Studies on non-premixed flame streets in a mesoscale channel

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Abstract

The effects of channel width, wall temperature, and flow rate on the dynamics of non-premix flames in a mesoscale combustor were studied in methane and propane–air mixing layers. A flame street structure which consists of multiple triple flamelets in the mixing layer of the reactants was observed experimentally for the first time. Depending on the flow rate, it was found that there are two different flame regimes, an unsteady bimodal flame regime and a flame street regime where there are multiple stable triple flamelets. It was found that the separation distance of the flamelets increased due to the dilution effect of the products and that the size of the flamelets was proportional to the width of the mixing layer. A scale analytical model was developed to qualitatively explain the mechanism of flame streets. The effects of flow velocity, wall temperature, and Lewis number were also investigated and the results showed that the occurrence of flame street regimes was a combined result of heat loss, curvature, diffusion, and dilution effect.

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1. Introduction

The development of portable power supplies and micropropulsion systems need to understand combustion in mesoscale (with flame size close to the quenching diameter) [1–5]. In most practical applications, in order to control fire safety and flame stability, fuel and oxidizer are injected separately into the combustion chamber and then mixed by turbulent flow. In small scale combustion, since the Reynolds number is small, species mixing will be primarily achieved by molecular diffusion. Due to the short flow residence time, reactants and oxidizers may not be able to be fully premixed before combustion. As such, non-premixed combustion plays an important role under most flow conditions. However, unlike the large scale flames, combustion in mesoscale is also strongly affected by wall heat losses and kinetic quenching due to the reduced diffusion time scale [6–9].

The couplings of enhanced heat loss and kinetic quenching, and reduced fuel/oxidizer mixing at mesoscale could induce new phenomena for non-premixed combustion. For example, in a microscale experiment, multiple isolated reaction zones or flame cells were observed both in conditions away from and close to the extinction limit in the Y-shaped diffusion burner [3,10]. The high-speed images from startup process clearly showed that the formation of the isolated flame cells was resulted from the pure extinction/reigni-
tion process. Unfortunately, due to the limitation of flame scale, the mechanism responsible for this diffusion flame instability in microscale combustors has not been well understood. It is not clear whether these flame cells were caused by cellular instability or local flame quenching or reignition. However, the presence of cellular flames causes incomplete combustion and fuel leakage, which significantly limits the performance of microscale combustors. As such, fundamental understanding of the impacts of mixing and flame–wall interaction on non-premixed flames in mesoscale combustion needs to be addressed in order to successfully develop microcombustors.

In addition to the development of microcombustors, studies of non-premixed flames in mesoscale combustor involving mixing and heat losses offers an alternative way to understand the dynamics of non-premixed flames in turbulent combustion [11]. Due to the limiting diffusion process, the ignition, flame propagation, and extinction of non-premixed flames in a turbulent flow obviously involve the triple flame-like structures [11–14]. Therefore, understanding the dynamics of triple flames and edge-flames subject to heat losses in mesoscale combustion also help to gain insights to explain ignition, propagation, and partial extinction of triple flamelets in turbulent non-premixed combustion [10,15]. Unfortunately, most of the previous studies on mesoscale combustion focused mainly on premixed flames. As such, the burning regimes, flame stabilization, and unsteady propagation of non-premixed flames in a mesoscale channel remain unknown. For large scale non-premixed flames, experimental, theoretical, and numerical studies have been conducted extensively to understand the flame propagation speed, lift-off height, and stability of triple flames [16–19]. It was found that the flame speed correlates well with flame curvature and mixture fraction gradient [16]. Other work has been conducted to study the heat release effects on laminar flame propagation in partially premixed flows [18] and the effects of Lewis number on triple flame speeds and extinction [19]. Unfortunately, little attention was paid to the effects of heat loss, flame scale, and reignition on the dynamics of triple flames. No reports are available on the dynamics of flame streets.

The goal of this paper is to study the steady and unsteady dynamics of multiple triple flames (flame street) in a mesoscale channel. First, a mesoscale combustor with controlled wall temperature was developed. Second, a stable flame street and an unsteady bimodal flame regime were observed and studied experimentally for methane and propane–air non-premixed flows. After that, a scale analysis was developed to explain the mechanism of flame streets, and finally the conclusion was made.

2. Experimental setup

A mesoscale combustor with temperature-controlled heating surfaces was built to study the non-premixed combustion with enhanced heat losses and increased diffusion time scale. The combustor (Fig. 1 (a)) consisted of two horizontal silicon carbide plates, 241 mm long (L), 95 mm wide and 6 mm thick. Two rectangular quartz windows were positioned between the two ceramic plates to allow the optical access and keep a constant channel height of 6 mm (H). The resulting mesoscale channel combustor size was delineated by the $241 \times 95 \times 6 \text{ mm}^3$ enclosure. The silicon carbide plates have a high thermal conductivity ($\sim$120 W/mK) and low thermal expansion coefficient, and can provide a uniform wall temperature distribution in a broad temperature range. The two plates are separated from the aluminum frame by using two ceramic support rims, which are made of machinable alumina silicate with a thermal conductivity of 1.3 W/mK. The support rims sit on a $241 \times 114 \times 50 \text{ mm}^3$ silica foam block with a thermal conductivity of 0.187 W/mK. Between the silicon carbide plate and the silica foam, a metal heating coil is used to control the temperature of the silicon carbide plates. The heating coil controlled by an AC power supply has a resistance of 11 Ω and gives a maximum heating power of 1 kW. The temperatures of the silicon carbide plates can be raised up to 700 and 1000 K, respectively, by using one or two heating coils. The surface temperatures of the plates were measured using a K-type thermal couple with the quartz plate taken off and the heating power fixed. Due to high heat conductivity of the silicon carbide and the insulations surrounding the plates, the maximum
surface temperature difference at full heating power is less than 15 °C.

At the inlet, a 400-cell honeycomb was mounted into the inlet connector. The ceramic honeycomb was divided into two separate parts, so that it could discharge uniform flows of fuel and oxidizer between the two parallel plates and generate a mixing layer between the fuel and air streams. The flow rates of fuel (methane and propane) and air were controlled by choked sonic nozzles. In order to visualize the flames in the mesoscale mixing layer, the top half burner was replaced with a quartz plate. A Canon Digital Rebel Xt 350D SLR camera was used to capture static images and a high-speed video camera (PHOTRON 120K) to record transient images.

3. Experimental results

3.1. Observation of non-premixed flame streets

The schematic top view of the formation of fuel/air mixing layer and the flame street (multiple flamelets) is shown in Fig. 1(b). A mixing layer is formed between the fuel and air streams along the flow direction from left to right. At the leading edge of the mixing layer, fuel and air mix quickly and form a partially premixed region with the stoichiometric line centered in the mixing layer. Therefore, experimentally, there is an anchored leading triple flame due to the lower flow speed at the splitter than the propagation speed of the triple flame. It is interesting to note that, different from the single triple flame structure observed in the conventional non-premixed flames, in mesoscale non-premixed combustion, a series of triple flame structures emerged in the mixing layer after the first anchored triple flame. Due to the similarity to the vortex street in a mixing layer, we call these multi-triple flamelet structures the flame street. The occurrence of the flame street in mesoscale combustion is due to the triple flame coupling with fuel diffusion and heat losses. First, after each triple flamelet the diffusion flame branch extinguishes due to the external heat loss, dilution of the burned products, and the insufficient diffusion of reactants. Second, the reactants continue to diffuse into the mixing layer. After a certain delay time, reignition occurs in the mixing layer and a new triple flame is formed. Third, the new triple flame propagates upstream at a decreasing flame speed and is stabilized at the location where the local flame speed is balanced by the flow speed. This process repeats and forms a series of triple flamelets until the reactant gradients across the mixing layer become so small that it cannot support a triple flame beyond the flammability limit. Therefore, the flame street structure will be dominantly affected by the flow residence time (diffusion time), the heat loss to the wall, and the temperature dependence of chemical kinetics. In order to examine the effects of fuel Lewis number and temperature dependence of chemical kinetics, methane and propane which have very distinct Lewis numbers and activation energies are investigated in the experiments.

By controlling the flow velocity and wall temperature, it was found that there exist two flame regimes: the stable non-premixed flame street regime and the unsteady bimodal flame regime. The flame regime boundary is shown in Fig. 2 for methane and propane. The unsteady bimodal flame regime exists at low flow rates where only repetitively unsteady propagating and extinction triple flames can be observed in the mixing layer. The stable flame street regime exists at high flow speed. With the increase of wall temperature, the flame street boundary becomes broader due to the extended flammability limit of the triple flame. At a higher wall temperature, the flame can burn at much leaner mixtures and stabilize at a lower flow speeds. The non-premixed flame street is comprised of one or multiple triple flamelets inside the mixing layer dependent on the wall temperature and the flow velocity. The onset mechanism of the triple flamelets was explained schematically in Fig. 1(b). Along the stoichiometric line, flame speed decreases due to both the dilution of the products from the previous flamelet, the heat loss to the wall, and the diffusion rates of reactants. Meanwhile, the flame curvature also increases and flame size decreases. If the flow velocity is too low, the flame will be extinguished due to the increased product dilution and heat loss as well as decreased reactant diffusion, leading to the unsteady bimodal flame regime. On the other hand, if the flow velocity is high enough, the flame can stabilize where the flow speed balances with the flame speed, leading to the stable flame street regime.

Figure 3b and c shows, respectively, the top and side views of a flame street with four stable flamelets (including the leading triple flame) and the wall, and the temperature dependence of chemical kinetics. In order to examine the effects of fuel Lewis number and temperature dependence of chemical kinetics, methane and propane which have very distinct Lewis numbers and activation energies are investigated in the experiments.

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Fig. 2. Flame street regimes of methane and propane flames.
the flame structure of these flamelets (a1–a4). It is seen that each flamelet has a triple flame structure. The two "wings" correspond to the two partially premixed flames, a rich flame on the fuel stream side and a lean flame on the air side. The luminescence intensity of the rich flame branch on the fuel side is stronger than that of the lean flame branch on the air side due to the higher concentrations of CH and C2 radicals on the rich side. The unburned fuel and oxidizer behind the two partially premixed flame branches diffuse toward each other and form a diffusion flame branch along the stoichiometric contour. The non-premixed flame branch is very weak due to the heat loss. The distance between the ith and the (i+1)th flamelets is defined as \(d_i\). Therefore, \(d_0\) is the length of the leading triple flame and \(d_1\) is the tail–head distance between the leading flame and the first flamelet.

In the current experiments, in order to avoid excessive unburned fuel, the flow speed of fuel stream is kept lower than that of the air stream. Due to the viscous stress on the wall, a higher flow velocity corresponds to a higher pressure drop in the channel (\(dp/dx \sim U_{\text{max}}\)). Since the exit pressure is the same, the stream with a higher flow speed has a higher pressure in the channel. Due to the pressure effect, the centerline of the mixing layer is pushed towards the fuel side when the air flow velocity is higher. Since oxygen in the air stream is only 21%, the stoichiometric line for methane–air mixture is on the air side of the centerline of the mixing layer. As a result, the flamelets are more sensitive to the air flow speed than the fuel flow speed. It was also observed experimentally that an increase of the fuel flow rate only slightly changed the flame separation distances.

### 3.2. Effects of wall temperature and air flow velocity

The top views of the flamelets at different wall temperatures in the flame street regime are shown in Fig. 4. The change of wall temperature affects the flame distance in two different ways. First, at a higher wall temperature, the heat loss from flame to the wall is reduced and the flame temperature will increase. As such, the flamelets can stabilize at more diluted conditions and the flame separation distance becomes shorter. Second, as the wall temperature increases, the mean flow velocity in the channel increases due to thermal expansion. As such, both fuel and oxidizer take longer distance to diffuse into each other. As a result, the flame distance increases linearly with the increase of flow speed. Since methane has a much higher activation energy (48.4 kcal/mol) than propane (30 kcal/mol) [20], due to the exponential dependence of flame speed on flame temperature, the methane flame speed is much more sensitive to the increase of mixture temperature than propane. Our experiments showed that, for methane flames, as the wall temperature increases, the first effect dominates (Fig. 4). However, for propane flames, the thermal expansion effect dominates, and the flame distance slightly increases. Figure 4 also shows that the length of the diffusion branch increases as the wall temperature increases. This increase implies that the heat loss to the wall plays an important role to the extinction of the triple flame. At a very high wall temperature around 500 °C, the diffusion flame branch does not quench and all flamelets merge, leading to a single triple flame structure, which is the case reported in the conventional triple flame studies.

In Fig. 5, it is seen that the distances between the flamelets increases nonlinearly with increasing air flow speed. In addition, at all wall temperature and flow rate conditions, the flame distance of the present flamelet is larger than that of the previous one. This increase of the tail–head distance is a result of the product dilution effect from the neighboring flamelet at upstream and the increase of diffusion length scale. After each flamelet, the reactants are consumed and the wake of the triple flame has a very high concentration of the burned products. Due to the growth of the mixing layer
and products dilution, it takes longer distance for diffusion before the reactants at the stoichiometric line reach the flammable limit.

3.3. Unsteady bimodal flame regime

In the unsteady bimodal flame regime where the flow rate is below the speed of the triple flame stabilization limit, a triple flame will propagate close to the anchored leading triple flame. Since the convection velocity is too low to transport the reactants into and the products out of the mixing layer, the propagating triple flamelet will be quenched by a small external heat loss via both radiation and heat conduction. This is also why a diffusion counter flow flame does not exist at low stretch rates due to the existence of radiation extinction limit and the slowdown of the reactant transport [21].

The triple flame propagation history is shown in Fig. 6(a). It is seen that both the flame size and the flame speed decreases as it propagates upstream. The flame size (in the transverse direction) is roughly proportional to the mixing layer thickness generated by the previous triple flamelet. The onset mechanism of Flame Street and the triple flame interaction in mesoscale non-premixed combustion can be clearly explained by the evolution of the unsteady bimodal flame regime shown in Fig. 6(b). Initially, there was only a single stable triple flamelet “A” formed in the upstream of the mixing layer. Then, a new triple flamelet “B” was formed at the downstream and propagated upstream. Both its size and flame speed decreased as it moved upstream. Due to the triple flame interaction between “A” and “B”, the triple flamelet “B” decelerated and finally stabilized in the product wake of the previous triple flamelet “A”. At $t = 0.16$ s, triple flamelet “A” extinguished and this change in the product dilution due to the extinction of triple flamelet “A” reached triple flamelet “B” at $t = 0.4$ s. Therefore, at $t = 0.48$ s, triple flamelet “B” grew in size and accelerated again as a propagating flamelet. It then stabilized at the same location as flamelet “A” and extinguished due to the heat loss. The extinction, reignition, and unsteady propagation processes repeated, resulting in the unsteady bimodal flame regime.

The wall temperature has a significant effect on the triple flames. At a heating power of $P = 360$ W, there exist three triple flamelets, leading to the stable Flame Street regime. When the heating power reduces to 160 W with the flow speed fixed, no stable flamelet exists, leading to the bimodal regime. Figure 7 shows the flame size as a function of the flame position at average flow speed of 20 cm/s. Position “0” corresponds to the end position of the anchored leading triple flame tail. It is seen that at the transient state when the flamelet propagates along the stoichiometric line in the mixing layer, it has a larger flame size compared to the stabilized flamelet inside the flame street. This is because the size of the flamelet is determined by the width of the mixing layer in the wake of the previous triple flamelet. The flame size will increase as the distance between two neighboring flamelets increases.

The sensitivity of flame position to the air flow velocity depends strongly on the location of stoichiometric line. Higher fuel diffusivity and stoichiometric air–fuel ratio shift the stoichiometric line to the air side. The measured distances of methane and

Fig. 5. Measured flame distances at $P = 670$ W, $U_{CH_4} = 12$ cm/s.

Fig. 6. Flame propagation history at heating power 160 W, $U_{CH_4} = 11$ cm/s, $U_{air} = 29$ cm/s: (a) one flamelet and (b) two flamelets.
propane flames are shown in Fig. 8 at the same wall temperature. It is seen that with the increase of the air flow speed, the flame distances for both methane and propane flames increase. Compared to propane, methane flame distance is affected more with the increase of the air flow speed. The larger the fuel diffusion velocity, the stronger the flame distance is affected by the increase of air flow speed.

4. Scaling analysis

The schematic of the flame street configuration is shown in Fig. 1(b). Following Ghosal and Vervisch [22], by assuming a constant density, zero thermal expansion, unity Lewis numbers, and using the characteristic diffusion length \( l_D = k/U_\infty \) for normalization, the governing equation of the fuel/air mixture fraction can be written as

\[
\frac{\partial Z}{\partial x} = \frac{\partial^2 Z}{\partial y^2}
\]

(1)

where the superscript “*” represents nondimensional variables, and \( Z \) is the mass fractions of fuel and oxidizer or the fuel mixture fraction. The analytical solution of the pure diffusion symmetric mixing layer problem can be easily solved [22].

The mixing layer thickness is derived as \( \delta(x^*) = 4\sqrt{x^*} \).

For a triple flame to be stabilized in the mixing layer, its local flame speed must be equal to the local flow velocity at the stoichiometric surface. The triple flame speed depends on many parameters such as the curvature of the partially premixed front, thermal expansion, heat loss, dilution, and preheating by the burning products. Following Ghosal and Vervisch [22], the normalized triple flame speed is given as a function of the dimensionless mixture fraction gradient

\[
S_t/S_L(x) = f \left( \frac{1}{Z} \frac{\partial Z}{\partial y}, x, \beta \right)
\]

(2)

where \( S_L(x) \) is the speed of a stoichiometric planar flame without curvature, and \( S_t \) is the triple flame speed; \( \beta \) is Zeldovich number; \( x \) is the thermal expansion rate.

The thermal expansion effect increases the flame speed by a constant factor and significantly modifies the triple flame speed [22,23]. The laminar flame speed with the thermal expansion effect is obtained by Ghosal and Vervisch [22]

\[
S_L(x) = (1 - x)^2 S_L(0)
\]

(3)

For a planar flame, it is well known that the normalized planar flame speed \( (m = S_t/S_e) \) depends on the normalized heat loss \( (H) \) as [24]

\[
\ln m = -2H/m^2
\]

(4)

\( H \) is normalized rate of heat loss rate on the inner wall surface defined as \( H = 2h_D T_F/(d\rho C_p S_{L,ad})^2 \); \( d \) is the characteristic channel width, \( D_T \) is the thermal conductivity, and \( h_i \) is the heat transfer coefficient on the wall.

The triple flame speed can also be modified by the dilution and preheat of the products from the previous flamelet. Let us consider a simple one-step combustion process with \( v_F \) molecules of a fuel react and \( v_O \) molecules of an oxidizer to form \( v_P \) product molecules. Without dilution, the mixture fractions of the reactants have to sum up to one: \( Y_O + Y_F = 1 \). As such, the reaction rate of adiabatic flame without dilution is as following

\[
a_0 = \left( \frac{\rho}{1 + r} \right)^{\nu_F} \left( \frac{\rho}{1 + r} \right)^{\nu_O} k(T)
\]

(5)

where \( r \) is the stoichiometric ratio. However, at the stoichiometric line behind a flamelet, the sum of the mixture fractions of the reactants is less than unity, and the laminar flame speed is reduced. Since the laminar flame speed is proportional to the square root of the reaction rate, the flame speed of a diluted flame is written as

\[
\frac{S_{L,ad}}{S_{L,ad}} = \left( \frac{a_0}{a_0} \right)^{1/2} = \left( (1 + r)Y_F \right)^{\nu_F/2} \left( \frac{1 + r}{r} Y_O \right)^{\nu_O/2}
\]

(6)
Therefore, the triple flame speed modified due to dilution of the products, heat loss and curvature can be expressed as following:

\[
\frac{S_t}{S_{L,ad}} = ((1 + r)Y_F)^{\nu/2} \left( \frac{1 + r}{r} \right)^{\sigma/2}
\]

\[
m(H)f\left(\frac{1}{Z_{F_s}}, \frac{\partial Z_{F_s}}{\partial y^*}, \alpha, \beta\right)
\]

(7)

where the subscript "s" represents the stoichiometric condition. The preheating effect from the previous flamelet might increase the laminar triple flame speed. However, a further analysis shows that this preheating effect can be ignored. In our experiment, the distance between the two ceramic plates is 6 mm. The flow velocity is in a range from 10 to 40 cm/s, which gives a Reynolds number of around 100. The thermal boundary layer thickness of a laminar flow is

\[
\delta_l = \frac{\delta}{1.026\sqrt{Pr}} = \frac{4.64\sqrt{\mu x/(\rho V)}}{1.026\sqrt{Pr}}
\]

(8)

A thickness of 3 mm gives a characteristic inlet length of 1 cm at \(U_\infty = 40\) cm/s. A simple analysis showed that the hot gas would be significantly cooled down close to the wall temperature within 2 cm, which is typically smaller than the average flamelet distance. Therefore, this preheating effect from the previous flamelet can be neglected.

For a stable triple flamelet, its triple flame speed is equal to the flow speed at the infinity, i.e., \(S_t = U_\infty\). Using Eq. (9), the flame position can be obtained. For a single propagating triple flame, the mixture fraction distribution is obtained using Eq. (1) and the flame curvature at the stoichiometric line can be derived as a function of the flame position

\[
\frac{1}{r_{cur}^*} = \kappa = -\frac{1}{4\sqrt{\pi}} \frac{\partial Z}{\sqrt{4V - 2\partial y^*}}
\]

(9)

\[
r_{cur}^* = \frac{\sqrt{\pi}x^* - 2}{\beta} = \frac{\sqrt{\pi}x - 2}{4\beta}
\]

(10)

As such, the flame size is roughly proportional to the size of the mixing layer at a transient state. The numerical procedure is as following: (1) a fully explicit method is used to solve Eq. (1) to obtain the mixture fraction distribution; (2) the first flame position is found by evaluating Eq. (7) and comparing the triple flame speed with the flow speed; (3) after that, Eq. (9) is used to get the flame surface profile. The flame surface is cut off when the gradient is larger than 10 (\(d\xi^*/dy^* > 10\)) such that the transverse flame size does not increase. The fractions of reactants are set to zero after the flame surface (infinite fast reaction rate). Based on the boundary conditions obtained after each flamelets, the mixture fraction distributions of further downstream can then be calculated and another flamelet is obtained.

In the current scaling analysis, the structure of the diffusion flame branch is not included. Nevertheless, the current model can qualitatively capture most of the phenomena identified in our experiments. The heating power is taken into account by changing the heat loss parameter, \(H\). Figure 9 shows the simulated fuel fraction distribution and the configuration of the flame street. \(S^*\) is the normalized flow speed by the adiabatic planar flame speed. It is seen that the distance between two neighboring flamelets increases as the flamelets move further away from the leading edge. Although the results are not shown here, the analysis also showed that an increase in either air flow speed or heat loss would increase the distance between two neighboring flamelets. All these results agree qualitatively well with our experiments.

The calculated flame sizes at a transient process and inside a flame street are shown in Fig. 10. The scales of \(x\) and \(y\) axes are normalized by the characteristic diffusion length. In a flame street, a flamelet that is stabilized further away from the leading edge is also slightly bigger than the previous flamelet. However, the size of flamelets in a flame street...
is much smaller than a triple flame in a transient state. Those results are also consistent with our experimental observation shown in Fig. 7. In the current case, using the mass diffusivity of methane (0.254 cm²/s) and the average inlet velocity (25 cm/s) of methane and air, the calculated characteristic diffusion length is about 0.1 mm. The calculated maximum flame sizes in a flame street and in a transient state are about 3 and 8 mm, respectively. The corresponding values in Fig. 7 are 4.4 and 7.9 mm, respectively. Considering the simplicity of the scaling analysis, the results agree qualitatively well with the experimental results. Therefore, the fuel–air mixing, wall heat loss, and triple flame–triple flame interaction dominate the dynamics of the flame street in mesoscale non-premixed combustion.

5. Concluding remarks

Non-premixed flamelets in a mesoscale mixing layer were studied. The occurrence of stable flame street and unsteady bimodal flame propagation was observed experimentally for different fuels for the first time. It was found that the stable flame street occurred at high air flow speeds and the unsteady bimodal flame regime appeared at low air flow speeds. For a stable flame street, the number of flamelets and the flame distance in the mixing layer depends on the flow rate, wall surface temperature, and fuel diffusivity. The distance between two neighboring flamelets increases with increasing flow speed. The onset of a flame street highly depends on the wall heat loss, production dilution effect, mixing layer thickness, and reignition. The size of the flamelets depends on the width of the mixing layer. The unsteady bimodal flame regime is dominated by the triple flame–triple flame interaction and heat loss induced triple flame extinction. A scaling analysis model was developed to describe the mechanism of the multi-flamelet flame street. The results of flame distance agree qualitatively well with the experimental results. A modified model that takes into consideration of the flame extinction and thermal expansion effect is necessary in order to give a better prediction of the flame streets.

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Appendix A. Supplementary data


References