WIND ACTION ON WHIRLING FLAME CHARACTERISTICS

by

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The behavior of whirling flame above a pool fire under cross wind was studied using a small wind tunnel. Whirling flames with different heat release rates were generated by an experimental rig. Effect of different wind speeds on the whirling flame was studied by an oil pool of two different diameters. Lateral images of the whirling flame collected were analyzed. Results show that under cross-flow, the whirling flame was deflected along the direction of incoming flow. With the increase in wind speed, the deflection angle increased gradually. The angle also increased with the increase in pool diameter. When the cross-flow increased to a certain value, the flame stopped swirling, and changed to an irregular shape. The maximum cross wind speed of the flame that did not stop flame rotation decreased with diameter. Cross wind with lower speed would raise the temperature of the whirling flame. When the wind speed was higher than a critical value, the temperature was reduced because burning rate decreased.

Key words: *whirling flame, cross wind, flame characteristics, wind tunnel experiment, fire pool size*

Introduction

Whirling flame is a rotating flame which would appear when certain conditions are satisfied. Swirling motion can be attenuated under appropriate air-flow driven by wind action on outdoor spaces such as forests and grasslands, or ventilation provisions in confined indoor spaces. More vigorous combustion in a fire whirl changes the heat and mass transfer process of the fire. In construction safety, disaster prevention and other aspects, the hazardous consequences of fire whirls have been extensively studied. However, up to now, the research of whirling flame has been focusing on the description of combustion phenomenon, and it is mainly based on the unrestricted whirling flame in large outdoor space. Studies of whirling flame in confined space is limited [1], with few experimental works [2]. For the whirling flame in a confined

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space, the air inflow and outflow through vents will have a significant impact on the formation and development of the flame due to shear force and suction resulting from swirling flow of flame [3]. At present, the behavior of whirling flame under the influence of cross wind has not received adequate attention. In this work, whirling flames were generated in a small wind tunnel, and whirling flame experiments with different velocities and heat release rates were carried out by simulating the flow through the vent in actual confined space with the cross wind generated by the wind tunnel. By collecting the images of the whirling flame, the effects of the cross wind speed and the heat release rate on the flame structure, flame height and motion modality were studied, and the rotation ability of the flame was explored. The research results provide reference for the study of whirling flame in confined space and experimental data for the establishment of a theoretical model.

Experiments to study the characteristics of whirling flame were reported in the literature. Snegirev *et al.* [4] studied the rotation and structure of the buoyancy whirling flame in a semi-closed room. The experimental results show that the formation and disappearance of the whirling flame are periodic. The small-scale whirling flame in a room is more complex than the large-scale fire whirlwind in open space. The size and wall around the flame in the room, as well as ventilation will affect the generation, maintenance and extinction of the whirling flame. Weng *et al.* [5] studied the empirical relationship between the height of whirling flame formed by the interaction of multiple independent fire sources and the distance between fire sources by using a fire source matrix composed of multiple independent fire sources. Kuwana *et al.* [6, 7] carried out 1/1000 scale model experiments in a large low speed annular wind tunnel. The results show that the formation of whirling flame is related to a certain transverse characteristic wind velocity, and the scale model was used to predict the critical wind speed. Chuah and co-workers [8, 9] carried out a small-scale rotation flame experiment, and analyzed the relationship between the heat release rate and the vortex structure of the whirling flame. Zhou and Wu [10] studied the influence of surrounding dispersed flames on the height of the central whirling flame by experiment and numerical simulation. Zou *et al.* [11] constructed a vertical square channel experimental device to conduct rotation flame experiment. The experimental results show that the size and shape of the oil pool and the width of the side slit have a great influence on the structure of the whirling flame. Chow *et al.* [12-14] and Zou *et al.* [15, 16] carried out a small-scale whirling flame experiment in a vertical channel with a single side slit, and studied the influence of the width and height of the side slit on the flame. Based on the results of experimental research, a lot of attention has been paid to whirling flame in theoretical analysis and numerical simulation [17-22]. Battaglia *et al.* [2] studied the relationship between the radius of the whirling flame and the height of the whirling flame based on the assumption of inviscid fluid, with consideration of rotation and chemical reaction. McDonough and Loh [23] used commercial software STAR-CD to simulate the whirling flame phenomenon in a rectangular channel. The numerical simulation results show that the vorticity generated by baroclinity decreases significantly with the increase of ground height, and the vorticity direction generated by shear force changes from parallel to approximately vertical with the increase of ground height. On the other hand, Floyd *et al.* [24], McGrattan *et al.* [25, 26], Wang *et al.* [27] made contributions to the establishment of combustion model and radiation model. Furthermore, Cheng *et al.* [28] studied the magnetic field generated by a whirling flame. Rotating air-flow in fire gives whirling flame.

Cross wind refers to ambient wind entering a room in the direction of crossing with the vertical buoyancy. The design of ventilation system and the application of air curtain in buildings may form cross wind in building space. Takada [29] was the first one to design a double-vent experimental scene to study the effect of natural ventilation on indoor combustion. On this basis, Kumar and Naveen [30, 31] proposed a simplified temperature estimation model based on energy and mass conservation. Himoto *et al.* [32] used active ventilation simulate the effect of different cross wind speeds on indoor fire overflow, and found that the cross wind can raise the initial velocity of fire overflow and lower the height of neutral plane. Ji *et al.* [33] studied the mechanism of fire development in adjacent corridor under the action of cross wind, and analyzed the changes of pool fire flame shape and burning velocity with cross wind speed.

Many results [34-36] on the formation and structure of whirling flame and cross wind were reported. But there are still many unsolved problems in their interaction. In particular, for the whirling flame in a confined space, the influence of cross wind caused by mass transport through vents on the formation, shape change and flame form of the whirling flame is less studied.

Low speed wind tunnel is often used in architectural design to study the air-flow field around buildings and the response of building structure, so as to provide useful information for building design and construction. In the present study, a small combustion wind tunnel [37] for investigating whirling flame was constructed. Effect of the cross-wind flow on the whirling flame was studied. Parameters such as flame height, flame shape and deflection angle were discussed. The formation conditions of the whirling flame under the influence of cross wind were explored. The results of the present study would contribute to fire safety management of buildings where a whirling flame might appear. It would provide information for fire protection design such as fire extinguishing system design and refuge floor design in building fire research.

Experimental study

High temperature and low density near a whirling flame will produce a suction effect on the surrounding gas. In addition, the pressure near the flame decreases due to rotation, which will also cause the flow of air.

When a whirling flame occurs in a confined space with a vent, the gas entering the space through the vent will form a cross wind, which will affect the combustion and development of the whirling flame. Experiments on whirling flame characteristics under the influence of cross wind were carried out.

Wind tunnel installation

A combustion wind tunnel of length 6 m with a cross-section of 1.5 m × 1.5 m square was set up. The generator of whirling flame was composed of a motor, a turntable and an oil pool. The wind tunnel device consisted of three parts: blowers, fairing and main channel, as shown in fig. 1(a). The four axial-flow blowers were located at the far left side of the device. The diameter of the single blower was 0.75 m, the height was 0.9 m, the thickness was 0.5 m, and the weight of the single blower was 50 kg. The blower was connected with the power regulating device through the cable, which could provide the flow with a wind speed of 0-10 m/s, and the velocity distribution is shown in fig. 1(b). The right side of the blower was the fairing with a length of 1.303 m. The flow from the four blowers could be integrated into a uniform flow with the same direction and speed. The right side of the fairing was the main tunnel of the wind tunnel. The inner part of the main tunnel was a steel truss structure with an outer covering skin. The size was 6 m × 1.55 m ×1.55 m.

The external structure of the wind tunnel is shown in fig. 1(c) and blowers in fig. 1(d).

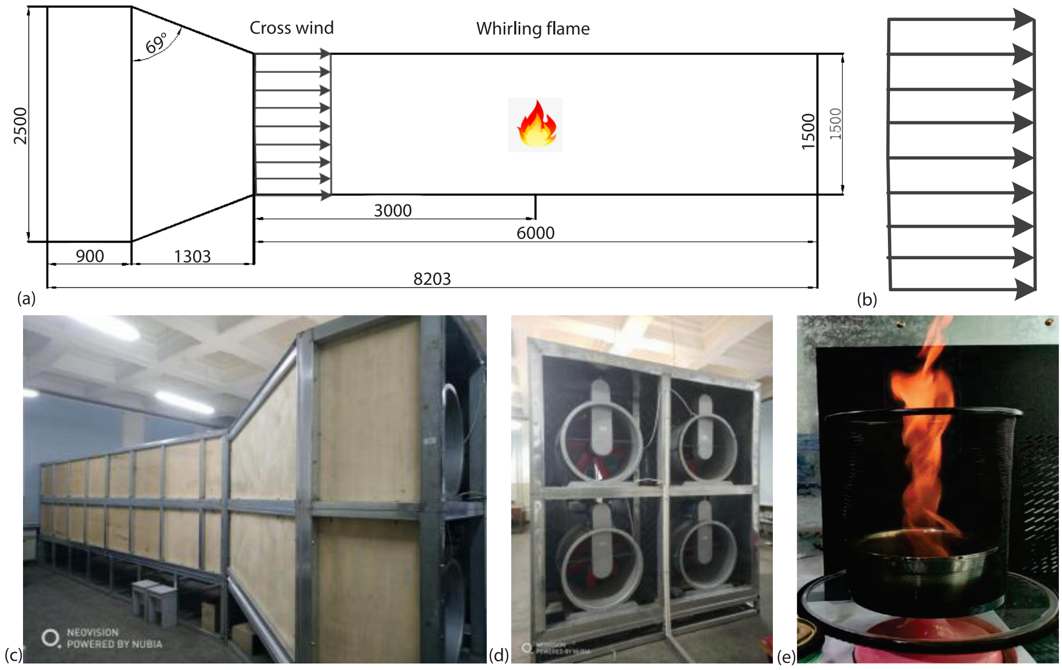

Figure 1. Wind tunnel; (a) schematic, (b) velocity distribution of cross wind, (c) external structure, (d) blowers, and (e) oil pool and whirling flame

Rotating system

The rotating mesh system [38, 39] was composed of a small motor, a turntable and an oil pool, as shown in fig. 1(e). This experimental rotating mesh rig can generate a stable whirling flame, because the angular speed can be adjusted. Lei *et al*. [39] proposed through experiments that this kind of fire whirlwind experimental device, the mesh screen only exerts circulation influence on the internal flow in the tangential direction, and has little resistance to the radial flow in the direction perpendicular to the surface of the mesh screen. Because the mesh screen can make the air-flow pass through, this experimental device can be used to study the influence of cross wind on fire whirlwind. The motor could provide a rotation speed of 180 rpm with a diameter of 0.1 m. The turntable had a diameter of 0.3 m and was connected with the motor through a toothed belt. According to the transmission law, the rotation speed of the turntable was 60 rpm. The experimental fire source was an oil pool fire with fast flame growth rate, and strong flame stability. The fuel was 95% ethanol, the diameter of oil pool was 0.11 m or 0.13 m, and the depth of the oil pool is 0.08 m. The oil pool was located at the middle of the wind tunnel, 3 m away from the exit of the wind tunnel. The oil pool is located in the center of a cylindrical mesh which is used to make whirling flame, the diameter of this cylindrical mesh is about 0.21 m. The mesh diameter around the flame is 2 mm. The motor, turntable and oil pool were constructed together to provide a stable whirling flame by adjusting the angular speed.

Image acquisition system

The GoPro hero9 black 5K motion camera was used to collect images. The video pixels were 1920 × 1080, and the acquisition frequency was 120 FPS.

Experimental conditions

In the experiment, the oil pools with different sizes were used to simulate the whirling flame under different heat release rates. The fuel used in the experiment was ethanol, the dosage was 25 ml for each experiment and the combustion calorific value was 26.9 kJ/g. The density of ethanol is 0.8 g/cm^3 at room temperature, so the heat released by combustion is 538 J in the experiment. The heat released per unit time is defined as heat release rate (HRR). In the actual process, HRR changes with time. The average HRR represents the heat release rate of the whole combustion period:

$$\overline{HRR} = \frac{q}{t} \tag{1}$$

where q is the total heat release and t – the burning duration.

Oil pools with diameters of 0.11 m and 0.13 m were used in this study with burning durations 30 seconds and 21 seconds, respectively in the quiescent state.

According to the rotation speed of the turntable, the maximum linear speed is:

$$v_1 = \omega \pi d \tag{2}$$

where ω [rps] is the rotation speed of the turntable and d [m] – the diameter of turntable.

The ratio of the cross wind speed v_2 to the maximum linear speed v_1 is defined as the dimensionless wind speed $\overline{v}$. By changing the power of the blowers, the cross inflow with different wind speeds can be obtained. The experimental conditions are shown in tab. 1.

The image data of whirling flame were collected. Through image processing, the variations of flame height, tilt angle, temperature and other parameters under different experimental conditions were studied.

Table 1. Experimental conditions

Code	Diameter of oil pool [m]	Heat release rate under static state [W]	Wind speed [ms^{-1}]	Dimensionless wind speed
1	0.11	17.7	0.0	0
2			0.2	0.21
3			0.4	0.42
4			0.6	0.63
5			0.8	0.84
6			1.0	1.05
1	0.13	25.6	0.0	0
2			0.2	0.21
3			0.4	0.42
4			0.6	0.63
5			0.8	0.84
6			1.0	1.05

Results and discussion

Flame shape

The change of whirling flame under different velocities of cross wind was studied experimentally. As shown in fig. 2, when the diameter of the oil pool was 0.11 m, the flame showed strong rotation characteristics when there was no wind, and the whirling flame extended vertically upward. As observed, the flame rotation axis inclined with an angle to the horizontal direction. According to the flame trajectories, the upward speed conforms to the law of whirling flame that increased first and then decreased with the increase of flame height [4, 40]. In the region near the oil pool, under the action of buoyancy, the upward speed of the flame increased gradually, and flame spiraled up. With the rise of height along the flame, buoyancy decreased gradually, and the rotation speed and upward speed of the flame also decreased gradually, and finally stopped rising and rotating.

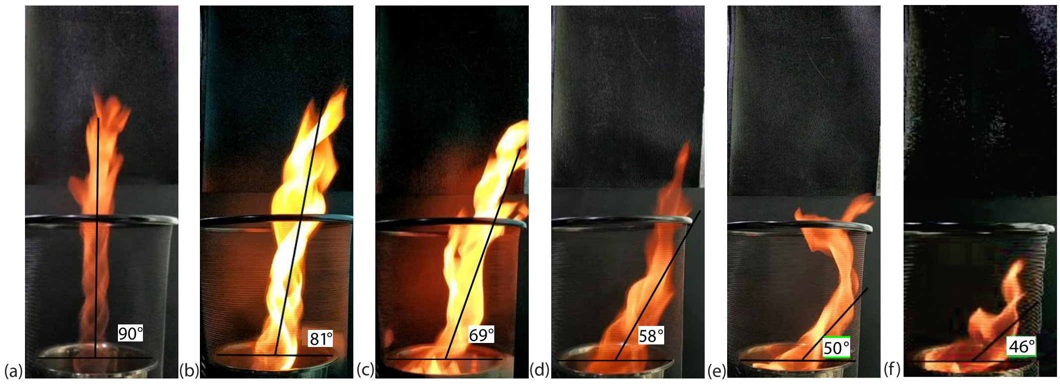

Figure 2. Whirling flame shape of oil pool with d = 0.11 m; (a) $\overline{v}$ = 0, (b) $\overline{v}$ = 0.21, (c) $\overline{v}$ = 0.42, (d) $\overline{v}$ = 0.63, (e) $\overline{v}$ = 0.84, and (f) $\overline{v}$ = 1.05

Under the influence of cross-flow, the whirling flame deviated along the flow direction. As the oil pool was fixed on the turntable, the bottom of the whirling flame could not move, and the upper part of the flame was offset to the right, thus forming a certain deflection angle. The line at the widest part of the upper edge of the oil pool is defined as the horizontal. Defining the angle between the flame axis and the horizontal direction as α, and the deflection angle of flame axis is $90° - \alpha$. Due to the unstable pulsation of the flame, the middle value of the deflection angle of the whirling flame from forming to dissipation is taken for comparison. With the increase of the wind speed, the deflection angle of the whirling flame increased gradually, and the angle a decreased gradually, taking values of 90°, 81°, 69°, 58°, 50°, and 46° in turn.

In the range of $\overline{v}$ from 0 to 0.84, although the whirling flame was deflected, its motion was always spiraling. When $\overline{v}$ = 1.05, the centrifugal force provided by the turntable was unable to form the whirling flame, and the flame beat violently, but the height was very small. In addition, because there was a mesh wall on the side wall of the turntable, fig. 1(e), and the rotating mesh wall would prevent the flame from passing through when the flame was close to the wall, it would rise against the wall, especially in the case $\overline{v}$ = 0.84.

Keeping the fuel weight unchanged, when the diameter of the oil pool increased to 0.13 m, the heat release rate and the diameter of the bottom of the whirling flame increased. Under the influence of cross wind, the whirling flame was deflected along the direction of the flow, with angles α of 90°, 74°, 58°, 44°, 41°, and 39°, respectively, as shown in fig. 3.

The comparison of deflection angles and angle errors of whirling flames in pools of different diameters is shown in tab. 2 and fig. 4(a). When the diameter of oil pool increased, the deflection angle became larger, indicating that the influence of cross-flow increased, and the stability of whirling flame decreased. However, the relative difference of deflection angle showed that with the increase of the wind speed, the difference decreased gradually. When

$\bar{v} \leq 0.63$, although there was a certain deflection angle, the whirling flame was no longer stable; when $\bar{v} \geq 0.84$, the flame showed an irregular pulsation state. Compared with the small oil pool, the maximum value of wind speed that did not stop the flame rotating was smaller.

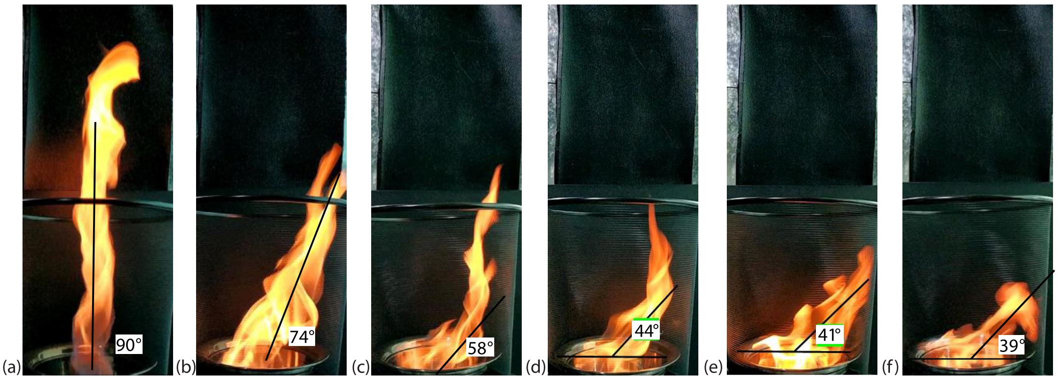

Figure 3. Deflected whirling flame shape of oil pool with d = 0.13 m; (a) $\bar{v}$ = 0, (b) $\bar{v}$ = 0.21, (c) $\bar{v}$ = 0.42, (d) $\bar{v}$ = 0.63, (e) $\bar{v}$ = 0.84, and (f) $\bar{v}$ = 1.05

The rotating vortex acts on the fuel surface to generate an upward drag force, which plays an important role in the formation and attenuation of the whirling flames. For an oil pool with a larger diameter, the volume of the flame is larger, and a higher drag force is required to form and maintain the whirling flame. That is, at the same rotating speed, the whirl is weaker for a pool with a larger diameter, and the influence of the cross-flow is relatively stronger, and the deflection angle is larger under the influence of the lateral flow.

Table 2. Flame deflection angle under the influence of cross wind

$\bar{v}$		0	0.21	0.42	0.63	0.84	1.05
α [°]	Diameter 0.11 m	90	81	69	58	50	46
	Diameter 0.13 m	90	74	58	44	41	39
$90 - \alpha$ [°]	Diameter 0.11 m	0	9	21	32	40	44
	Diameter 0.13 m	0	16	32	46	49	51
Relative difference of $90 - \alpha$ [%]		–	43	34	30	18	13

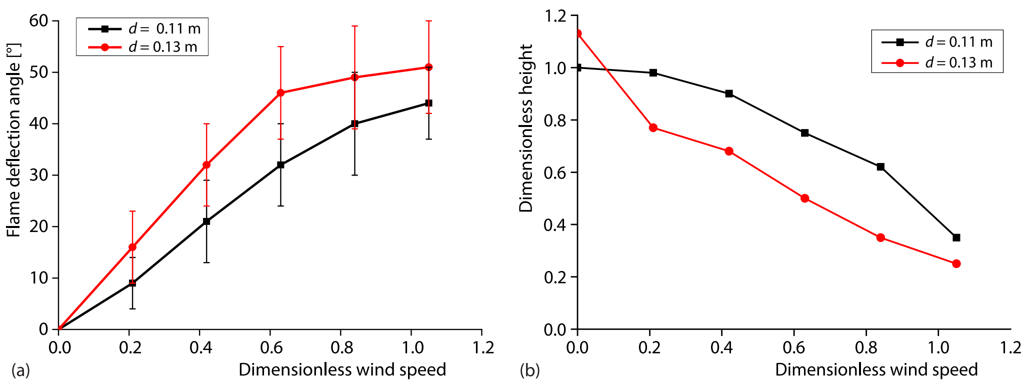

Figure 4. Effect of cross wind; (a) flame deflection angle and (b) flame height

When the whirling flame deflection angle was at the middle value in each experiment, flame height was measured. Taking the whirling flame height, h, of the oil pool with the diameter of 0.11 m without wind as the reference value, the flame height data in vertical direction of the other cases can be obtained from the image data, as shown in tab. 3. In the case of no wind, the whirling flame of the large oil pool was higher than that of the small oil pool. In the case of cross-flow, the whirling flame height of the large oil pool was lower than that of the small oil pool due to a larger deflection angle and lower flame stability. When $\overline{v}$ = 0.84, there was a big height difference between the two cases. This is because the flame in the small oil pool was still a whirling flame, and the flame in the large diameter oil pool started to beat irregularly.

Table 3. Flame height data

$\overline{v}$		0	0.21	0.42	0.63	0.84	1.05
Flame height in vertical direction, h	Diameter 0.11 m	1	0.98	0.90	0.75	0.62	0.35
	Diameter 0.13 m	1.13	0.77	0.68	0.50	0.35	0.25
Difference, h		–0.13	0.21	0.22	0.25	0.27	0.1

The difference in flame height is shown in fig. 4(b). For the small oil pool, when $\overline{v} \leq 0.84$ due to the strong stability of the whirling flame, the cross-flow only changed the deviation angle of the flame, and the flame height decreased approximately linearly. When $\overline{v} \geq 0.84$, the flame height dropped rapidly, and the flame changed from rotation the pulsation state. For the large oil pool, the presence of the cross wind not only caused the deflection of the whirling flame, but also weakened the stability of the flame, resulting in a rapid drop in flame height. When $\overline{v} \leq 0.63$, the flame did not rotate anymore, and the height of the flame decreased approximately linearly under the influence of the cross wind.

Flame temperature change

In the experiment carried out in this work, temperature sensor was not installed to measure the temperature of the whirling flame, but according to [40], the flame refers to the gas-phase combustion region with light emission, and the flame color corresponds to the combustion temperature, as shown in tab. 4. The flame temperature was thus determined by referring to the visible flame color. This part is subjective and may have large errors. The purpose is only to discuss the trends of the observed phenomena.

Table 4. Flame temperature and color

Flame color	Flame temperature [°C]
Dull red	<400
Slightly red	500
Oxblood red	700
Cherry red	900
Bright Fuchsia	1000
Orange yellow	1100
Bright orange	1200
White	1300
Dazzling white	>1300

In the whirling flame, with the increase of flame height, the flame temperature decreased gradually. To facilitate comparison and discussion, the maximum and minimum values of temperature in a single experiment are taken as the temperature at the bottom and top of the whirling flame, and the flame temperature at other heights are obtained according to the linear interpolation rule, as shown in fig. 5.

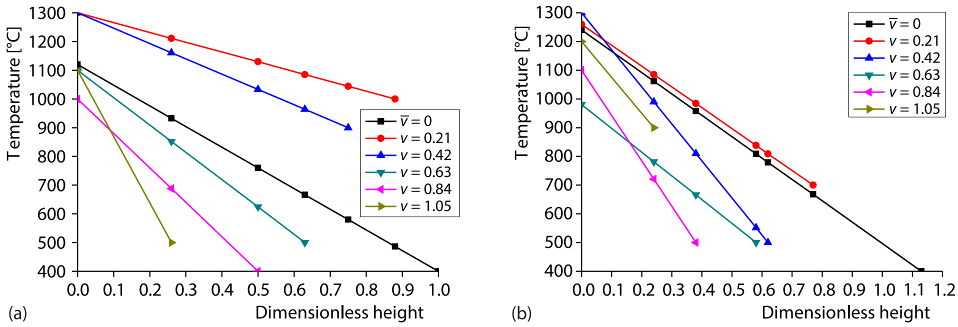

Figure 5. Change of flame temperature along the height direction; (a) oil pool diameter 0.11 m and (b) oil pool diameter 0.13 m

On one hand, the cross wind injects air into the combustion region, which intensifies the combustion. On the other hand, the high wind speed will strengthen the convection heat dissipation and reduce the flame temperature. For the small oil pool, when $\bar{v}$ = 0.21, the combustion intensifying effect of crosswind was strong, and the flame temperature increased. With the increase of wind speed, the convection heat dissipation effect of crosswind increased, and the flame temperature decreased. When $\bar{v}$ = 1.05, the flame height decreased, and the combustion intensifying effect of cross wind became the main factor again, and the flame temperature increased.

The experimental results of the large oil pool also conformed to this rule.

Conclusions

A small combustion wind tunnel was built to study the characteristics of whirling flame under the influence of cross wind. By adjusting the power of the wind tunnel, the cross air-flow with different wind speeds was obtained. The whirling flames with different heat release rates were obtained by using the motor, turntable and oil pools. The image data of the change in characteristics of the whirling flame were collected and analyzed in the experiment. Parameters such as flame height, flame shape, deflection angle and flame temperature were discussed.

Under the influence of cross wind, the whirling flame was deflected along the direction of the incoming flow. For the same fire pool, with the increase of wind speed, the deflection angle increased gradually. For different fire pool size, the deflection angle increased with the increase of oil pool diameter. In the experiment of this paper, when the dimensionless wind speed increases to greater than 0.84, the flame in oil pool with diameter of 0.11 m could not keep rotating. When the diameter of the oil pool is 0.13 m, this wind speed value is 0.63. The maximum cross wind speed that the flame could keep rotating decreased with the increase of the diameter of the oil pool. The influence of cross wind on the flame height was larger for the large oil pool than for the small oil pool, although the flame height of the large oil pool was greater than that of the small oil pool when there was no wind. As far as the flame temperature is concerned, a low wind speed is contributive to increasing the combustion temperature of the whirling flame, but there is a certain critical value. When the cross wind speed is higher than this critical value, the combustion is weakened and the flame temperature is reduced.

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