

Article

Fire Extinction Analysis and OH-PLIF Visualization of the Methane–Air Premixed Laminar Flame Interacting with the Downward Water Mist

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Abstract

In this study, a McKenna burner made for calibration is used to generate the laminar flame with the equivalence ratio of 0.78~2.0. The effect of the downward water mist spray on the extinction of the methane–air premixed laminar flame is investigated using hydroxide planar laser-induced fluorescence (OH-PLIF). The variation of the water flow rate for flame extinction is analyzed by the hydroxyl radical concentration distribution and the effective water mist flow rate. The required water flow rate for flame extinction is higher in the cases of rich fuel mixtures. The maximum critical extinguishing water flow rate for the methane–air premixed laminar flame is about 9.55 L/min under the conditions of water mist spray with a 45° solid cone spray angle and a 24 µm droplet size. Furthermore, the evolution of OH-PLIF flame behavior revealed that the stability of the hydroxyl radical concentration at the base of the flame mainly contributed to the flame extinction. This study provides a theoretical reference for the critical extinguishing conditions of water mist in the application of an active fire suppression system.

Keywords: water mist; flame extinction; premixed laminar flame; combustion diagnostics; OH-PLIF; McKenna burner



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1. Introduction

As a good alternative to halon extinguishing agents that have been phased out due to environmental friendliness issues, water mist has gained a wide range of development because of its advantages of clean and efficient fire extinguishing performance, environmental friendliness, and life safety [1–4]. The performance of water mist for fire protection has been evaluated in industrial buildings such as pool fires [5–8], tunnel fires [9,10], lithium-ion battery warehouse fires [11,12], gas explosions [13,14], etc. Gas turbines, as important combustion power generation equipment for the power industry, and their premixed combustion technology are constantly being developed for environmental friendliness [15]. Typically, the fire safety of the premixed combustion is a growing concern. The intervention of water in premixed combustion is an effective means of flame extinction [16,17].

Since the 1990s, researchers have focused on gaseous flame extinction by water mist. Many pioneering studies are conducted on flame extinction/quenching in pool fire burners [18], cup burners [19], co-flow cup burners [20], and counterflow burners [21], respectively. The previous works verify that the water mist has comparable fire extinguishing

efficiency with halon extinguishing agents under extinguishing gaseous flames. On the other hand, it provides a solid theoretical basis for subsequent research into fire protection. Experimental and computational studies on non-premixed flame extinction using water mist are investigated with counterflow burner flames [22], co-flow burner flames [23,24], pool fires [5–8,25], and jet flames [24,25].

In terms of premixed flame extinction or inhibition by water mist, the inhibition effect of water mist has been experimentally found to be better than N_2 , CF_4 , and it is especially comparable to halon extinguishing agents on a mass basis [26]. Thomas's computational investigation reveals that droplets with diameters of less than 50 μm play a key role in the flame extinction in the polydisperse water sprays [27]. At the same time, Chelliah et al. [28] discuss the effect of chemical additives (e.g., KOH, NaCl, and NaOH) on the extinction of laminar premixed flames. With the help of a Phase Doppler Particle Analyzer (PDPA), the behavior of large droplets accumulating in the flame region is observed under a single jet plate configuration [29], and the flame extinction is mainly dependent on the cooling and oxygen displacement via the CHEMKIN simulations [30]. Recently, Fan et al. obtained the velocities of gaseous flow and mist droplets simultaneously, and the results indicate that water mist droplets reduce the flame speed at high-flame strain rates [31]. Further, the thermal, chemical, and dynamical mechanisms acting on the laminar or turbulent premixed flame are investigated numerically [32,33].

To evaluate the flame extinction protection performance of water mist systems in premixed combustion system fire incidents, the premixed laminar flame extinction by downwardly applied polydisperse water mist spray is investigated experimentally. A McKenna burner and a calibration burner are used to generate the flat premixed laminar flame under the methane/air equivalent ratio of 0.78–2.0. The whole evolution of OH^* chemiluminescence intensity distribution is visualized during flame extinction or extinction. Critical fire extinguishing characteristics are analyzed by the effective water mist flow rate and corresponding hydroxyl radical concentration. This study aims to characterize methane–air premixed laminar flame extinction or extinction under the downwardly applied configuration of polydisperse water mist spray. Further, the results indicate that the flame extinction performance deteriorates when methane–air mixtures transition from lean fuel to rich fuel, which gives references to optimize the design of water mist systems for fire safety engineering in premixed combustion systems.

2. Experimental Setup

Figure 1a shows a schematic diagram of the experimental apparatus and laser optical system. A McKenna burner (or flat flame burner) consists of a bronze-made water-cooling coil, a porous plate (60 mm diameter), and an optional ring for shielding gas. The detailed structure of the flat flame burner can be referenced elsewhere [34]. The methane and airflow rates are controlled by separate mass flow controllers with $\pm 1\%$ accuracy (EL-FLOW Select F-201AV-50K, Bronkhorst, Netherlands) for each output. The burner chamber is premixed to produce methane-to-air premixed flames with different equivalence ratios. The temperature of the burner head can be maintained at 15 $^{\circ}C$ during the flame burning via a cooling chiller (Minichiller CC1, Huber, Germany).

In the OH-PLIF measurement system, an Nd:YAG laser (Quintel Q-smart 850, France), including a 1064 nm pump laser and a frequency doubling crystal, generated a 532 nm line laser beam with a 10 Hz repetition rate (exposure time: 200 ns). Bypassing the mirrors and laser shutter, the 532 nm laser is eventually modulated to a 283.00–283.90 nm UV light via a dye laser (dye: Rhodamine 6G, PrecisionScan, Germany). Then, sheet optics are used to generate the UV laser sheet to illuminate the flame and stimulate hydroxyl radicals in the combustion zone. In terms of data acquisition and post-processing, an Intensified

Charge-Coupled Device (ICCD) camera with a resolution of 1024×1024 pixels and a scale factor of 2.81 pixel/mm positioned perpendicular to the plane of the UV laser sheet is used to obtain the OH*. Davis 10.0 is adopted to post-process the OH-PLIF images. The Field of View (FoV) of the OH-PLIF measurement is shown in Figure 1b. A measurement area of $364.6 \text{ mm} \times 364.6 \text{ mm}$ is immediately adjacent to the burner. To obtain the optimal fluorescence signal of the OH radical in the flat flame, the maximum average hydroxyl radical intensity of the methane/air premixed laminar flame is found under the excitation of a 283.02 nm laser sheet, and the 283.02 nm UV laser with the energy of 18 mJ is used to excite the cases with an equivalence ratio of 0.78–2.00.

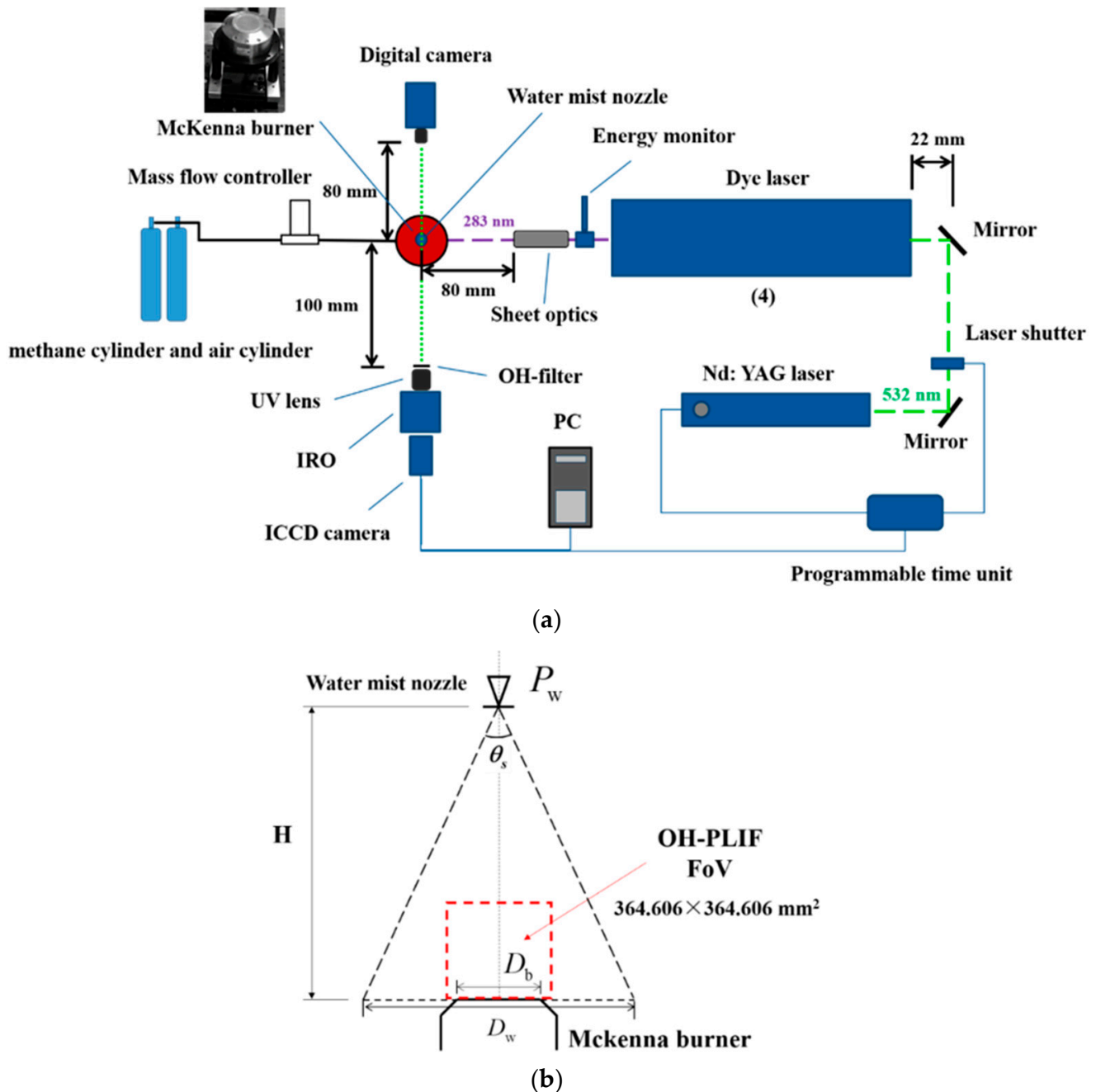


Figure 1. (a) Experimental apparatus and (b) the layout of the OH-PLIF measurement system and setup details, e.g., Field of View (FoV) and experimental cases.

In the water mist spray system, a 0.20 mm orifice nozzle is installed 500 mm or 650 mm ($H = 500 \text{ mm}$ or 650 mm) above the burner. The pure water spray is generated by

pressure atomization, where the working pressure is monitored by a digital pressure gauge (MIK-Y180, Asmik, China) with $\pm 0.4\%$ F.S. measuring accuracy. The water flow discharge coefficient of the nozzle is $0.01039 \text{ L min}^{-1} \text{ MPa}^{-1/2}$, and water mist spray with a 45° solid cone spray angle has a $24 \mu\text{m}$ Sauter mean diameter under a 2.5 bar working pressure.

Initial conditions are fixed under the ambient environment of 24°C room temperature and 50% RH. Table 1 shows the flame extinction tests in all cases. The equivalence ratio of the fuel–air mixture is from $\phi = 0.78$ to $\phi = 2.00$, where the laminar flame covers the combustion transition from rich fuel to lean fuel.

Table 1. The details of experimental cases.

Case No.	P_w (MPa)	ϕ	H (mm)	Results *
A	0.25	0.78/0.81/0.85/0.9/1.0/1.25/1.5/2.0	650	×
B	0.25	1.0/1.25/1.5/2.0	500	×
		0.78/0.81/0.85/0.9		✓
C	0.30	0.78/0.81/0.85/0.9/1.0/1.25/1.5/2.0	500	✓

* ✓, the flat flame is successfully extinguished; ×, the flat flame failed to extinguish.

In experimental uncertainty and limitations, the OH-PLIF measurement is used to obtain the semi-quantitative OH* intensity/concentration in this study. Due to the presence of scattering of laser-induced fluorescence via liquid droplets, the flame structure of OH* imaging may strictly have some deviation. Additionally, the random error from the mass flow controllers and a pressure gauge is less than 2%. The main limitations of the experimental results come from the absence of the characterization of droplets, such as droplet concentration. Additionally, the surface of the McKenna burner can influence flame stability and, consequently, extinction limits due to its porous nature [35]. The measurement uncertainty from the optical system can be referenced in our previous work [25].

3. Results and Discussions

The results are discussed quantitatively based on the analysis of combustion characteristics, OH-PLIF imaging, and critical fire extinguishing characteristics.

3.1. Combustion Characteristics Analysis

The average Reynolds number Re_{avg} is used to characterize the initial Reynolds number of the methane and air mixture, and the expression is presented as

$$Re_{\text{avg}} = \frac{\rho_{\text{mix}} v_{\text{avg}} D_b}{\mu_{\text{avg}}} \quad (1)$$

where ρ_{mix} is the average density of the mixture; v_{avg} is the average initial velocity of the mixture; and μ_{avg} is the average viscosity of the mixture. Table 2 shows the average Reynolds number of the laminar flame in the burner outlet. To facilitate the adjustment of the required oxidant flow rate for different methane/air equivalent ratios, the standard volume flow rate of methane is set to 2 L min^{-1} for all cases. Figure 2 presents the flame appearance under the equivalence ratio of 0.78~2.00. Typically, the flat flame exhibits flame pulsation with a flame height pulsation frequency of up to 12.5 Hz under the cases of $\phi = 2.00$. The variation of the burning velocities of laminar flames with methane/air equivalent ratios is summarized by previous studies [36–38]. It shows that the burning velocities increase with the increase in the equivalence ratio when $\phi < 1.00$, while the opposite is true when $\phi > 1.00$. The flame morphology has changed from a “conical” to a “flat” flame when the equivalence ratio is close to 1 (see Figure 2). When the average Reynolds number exceeds 648, the laminar flame structure begins to appear unstable. It

is manifested in the flame structure by the appearance of multiple “finger-like” flames (see Figure 2). With the increase in the average Reynolds number, the structure of the flame base gradually becomes unstable when $\phi > 0.78$.

Table 2. Calculated average Reynolds number corresponding to the experimental cases.

$\dot{Q}_{\text{methane}}(\text{L/min})$	$\dot{Q}_{\text{air}}(\text{L/min})$	ϕ	$\rho_{\text{mix}}(\text{kg/m}^3)$	$v_{\text{avg}}(\text{m/s})$	$\mu_{\text{avg}}(10^{-5}\text{kg/m}^3)$	Re_{avg}
2	24.40	0.78	1.2484	0.1556	1.6627	701
2	23.40	0.81	1.2467	0.1497	1.6606	674
2	22.40	0.85	1.2449	0.1438	1.6584	648
2	21.16	0.90	1.2423	0.1365	1.6553	615
2	19.04	1.00	1.2374	0.1240	1.6493	558
2	15.23	1.25	1.2253	0.1016	1.6348	457
2	12.70	1.50	1.2137	0.0866	1.6210	389
2	9.52	2.00	1.1922	0.0679	1.5951	305

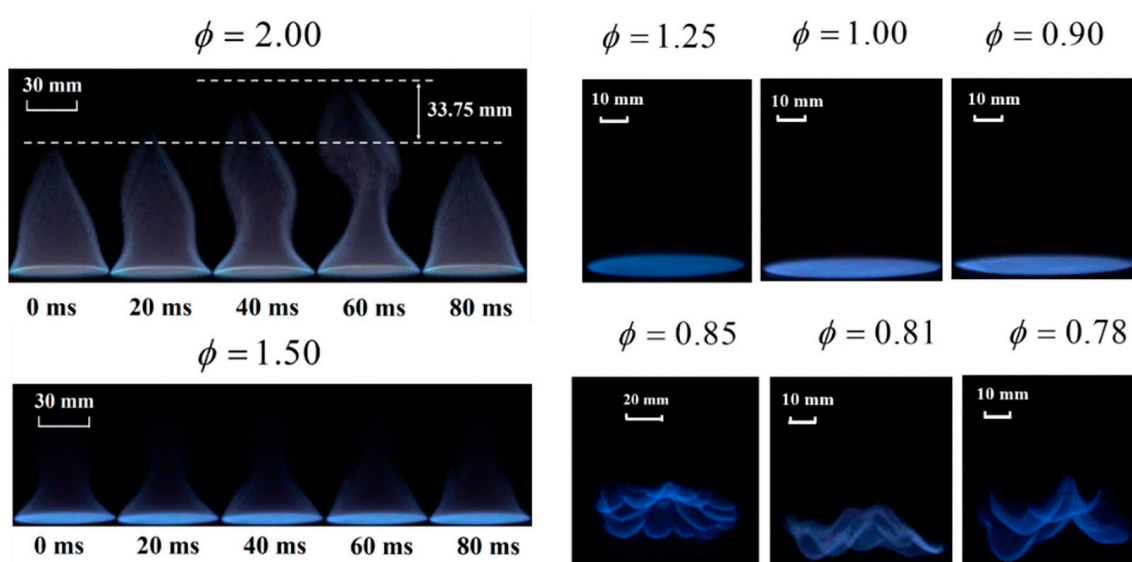


Figure 2. Direct photographs of flame appearance under the equivalence ratio of 0.78 ~ 2.00.

In the OH-PLIF measurement, the dimensionless OH-PLIF intensity parameter is used to characterize the OH radical intensity concentration [25]. Referring to the manual of LaVision Tunable LIF measurement [39], a minimum concentration area, usually as the background, and a maximum concentration area can be manually defined in the “Sample concentration” module in DaVis 10.0 software. As shown in Figure 3a, the area selected as the minimum or maximum concentration region is controlled to 10-pixel units (i.e., the actual flame area of 1~4 mm²) for improving the accuracy of the concentration inversion calculation. After averaging the unit pixel intensities in the 0% and 100% concentration areas, the hydroxyl radical concentration baseline at a specific operating condition can be obtained by linear fitting of the data, and then the initial hydroxyl radical imaging can be transformed into a concentration distribution map (as shown in Figure 3a).

Figure 3b illustrates the average flame hydroxyl radical concentration distribution for all methane/air equivalent ratios, i.e., the average processing of 300 consecutive images of hydroxyl radicals under steady combustion. Combined with Figure 3b, under the cases of typical rich fuel combustion ($\phi > 1.25$), the concentration distribution of hydroxyl radicals can be seen to be mainly concentrated at the periphery of the inner hollow cone due to the low percentage of air in the premixed gas. It results in a large combustion area concentrated near the external air contact surface. Compared with the cases of higher equivalence ratios,

the concentration distribution of hydroxyl radicals in the oxygen-depleted flame at a lower equivalence ratio gradually converges to the inner hollow cone. When the hydroxyl radical concentration distribution is mainly concentrated in the inner region, it can be concluded from the hydroxyl radical imaging that the premixed laminar combustion tends to be non-premixed when the initial Reynolds number is lower than 457. As the initial Reynolds number increases, the hydroxyl radical structure of the flame near the surface of the burner begins to appear as an unstable pushing phenomenon. The flame is “blown up” and lifted when $\phi > 0.78$. Due to the fuel-rich conditions, OH* imaging reveals that the actual combustion reaction zone within the flame exhibits a hollowed-out conical shape, with extremely low reaction intensity within the cone’s interior. Conversely, a standard digital camera clearly captures the outline of the conical line (denoting the interface between the lean premixed gas and air, where combustion is most intense). Thus, while the visualization photograph reveals a conical shape, OH* imaging distinctly shows a hollowed-out cone (see $\phi = 2.0$ in Figures 2 and 3).

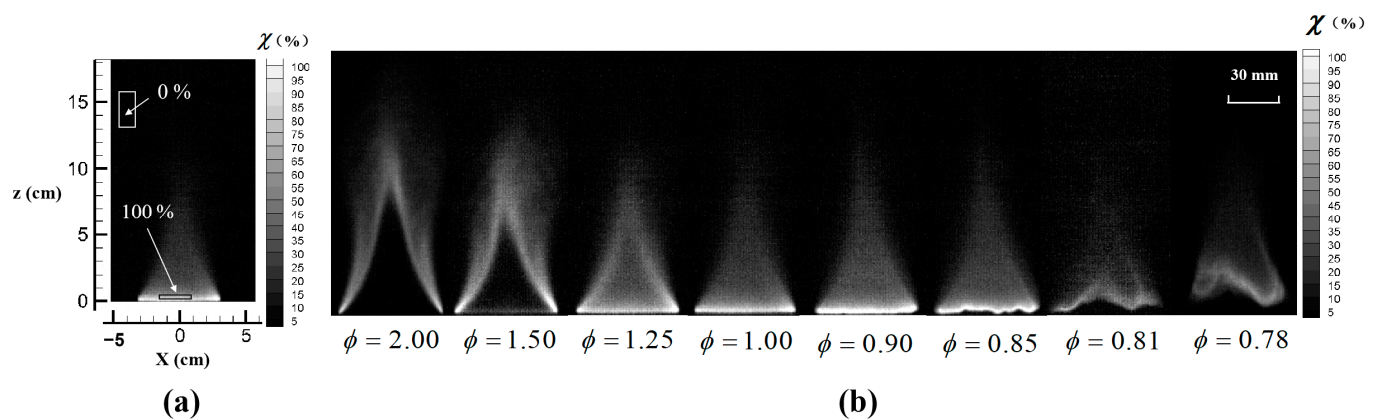


Figure 3. (a) Calculation of hydroxyl radical concentration distribution in the whole field and (b) average hydroxyl radical concentration distribution at different equivalence ratios.

As shown in Figure 4a, FoVs are divided into region #1, which covers all visible flame areas, and regions #2 and #3, which are divided mainly for lean fuel cases. The divided FoV regions are merely an artificial division established for the quantitative processing of OH images. Figure 4b shows the average incremental concentration of hydroxyl radicals in regions #1 and #3 at different equivalence ratios. The hydroxyl radical concentration distribution and the corresponding flame morphology showed an inhomogeneous distribution along the axial direction, especially with the increase in the equivalence ratios.

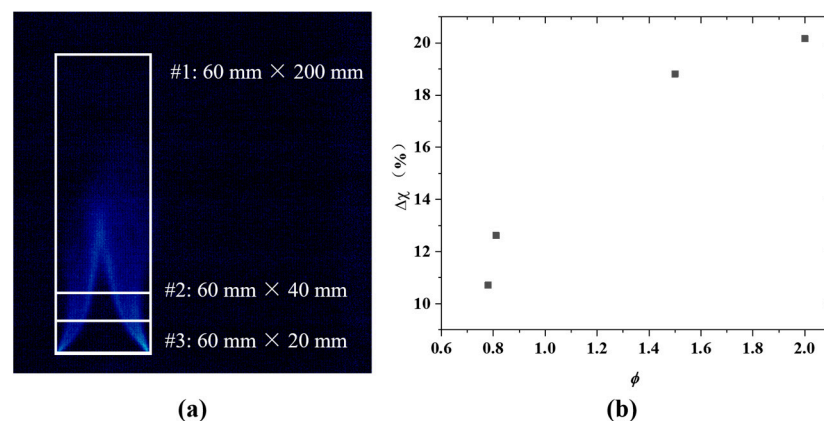


Figure 4. (a) Schematic diagram of divided FoV regions and (b) average incremental concentration of hydroxyl radicals in regions #1 and #3 at different equivalence ratios.

3.2. Flame Extinction Analysis Based on OH-PLIF Imaging

Figure 5 shows the evolution of the OH-PLIF flame structure with the discharge of water mist spray. Due to the similarities with the non-premixed laminar flame, the flame extinguishing process can be summarized as follows: phase I, flames are quickly suppressed after the initial discharge of water mist spray; phase II, the water mist and premixed flame interaction phase; and phase III, flame extinction.

Figure 5 demonstrates the hydroxyl radical concentration distribution under the equivalence ratios of $\phi = 0.78\sim 2.00$. The large number of droplets being entered into the combustion region affects the efficiency of hydroxyl radical participation in the reaction, and the process of interaction between the laminar flame and the water mist spray is, to some extent, expressed as competition for the combustion reaction region.

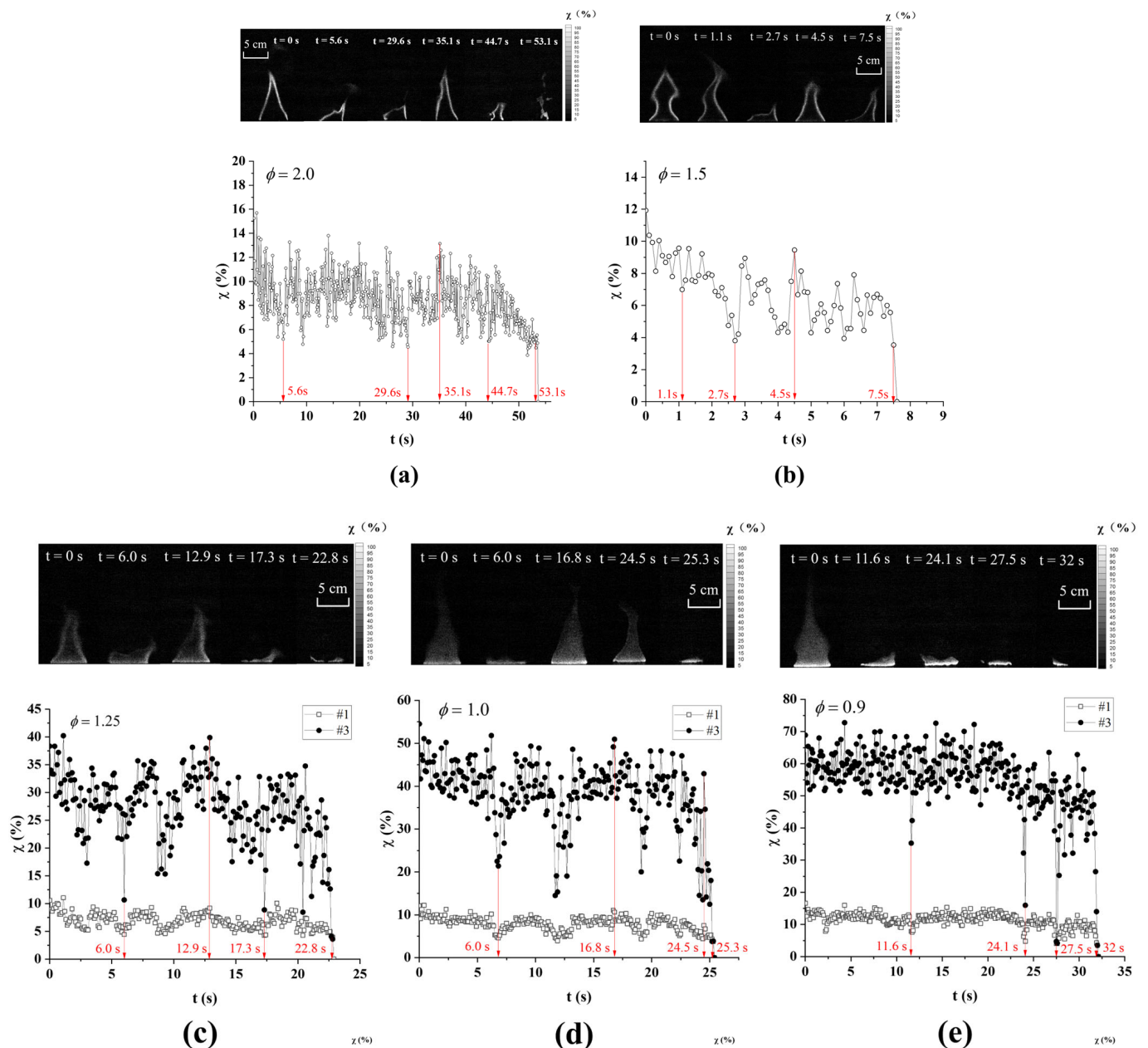


Figure 5. Cont.

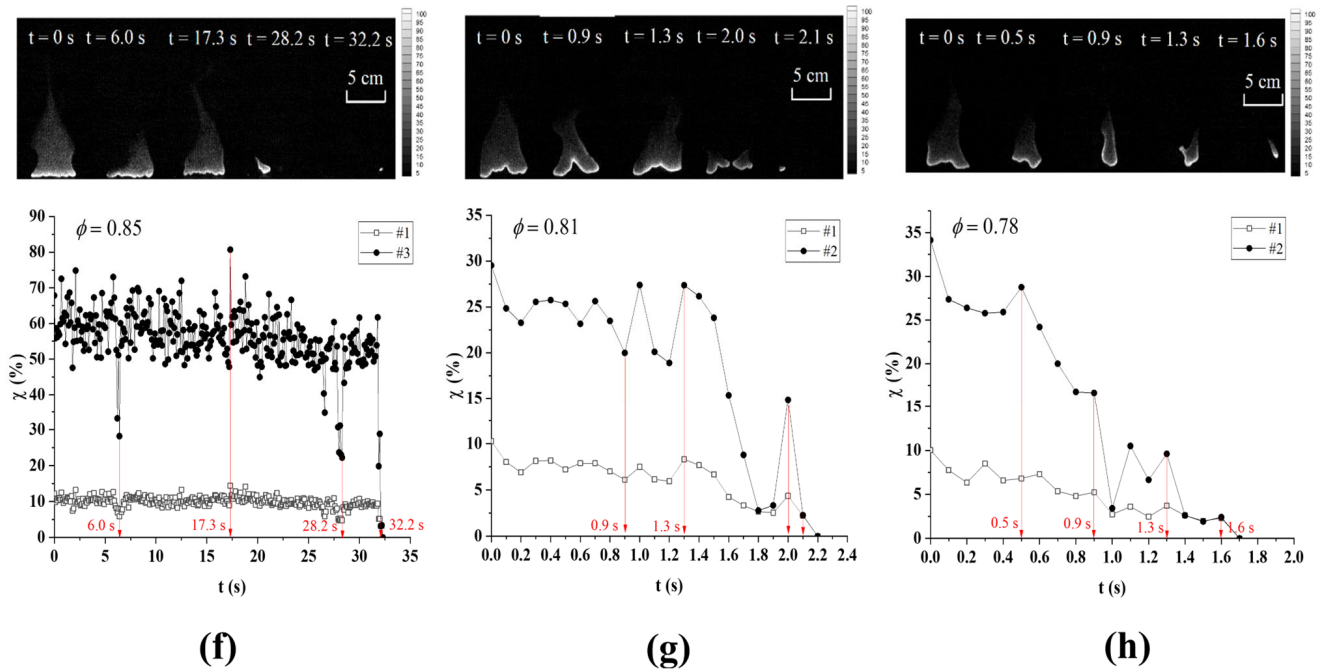


Figure 5. Hydroxyl radical concentration distribution of a typical rich fuel combustion laminar flame in the case of C and the corresponding average hydroxyl radical concentration in regions #1 or #3 under the equivalence ratios of (a) $\phi = 2.0$, (b) $\phi = 1.5$, (c) $\phi = 1.25$, (d) $\phi = 1.0$, (e) $\phi = 0.90$, (f) $\phi = 0.85$, (g) $\phi = 0.81$ and (h) $\phi = 0.78$.

Figure 5 visualizes the hydroxyl radical concentration and the corresponding flame structure. In the moment of critical extinguishing, the burning area at the base of the flame starts to be “occupied” by the mist droplets, and the laminar flame is then completely extinguished. Moreover, the results indicate that the radial distribution of hydroxyl radicals showed a clear peak-like distribution when the flame is nearly extinguished (see Figure 5). Combined with the hydroxyl radical flame structure diagram shown in Figure 5, the gradual reduction in the basal combustion region directly leads to its distinct peak-like distribution. Figure 3 reveals the observed reduction in water mist effectiveness at higher equivalence ratios due to the structural changes in the flame. Specifically, the transition to a shell structure in fuel-rich flames likely shields the reaction zone of the base flame from mist penetration, whereas the accessible reaction zone in lean flames remains highly vulnerable to quenching (see Figure 5a,b).

With increasing air percentage, the methane–air premixed mixture with a larger initial Reynolds number leads to a smaller whole burning area and the corresponding burning velocities [39]. It is evident from Figure 6 that the extinguishing time is reduced to approximately 2 s when the equivalence ratio decreases to 0.78.

In case B, the water mist discharge flow rate is lower compared to case C. As a result, case B has a longer extinguishing time than case C for all extinguishing scenarios. In particular, the difference is noticeable in the cases of $\phi = 0.81$ (see Figures 6 and 7). A “sufficiently” long interaction between the water mist and the laminar flame occurs, despite the already unstable flame lift-off behavior (see Figure 7). With the increase in the equivalence ratio, the laminar flame cannot be extinguished, especially when $\phi > 0.90$.

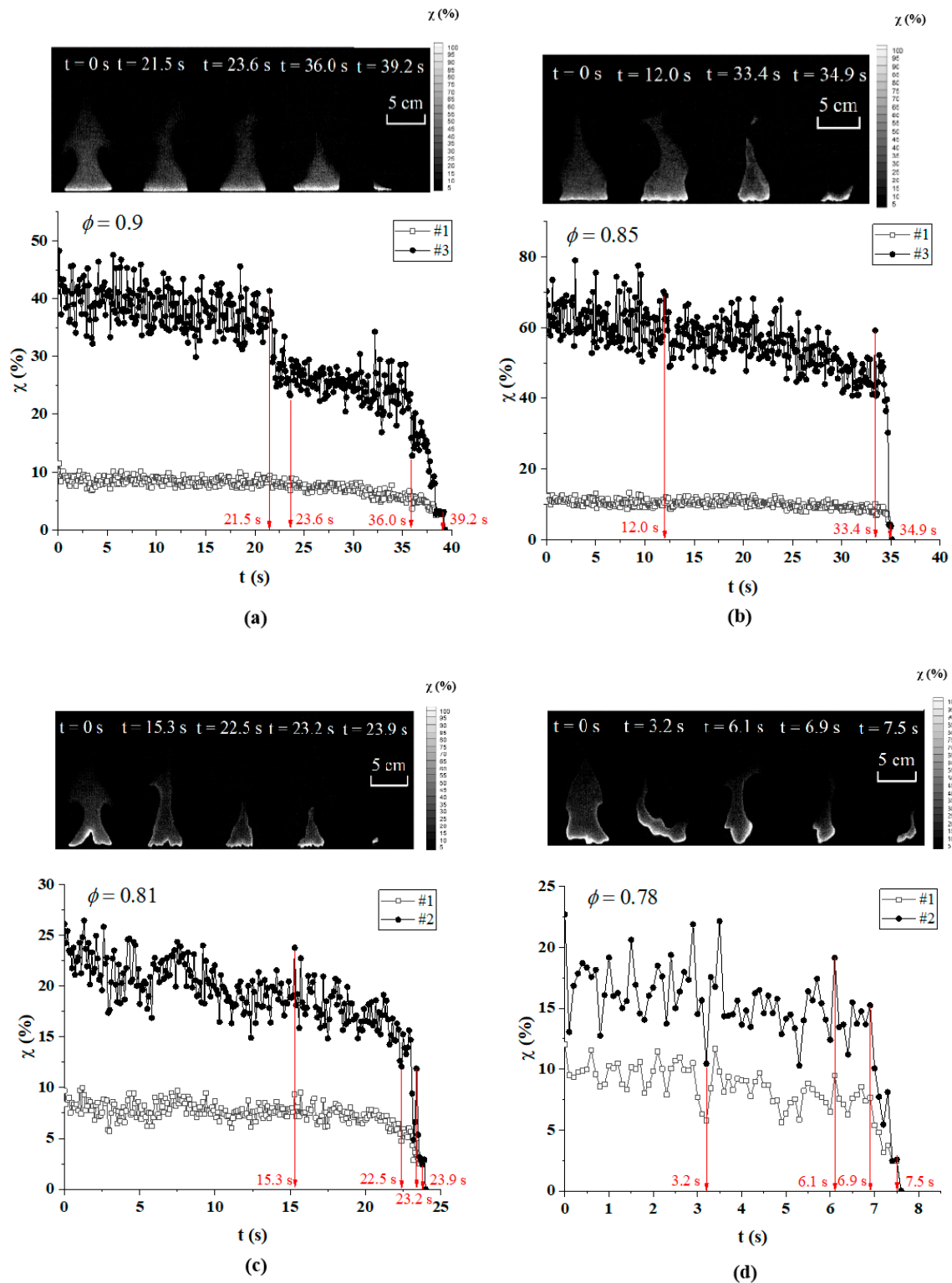


Figure 6. Hydroxyl radical concentration distribution at case B and the trend of average hydroxyl radical concentration in regions #1~#3 under the equivalence ratios of (a) $\phi = 0.90$, (b) $\phi = 0.85$, (c) $\phi = 0.81$, and (d) $\phi = 0.78$.

As shown in Figure 7, the hydroxyl radical flame structure appears to be suppressed for a short period, but the burning area of the flame base does not become smaller. Take the cases of $\phi = 1.25$ as an example, combining the data of $t = 17.3$ s in Figure 5c and $t = 2.9$ s in Figure 7b, both hydroxyl radical concentrations are at the level of the lowest value. And, it can be found that the flame base is not affected in case B, which maintains the continuous

and stable flame structure. The size of the flame base area is greatly reduced in case C, conversely, which causes an insufficient OH radical intensity to maintain the flame stability during the subsequent flame–spray interaction.

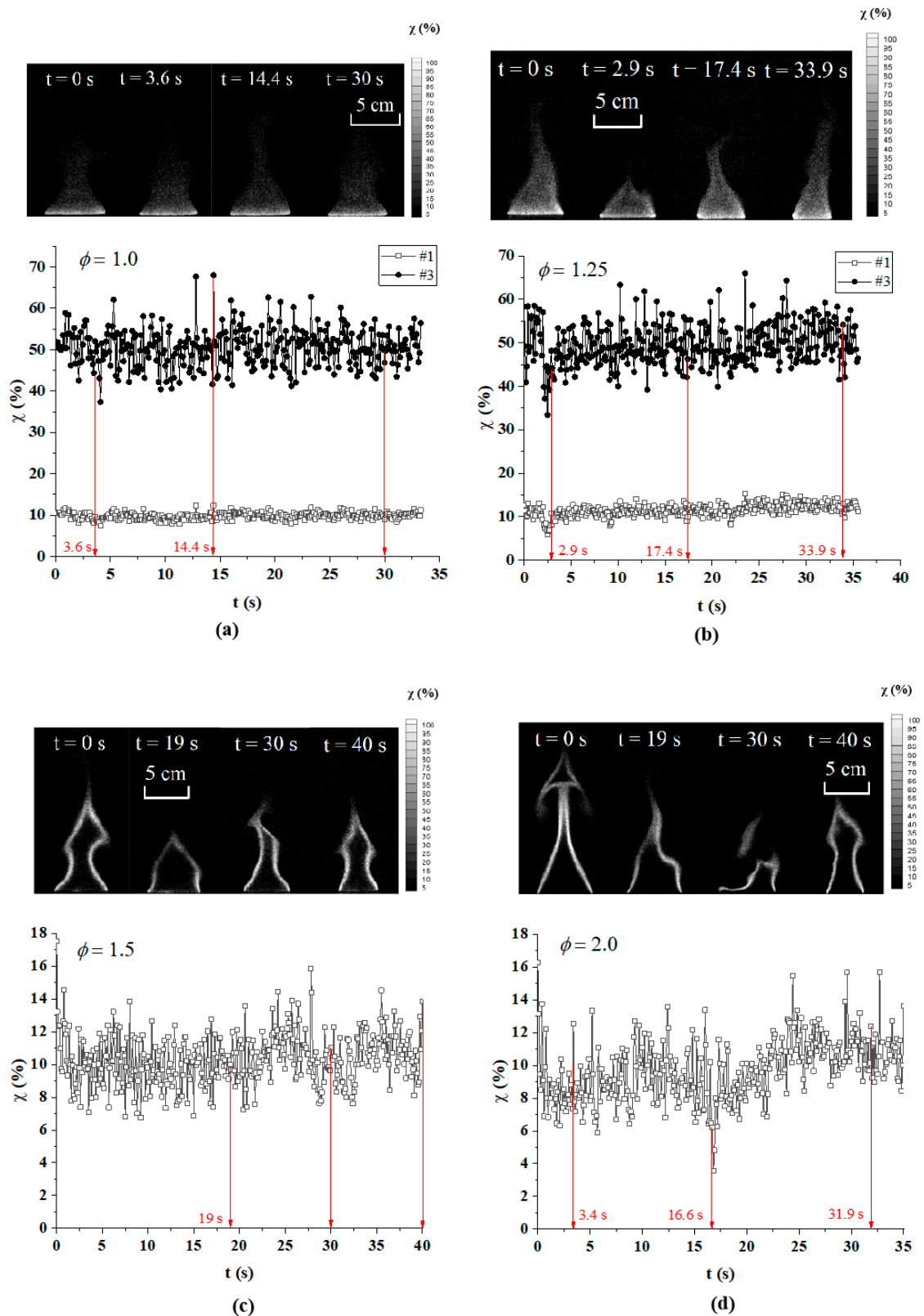


Figure 7. Hydroxyl radical concentration distribution at case B and the trend of average hydroxyl radical concentration in regions #1/3 under the equivalence ratios of (a) $\phi = 1.00$, (b) $\phi = 1.25$, (c) $\phi = 1.50$, and (d) $\phi = 2.00$.

Compared to case B, increasing the distance between the water mist nozzle and the burner surface leads to a decrease in the mist flux at the surface of the burner. Therefore, the laminar flame with the lean fuel mixture in case A is not effectively suppressed. The average concentration of hydroxyl radicals in regions #1~#3 shows that there is no significant fluctuation in the concentration of hydroxyl radicals in the unextinguished cases (see Figure 8). In addition, the base of the flame, where the combustion is most intense, is not subjected to the water mist that brings about a reduction in the concentration of hydroxyl radicals. The radial hydroxyl radical concentrations located at $z = 0.15/0.65/1.15$ cm are mainly concentrated at 80%~100%, 50%~80%, and 30%~60%, respectively (see Figure 9). In the fire extinguishing mechanism, the typical methane ignition and combustion part of the important reactions are as follows [39]: $2O \rightarrow O_2$; $O + H_2O \rightarrow 2OH$; $O + CH_2O \rightarrow H + OH + CO$. It can be seen that the above reaction rate is decreased due to the cooling effect of the application of water mist, which eventually leads to a decrease in the rate of OH radical generation and thus affects the combustion or flame stability. On the other hand, the kinetic blowing-off effect of the water mist also has an impact on flame extinction. The kinetic blowing is an aerodynamically driven extinction mechanism where the water mist flow field increases the flame's Karlovitz number beyond a critical threshold. This destabilizes the flame through excessive strain, leading to local quenching, structural disintegration, and ultimately, global blow-off, complementing the thermal and chemical inhibitory effects of the mist.

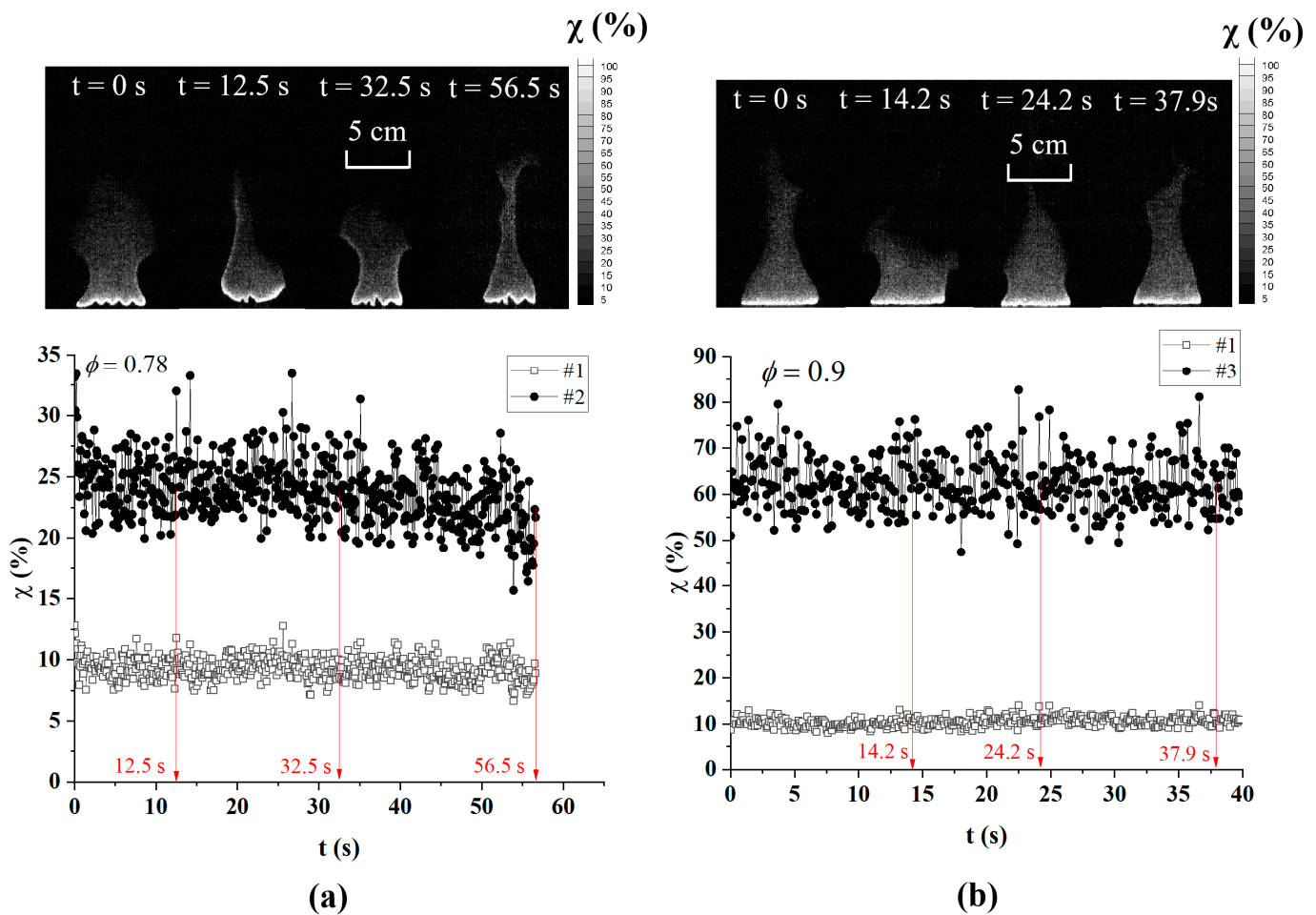


Figure 8. Hydroxyl radical concentration distribution at case A and the trend of average hydroxyl radical concentration in regions #1/3 under the equivalence ratios of (a) $\phi = 0.78$ and (b) $\phi = 0.90$.

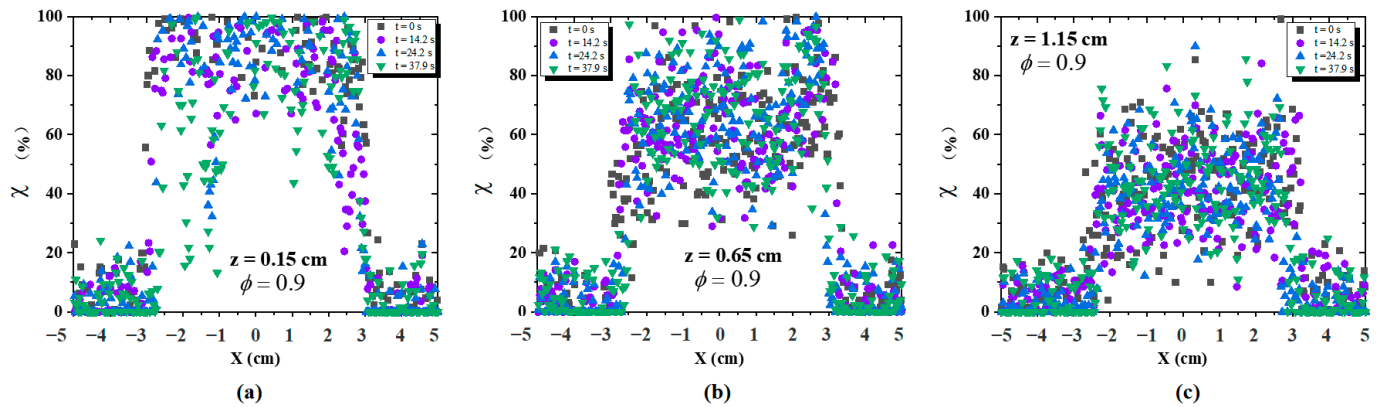


Figure 9. Radial distribution of hydroxyl radicals at (a) $z = 0.15$ cm, (b) $z = 0.65$ cm, and (c) $z = 1.15$ cm from the burner outlet surface in the case A ($\phi = 0.90$).

3.3. Critical Fire Extinguishing Characteristics Analysis

Based on the idealized assumptions, the effective water mist flux in the combustion reaction zone for quantitative analysis to obtain the effective fire extinguishing critical conditions is introduced. Before defining the effective water mist flow, make the following idealized assumptions. (1) The water mist flux distribution can be approximated as a normal distribution. (2) The droplets acting on the burner surface can be effectively involved in the water mist–flame interaction.

The water mist flux distribution can be assigned a normal distribution based on a Gaussian distribution-like profile of the water flux density of the nozzle. An empirical rule (3-sigma rule) is adopted to represent the spray-blocked ratio at a certain obstacle setup height.

The maximum spray diameter is defined as the maximum diameter of the conical spray covering the upper surface of the burner. According to the statistics principle of $\Phi(\mu, \mu \pm 3\sigma) = 99.7\% \approx 1$ in the empirical rule, the spray maximum diameter is defined as $D_w = 2 \cdot (3\sigma)$ (see Figure 1), where μ is the expected value and σ is the variance.

The normal distribution can be expressed as $N(\mu, \sigma^2)$, where $\mu = 0$, $\sigma = 0.5D_w/3$, and $D_w = (2h_s \tan(\theta_s/2))$ in this work. The effective water mist flow rate can be expressed as follows:

$$\dot{Q}_{w, \text{effective}} = K\sqrt{10P_w} \cdot 2 \int_0^{D_b/2} N\left(0, (D_w/6)^2\right) dX = K\sqrt{10P_w} \cdot 2 \int_0^{D_b/2} N\left(0, (H \tan(\theta_s/2)/3)^2\right) dX \quad (2)$$

where K is the water flow discharge coefficient of the nozzle ($K = 0.01039 \text{ L min}^{-1} \text{ MPa}^{-1/2}$), P_w is the water mist nozzle working pressure, D_b is the diameter of the obstacle, H is the height of the upper surface of the burner from the water mist nozzle, and θ_s is the spray angle ($\theta_s = 45^\circ$).

Table 3 gives the effective water flow rate corresponding to all experimental cases. The results show that the effective water flow rate of critical extinguishing is in the range of $8.83 \text{ mL min}^{-1} \sim 9.55 \text{ mL min}^{-1}$ for a typical rich fuel mixture case; the effective water flow rate of critical extinguishing is in the range of $8.44 \text{ mL min}^{-1} \sim 8.83 \text{ mL min}^{-1}$ for a typical lean fuel mixture case. In general, the maximum critical extinguishing water flow rate required for the McKenna premixed laminar flame used in this experiment is about 9.55 L min^{-1} .

Table 3. Summary of the effective water flow rate for experimental cases.

P_w (MPa)	ϕ	H (mm)	$\dot{Q}_{w, effective}$ (mL min ⁻¹)	Results *
0.25	0.78~2.0	650	8.44	×
0.25	1.0~2.0	500	8.83	×
	0.78~0.9			✓
0.3	0.78~2.0	500	9.55	✓
0.5		650	11.40	✓

* ✓, the flat flame is successfully extinguished; ×, the flat flame failed to extinguish.

4. Conclusions

This study addresses the issues of hydroxyl radical concentration distribution, flame structure, and critical fire extinguishing conditions for the interaction of water mist with the laminar flame generated by a McKenna premixed burner, adopting the OH-PLIF measurement and the construction of an effective water flow rate relational equation based on an approximately normal distribution. The water mist suppresses the laminar flame of the lean fuel mixtures more effectively than the rich fuel mixtures conditions when the same water flow rate is applied. The results revealed that the laminar flame extinction performance is influenced by both the methane/air equivalent ratio and the effective water flow rate. Moreover, flame extinction is directly related to the stability of the hydroxyl radical concentration in the combustion reaction zone at the base of the flame. The effective water flow rate required for maximum critical quenching of a McKenna premixed laminar flame is 9.55 mL min⁻¹ under the mist droplets of a 24 μ m Sauter mean diameter. This study helps with the optimization of water mist spray systems for fire protection scenarios in the processes of premixed combustion systems. Further, it will deepen the understanding of premixed flame extinction with the downward water mist spray. Future work will focus on the investigation of flame extinction domains and flammability limits at different equivalence ratios by reducing Reynolds number variation with new measurements.

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Conflicts of Interest: The authors declare no conflicts of interest.

Nomenclature

The following nomenclatures are used in this manuscript:

D_b	Diameter of obstacle (mm)
D_w	Spray max diameter at obstacle height (m)
Fr_f	Flame Froude number (-)
H	Height of the upper surface of the burner from the water mist nozzle (mm)
K	Water flow discharge coefficient of the nozzle
P_w	Water mist nozzle working pressure (MPa)
$\dot{Q}_{air}$	Air volumetric flow rate (L min ⁻¹)
$\dot{Q}_{methane}$	Methane volumetric flow rate (L min ⁻¹)
$\dot{Q}_{w, effective}$	Effective water mist flow rate (mL min ⁻¹)
Re_{avg}	Average Reynolds number (-)
v	The velocity of the methane–air mixture at the burner outlet (m/s)

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