit was designed close to the swirl air outlet, ensuring that the hot mixed fuel was kept close to the swirl air. The surrogate of jet fuel used in this work was composed of n-decane 80 % and 1,2,4-trimethylbenzene 20 % by weight, previously reported by Honnet [35], with good resemblance in many combustion characteristics of aviation kerosene. The liquid fuel was supplied from a nitrogen-compressed container. A heater was set at 250 °C to evaporate the liquid jet fuel whose flowrate was controlled by a liquid mass flow controller (Coda, Alicat), and a proportion of hydrogen was used as a carrier gas to carry the fuel mixture into the burner, controlled by an Alicat gas flow controller. A portion of nitrogen was also included in the carrier gas to keep the total volumetric flow rate at the annular fuel exit the same for each condition. A mixing tank was used to ensure a uniform mixture of hydrogen and pre-evaporated jet fuel. The whole burner was covered by electric heating belts and insulation cotton to prevent the liquidation of jet fuel. The experimental conditions are listed in Table 1. To facilitate maintaining the steady flow field, the airflow rate (m_A) was kept constant while the mass flow rates of jet fuel (mL) and hydrogen (mH) were adjusted to match the conditions with different hydrogen enrichment rates ($\alpha_{\rm H}$). The Reynold number (Re) of airflow was kept at 6880 for turbulent combustion. The global equivalence ratios (Φ_g) for each H₂ enrichment rate were set at 1.1 and 0.8, defined as

$$\Phi_g = \frac{(m_A/(m_L + m_H))_{stoich}}{(m_A/(m_L + m_H))_{actual}}$$
(1)

where $(m_A/(m_L + m_H))_{stoich}$ is stoichiometric air-fuel ratio and $(m_A/(m_L + m_H))_{actual}$ is the actual air-fuel ratio.

The low heating values of hydrogen and Honnet jet fuel are 119.9 MJ/kg (LHV_{H_2}) and 43.59 MJ/kg ($LHV_{jet-fuel}$), respectively, and the H₂ enrichment rate (α_H) was derived by the ratio of the total heating-value of hydrogen to total heat input, defined as

$$\alpha_{H} = \frac{m_{H} \times LHV_{H_{2}}}{m_{H} \times LHV_{H_{2}} + m_{L} \times LHV_{jet-fuel}}$$
(2)

For each global equivalence ratio, the total energy input rates (P_{th}) were kept constant with different α_{H_2} as shown in Table 1. For the current



Fig. 1. (a) Inverse swirl diffusion (ISD) burner. (b) Experimental setup for ISD co-combustion of rich-doping H₂ and pre-evaporated jet fuel, together with the OH-CH₂O- PLIF optical measurement system.

 Table 1

 All recorded experiment conditions during optical diagnostics.

| Case | $\alpha_{\rm H}$ (%) | $\Phi_{\rm g}$ | m _L (g/ h) | m _H (g/ h) | m _A (L/ min) | Re | P _{th} (kW) |
|------|----------------------|----------------|--------------------------|--------------------------|----------------------------|------|----------------------|
| A1 | 30 | 1.1 | 176 | 27.5 | 43.5 | 6880 | 3.1 |
| A2 | | 0.8 | 128 | 20.0 | 43.5 | 6880 | 2.2 |
| B1 | 40 | 1.1 | 154 | 37.2 | 43.5 | 6880 | 3.1 |
| B2 | | 0.8 | 112 | 27.0 | 43.5 | 6880 | 2.2 |
| C1 | 50 | 1.1 | 130 | 47.5 | 43.5 | 6880 | 3.1 |
| C2 | | 0.8 | 94 | 34.5 | 43.5 | 6880 | 2.2 |

work, when α_H below 30 %, pollutant emissions increase significantly and the flame tends to blow off (seen in Section 3.1). Given the worst incomplete combustion and instability, the studied flames for investigating the H₂ doping effects are those with α_H over 30 %.

2.2. Optical laser diagnostics

2.2.1. Planar laser-induced fluorescence of hydroxyl, formaldehyde and fuel (OH-CH₂O-Fuel-PLIF)

The setup of the simultaneous OH-CH₂O-PLIF optical system is included in Fig. 1 (b). For OH-LIF measurement, a 10 Hz Nd:YAG laser (Powerlite DLS 8010, Continuum) was used to pump the Rhodamine 590 dye to generate 566 nm laser, and after frequency doubling, the needed 283 nm UV laser was generated. 284.41 nm was selected corresponding to the spectral location of the Q1(8) rotational transition of the $A^2\Sigma^+ \leftarrow$ $X^2\Pi$ (1,0) electronic band. For CH₂O-LIF measurement, given the CH₂O radicals with enough sensitivity to 355 nm UV laser [36,37], the 355 nm laser of third harmonic fundamental output from a Nd:YAG laser (Radiant 355LD, OPOTEK) was used to excite the formaldehyde fluorescence. The laser power was kept at 5 mJ/pulse for OH-PLIF and 300 mJ/pulse for CH₂O-PLIF, respectively. The two combined UV laser beams were passed through a concave lens (f = -100 mm) and a convex lens (f = +500 mm) to form a planar laser sheet with a height of 40 mm and thickness of about 200 µm. The OH and CH₂O fluorescence were recorded simultaneously by two ICCD cameras (PI-max 4 emICCD, Princeton Instrument). The OH camera was equipped with a 105 mm, f/4.5 UV-NIKKOR lens, a 310 nm narrow-band filter (FWHM of 10 nm, peak transmittance of \sim 60 %, Alluxa) and a 305 nm long-pass filter (305FG01-50, Andover), while the CH₂O camera was equipped with two 400 nm long-pass filters (FELH0400, Thorlabs) and a 500 nm short-pass filter (FESH0500, Thorlabs). The nominal resolution of the imaging system was 0.11 mm/pixel, and the gate widths of two ICCD cameras were both set as 50 ns. Raw PLIF images were firstly corrected from the distortion and spatial energy distribution of the laser sheet, and then

were filtered with a two-dimensional 3 \times 3 median filter after size calibration.

For capturing fuel-LIF, the trimethylbenzene in the formulated Honnet jet fuel could be used as a fuel tracer during PLIF experiments because the fluorescence of one-ring benzene component could be excited under UV lasers with a wide range of wavelengths below 300 nm [38]. Thus the trimethylbenzene-LIF was also recorded simultaneously during the OH-PLIF to exhibit the fuel distributions.

2.2.2. Two-line atomic fluorescence (NTLAF) thermography imaging

The optical measurement system for NTLAF thermography imaging is similar to our previous work [39]. Base on the arrangement shown in Fig. 1 (b), the LDS821 dye was excited to generate 820 nm laser, and the needed 410 nm Stokes laser was generated after frequency doubling. The 451 nm anti-Stokes laser was produced by tuning the OPO crystal module of the OPO tunable laser. The power of the Stokes laser and anti-Stokes laser were both kept at $\sim 2 \text{ mJ/pulse}$. The time interval between two laser beams was maintained at 100 ns. The indium-LIF signals were recorded by two ICCD cameras equipped with 105 mm, f/4.5 NIKKOR lenses. The signals were spectrally selected using two customized ultranarrow bandpass filters (Alluxa) with full widths at half maximum (FWHM) of 1.2 nm (Stokes) and 1.1 nm (anti-Stokes) because the ultranarrow bandpass filters were confirmed to be vital for inhibiting other interference from PAHs or laser scattering [32]. The ICCD gate widths were set as 50 ns. Over 200 images were taken by each ICCD camera for NTLAF temperature calculation. Additionally, to seed the needed temperature tracer into the flames, an ultrasonic atomizer was used to generate the aerosol of indium chloride which is carried by a small amount of nitrogen into the axial air of the ISD burner. The temperature calibration and the evaluation of NTLAF measurement accuracy were conducted in a planar laminar premixed methane flame, identical to our previous work [39].

3. Results and discussion

3.1. Exhaust gases emissions and flame observation

Firstly, in order to macroscopically demonstrate the combustion performance of the ISD burner, the exhaust gases emissions measured by a flue gas analyzer (Testo 350, Germany) and the flame photographs taken by a DSLR camera are shown in Fig. 2. The burner was equipped with a quartz tube during flue gas measurement, and the exhaust gases at the tube exit were sampled by the quartz probe of the Testo analyzer. In Fig. 2 (a), the CO emissions under $\alpha_{\rm H} = 0, 10$ %, 20 % are significantly high, and the flames can't be stabilized even under fuel-rich conditions ($\Phi_{\rm g} > 1.2$), lifting off seriously, as shown in the pictures of the flames



Fig. 2. Exhaust gases emissions at the exit of the burner quartz tube, recorded by a flue gas analyzer (Testo 350, Germany) and flame photographs taken by a DSLR camera. (a) The CO concentrations under different Φ_g with different H₂ doping rates, together with the flame pictures. When α_H below 30 %, the flame tends to blow off and can't be stabilized even under fuel-rich conditions. (b) (c) The CO₂ and NO_x emissions with different H₂ doping rates.

under conditions of nearly blow-off. Thus, the main flames currently used for structural analysis are those flames with $\alpha_{\rm H}$ over 30 %, whose CO emissions are extremely low at the quartz tube exit under global-lean conditions for inhibiting pollutants emissions. For the $\alpha_{\rm H} > 30$ % conditions, the CO emission data demonstrate negligible variation with increments in α_{H} . Potential explanations for this encompass the slowdown of reduction in CO emissions with higher hydrogen-doping level, reported in other literature [1], and the inherently low theoretical CO emissions due to the extremely decrease in carbon source fuel content with the increase of zero-carbon hydrogen blending. Importantly, these flames can attach to the burner outlet plane under lean conditions, exhibiting special inverse diffusion flame structures. Even though the fuel blend includes jet fuel, which tends to produce soot, these diffusion flames consistently display a blue hue, with no yellow flame areas in sight, probably suggesting the effectiveness of inhibiting the incomplete combustion found in typical diffusion flames. However, more in-depth effects of hydrogen enrichment on ISD flame structure and stability require further analysis of laser-based diagnostic data.

In addition, as shown in Fig. 2 (b), with increasing H₂ enrichment rate, the CO₂ concentration at the exit of the quartz tube decreases significantly, indicating the considerable CO₂ inhibiting effects with the significant reduction of hydrocarbon fuel. For example, the CO₂ emission at $\alpha_{\rm H} = 20$ % is 16.3 vol% while 11.5 vol% at $\alpha_{\rm H} = 50$ % ($\Phi_{\rm g} = 1.1$), showing a well CO₂ emission reduction. However, as seen in Fig. 2 (c), under the same energy input rate, the introduction of hydrogen also increased the NO_x emission, which is consistent with many literature conclusions [1,17,22,23,40,41] that hydrogen leads to localized overheating of the flame temperature, resulting in increased thermal NO_x

emission. Unfortunately, the interpretation of flame temperature still relies on thermocouple measurements, making instantaneous imaging of turbulent flame temperatures particularly important, which will be discussed in Section 3.4. The comparisons of NO_x emission based on Emission Index expressed in mg/MJ between this work and Ref. [3] (H₂-enriched kerosene combustion in a gas turbine) are also included in Supplemental Materials. Although hydrogen promotes NO_x production, a practical approach is that global-lean combustion can significantly reduce NO_x emissions, whose achievement correspondingly depends on the promoting effects of urtal-rich-H₂ on flame stability. These results highlight the feasibility of the lean pre-evaporated co-combustion of urtal-rich-H₂ and jet fuel. Thus, the effects of H₂ on the ISD flame structure and temperature distribution deserves further investigations.

3.2. OH-CH₂O-Fuel images and flame structure

The images of OH, CH₂O, fuel fluorescence, and their combined images are shown in Fig. 3. Each individual picture contains an instantaneous image and a time-averaged image. The image color bar for each type of fluorescence is kept fixed for comparison purposes. As seen in fuel-LIF images in Fig. 3 (g)(h)(i), beyond 10 mm above the burner outlet plane, the fuel-LIF almost disappears, indicating that the fuel ejected from the annular fuel exit of the ISD burner can be rapidly carried away by the strong central swirl air flow, beneficial for rapid fuel dilution and the prevention of local fuel accumulation. Additionally, as H₂ enrichment rate increases, under the same thermal heat input rate (i. e. the same Φ_g), the CH₂O fluorescence intensity in the ISD flames decreases quite significantly. Such as the flames at $\alpha_H = 50$ % (Fig. 3 (o)),



Fig. 3. Images of (a) (b) (c) OH fluorescence, (d) (e) (f) CH₂O fluorescence, (g) (h) (i) fuel fluorescence, and combined OH + CH₂O + fuel of (j) (k) (l) $\Phi_g = 1.1$ and (m) (n) (o) $\Phi_g = 0.8$. Each individual figure contains an instantaneous image (left) and a time-averaged image (right). From top, $\alpha_H = 30$ %, 40 % and 50 %. The white dashed lines in (c) denote the rough schematic for the shearing layers of air swirl flow in ISD flames. The white dashed box in (b) denotes the flame's overall morphology. The white dashed circles in combined OH + CH₂O + fuel images denote some isolated regions in ISD flames.

the CH₂O fluorescence nearly disappears. In the current work, since the fuel mass flow rate is kept the same if at the same power input condition, an increase in hydrogen means a decrease in jet fuel instead. It can be inferred that when the proportion of hydrocarbon fuel in the fuel blend is significantly reduced, the generation of CH or CH₂O radicals upstream of the ISD flame is greatly suppressed, and CO or CO₂ is thus reduced at the initial stage of combustion. At the same time, the reduction of CH or CH₂O radicals is somewhat conducive to the suppression of prompt NO_x production [42,43]. These observations verify the positive role of hydrogen in reducing the production of some pollutants.

Additionally, the ISD flames present typical M-shaped patterns (e.g., white dashed box in Fig. 3 (b)) which are characteristic of a typical swirling flame with inner and outer recirculation zones [11]. The approximate positions of the shearing layers of swirl flow in such typical swirling flames are indicated by a rough schematic (region A) of Fig. 3 (c), where most of the fresh fuel blend entrained by the central swirl starts to ignite and release radicals like OH and CH_2O . To validate the description of the ISD flow field, numerical simulations using ANSYS FLUENT code were also carried out in this work. Since the flow field of swirl flow relying on the mixing and shearing of radial and tangential airflows [34] is quite simple, the use of FLUENT turbulence model

would help reproduce the such flow field. As shown in Fig. 4 (a), the mesh was built according to the bottom geometric features of the ISD burner used in the study. The RNG k-epsilon model was used as the turbulence model to simulate the flame flow field, and the eddy dissipation model was used as the species transport model to simulate the flame combustion. The built-in kerosene vapor and hydrogen of the software were used to simulate the actual mixed fuel as the fuel velocity inlet. As seen in Fig. 4 (b), the flow field of the ISD flame presents typical inner and outer recirculation zones (IRZ, ORZ), as well as inner and outer shear layers (ISL, OSL). The exit tangent velocity (Fig. 4 (c)) also exhibits sufficient strength. The central area of the swirl flame demonstrates characteristic features of an inner recirculation zone with a larger size of recirculation vortices (Fig. 4 (d)). The comparison of numerically and experimentally-measured time-averaged temperature distribution is also included in Supplemental Materials, to some extent, shows the effectiveness of the simulation. However, the simulation accuracy is constrained by the lack of a hydrogen-promoted kerosene reduced mechanism suitable for turbulent combustion simulation and the lack of an efficient swirl diffusion flame model, which is awaiting the development of subsequent simulation methods.

Importantly, as seen in the white dashed circles of the combined



Fig. 4. (a) The mesh used for the flow field simulation according to the bottom geometric features of the ISD burner used in the study. (b–d) The simulated flow field of ISD flame ($\alpha_{\rm H} = 50$ %, $\Phi_{\rm g} = 1.1$): (b) velocity vectors overlaid the contour plot of vertical velocity components, (c) the tangent velocity components, (d) streamlines plot.

images in Fig. 3, there are some discernible isolated kernels of OH or CH₂O (i.e. regions with only OH or CH₂O) in these ISD flames. During turbulent diffusion combustion, although most of the fuel blend at the annular exit has already burned upstream under the effects of the strong swirl flow, a small portion of the fuel is still "thrown away" to other locations, forming some isolated ignition kernels. These small isolated islands actually reflect the localized blow-off characteristics of ISD flames, contributing to the increase in flame instability. In order to count these localized blow-off regions, Fig. 5 presents the total number of isolated reaction islands found in successive 100 combined images of ISD flames under different H2 enrichment rates. Due to the lack of efficient statistical algorithms, these small isolated islands were counted manually on multiple consecutive OH-CH₂O images. Given the variety of shapes, the sizes of these isolated islands counted by the human eye can't be accurately categorized. As long as they conform to typical isolated kernel characteristics, they will be counted in the total. Some pictures of typical isolated islands under corresponding conditions are also shown on the top of Fig. 5. As illustrated by the statistics in Fig. 5, with increasing α_{H} , the generation of isolated reaction islands is inhibiting. For example, under the same Φ_g of 0.8, the number of isolated reaction islands is 282 per 100 images at $\alpha_H = 50$ % while 442 at $\alpha_H =$ 30 %. At the leaner conditions of $\Phi_g = 0.7$, the isolated island number is 338 per 100 images at $\alpha_H = 50$ % while 536 at $\alpha_H = 30$ %, a 37 % reduction. This indicates that the enhancement of hydrogen enrichment level can significantly suppress the formation of isolated islands, inhibiting the localized blow-off in ISD flames and contributing to the flame stabilization.

Furthermore, at the flame bottom, there are two thin flame wings found attached to the burner outlet plane, as shown in Fig. 6 (a). These flame wings are consistently present in OH-CH₂O-Fuel images under various operating conditions (as seen in the combined images in Fig. 3), exhibiting a distinct inward concavity that appears to be influenced by the central swirl airflow. This feature is crucial for flame root stabilization. As illustrated in Fig. 6 (b), there is a noteworthy contrast between the time-averaged OH-PLIF image of the flame with $\alpha_{\rm H} = 50$ % and 20 %. For the flame of $\alpha_{\rm H} = 20$ %, the flame outer layer is relatively faint. Correspondingly, the flames of $\alpha_{\rm H} = 20$ % exhibit a tendency to lift off, and a propensity to blow-off is observed when $\Phi_{\rm g}$ drops below 1.25.



Fig. 5. Total number of isolated reaction islands found in successive 100 combined images of ISD flames under different H_2 doping rates. Top: the typical isolated reaction islands shown in OH-CH₂O images.

Upon close inspection, it can be observed that these thin flame wing areas are near the fuel LIF zones, with virtually no CH2O signals detectable in the vicinity. A reasonable inference could be that the emergence of these flame wings may be attributed to the initial ignition of some reactive hydrogen inside the fuel blend at the burner exit. As shown in Fig. 6 (c) (d), as the H_2 enrichment rate increases, a contrasting trend appears at the position of the flame wing, where the peak of fuel-LIF (i.e. trimethylbenzene fluorescence) progressively diminishes, and, conversely, that of OH-LIF gradually escalates. In the current experiment, the generation of fuel-LIF relies upon the fluorescence from trimethylbenzene in the fuel blend under the excitation of UV laser. As the proportion of hydrogen increases, the content of jet fuel within the fuel blend diminishes, resulting in a reduced amount of trimethylbenzene and, consequently, a decrease in the intensity of fuel-LIF. In contrast, the rise in hydrogen content promotes the early ignition of hydrogen at the location of the flame wing, thereby amplifying the OH-LIF at this position. These observations confirm the positive role of hydrogen in flame root stabilization

3.3. Distributions of heat release zone

Existing literature [44] has substantiated that the HCO radicals present on localized flame fronts serves as the most accurate indicator for the heat release zone from the hydrocarbon combustion. Given that HCO [45] originates from the reaction between formaldehyde and hydroxyl radicals (CH₂O + OH \rightarrow HCO + H₂O), the simultaneous measurement of OH and CH_2O (OH \times CH₂O) is deemed a crucial method for visualizing the heat release zone [20,46-49]. To facilitate the understanding of the heat release in ISD flames, Fig. 7 displays instantaneous and time-averaged $OH \times CH_2O$ images under corresponding conditions. The intensity of $OH \times CH_2O$ is normalized and each instantaneous $OH \times$ CH₂O image corresponds to each instantaneous combined image in Fig. 3. It can be observed that the heat release zone of these ISD flames also exhibits a typical M-shaped structure, consistent with the description of Fig. 3. And the heat release is essentially completed within a height of 20 mm above the burner outlet plane, emphasizing that the main combustion area of ISD flames is comparatively short. Additionally, as seen in the instantaneous $OH \times CH_2O$ images, there are some conspicuous discontinuous reaction chunks along the heat-release zone, indicating the existence of certain disordered combustion reaction sites inside these ISD flames.

Due to the strong interaction along the burner central axis between the inner recirculation zone and the inflow jet, the heat release transition on the axis can well reflect the fluctuation of the flame. Significantly, as illustrated in Fig. 8, with the increase of doping hydrogen content, the axial position of the heat release zone shifts towards the upstream of the burner outlet, drawing nearer to the outlet plane. This implies that the high-temperature exhaust gases from the downstream flame can approach the fuel exit more closely, facilitating the early ignition of fresh fuel-air flow and enhancing the blow-off resistance. Such an upstream offset has also been reported by many studies of premixed swirl combustion of hydrogen-doped hydrocarbon fuels [22,40], highly related to the high diffusivity, high flame speed, and high reactivity of hydrogen. On the contrary, as also seen in the curves, the flame lift-off is inclined to occur in the ISD flames when there is insufficient hydrogen in the fuel blend. Taking the ISD flame with α_H of 20 % as an example, a reduction in doping hydrogen rate would lead to an axial heat release diverting from the burner outlet, coupled with the aforementioned disappearance of flame wing on the flame outer layer, jointly contributing to the pronounced blow-off propensity of the flames with low $\alpha_{\rm H}$.

3.4. Temperature field and flame stability

To further explain the ISD flame stability of hydrogen-enriched hydrocarbon fuel, Fig. 9 (a)–(f) presents the temperature distributions



Fig. 6. (a) An enlarged figure of flame wings found in the bottom of ISD flames, including the location of radial profile data (yellow dashed line). The grey blocks indicate the burner base, and the size of the annular fuel inlet and the central swirl air inlet. (b) A comparison of flame wing and flame outer layer between time-averaged OH-PLIF images of the flame with $\alpha_{\rm H} = 50$ % (left) and $\alpha_{\rm H} = 20$ % (right). (c) (d) Radial profiles of intensity of OH fluorescence and trimethylbenzene fluorescence at the position of flame wing. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)



OH×CH₂O (*Heat release intensity*)

Fig. 7. Corresponding distributions of $OH \times CH_2O$ intensity. Each individual figure includes an instantaneous image (left) and a time-averaged image (right). The letters in the figures represent the corresponding conditions labelled in Table 1.

measured through NTLAF thermography imaging under corresponding conditions. As for the current NTLAF method [29], the turbulent temperature field derivation depends on the fluorescence emitted from the indium atoms formed during the reduction of indium chloride on the flame front [29], demonstrating excellent temperature sensitivity. However, due to the significant uncertainty in the measurement of the local temperature below 600 K [31,33], during the current data

processing, temperatures below 800 K are designated as the hypothetical background temperature of 500 K.

A scrutiny of the temperature field images in Fig. 9 reveals a clear decline in the average temperature on the outer wing of the flame as H_2 enrichment rate decreases under the same total energy input. This corresponds to the prior discussions surrounding the attenuation of the flame wing, in which the weak flame wing due to the reduction of



Fig. 8. Axial profiles of mean normalized OH × CH₂O derived along the burner centerline with different hydrogen doping rates.



Fig. 9. (a)–(f) Temperature distributions measured through NTLAF thermography imaging under corresponding conditions. Each individual temperature image includes an instantaneous image (left) and a time-averaged image (right). (g)–(i) Time-averaged OH \times CH₂O images overlaid with isocontours of mean T = 1100 K.

doping hydrogen would result in a cold flame outer layer prone to inducing fluctuations. Additionally, instantaneous temperature images reveal that the reduction of doping hydrogen also leads to cold regions near the burner outlet center. A discernible change can be seen when comparing the central dashed circles in Fig. 9 (d) and (f). The relatively cold regions suggest the shift of the initial combustion area above the burner outlet plane.

More precise evidence can be derived from Fig. 9 (g)-(i). As the doping hydrogen reduces, the 1100 K temperature isocontours lift overall off the exit plane, which corresponds to the offset of the heat release zone observed in Fig. 8. This validates the crucial significance of hydrogen addition for the stability of flame propagation. As observed in Fig. 9 (g)-(i), the high-temperature zone of the ISD flame is generated from the heat release of preheated fresh fuel from the cold zone into the main combustion zone. The shift of the high-temperature zone away from the outlet plane, i.e. the enlargement of the cold zone near the burner outlet, verifies the lift-off of the heat release zone in ISD flames with low α_{H} , which is detrimental to the stability of the ISD flame. Such shift can be also found more visually in the axial profiles of mean temperature derived along the burner centerline and pathline shown in Fig. 10. Corresponding to the heat release completed in a short height above the burner, all ISD flames essentially reach their maximum temperatures within 25 mm above the burner exit plane, but flames with a higher $\alpha_{\rm H}$ can achieve high-temperature plateaus more promptly.

Furthermore, the temperature fluctuation and flame stability can be analyzed even further from the probability distribution functions (PDF) of temperatures. Fig. 11 shows the PDF of temperatures derived along the burner centerline (r = 0 mm) and pathline (r = 9 mm), counted from 150 successive instantaneous temperature images. Each temperature PDF is counted from 500 to 2600 K, with bins of 100 K. As shown in the temperature PDF of Fig. 11, as $\alpha_{\rm H}$ increases, the probability value of the assumed "500 K" defined in the NTLAF temperature calculation decreases (as shown on the left side of each PDF image), indicating that ultra-low local temperatures occur less frequently, producing more sufficient indium atoms and more effective calculated temperatures. At the same time, the statistical distributions of temperatures above 500 K reveal that the PDF peaks become steeper and higher as the H₂ enrichment rate increases, which further suggests that, overall, local temperatures are more concentrated and less variable with higher $\alpha_{\rm H}$. This implies that the temperature fluctuations in the flame will be smaller along some critical axial locations, indicating that the increase in doping hydrogen is beneficial to reducing the local flame fluctuations.

However, despite favoring flame stabilization, the increase in flame temperature resulting from the increase in hydrogen can also lead to an increase in NO_x emissions. For example, as shown in the ensemble-average temperatures in Fig. 10, the overall temperature level will be always higher with higher α_{H} , which will cause an increase in NO_x formation in the main combustion zone. This is consistent with the findings of most studies of hydrogen-enriched flames. Although the change in CH₂O fluorescence in Section 3.2 implies that some of the prompt NO_x may be suppressed, the increase in the overall temperature level ultimately leads to a promotion in NO_x generation. An effective de-NO_x approach is to perform global-leaner ISD combustion to reduce total thermal input and overall temperature level, however, the achievement



Fig. 10. Axial profiles of mean temperature derived along (a) (b) the burner centerline (r = 0 mm) and (c) (d) pathline (r = 9 mm) with different H₂ enrichment rates.



Fig. 11. Probability distribution functions (PDF) of temperatures derived along axial positions for ISD flames with different H_2 enrichment rates. Data taken from (a) (b) the burner centerline (r = 0 mm) and (c) (d) pathline (r = 9 mm), with bins of 100 K, from 150 images.

of leaner combustion of H₂-enriched jet fuel also relies on the stabilizing effect of doping hydrogen as previously described. Therefore, considering the simplicity, economy and safety of ISD burners, the discussion in this work on the structural analysis and flame propagation stability of ISD flames is important for co-combustion of ultra-rich hydrogen and conventional fossil fuel in the future.

4. Conclusions

In this study, to investigate the combustion characteristics of inverse swirl diffusion (ISD) flame for the co-combustion of rich doping hydrogen and jet fuel, OH-CH₂O-trimethylbenzene-PLIF and NTLAF thermography imaging are used for analyzing the effects of H_2 on flame stability and temperature fluctuation across a serious of ISD flames of pre-evaporated H_2 -enriched jet fuel. The conclusions are drawn as

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follows:

org/10.1016/j.fuel.2024.131704.

- (1) The ISD flames display a blue hue with no yellow flame areas in sight and the increase in doping hydrogen helps the ISD flames stabilize under global-lean conditions with almost no CO emission at the chamber exit. The CO_2 emissions are effectively inhibited by the addition of hydrogen, but the NO_x emissions are promoted instead.
- (2) By analyzing the OH-CH₂O-fuel images, the ISD flames present typical M-shaped patterns and well incomplete-combustion resistance. The rich H₂ contributes to inhibiting the CH₂O formation, which is beneficial for the reduction of CO or CO₂ at the initial stage of combustion.
- (3) The presence of isolated ignition kernels and flame wings are the special features found in current ISD flames of H₂-enriched jet fuel, related to the isolated reaction islands of scattered fuel and the initial ignition of some reactive hydrogen, respectively. Interestingly, the increased doping H₂ helps to reduce the generation of these isolated islands and promote the strength of the flame wings, favoring the suppression of flame instability and the stabilization of the flame outer layer.
- (4) Through the analysis of OH × CH₂O, the heat-release is essentially completed in a short height above the burner, but when at low H₂ enrichment rate, the heat release zone tends to lift off the burner exit plane, consistent with the shift of the high-temperature zone and the enlargement of the cold zone during NTLAF temperature analysis.
- (5) The analysis of the probability distribution functions (PDF) of temperatures confirms the effective effects of hydrogen on inhibiting the local flame fluctuations. Although the increase in the overall temperature level due to the hydrogen addition would lead to a promotion in NO_x generation, the discussion on the structural analysis and flame propagation stability of ISD flames is important for the achievement of leaner low- NO_x combustion of ultra-H₂-enriched jet fuel in the future.

CRediT authorship contribution statement

Shirong Xin: Writing – original draft, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. Fan Yang: Writing – review & editing. Xiaobo Wang: Writing – review & editing. Yong He: . Wubin Weng: Writing – review & editing. Zhihua Wang: Writing – review & editing, Validation, Investigation, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.

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