FLAME CHARACTERISTICS INFLUENCED BY THE ANGLE OF BURNERS FOR NON-PREMIXED C_3H_8/ AIR

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The study of micro flame characteristics is an essential basis for developing micro combustors. Therefore, the non-premixed C_3H_8/air micro flame characteristics were experimentally studied. Flame length, flame shape and blow-out limit were studied by varying the equivalence ratio (Φ), the inlet velocity of C_3H_8/air (v) and angles of the burner. The results showed ignited non-premixed C_3H_8/air had 3 combustion states: no flame, a stable flame, and a blow-out flame. Whether ignited non-premixed C_3H_8/air could form a stable flame mainly depended on Φ and v. In addition, total flame lengths increased with the increase of Φ and v firstly. However, when Φ increased to a certain value, total flame lengths were independent of Φ and only affected by v. Moreover, flame length and shape were affected by the angle of the burner. Instead, the blow-out limit was found to be associated solely with Φ, but not the burner angle. The findings of this study provided fundamental data for the development of high-efficiency micro combustors.

Key words: *Blow-out limit, flame stability, flame shape, flame length, non-premixed flame*

1. Introduction

Micro energy system based on hydrocarbon combustion has higher energy density than traditional batteries, which is a trending research topic. A micro combustor is one of the most important components of a micro energy system. The research of micro flame [1, 2] is the basis for the development of high-efficiency and high-reliability micro combustors. Research of flame on a small scale [3, 4] is significant to completely understand micro combustion characteristics.

When the combustible gas and oxidant are thoroughly mixed before ignition, the flame is a premixed flame. Several researchers [5, 6] have studied the characteristics of premixed flame. Liqiao Jiang et al. [7] determined the flame height and blow-out limit of premixed methane/air flames. The results show that the flame height is proportional to the incoming flow velocity. N-heptane/air [8] and n-butane/air [9] premixed flame characteristics were also studied experimentally. Moreover, Jianlong Wan et al. [10] illustrated the blow-off mechanisms of methane/air premixed flame. The previous studies have made outstanding contributions to understanding premixed flame structure [11, 12].

However, most of the studies are focused on the premixed [13] rather than non-premixed flame. The influencing factors of non-premixed flames are complex [14]. Recently, researchers [15, 16] also studied non-premixed flame. Xing Li et al. [17] conducted experiments to investigate the effect of external air on the characteristics of non-premixed methane/air flame. Daiqing Zhao et al. [18] found a thermal coupling between micro flame and nozzle, and the influence of the nozzle on the flame was significant. In previous studies, hydrogen, methane, n-butane, etc., were primarily used as combustible gas. However, studies on propane/air non-premixed combustion are not sufficient, and the impact of burner angle on flame characteristics is seldom studied.

Due to the lack of studies on the flame characteristics of non-premixed C_3H_8/air combustion, especially the influence of burner angle on flame characteristics, this paper developed a non-premixed C_3H_8/air combustion experiment setup. In the present study, the effects of equivalence ratio (Φ), the velocity of non-premixed C_3H_8/air (v) and the placement angle of the burner on the flame characteristics such as blow-out limit, flame length, and flame shape were studied. This work is expected to provide fundamental data for micro-scale non-premixed combustion.

2. Experimental design and specifications

A schematic diagram of the experimental setup is presented in Fig. 1. A high pressure gas cylinder released propane. An air compressor provided air. The volume flow rates of propane and air were regulated by high precision mass flow controllers (MKS 1179A) with an accuracy of ±1% and the response time was not more than 1 s. A tube with an outer diameter of 5 mm and a wall thickness of 1 mm was used to connect the propane cylinder or the air compressor, ball valves, and mass flow controllers. Propane and air were mixed in the tee, then entered the burner. The burner was a round stainless steel tube with an outer diameter of 5 mm and a wall thickness of 1 mm. An igniter was used to ignite C_3H_8/air at the burner outlet. When ignited C_3H_8/air formed a stable flame, the flame length was measured using a ruler. The camera (Cannon EOS M6 MRK II) captured the flame shape.

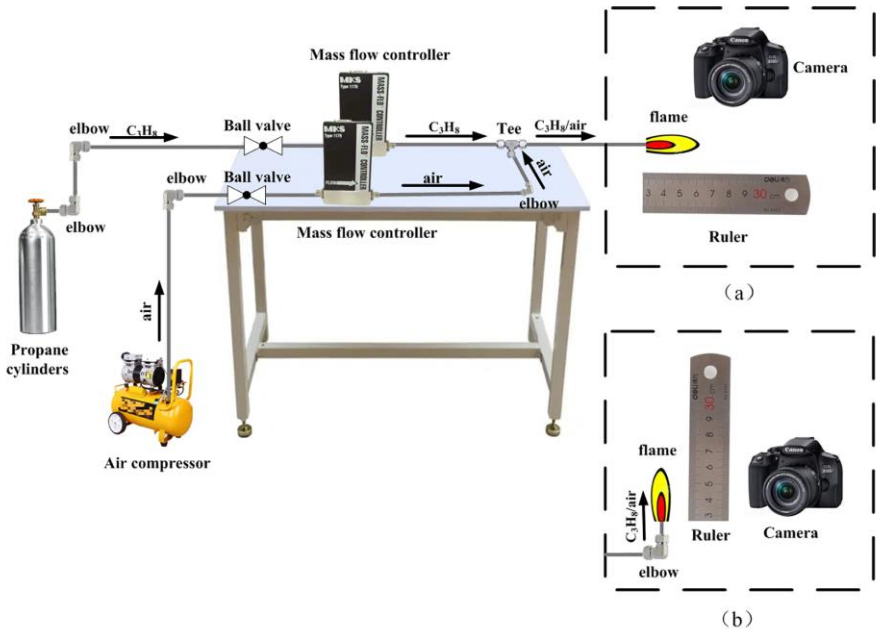

Figure 1. Schematic of the experimental setup: (a) with the horizontal burner; (b) with the vertical burner.

Equivalence ratio ("Φ") is the mole ratio of air required for complete combustion of fuel in theory to air actually supplied, which is equal to actual fuel air mole ratio divided by stoichiometric fuel air mole ratio for complete combustion. For example, if volume flow rates of C_3H_8 and air are 0.10 L/min and 0.7 L/min respectively, the actual fuel air mole ratio is 0.1/0.7 = 0.143. However, for complete combustion of 1 mol C_3H_8, 23.8 moles air are required, which means the stoichiometric fuel air ratio is 1/23.8 = 0.042. Thus, Φ = 0.143/0.042 = 3.40. The velocity of non-premixed C_3H_8/air ("v") is equal to the volume flow rate of non-premixed C_3H_8/air divided by the cross-sectional area which is calculated based on the inner diameter of the burner.

3. Results and discussions

3.1 Blow-out limit

Affected by Φ and v, ignited non-premixed C_3H_8/air had 3 states: no flame, a stable flame, and a blow-out flame. Only when Φ reached a specific value, ignited non-premixed C_3H_8/air in a specific range of v could form a stable flame. However, when v further increased beyond a certain value, the flame was blown out. The certain value of v was the blow-out limit of C_3H_8/air at a certain Φ. To study the relationship between Φ and blow-out limits, the following experiments were conducted.

Firstly, blow-out limits of non-premixed C_3H_8/air with different Φ were measured for the horizontal burner shown in Fig. 1a. The process was divided into 2 steps. Step 1 involved the measurement of blow-out limits of non-premixed C_3H_8/air with a certain Φ. Taking Φ = 3.40 as an example. The volume flow rate of C_3H_8 was set at 0.10 L/min at first because the minimum volume flow rate that the propane mass flow controller can stably control was 0.10 L/min. Subsequently, the air volume flow rate was set at 0.7 L/min. After that, to observe the combustion state of C_3H_8/air, C_3H_8/air was ignited at the outlet of the burner. If the flame was not blown out, the next experiment was proceeded. The volume flow rate of C_3H_8 increased at the interval of 0.01 L/min, while the volume flow rate of air increased at the interval of 0.07 L/min. As the volume flow rates of C_3H_8 and air increased, v increased. When the flame was blown out, the value of v was the blow-out limit of C_3H_8/air at Φ = 3.40. In step 2, Φ was changed, and corresponding blow-out limits were measured. Thus, blow-out limits of C_3H_8/air at different Φ for the horizontal burner were obtained.

Next, the burner angle was adjusted horizontally to vertically by adding a 90º elbow, and a burner which size was the same with the horizontal burner. The vertical burner is shown in Fig. 1b. Furthermore, steps 1 and 2 were repeated to obtain blow-out limits of C_3H_8/air at different Φ for the vertical burner. Comparisons of blow-out limits for the horizontal and vertical burner are shown in Fig. 2.

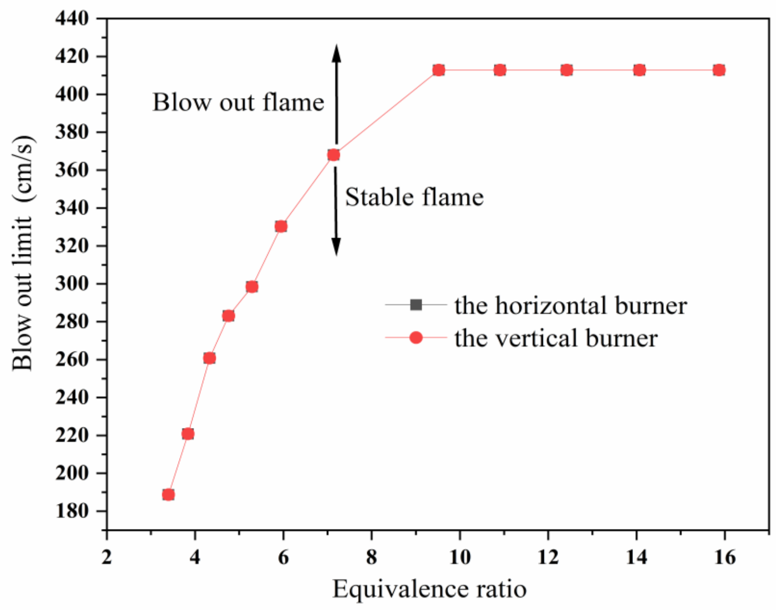

Figure 2. Comparisons of blow-out limits for burners with different directions.

In Fig.2, the red and black solid line represented blow-out limits for the vertical and horizontal burner, respectively. When v was bigger than the blow-out limit, the flame was blow out. However, when v was equal to or smaller than the blow-out limit, the flame was stable. As seen from Fig. 2, the red and black solid line coincided completely, which suggested that burner angles did not affect blow-out limits. Furthermore, with the increase of Φ, blow-out limits noticeably increased. For instance, when Φ were 3.40 and 9.52, blow out limits were 188.7 cm/s and 412.8 cm/s, respectively. Stated differently, for $v \geq 188.7$ cm/s, ignited non-premixed C_3H_8/air at $\Phi \geq 3.40$ could form a stable flame. However, when v increased to be greater than 412.8 cm/s, no matter how Φ increased, the flame was blown out. That was to say, the value (v = 412.8 cm/s) was the blow-out limit of C_3H_8/air at $\Phi \geq 9.52$. Besides, it was found that Φ and v affected the flame length and shape.

3.2 Flame length

A series of experiments were designed to study the effects of Φ and v on flame lengths. Taking Φ = 4.76 as an example, the experimental design is listed in Tab. 1.

Table 1. Experimental design for Φ=4.76.

No.	1	2	3	4	5	6	7	8	9	10
Volume flow rate of C_3H_8, L/min	0.10	0.11	0.12	0.13	0.14	0.15	0.16	0.17	0.18	0.19
Volume flow rate of air, L/min	0.50	0.55	0.6	0.65	0.7	0.75	0.8	0.85	0.9	0.95
Volume flow rate of C_3H_8/air, L/min	0.60	0.66	0.72	0.78	0.84	0.90	0.96	1.02	1.08	1.14
v, cm/s	141.5	155.7	169.9	184.0	198.2	212.3	226.5	240.6	254.8	268.9

Firstly, volume flow rates of propane and air were set on two mass flow controllers, respectively. For example, the volume flow rate of C_3H_8 was set at 0.10 L/min. Then, the air volume flow rate was determined to be 0.50 L/min for Φ = 4.76. Non-premixed C_3H_8/air was subsequently ignited at the burner outlet. In this case, ignited C_3H_8/air could form a stable flame. Then, the total flame length was measured with a ruler. Thus, the total flame length was recorded for v = 141.5 cm/s and Φ = 4.76. Secondly, v was changed while Φ was kept constant at 4.76 by changing volume flow rates of C_3H_8 and air in proportion. The data of total flame lengths for different v were recorded one by one until the flame was blown out. Finally, a series of experiments with various v as shown in Tab. 1 were performed for Φ = 4.76.

Following this, experiments were carried out for Φ = 3.38, 3.95, 5.95, and 6.81. Experimental results are summarized in Fig. 3.

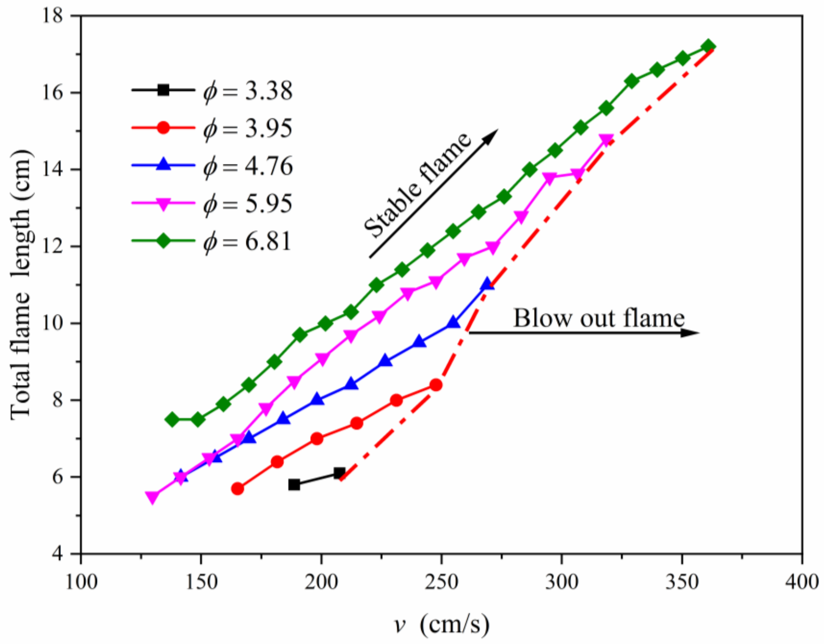

Figure 3. Total flame lengths versus v for the horizontal burner.

As shown in Fig. 3, when Φ was at the range of 3.38 - 6.81, the following rules were obtained. Firstly, the larger the Φ, the larger the blow-out limit (see the red dash-dotted line in Fig. 3) and the wider the range of v for stable flame. Secondly, when non-premixed C_3H_8/air at the same v and different Φ was ignited to form a stable flame, the larger the Φ, the larger the total flame length. Thirdly, the total flame length increased with increasing v. To compare effects of burner angles on total flame lengths, total flame lengths for the horizontal burner were compared with those for the vertical burner at the condition of v = 200.5 cm/s. The results are presented in Fig. 4.

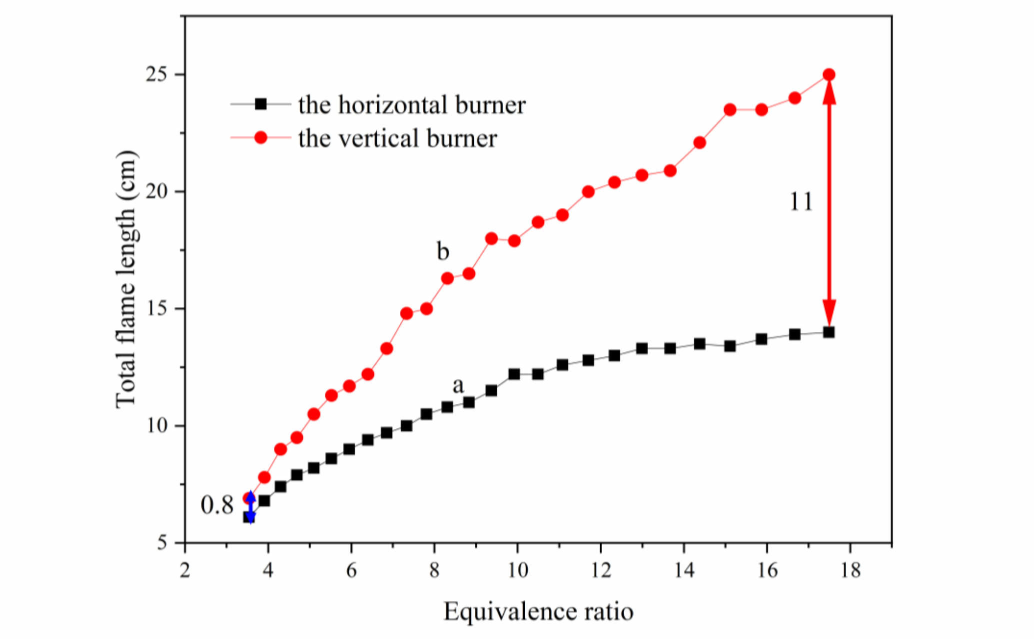

Figure 4. Total flame lengths versus *Φ* when *v* = 200.5 cm/s (a. The burner was placed horizontally, b. The burner was placed vertically).

From Fig. 4, the following rules can be observed. Firstly, when *v* = 200.5 cm/s, at the same *Φ*, the total flame length for the vertical burner was greater than that for the horizontal burner. Secondly, the larger the *Φ*, the bigger the difference of total flame lengths for the horizontal and vertical burner. For instance, when *Φ* was 3.54, the total flame length for the vertical burner was only 0.8 cm greater than that for the horizontal burner. However, when *Φ* increased to 17.49, the difference increased to 11 cm. The reason was that flame lengths are controlled by both buoyancy and momentum [19]. Buoyancy lifted the flame in vertical direction which resulted in the elongated flame for the vertical burner and the upward bending flame head for the horizontal burner.

Besides, non-premixed C_3H_8/air in the range of *v* = 150 cm/s ~ 250 cm/s burnt stably in a large range of *Φ*. Therefore, the effects of *Φ* on the flame length, flame structure and shape were investigated under three conditions: *v* = 153.3 cm/s, *v* = 200.5 cm/s, *v* = 247.7 cm/s. For further study, *v* = 153.3 cm/s was selected as an example. When *v* = 153.3 cm/s, the volume flow rate of non-premixed C_3H_8/air was 0.65 L/min. First, the volume flow rates of C_3H_8 and air were set as 0.10 L/min and 0.55 L/min, respectively. Later, volume flow rates of C_3H_8 increased at an interval of 0.01 L/min, while volume flow rates of air decreased at an interval of 0.01 L/min. Therefore, *Φ* changed while *v* remained the same (*v* = 153.3 cm/s). The experimental design is presented in Tab. 2.

Table 2. Experimental design when *v* =153.3 cm/s.

No.	1	2	3	4	5	6	...	29
Volume flow rate of C_3H_8, L/min	0.10	0.11	0.12	0.13	0.14	0.15	...	0.38
Volume flow rate of air, L/min	0.55	0.54	0.53	0.52	0.51	0.50	...	0.27
Φ	4.33	4.85	5.39	5.95	6.54	7.14	...	33.51

Total flame lengths influencing by *Φ* and *v* are shown in Fig. 5 under the following conditions: *v* = 153.3 cm/s, *v* = 200.5 cm/s, *v* = 247.7 cm/s.

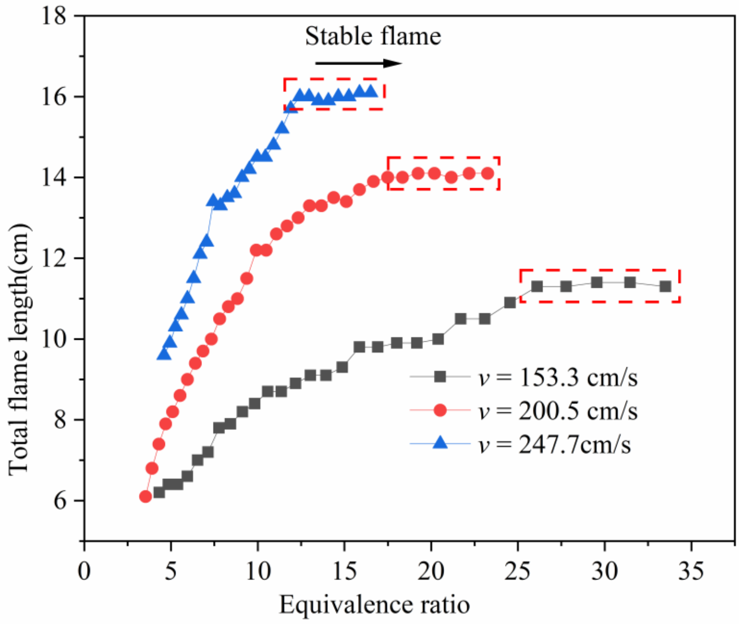

Figure 5. Total flame lengths under various *Φ* for *v* = 153.3cm/s, 200.5 cm/s, 247.7 cm/s (The burner was placed horizontally).

As shown in Fig. 5, firstly, for *v* =200.5 cm/s, the minimum *Φ* when ignited non-premixed C_3H_8/air could form a flame, was 3.54 . However, for *v* = 247.7 cm/s, only when *Φ* increased to 4.62 or higher, ignited non-premixed C_3H_8/air could form a stable flame. As a result, the following conclusion was drawn: the greater the *v*, the greater *Φ* was needed when ignited non-premixed C_3H_8/air could form a stable flame. However, when ignited non-premixed C_3H_8/air could form a stable flame, the minimum *Φ* for *v* = 153.3 cm/s （*Φ* = 4.33) was bigger than that for *v* = 200.5 cm/s（*Φ* = 3.54). It seemed to be inconsistent with the conclusion; however, there was a reason. For *v* = 200.5 cm/s, the volume flow rate of non-premixed C_3H_8/air was 0.85 L/min. Since the minimum volume flow rate that the mass flow controller of C_3H_8 can stably maintain was 0.10 L/min, so volume flow rates of C_3H_8 and air were set as 0.10 L/min and 0.75 L/min respectively in the first experiment for *v* = 200.5 cm/s. In this case, *Φ* = 3.19. But ignited non-premixed C_3H_8/air could not form a stable flame. That is, ignited non-premixed C_3H_8/air was in no flame state for *Φ* = 3.19 when *v* = 200.5 cm/s. Next, volume flow rates of C_3H_8 and air were set as 0.11 L/min and 0.74 L/min, respectively. In this case, *Φ* = 3.54. In the second experiment for *v* = 200.5 cm/s, ignited non-premixed C_3H_8/air could form a stable flame with 6.1 cm length. So the minimum *Φ*, ignited non-premixed C_3H_8/air with which could form a stable flame, was 3.54 for *v* = 200.5 cm/s. Likewise, for *v* = 153.3 cm/s, the volume flow rate of non-premixed C_3H_8/air was 0.65 L/min. Volume flow rates of C_3H_8 and air were firstly set as 0.10 L/min and 0.55 L/min respectively. In this case, *Φ* = 4.33. The experiment demonstrated ignited non-premixed C_3H_8/air could form a stable flame with 6.2 cm length. According to the blow-out limit results shown in Fig.2, the following may be noticed: the smaller the *v*, the smaller the *Φ* of non-premixed C_3H_8/air. When Φ was 3.40, blow out limit is 188.7 cm/s. Therefore, the minimum Φ for v = 153.3 cm/s, ignited non-premixed C_3H_8/air with which could form a stable flame, was a value smaller than 3.40. That was to say, the minimum Φ for v = 153.3 cm/s （Φ < 3.40) was smaller than that for v = 200.5 cm/s（Φ= 3.54). Thus, the following conclusions can be drawn: the greater the v, the greater Φ was needed ignited non-premixed C_3H_8/air with which value could form a stable flame. Secondly, the total flame length first had a marked increase and then appeared to flatten as Φ increased. Fig. 5 revealed that the larger the v , the larger the slope of total flame length curve. It indicated that the larger the v, the faster the total flame length increased. However, when Φ increased to a certain value, the total flame length did not increase (Fig. 5, see the red dashed rectangular box). The red dashed rectangular box indicated the increase of the total flame length went to a plateau phase. This suggested that the total flame length was determined by Φ and v, but determined by v only when Φ increased to a certain value. In particular, there was a phenomenon: the larger the v, the smaller the Φ at which value the plateau phase appeared. This phenomenon for non-premixed flame was consistent with the previous study [20] for premixed flame.

3.3 Flame shape

The flame shape for the horizontal burner was studied first. When v = 200.5 cm/s and Φ was 3.54, 4.30, 5.10, 7.33, 11.70, and 16.67, the flames were photographed and the results are shown in Fig. 6.

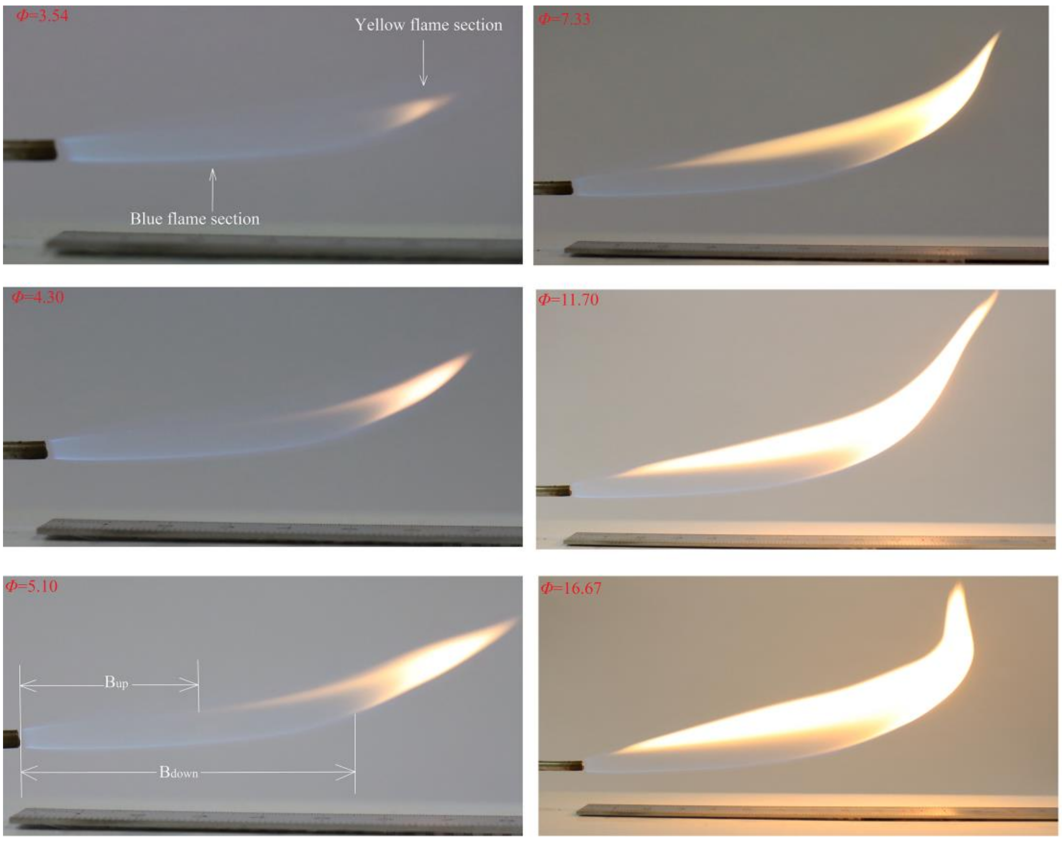

Figure 6. Images of flames at different Φ for v = 200.5 cm/s (The burner was placed horizontally).

As shown in Fig. 6, the flame consisted of a blue flame section near the outlet of the burner and a yellow flame section far away from the outlet of the burner (see Fig. 6. Φ = 3.54). With the rise of Φ, the yellow flame section increased and the ratio of yellow flame section length/total flame length became larger. Moreover, when Φ was smaller, the flame head was kept in the horizontal direction. However, as Φ increased, the flame head gradually bent from the horizontal direction towards vertical. The stretching of the flame head from the horizontal direction towards vertical caused the length difference between the down blue flame section (B_{down}, as shown in Fig. 6. Φ = 5.10) and the up blue flame section (B_{UP}, as shown in Fig. 6. Φ = 5.10) to be larger and larger. Therefore, B_{down} and B_{UP} were measured. Subsequently, ratios of the length of the up blue flame section to the total flame length (B_{UP}/L) and the length of the down blue flame section to the total flame length (B_{down}/L) were calculated, respectively. The results are shown in Fig. 7.

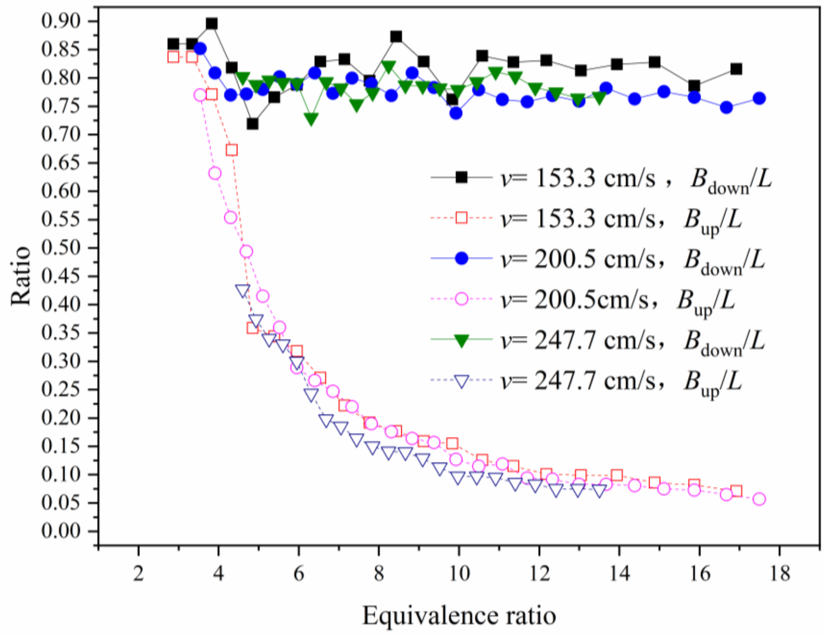

Figure7. B_{up}/L and B_{down}/L under various Φ (The burner was placed horizontally).

Fig. 7 showed that B_{down}/L remained largely unchanged, but B_{UP}/L significantly decreased with the increase in Φ under the conditions of v = 153.3 cm/s to 247.7 cm/s. This phenomenon was due to the fact that as Φ increased, L and B_{down} increased, but B_{UP} decreased. The flame was affected by the buoyancy effect, which was one of the causes of the vertically bent flame head. Moreover, incoming speeds and directions of propane and air both were different. First, the propane speed increased and air speed decreased as Φ rose. Consequently, the difference between propane speed and air speed became larger and larger as Φ rose. Therefore, propane and air could not be fully mixed at the tee. Second, the incoming direction of air was perpendicular to the C_3H_8/air direction, while the incoming direction of propane was aligned with the C_3H_8/air direction (see Fig. 1). These two differences led to different effects of propane and air on the flame of non-premixed C_3H_8/air. Thus, the phenomenon that the flame head bent upward as Φ increased for the horizontal burner was unique to non-premixed C_3H_8/air. For premixed C_3H_8/air, the phenomenon disappeared since propane and air were fully mixed. An experimental device as depicted in Fig. 1b was established to verify this inference. By adding a 90º elbow and a burner same as the horizontal one, the direction of C_3H_8/air was changed from the horizontal direction to vertical. Finally, flames for the vertical burner were photographed when v =200.5 cm/s. The results are depicted in fig. 8.

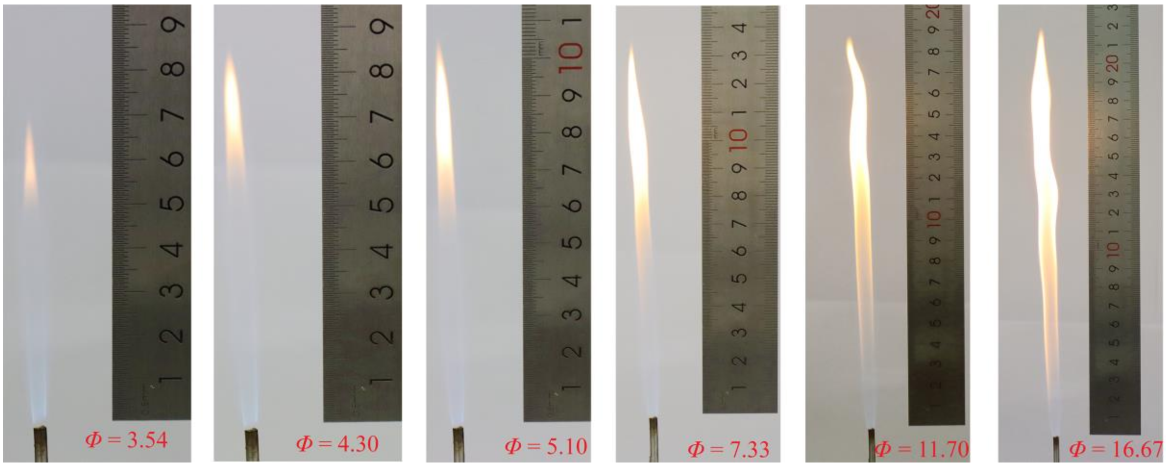

Figure 8. Images of flames at different Φ for v = 200.5 cm/s (The burner was placed vertically).

As illustrated in Fig. 8, with the rise of Φ, the ratio of yellow flame section length/total flame length became larger which was consistent with that for the horizontal burner. However, the flame head did not bend from horizontally to vertically for the vertical burner, i.e. the flame stability for the vertical burner was better than that for the horizontal burner. The elbow of 90 degrees could not change incoming speed differences between propane and air, but it can avoid the influence of incoming directions of propane and air on the flame by changing the direction of C_3H_8/air. Therefore, to make the non-premixed flame stable, the piping layout of non-premixed C_3H_8/air should be fully considered.

4. Conclusions

The present work established a non-premixed C_3H_8/air combustion experimental setup. The effects of Φ, v, and the burner placement angle on the flame length, shape, and blow-out limit were studied. The following conclusions can be drawn:

（1）Affected by Φ and v, ignited non-premixed C_3H_8/air had 3 combustion stages: no flame, a stable flame, and a blow-out flame. Only when $v \leq 412.8$ cm/s, ignited non-premixed C_3H_8/air could form a stable flame. The larger the Φ, the larger the range of stable combustion and the bigger the blow-out limit. Besides, the larger the v, the larger Φ was needed to keep the combustion stable. Moreover, the total flame length increased first and then remained constant as v increased. It indicated that the total flame length was determined by Φ and v, but determined only by v when Φ increased to a certain value.

（2）Φ affected the color distribution of the flame. The flame color consisted of the blue section near the burner and the yellow section far away from the burner. The ratio of yellow flame section length/total flame length became larger as Φ increased.

（3）The placement angle of the burner had no impact on blow-out limits of non-premixed C_3H_8/air, but it affected the flame length and shape. When Φ and v were constant, the total flame length was longer for the vertical burner than the horizontal burner. Furthermore, the difference between the total flame length for the vertical and horizontal burner increased with the increase in *Φ*. In addition, when the burner was placed horizontally, the flame head bent upward as *Φ* increased. However, when the burner was placed vertically, the flame head upward phenomenon disappeared. Adding an elbow of 90 degrees could avoid the influence of incoming directions of propane and air on the flame, and the flame was more stable. Therefore, to make the non-premixed flame burn stably, the piping layout of non-premixed fuel/air should be fully considered.

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Nomenclature

B - length of the blue flame section[cm]

L - length of the total flame[cm]

v - velocity of non-premixed C_3H_8/air[$cm \cdot s^{-1}$]

Greek symbols

Φ - propane air equivalence ratio

Subscripts

up - the up blue flame section

down - the down blue flame section

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.

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