Fuel 279 (2020) 118473

Contents lists available at ScienceDirect

Fuel

journal homepage: www.elsevier.com/locate/fuel

Full Length Article

Dynamics of a holder-stabilized laminar methane-air premixed flame in a preheated mesoscale combustor at ultra-lean condition

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ARTICLE INFO

Keywords:
Heat recirculation
Flow recirculation
Ultra-lean condition
Flame dynamics
Blow-off

ABSTRACT

The flame dynamics at ultra-lean condition under the synergistic effect of heat recirculation and flow recirculation is experimentally studied in this work. The previously reported anomalous blow-off of lean H_2/CH_4/air premixed flame with Lewis number $Le < 1.0$ is obtained for the lean CH_4/air premixed flame at $Le \approx 1.0$, and the underlying mechanisms are analyzed in terms of heat recirculation, flow recirculation, preferential diffusion, and stretch effects. An anomalous standoff distance between the stable flame root and flame holder is also observed for the lean CH_4/air premixed flame. The blow-off dynamics at large and small values of Reynolds numbers are quite different. The flame with local extinction and reignition appears in the blow-off process at large Reynold numbers ($\geq$100), whereas it is absent at small Reynold numbers (< 100). The results attained in this study can help to gain insights into flame dynamics in many practical combustors.

1. Introduction

Flame holders such as bluff-bodies [1–3] and cylindrical rods [4–6] are widely used to improve flame stability. The recirculation zone behind the flame holder can significantly anchor the flame, the heat recirculation effect of flame holder can preheat the unburned fuel mixture, and the preferential transport effect can supply a suitable ignition condition [7,8]. Under some extreme combustion conditions (e.g., ultra-lean condition and large Reynolds number *Re* condition), flame blow-off can still occur. Understanding the blow-off dynamics of laminar flames stabilized by a flame holder is critical to improve the flame stability. Kedia and Ghoniem [9] found that if the gradient of flow velocity normal to the flame front is larger than that of the flame displacement speed, flame local extinction and blow-off would occur. Vance et al. [10] pointed out that an excessive flame stretch can also result in the local extinction of laminar premixed flame of $Le < 1.0$, even though it was stabilized by a cylindrical flame holder. Shoshin et al. [11] experimentally observed an anomalous blow-off (the blow-off limit decreases with decreasing *Re*, or the second flame blow-off can occur at a certain equivalence ratio with a smaller *Re*) of H_2/CH_4/air laminar flame stabilized by a cylindrical rod, and this phenomenon was recently reproduced by Jiménez et al. [12,13] via direct numerical simulation (DNS). Chang et al. [14] indicated that the dynamic characteristics of a bluff-body stabilized flame at low *Re* were different with that at high *Re*. Guo et al. [15] found that the hydrogen addition leads to the CH_4/air lean premixed flame brush attachment leave the inner shear layer, which is beneficial to improving the flame stability. These results have helped to obtain insights into dynamics of flames stabilized by flame holders. Nevertheless, the conjugate heat exchange between the flame and combustor wall was not considered in these works.

In many practical combustors (such as aeroengines), the interaction between the flame and combustor wall is strong, and hot combustor walls usually need to be cooled by the cold air outside. The preheated air (or premixed air/fuel) enters the combustion chamber with the bluff body, and the heat recirculation effect cannot be ignored. In other words, the flame dynamics in most practical combustors are influenced by both heat recirculation and flow recirculation. However, flame dynamics under the synergistic effect of these two processes has not been studied systematically. With this regard, we manufactured a mesoscale combustor with a plate flame holder and preheated channels to investigate the flame dynamics under the synergistic effect of heat and flow recirculation. We reported the topological structure of the laminar methane/air premixed flame [16] and the effect of the thermal condition of solid wall on the flame behavior [17] under stable operating conditions. More recently, the flammability limits of methane-air premixed mixture in the present combustor were investigated experimentally [18]. In the present work, we provided some interesting and novel flame propagation characteristics at the ultra-lean condition. Further insights into the flame dynamics near limit condition can provide the theoretical basis to improve the flame stability in many practical

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https://doi.org/10.1016/j.fuel.2020.118473
Received 15 April 2020; Received in revised form 12 June 2020; Accepted 18 June 2020
Available online 26 June 2020
0016-2361/

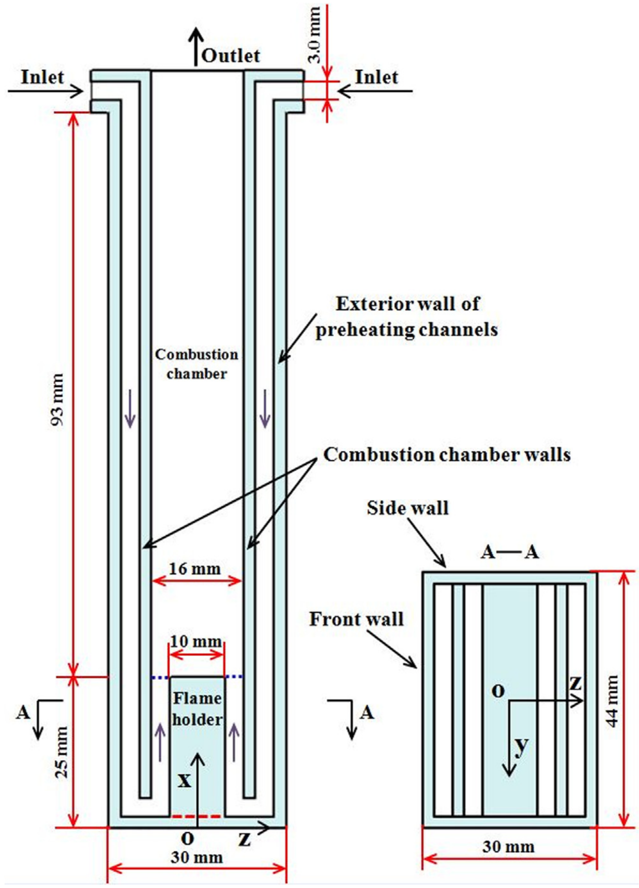

Fig. 1. Cross-sectional schematic of the mesoscale combustor with a plate flame holder and preheated channels.

combustors, which is the main objective of the present work. The current paper first displays the regime diagram of the flame behavior for different Reynold numbers and equivalence ratios. Subsequently, the morphological characteristics of stable flame are investigated. Finally, the flame blow-off dynamics are presented and discussed.

2. Experimental approach

Fig. 1 shows the geometrical structure of a mesoscale combustor with a plate flame holder and preheated channels, which is manufactured using transparent quartz glass and is vertically placed. The combustor channel is divided into the combustion chamber and preheated channels, as separated by the two blue dashed lines along the upper wall of the flame holder. The fresh fuel mixture can be preheated effectively in the preheated channels before entering the combustion chamber, which can significantly affect the flame propagation characteristic. The geometrical dimensions are also presented in Fig. 1. In addition, details of the three-dimensional geometry of the combustor used in this study can be found in our previous paper [16].

Fig. 2 shows the schematic diagram of the present experimental system. In this work, methane and air are well-mixed in a mixing tank before being introduced into the combustor via a stainless-steel pipe (outer diameter: 1/4 in.; inner diameter: ~5.0 mm). It has been experimentally determined that the thermal time (*i.e.*, the time needed to reach thermal equilibrium once changing the operating condition) of the experimental setup is < 5.0 s. To ensure that the setting case is completely achieved, we do not shoot the flame until 10.0 s after the setup of the operating condition, *i.e.*, $t = 0.0$ s in the following figures corresponds to 10.0 s after changing the operating condition. At the beginning of the experiment, the fresh fuel mixture is ignited at an equivalence ratio (ϕ) of 0.60 and inlet velocity (V_{in}) of 1.0 m/s (*i.e.*, *Re* is 200), which allows the flame to stabilize in the combustion chamber. Thereafter, maintaining a constant inlet velocity, we gradually reduce the equivalence ratio of fuel mixture at a decrement of 0.002 until the flame blows off. The standoff distance (SD) between the stable flame and the flame holder at different *Re* is quantitatively obtained. The width of the flame holder (10 mm) is used as the standard measuring scale to determine the SD. As the premixed flame at ultra-lean condition is not bright, the 30% increment of brightness and contrast are applied to the original photographs of the flame to distinguish the location of the flame root. Therefore, the present standoff distances are obtained based on the flame images with the increased 30% brightness and contrast. A similar experiment is then conducted at different inlet velocities. The inlet velocity is decreased at a decrement of 0.1 m/s (from $V_{in} = 1.0$ to 0.7 m/s and from $V_{in} = 0.5$ to 0.2 m/s) or 0.05 m/s (from $V_{in} = 0.7$ to 0.5 m/s). More details about the experimental setup and methods can be found in our previous publication [16].

3. Results and discussion

3.1. Regime diagram of flame behavior

Fig. 3 shows that the flame can always remain stable before blow-off, and the preheating effect on the fresh fuel mixture in the present combustor makes the blow-off limit very low. It is interesting to note that the flame blow-off limit first decreases gradually and then increases sharply with a decrease in *Re*. This non-monotonic change in the blow-off limit as a function of the Reynolds number includes two blow-off types, *i.e.*, normal blow-off (blow-off limit increases with decreasing *Re*) and anomalous blow-off [11,13]. Shoshin et al. [11] and Jiménez et al. [13] ascribed the anomalous blow-off of a lean H_2/CH_4/air premixed flame (Lewis number $Le < 1.0$) to the preferential diffusion effect. Generally, the flame dynamics in the combustors of confined spaces with flame holders is mainly determined by the heat loss of the flame to the flame holder, the heat recirculation effect, the flow recirculation effect, the preferential diffusion effect, and the stretch effect [19]. Our recent study [18] had indicated that the heat loss of the flame to the flame holder does not contribute to the anomalous blow-off in this study. It should be pointed out that the buoyancy effect, as caused by the difference between the densities of burned and unburned gaseous mixtures, increases with the decrease of *Re*. The Froude number (*Fr*), which is the ratio between the convective momentum and buoyancy, is smaller than 1.0 for the present ultra-lean methane/air premixed flame at $Re < 100$. This indicates that the buoyancy effect probably has a significant effect on the flame behavior. For $Re < 100$, the oscillating behaviours at the blow-off limits were indeed observed. However, unlike the oscillating lifted non-premixed flame results in Ref. [20], only the premixed flame root oscillates with a small amplitude over time, and the flame top stays at nearly the same location all the time. In addition, Van et al. [20] pointed out that the negative buoyancy due to a heavier fuel stream compared to the co-flow, initiates the oscillation of the lifted non-premixed flame, but this negative buoyancy effect is absent in the present study. Therefore, we deduce that the buoyancy does not have a significant effect on the present flame stabilization. Van et al. [21] observed that the standoff distance between the methane jet flame and the nozzle first decreases and then increases with the increase of *Re*, and they indicated that the radiation effect is insignificant for the occurrence of this phenomenon. For the current ultra-lean premixed flame, the flame temperature and lightness are remarkably lower than that of the methane jet flame in Ref. [21]. Thus, it is deduced that the radiation effect is also insignificant for the present flame stabilization. Therefore, the present anomalous blow-off phenomenon is highly dependent on the competition among the heat recirculation, flow recirculation, preferential diffusion, and stretch effects. For $Re > 110$, the positive effects (weaker stretch effect) play a key role in determining the blow-off limit. Therefore, it increases with

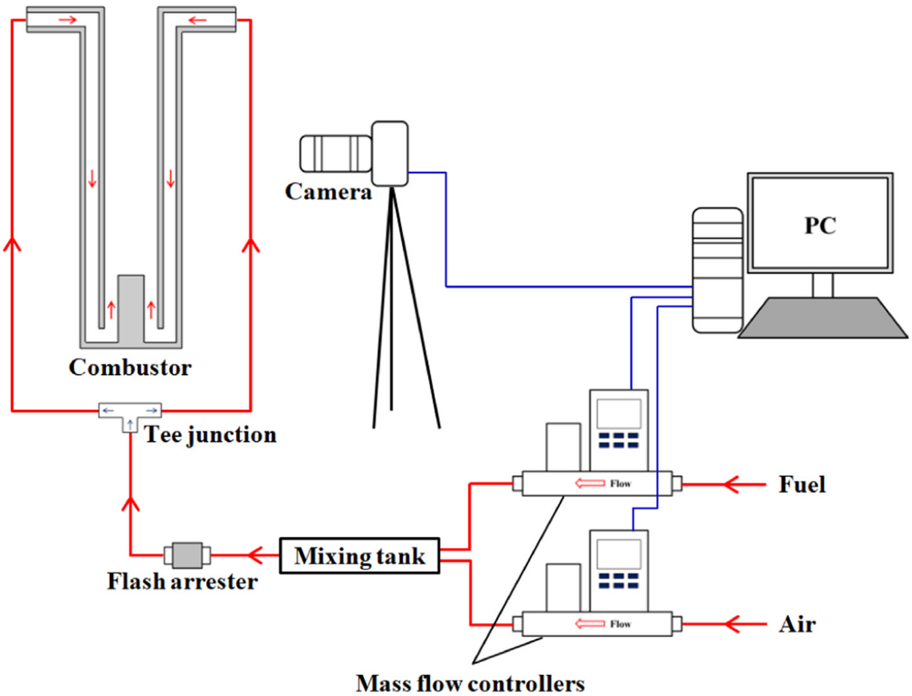

Fig. 2. Schematic diagram of the experimental system.

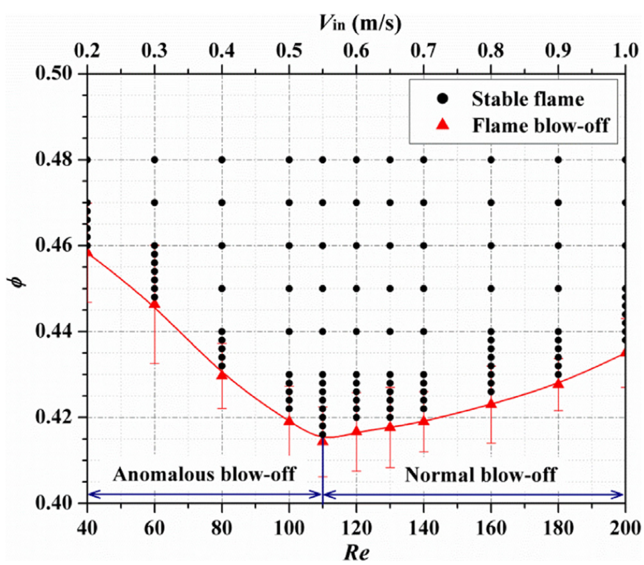

Fig. 3. Regime diagram of flame behavior at different Reynolds numbers and equivalence ratios.

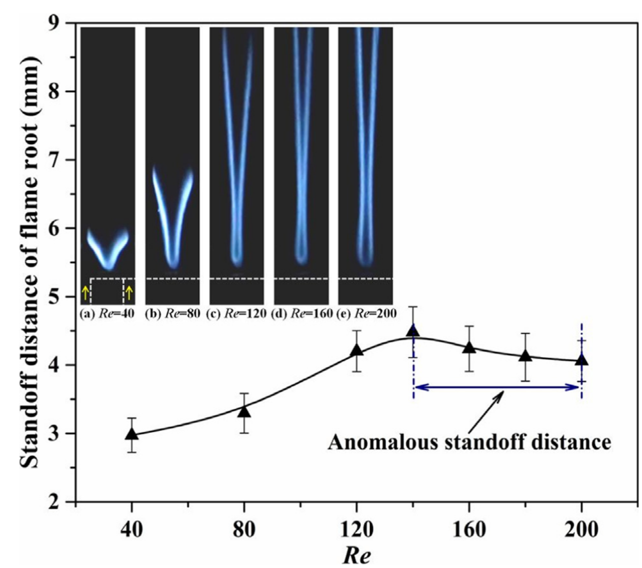

Fig. 4. Standoff distance for different Reynolds numbers at ϕ = 0.48 (inset is the stable flame photographs (30% brightness, 30% contrast); the end wall of flame holder is marked by the horizontally dashed lines, and the yellow arrow indicates the flow direction of unburned mixture).

the decrease of *Re*. For $Re < 110$, the blow-off limit is mainly determined by the negative effects (worse flow recirculation, preferential diffusion, and preheated effects on fresh fuel mixture). Accordingly, it decreases with the decreasing *Re*. More explanations about the current anomalous blow-off limit and the underlying mechanisms can be found in our recent publication [18].

3.2. Stable flame

For quantitative description, the upstream part of the flame front just behind the flame holder is defined as the flame root, while the downstream part near the combustion chamber wall is defined as the flame top [16]. The inset of Fig. 4 presents the typical flame photographs under different *Re* at a fixed ϕ (0.48). As *Re* increases, on the one hand, the increasing stretch effect of incoming flow pushes the flame top downstream; on the other hand, as the flame consumption speed at ultra-lean condition is very slow, the movement downstream of the flame top decreases the angle between the flame front and incoming flow, which makes the flame consumption speed reach a balance with the incoming flow again. However, the flame root still stays near the flame holder. The well stabilization of the flame root is ascribed to the synergistic effect of flow recirculation and preferential diffusion behind the flame holder [7,12,22]. The SD at varying *Re* is quantitatively obtained. As presented in Fig. 4, there exists anomalous SD at large *Re*, *i.e.*, the SD increases as *Re* decreases. The error bar in Fig. 4 is from flame fluctuation caused by environment perturbation. The similar anomalous SD was also observed by Shoshin et al. [11] via experiment and Jiménez et al. [12,13] via DNS for the lean H_2/CH_4/air premixed flame

($Le < 1.0$) stabilized by a cylindrical rod, which were ascribed to the strong preferential diffusion effect behind the flame holder [12]. However, we argue here that the present anomalous SD is dependent on the competition among the preheated effect on the fresh fuel mixture, flow recirculation effect, preferential diffusion effect, and stretch effect. Under a constant ϕ, the heat release amount decreases with decreased *Re*, which decreases the temperature of the combustor wall. Consequently, the preheated effect on the fresh fuel mixture decreases with the decreased *Re*. From $Re = 200$ to 140, the flame root location is mainly determined by the reduced preheated effect on the fresh fuel mixture, the flow recirculation effect, and the preferential diffusion effect (three negative effects for the flame root stabilization), which leads to the downstream movement of the flame root, *i.e.*, anomalous SD. From $Re = 140$ to 40, the flame root location is mainly influenced by the stretch effect, and the decreased stretch effect (positive effect for the flame root stabilization) results in the upstream movement of the flame root. In addition, under a constant *Re*, the SD decreases with the decrease in equivalence ratio. More information about the flame behaviors at different equivalence ratios can refer to our previous work [16].

3.3. Flame blow-off dynamics

The blow-off dynamics at large Reynolds number ($Re \geq 100$) and small Reynolds number ($Re < 100$) are quite different. The flame with local extinction and re-ignition appears at large *Re* while they are absent at small *Re*. As typical examples, two Reynolds numbers of 200 and 60 are adopted here to illustrate the flame blow-off dynamics in the present combustor.

3.3.1. Flame blow-off dynamics at large Reynolds number ($Re \geq 100$)

Fig. 5 shows the first stage of the flame blow-off dynamics (the flame with local extinction and reignition) at $Re = 200$ and $\phi = 0.436$. The left and right flame fronts in the downstream chamber gradually shift toward each other, and the flame front presents a constricted "waist" in the middle of the chamber. A similar phenomenon was observed in previous studies [10,23]. This corresponds to a dynamic process in which the flame consumption speed continuously self-adjusts to match the incoming flow velocity at the flame front. Then, the local extinction and reignition phenomena occur, which is a precursor to flame blow-off. The whole flame splits into two parts (an upstream part next to the flame holder and a downstream part close to the combustor exit) after local extinction. The downstream part is pushed out of the combustor over time. Meanwhile, the upstream part is still anchored by the flame holder, which is referred to as the residual flame [9]. Thereafter, the residual flame ignites the incoming unburnt fuel and subsequently propagates downstream. A similar phenomenon was observed by Chaudhuri et al. [24] in a turbulent propane/air premixed flame stabilized by a triangular flame holder for a high Reynolds number; this was probably attributed to the partial extinction of the shear layer on one side. However, Kedia and Ghoniem [9] pointed out that, for the laminar premixed flame, local extinction does not exist in the shear layer during the blow-off process. Their numerical results showed that the flame blows off after the flame local extinction, and the reignition phenomenon did not occur, which is clearly different from our observations. Here, as the period of the flame for local extinction and reignition is very short (0.40 s at $Re = 200$), the fresh fuel mixture remains at the preheated temperature during this period owing to thermal inertia. In other words, the preheated effect on the fresh fuel mixture is insignificant for the present phenomenon. The flow recirculation zone for a large *Re* is great, which results in good stabilization of the flame root. As a result, the flame root hardly escapes from the flame holder in the blow-off process, which probably indirectly induces the local extinction near the middle of the flame. The stretch effect out of the recirculation zone near the middle of the flame is large, which makes the flame easily locally extinguish around this location. It should be pointed out that, although the heat loss of the flame root to the flame holder is insignificant to determine the blow-off limit and standoff distance at different *Re*, it is still detrimental to flame root stabilization, which might influence the flame propagation mode at the same operating condition. At the first stage, the flame holder temperature is not so low, so the heat loss from the flame root to the flame holder is not large, which is beneficial for the reignition of fuel mixture. The preferential transport effect is also strong in/near the recirculation zone behind the flame holder due to the significant flow two-dimensionality, which provides a beneficial condition for the residual flame propagates downstream. In summary, the local extinction of the flame is induced mainly by the large stretch effect and recirculation

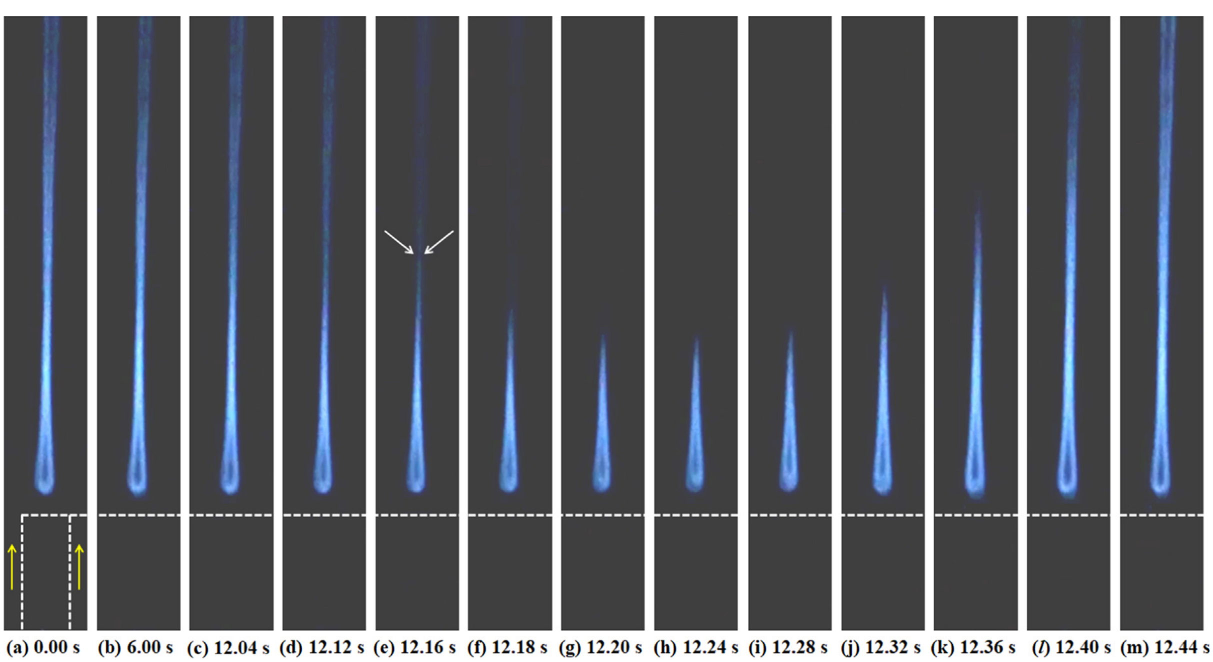

Fig. 5. Side-view images of first stage of flame blow-off dynamics (flame with local extinction and reignition) at $Re = 200$ and $\phi = 0.436$ (the upper wall of flame holder is marked by horizontal dashed lines, the yellow arrow indicates the flow direction of unburned mixture) (50% brightness, 50% contrast).

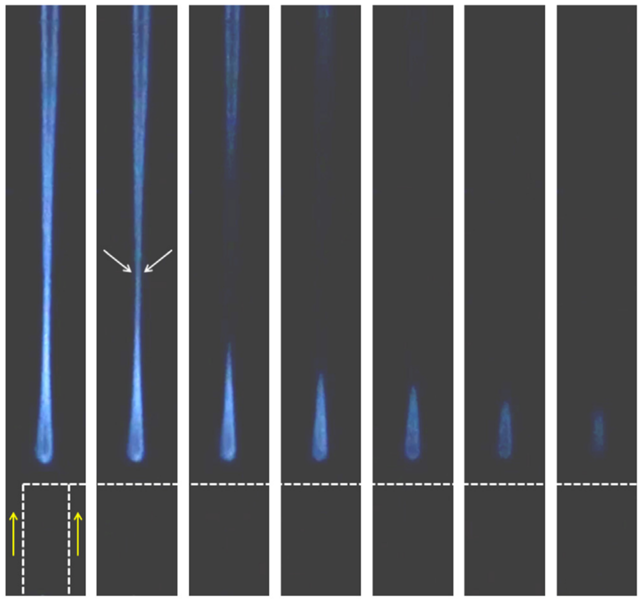

Fig. 6. Side-view images of second stage of flame blow-off dynamics (flame blows off) at $Re = 200$ and $\phi = 0.436$ (50% brightness, 50% contrast).

zone. A smaller heat loss from the flame root to the holder and a better preferential transport effect contribute to the reignition of fuel mixture [25]. In addition, the periods of the flame with local extinction and reignition at different *Re* are different. It is obtained that the periods of the local extinction and reignition phenomenon at $Re = 100$, 120, 140, 160, 180, and 200 are 0.74, 0.72, 0.66, 0.62, 0.56, 0.40 (=12.44–12.04) s, respectively, which means that the period of the above phenomenon decreases with increased *Re*. This is probably because the larger stretch effect at greater *Re* values accelerates the process of local extinction and reignition.

Subsequently, the local extinction of flame occurs in the downstream channel, and the flame is completely extinguished, as displayed in Fig. 6. Because of the local extinction (white arrows in Fig. 6b), the flame splits into two parts. The downstream part of the flame is pushed out of the combustion chamber by the incoming gaseous mixture. The upstream part (residual flame) shrinks toward the flame holder, and it ultimately disappears within the recirculation zone behind the flame holder. A similar phenomenon was observed by Kedia and Ghoniem in the bluff-body combustor without wall thickness via DNS [9]. However, continuously dynamic residual flame was observed by Kurdyumov et al. [26] for a cylindrical rod stabilized premixed flame with $Le = 0.5$ and by Jiménez et al. [13] in a plate combustor with a bluff body for a mixed fuel of 40% H_2/60% CH_4 at $\phi = 0.315$ via DNS. They concluded that the addition of fast-diffusing species (H_2), which can significantly enhance the preferential diffusion effect just behind the flame holder (the local equivalence ratio near the flame holder can increase ~31%), is beneficial for the stability of residual flame. In other words, a weak transport effect can induce the extinction of the residual flame. In the present case, as the flame holder temperature decreases over time, the heat loss of the flame root to the holder increases. Compared with the first stage, the flame holder temperature is very low in the second stage. Therefore, the heat loss from the flame root to the flame holder is large, and the preferential transport effect is weak. These negative effects extinguish the residual flame [25].

3.3.2. Flame blow-off dynamics for a small Reynolds number ($Re < 100$)

The flame for a small *Re* pulsates up and down in initially (see Fig. 7) for seconds to dozens of seconds. As the flame front shifts toward the channel, the flame root narrows. The flame front does not exhibit a constricted "waist" as observed for a large *Re*. This is mainly because,

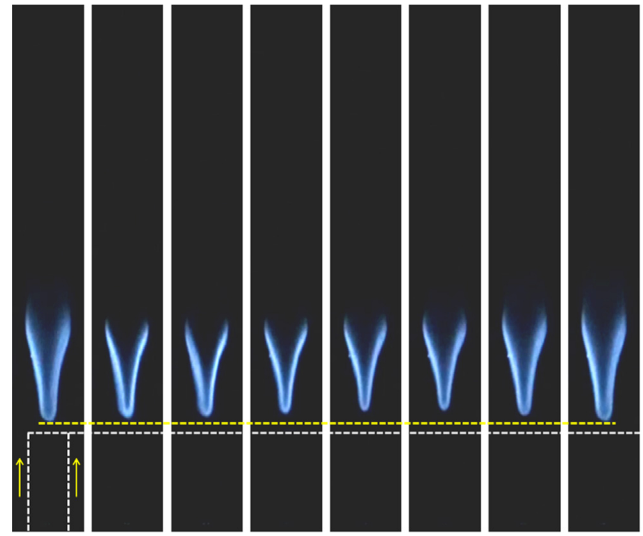

Fig. 7. Side-view images of first stage of flame blow-off dynamics (oscillating flame) at $Re = 60$ and $\phi = 0.446$ (30% brightness, 30% contrast).

on the one hand, the stretch effect at low-velocity incoming flow is small; on the other hand, the fuel amount at smaller inlet velocities is low, so the flame consumption speed is in balance with the incoming flow velocity in a more upstream channel. The appearance of the oscillating flame may be due to the heat loss of the flame root to the flame holder. The heat loss is detrimental to flame root stabilization, and its importance is greater for smaller *Re* because the flow recirculation and preferential diffusion effects (positive effects for flame root stabilization) are weaker [12]. At $t = 0$ ms in Fig. 7, the SD is minimum (~3 mm); therefore, the heat loss from the flame root to the flame holder is the greatest, which decreases the flame speed. As a result, the larger incoming flow velocity pushes the flame root downstream. When $t = \sim 400$ ms, the SD is maximum (~8 mm). The longer SD decreases the heat loss of the flame root to the holder, which increases the flame speed. Subsequently, the greater flame speed shifts the flame root upstream. The oscillating propagation of flame is attributed to the flame speed self-adjusts to match the local flow velocity normal to the flame front surface. Over time, the flame root oscillates up and down. The Froude number (*Fr*) is ~0.1 for the present ultra-lean methane/air premixed flame, which implies that the buoyancy effect, as caused by the difference between the densities of burned and unburned gaseous mixtures is significant [27]. For the present case, the flame root is in the recirculation zone behind the flame holder [12]; therefore, the stabilization of the flame root is better than that of the flame top. However, Fig. 7 demonstrates that the flame root oscillates up and down, and flame top stays at nearly the same location during this stage. Therefore, we deduce that the buoyancy affects the flame shape at most, which is nearly insignificant for the oscillating flame. In addition, the oscillating frequencies at $Re = 80$, 60, and 40 are 1.22, 1.78, and 2.08 Hz, respectively, which indicates that the oscillating frequency increases with a decrease in *Re*.

After the flame pulsates for tens of seconds (~18.06 s in this case), it finally blows off, as shown in Fig. 8. The flame increasingly darkens over time, which implies that the combustion reaction becomes increasingly weaker. Meanwhile, the combustor walls cool over time owing to the heat loss to the ambient environment. As a result, the heat loss of the flame root to the holder increases with time, leading to a lower flame consumption speed. When the flame consumption speed near the flame root becomes very small, the larger incoming flow velocity pushes the flame root downstream. Interestingly, the flame root convects downstream with time, whereas the flame top remains at nearly the same location during this stage. It is deduced that the flame

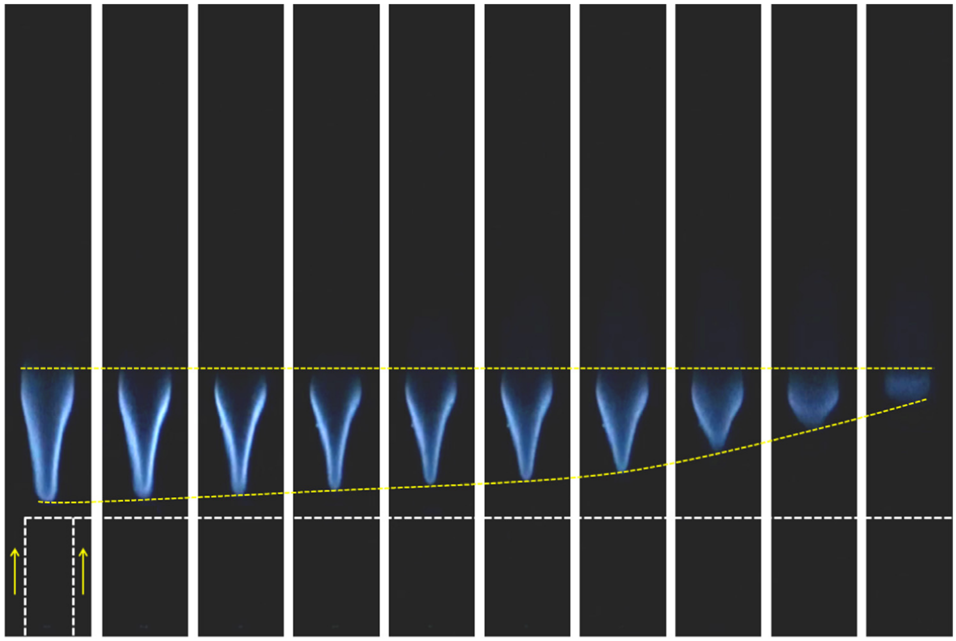

Fig. 8. Side-view images of second stage of flame blow-off dynamics (flame blows off) at $Re = 60$ and $\phi = 0.446$ (30% brightness, 30% contrast).

consumption speed near the flame top approaches a static balance with the local flow velocity. The flame root gradually shifts downstream with an approximately constant moving speed initially, and then rapidly moves downstream. This indicates that the stability of the flame root sharply deteriorates when it is at a sufficient distance from the flame holder. At the same time, the flame becomes increasingly smaller, leading to decreasing heat release (*i.e.*, flame consumption speed becomes slower). Finally, the increasingly weaker flame is completely extinguished at nearly the same location as the flame top. The consumption time required for the flame blow-off process has a positive correlation with the cooling time of the combustor walls. In other words, a longer consumption time means a longer cooling time. The consumption times of the flame blow-off process at $Re = 80$, 60, and 40 are 38.02, 18.56, and 11.58 s, respectively, which implies that the cooling time is shorter for a smaller *Re*. A similar blow-off process was observed in our previous work for a structurally similar but smaller microscale combustor via numerical simulation [28].

4. Conclusions

The present work reports the flame dynamics at ultra-lean conditions in a special combustor with a flame holder and preheated channels. The experimental results show that the flame is always stable before blow-off. The anomalous blow-off limit is observed for the methane/air premixed flame at $Le \approx 1.0$. The anomalous standoff distance with respect to the stable flame is also observed, *i.e.*, the standoff distance between the flame root and the flame holder increases initially and then decreases with a decrease in the Reynolds number *Re*. The blow-off dynamics for a large *Re* and small *Re* display quite different characteristics. When $Re \geq 100$, at the blow-off limit, the left and right flame fronts continuously shift toward each other, and then the local extinction and reignition phenomenon is observed. Subsequently, the local extinction of flame occurs, and the flame splits into two parts. The upstream part (the residual flame) is extinguished within the recirculation zone, and the downstream part is blown out of the combustor. When $Re < 100$, the flame at the blow-off limit continuously pulsates up and down initially. After seconds to tens of seconds, the flame root moves downstream while the flame top remains at nearly the same location, and then the whole flame is completely extinguished within the combustion chamber.

It can be seen that the flame dynamics under the synergistic effect of heat and flow recirculation is different from that only under the flow recirculation effect. The reported anomalous blow-off and standoff distance of lean H_2/CH_4/air premixed flame with $Le < 1.0$ are observed in the present combustor using the lean CH_4/air premixed mixture with $Le = 1.0$. Therefore, the heat recirculation significantly affects on the flame propagation characteristics, which should be considered in the investigation on the flame dynamics in practical combustors. The heat recirculation performance of the combustor walls can be managed by specially designing the combustor configuration and reasonably choosing the solid material. In our next work, the underlying mechanisms that are responsible for the anomalous blow-off limit and standoff distance will be revealed by numerical simulation. The weights of the heat recirculation, flow recirculation, preferential diffusion, and stretch effect on the flame behavior in the present combustor will be quantitatively evaluated.

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.

CRediT authorship contribution statement

Jianlong Wan: Conceptualization, Methodology, Formal analysis, Investigation, Data curation, Writing - original draft, Visualization. **Haibo Zhao:** Writing - review & editing, Validation, Supervision.

Acknowledgements

This work was supported by the National Natural Science Foundation of China (No. 51706080) and the Fundamental Research Funds for the Central Universities (2019kfyXJJS110).

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