ASSOCIATION OF FLAME-OSCILLATION FREQUENCY UNDER CROSS WIND DIFFUSION

Bo Lou[1*], Eric Hu[2], Ye Wang[1]

(1. School of Electric Power, South China University of Technology, Guangzhou, Guangdong Province, China,; 2. School of Mechanical Engineering, the University of Adelaide, Adelaide, Australia)

***Abstract**: Turbulent flame-oscillation frequency and combustion efficiency are the important parameters in combustion. It is a useful study to judge combustion efficiency by intuitive flame frequency.Based on a combustion wind tunnel experimental setup, the variation law of combustion flame-oscillation frequency and combustion efficiency using external wind speeds was studied via the color flames image sequence of oil pan combustion and flue gas composition. The oscillation frequency was calculated with the upper edge of the fire plume which recorded flame image sequence using a high-speed video, combined the MATLAB image processing technique. The combustion efficiency was calculated combined with the C and H element mass of the liquid fuel in the oil pool and CO_2 and H_2O concentrations in the flue gas. The results show that the oscillation frequency of the flame revealed a tendency to increase followed by a decrease with increasing wind speed, while the overall trend of combustion efficiency increased first and then decreased. The combustion efficiency could be judged by observing the oscillation frequency of the flame image. In addition, the combustion efficiency may ensure in right way when the turbulence oscillation frequency of the oil pan flame ranged between 15 HZ and 18 HZ.*

***Keywords**: cross wind; combustion characteristics; flame-oscillation frequency; combustion efficiency; flame image*

1. Introduction

Flame oscillation generally represents the instability of a flame, low oscillation frequency of the flame occur in the vicinity of the boundary between the outer flame and the surrounding air stream[1],and it can reflect the specific characteristics of combustion[2]. The intrinsic cause of flame oscillation is the result of vortex movement within the flame plume, which is the macroscopic representation of the small-size structure within the flame. In 1984, Zukoski *et al.* [3] reported that the flame diameter at the top of the sump periodically shrank to form a regular flame cluster, while the flame showed periodic oscillations. It was suggested that the oscillation was mainly caused by the flame in the thermal buoyancy of the surrounding air, which caused the periodically generated vortex, transmission, and shedding. Cetegen *et al*. [4] suggested an empirical relationship for predicting the flame-oscillation frequency , which showed that the oscillation frequency of the oil pan has a relation with dimensionless Froude number *Fr*, and furthermore reported that the fuel outlet flow rate and the heat release rate were not significantly related to the pulsation frequency for a fixed-diameter flame.

In generally, most studies of the flame-oscillation frequency are concentrated in the windless conditions. However, cross wind combustion is a common form of combustion, which will change the flame shape and flame oscillation frequency. Atzler *et al.*[5] studied flame oscillations and burning rates with globally homogeneous two phase mixtures, the results show association between the flame burning rates and the oscillation frequency in premixed flames. Kelso *et al.* [6] Fric and Roshko

[7]experimentally described the shear-layer vortices, the horseshoe vortices, the counter-rotating vortex pair, and the wake vortices of pool fire under the action of cross wind, thus revealing the intrinsic mechanism of flame-oscillation from a microscopic point of view.

There is a certain relationship between cross wind and fuel combustion efficiency. Tsue *et al.*[8] proposed a test method to measure the efficiency of jet diffusion flame combustion under cross wind conditions and found that lateral airflow reduced combustion efficiency. Bourguignon *et al.* [9] studied the effects of external wind speed, fuel flow rate, and fuel composition on combustion efficiency in 1999, using a closed-loop wind tunnel system. In their experiment, the combustion efficiency of the fuel was calculated via carbon atom conservation under the assumption that the combustion products are both gas and without carbon black. Gogolek *et al.*[10] focused on the effects of wind flow patterns (laminar flow and turbulence) on combustion efficiency. Johnson *et al.*[11-12] studied the effect of fuel type, jet exitvelocities, and nozzle type on combustion efficiency under the action of cross wind, and presented an empirical model to characterize fuel combustion efficiency.

Buoyancy and momentum are two major driving forces that affect the behavior of diffusion flames, Fang *et al* [13] investigates both buoyancy (B)- and momentum (M)-driven methane laminar diffusion flame shapes with the different fuel mass flow rate and under the ambient pressure range of 0.45 – 1.00 atm. Radiation, and the oscillation frequency of the observed flame flickering motions are determined and analyzed to reveal the effects of pressure on the two dominating mechanisms of flames. Ping *et al* [14]presents an experimental investigation on mass burning rate and flame geometry characteristics of crude oil boilover fire under cross air flows, whose cross air flow speed ranges from 0 to 1.5 m/s, and the results show that the response of steady mass burning rate to cross air flow velocity showed a non-monotonic trend.Cross wind has a great influence on the combustion oscillation frequency and combustion efficiency.Therefore, a quantitative analysis of the combustion oscillation law and the relationship between the oscillation frequency and the combustion efficiency of the flame is vitally important to reveal the combustion mechanism and its application, something that previous studies in this area lacked.

The experimental data of Flame-Oscillation Frequency were obtained by using three techniques namely, pressure fluctuation， measurements, thermal imaging and high-speed video photography[15]. Pressure fluctuation measurement in flame need a high-precision measuring instrument and usually is difficulty, high-speed video photography is actually easier to observe the fluctuations with the thermal contour map. In this study, the flame oscillation frequency under the action of the cross wind was obtained via a combustion wind tunnel experiment and high-speed video photography.Furthermore, a quantitative analysis of combustion efficiency was conducted considering changes in wind speed. This study is to correlate the frequency of combustion flame with combustion efficiency, which will be helpful for judging combustion efficiency by flame frequency in the future.

2. Experimental setuo and method

The experiments were conducted in a combustion wind tunnel with an internal dimension of 5000 mm (length) ×300 mm (width) × 500 mm (height). The wind tunnel was divided into a front section, a combustion section, and a latter part of the three parts, of which the front length was 1800 mm. The front section of the port was equipped with a variable frequency fan, which has an adjustable frequency range of 0-50 HZ; a two-tier manifold was located behind the fan exhaust to ensure uniform airflow into the combustion section, and following the flow of the network set was a wind speed detection hole. The combustion section length was 1200 mm, the observation surface was covered with 5 mm thick tempered glass, the other surfaces were covered with 5 mm steel plates, and all gaps were filled with sealant. At the top of the combustion section, a temperature sensing hole enabled measurement of the flame temperature, and the bottom of the center contained fuel for the light diesel oil pool with a size of 120 mm (length) ×50 mm (width) ×50 mm (height). The cetane number of diesel oil is 51，its carbon mass fraction is 88.7%, the hydrogen is 11.3%, and the low calorific value is 42.6MJ/kg. Situated underneath the oil tank was an electronic balance (mass accuracy 0.1 g, sampling frequency 2 Hz), used to measure the changes of fuel mass during the combustion process. A color high-speed camera (Canadian NORPIX, model FR340-10G) was placed on the front of the combustion zone, recording the burning process of the oil mist at 150 frames per second (FPS) or other at different wind speeds to obtain the flame image sequence as a function of wind speed. At the top of latter section, several temperature detection holes were set to measure flue gas temperature. In addition, a German testo340 flue gas analyzer was installed at the end of the exhaust channel to measure the O_2, CO, and C_nH_m concentrations in the flue gas. The experimental setup and measurement arrangement are shown in Fig. 1.

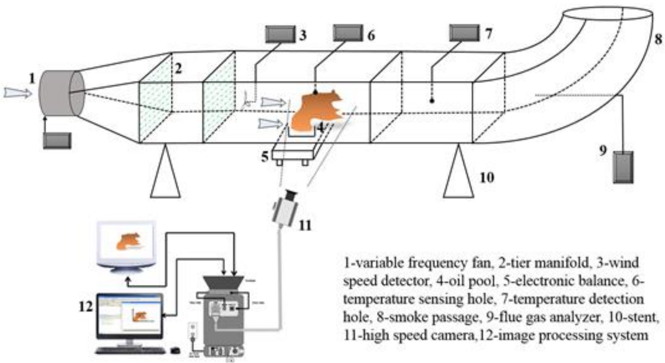

Fig.1 Experimental system diagram

In the preliminary experiment, it is found that the fan frequency was below 2 Hz will result to wind speed below 0.11 m/s, the flame did not have a significant impact, and the fan frequency was higher than 22 Hz, the oil tank was close to the bottom of the wind tunnel which also made high-speed camera recording image of poor quality. Therefore, the experimental fan frequency was set to 2-22 Hz in this study. According to the results of the combustion section wind speed measuring instrument, the relationship between frequency verses with wind speed of the inverter fan was study in preparatory experiment.

The burning process of the flame at different wind speeds were recorded with a high-speed camera and then were transmitted to a batch processor, which used self-contained software to obtain a flame image sequence at different wind speeds. Fig. 2 shows the combustion flame images at several different wind speeds.

The flame image sequence in Fig. 2 shows that as the wind speed increases, the angle of the flame that deviates from the vertical direction increased [16], and the visible area of the flame plume decreased [17].

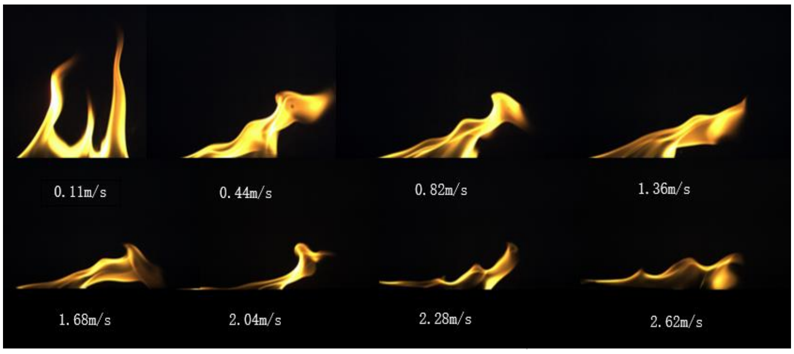

Fig.2 Burning flame images at different wind speeds

3. Experimental results and analysis

Unlike a stationary fire, the flames of combustion are mainly affected by buoyancy in vertical direction, and the combustion under cross wind is also affected by the horizontal force.

3.1. Effect of cross wind on the flame

To investigate the action of jet diffuse flames under the action of cross wind, Gollahalli *et al.* [18] used the momentum flux ratio of the external wind speed and the jet exit speed to measure the effect of the interaction on the combustion. The fuel outlet speed of the oil pool flame was difficult to measure, however, an accurate R value could not be obtained. Maughan *et al.* [19] analyzed the heat transfer of the mixed convection between the flame and the air under the action of external airflow, using $\mathrm{Gr}/\mathrm{Re}^2$ as the criterion to judge the degree of natural convection. Using a similarity analysis method reveals that the Gr number contains the ratio of the buoyant force to the viscous force. Re is the ratio of inertial force to viscous force, then the ratio of buoyancy to inertia can be obtained from Gr and Re. To highlight the role of the wind, this study applied $\mathrm{Re}_\mathrm{w}^2/\mathrm{Gr}_\mathrm{f}$ to analyze the extent of the impact of the wind on the combustion of the oil pan. The formula is as follows:

$$\frac{Re_w^2}{Gr_f}=\frac{u_w^2 l_w^2}{\nu_w^2} * \frac{\nu_f^2}{g\alpha_V \Delta T l_w^3} \qquad (1)$$

Following the previous principles [19], when $\mathrm{Re}_\mathrm{w}^2/\mathrm{Gr}_\mathrm{f} < 0.1$,flame is mainly influenced by buoyancy, and $0.1 \leq \mathrm{Re}_\mathrm{w}^2/\mathrm{Gr}_\mathrm{f} \leq 10$ is the mixing stage. when $\mathrm{Re}_\mathrm{w}^2/\mathrm{Gr}_\mathrm{f} > 10$,the influence of cross wind on the flame is dominant. Fig. 3 shows the variation curve of $\mathrm{Re}_\mathrm{w}^2/\mathrm{Gr}_\mathrm{f}$ in the range of experimental wind.

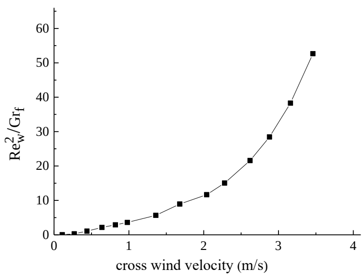

Fig.3 Re_w^2/Gr_f change curve in the different wind speeds

Fig. 3 and the flame image in Fig. 2 show that when the wind speed 0< u_w <0.44m/s, the $\mathrm{Re}_w^2/\mathrm{Gr}_f < 0.1$, and the compulsory force from the cross wind speed may be negligible. Then,The oil combustion flame is mainly affected by buoyancy in the vertical direction. When 0.44m/s< u_w <1.68m/s and 0.1≤ $\mathrm{Re}_w^2/\mathrm{Gr}_f$ ≤10， the combustion is in the mixed phase. The buoyancy force and the inertial force formed by the external wind speed interact with each other, and the upper edge of the flame shows obvious fluctuation. When u_w>1.68m/s and $\mathrm{Re}_w^2/Gr_f > 10$, the effect of forced cross flow wind to fire becomes dominant and the flame remains close to the bottom of the wind tunnel.

3.2. Turbulent fluctuation of flame

The pool flame exhibited periodic shrinkage and expansion as one of the most striking phenomena observed in the experiment. The contraction of the flame cross-section led to an increase in height and a decrease in cross-section expansion, which is due to the entrainment effect in the formation of vortex flame propagating upward and shedding [20]. In the absence of wind conditions, the oscillation of the flame can be described by a periodic variation of the flame height in the vertical direction. Under the action of wind, the influence of the external air force and its own buoyancy not only changes the shape of the flame (including height, area, and tilt angle) [20-21], but also the vortex formed at the periphery of the flame. The shear layer vortex generated by the cross wind was mainly caused by the formation of Kelvin-Helmholtz instability [7], *i.e.*, when air and flame of these two different density fluids met on the interface, the difference of speed caused a pressure difference,then forming torque and growing into a vortex. The eddy current near the fuel side moves along the direction of the plume, which merged with the downstream vortices to form a certain period of turbulent flame pulsation.

The fluctuation of the upper edge of the flame was observed in the flame image, which showed the periodic turbulence pulsation formed by the shear layer vortex. The turbulence oscillation frequency could be obtained by tracking the average cycle time of the upper edge of the flame. Each image in MATLAB was composed of a two-dimensional array, and its value representing the pixel value. Selection of flame image sequences of a time interval , and the lower left corner of the numerical position as the origin of coordinates, then the number of horizontal numerical in the array is the abscissa x, and the number of vertical numerical is the ordinate Y. Extracting the Y-value of the upper edge of the flame in each image x = 800, Fig.4 can be drawn. Because of the same overall oscillation frequency, the flame at other locations is also acceptable. For the same wind speed, the upper edge of the flame fluctuated over time, resulting in a change in height (Y-value) of the upper edge of the flame at a fixed abscissa, which reveals the fluctuation period of the upper edge of the flame at this wind speed. Three flame images in fig. 4 are shown with wind speed *v* = 0.82 m/s, the time interval between each two images was 0.016 s, and the corresponding y1, y2, and y3 at x = 800 were the heights of the upper edge of the flame.

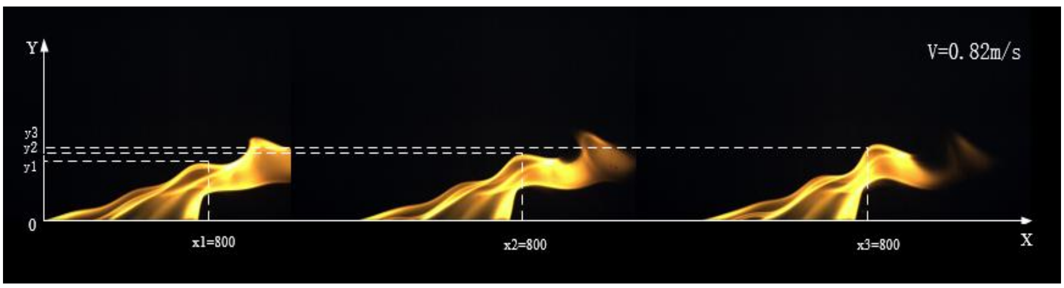

Fig.4 The height of upper edge of the flame at different times in the same wind speed *v* = 0.82 m/s,X=800, time interval 0.016 s.

Selecting the wind speed u_w = 0.82 m/s and setting the high-speed camera to 150 FPS , it may produced 750 flame image sequences (*i.e.*, the burning time of 5 sec). The time-varying law of Y value of flame upper edge at x=800 in image sequence was obtained via using MATLAB.The result was shown in Fig. 5.

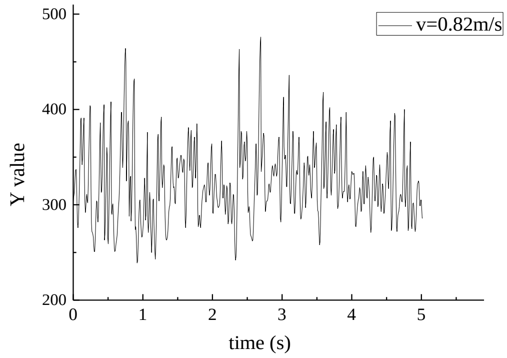

Fig.5 The time-varying law of the upper edge of the flame at x = 800, in a flame image with a wind speed *v* = 0.82 m/s ,the burning time of 5 sec, setting high-speed camera 150 FPS

In Fig. 5, the mean time interval of the adjacent peak points was calculated to obtain the average fluctuation period of the curve. At the same wind speed, the experiment was repeated 5 times under the condition of u_w = 0.82 m/s, and then verage the the flame-oscillation frequency. Next, using the same method at different wind speeds reveals the change rule between flame-oscillation frequency and cross wind speed.

Fig. 6 shows the variation of the flame-oscillation frequency with the cross wind speed when the frame rates were 150 FPS and 125 FPS. Under the condition of different frame rates, the trend was very close after the wind speed increased, the wind turbulence speed was slightly different at 1.0 m/s. So,The frequency of flame oscillation has little correlation with frame rate of high-speed camera.In this study results are based on the high-speed video photography of 150 FPS.

When 0.11m/s < u_w < 0.64m/s, oscillation frequency increased as wind speed increased, and the oscillation frequency reached a maximum value. The flame-oscillation frequency decreased ,when 0.64 < u_w < 1.36 m/s. Then the turbulence increased with increasing wind speed after u_w > 1.36 m/s. It can be seen that in the range of wind speed, the oscillation frequency of the flame first increased, then decreased, and then increased again.

The range of $\mathrm{Re_w^2/Gr_f}$ in Fig.3 shows that when the wind speed was 0.11m/s < u_w < 0.44 m/s, then $\mathrm{Re_w^2/Gr_f} < 0.1$,the influence of wind was weak, and the flame was mainly affected by the buoyancy. However, increasing wind speed exacerbates the perturbation between ambient air and flame, the acceleration and extinction of the vortex in the upper edge of the flame increased the turbulence oscillation frequency of the flame. When 0.44 m/s≤ u_w ≤1.68 m/s, 0.1≤ $\mathrm{Re_w^2/Gr_f}$ ≤10, the interaction between external airflow and buoyancy force changed the force on the flame plume during the mixing stage. At this time, the oscillation frequency fluctuated, it remained in the range of

15 Hz - 18 Hz. As the wind speed increased (when u_w> 1.68 m/s, $\mathrm{Re_w^2/Gr_f} \geq 10$), the external wind extracted a large amount of heat, then reduced flame temperature and buoyancy. The force of the wind swept is on the dominant position and the difference enlarged between the two forces of buoyancy and cross wind ,then make a horizontal tilt of the flame (see Fig. 2) and the flame-oscillation frequency continued to increase .

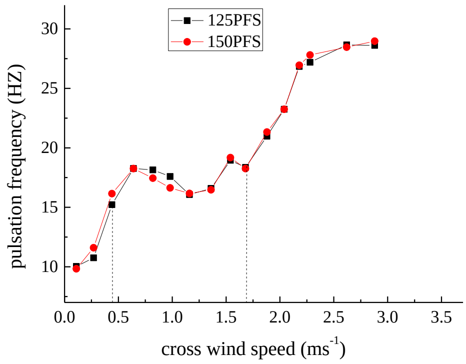

Fig.6 Curve diagram of flame oscillation frequency versus wind speed at 150FPS and 125FPS

3.3. Combustion efficiency

In the diffusion combustion process, the combustion rate of liquid fuel was determined by the heat transfer from the surrounding high temperature flue gas to the fuel. High temperature flue gas fed the heat into the liquid fuel via radiation, heat conduction, and convection to evaporate the liquid fuel into combustible gas, so that the amount of liquid fuel heat absorption directly determined the degree of flame burning. However, under the effect of cross wind, the burning process becomes more complicated due to the influence of heat transfer between oil and wind. The calculation of combustion efficiency in the study was obtained by measuring the mass loss rate of the liquid fuel in measurement interval, specifically by measuring the mass-change curve of the oil tank using the electronic balance below the oil pool.the mass loss rate of the light diesel oil were gotton in different cross wing speed, The result was shown in Fig. 7.

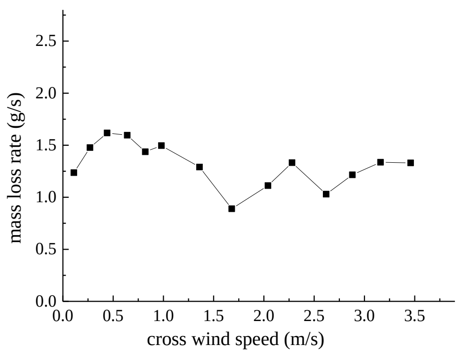

Fig.7 Variation curve of fuel mass loss rate at different wind speeds

Fig. 7 shows that the mass loss rate of the fuel increased with increasing wind speed when 0.11

m/s < u_w < 0.44 m/s. Wind accelerated the gasification rate of the oil in the oil pool, made combustion intensify and the temperature increase. When 0.44 m/s < u_w < 1.68 m/s, the mass loss rate showed a downward trend. The combustion rate of the liquid fuel depended mainly on the amount of heat absorbed by the fuel, which was decided by on the temperature difference between fuel and oil pool wall. Hu *et al.* [22] showed that with increasing wind speed, the flame tilted to the plane, resulting in a small fuel view surface, greatly reducing fuel surface of the received heat. While the oil pool surface temperature reduces, caused a decrease of fuel gasification rate and led to a reduction in the mass loss rate of the fuel. When the cross flow speed u_w > 1.68 m/s, flame caused severe tilt and even became parallel with the bottom of the wind tunnel (Fig. 2). The wall surface of the oil pool was directly heated by heat convection and heat radiation of the fire , and increasing the mass loss rate[23].

The combustion efficiency was defined as the ratio of actual heat, released during the burning process, to its complete combustion. The C element in the fuel was completely burned to produce CO_2 gas, while the H element burned into H_2O. The CO_2 and H_2O concentrations in the flue gas after complete combustion can be calculated by measuring the C and H element mass of the liquid fuel in the oil pool. However, during the actual process, the calculation of combustion efficiency requires the CO and CnHm concentrations in flue gas owing to incomplete combustion. The combustion efficiency can be expressed as:

$$\eta = 1 - \frac{\text{CO and CnHm concentrations in flue gas} * \text{Volume flow}}{\textit{The amount of } CO_2 \textit{ and } H_2O \textit{ produced by complete combustion per unit time}} \quad (2)$$

CO concentrations and CnHm concentrations were measured with the on-line flue gas analyzer (Testo 350, TestoSE & Co. KGaA,Germany).The change in combustion efficiency at different wind speeds was calculated according to the previous rate of fuel mass loss and formula (2), the results were shown in Fig. 8.

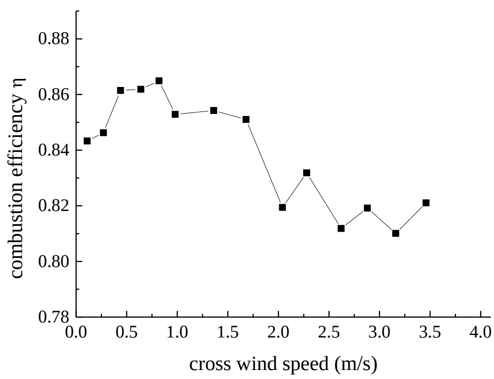

Fig.8 Curve of combustion efficiency at different wind speeds

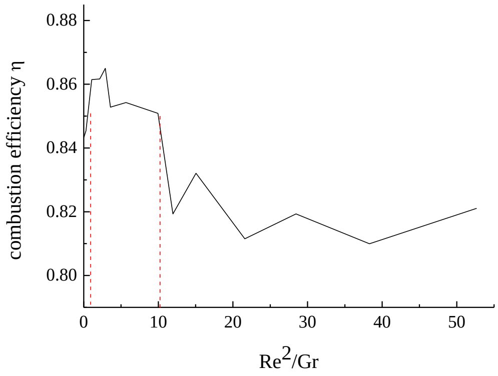

Fig.9 Combustion efficiency changes with Re_w^2/Gr_f

Fig. 8 shows that the overall trend of combustion efficiency first increased and then decreased as the lateral wind speed increased. When 0.11 < u_w < 0.64 m/s, the combustion efficiency increased and reached a maximum at v = 0.64 m/s. When u_w > 0.64 m/s, the combustion efficiency was gradually reduced, ultimately nearly stabilizing, although fluctuations could still be observed. Fig. 9 shows the relationship between combustion efficiency η and $\mathrm{Re}_\mathrm{w}^2/\mathrm{Gr}_\mathrm{f}$. The dotted area in Fig. 9 showed that the combustion efficiency is higher when $0.1 \leq \mathrm{Re}_\mathrm{w}^2/\mathrm{Gr}_\mathrm{f} \leq 10$, combustion is at a mixed convection stage and the combustion efficiency η values are higher but fluctuated. When $\mathrm{Re}_\mathrm{w}^2/\mathrm{Gr}_\mathrm{f} >$ 10, the combustion efficiency is reduced and remains stable at a lower value.

3.4. Relationship between flame-oscillation frequency and combustion efficiency

The oscillation frequency and combustion efficiency of the flame were both related to the range of different $\mathrm{Re}_\mathrm{w}^2/\mathrm{Gr}_\mathrm{f}$ from the analysis before. The relationship between oscillation frequency and efficiency can be used to visually observe through the oscillation frequency of the flame image (feel from the human eyes) to estimate combustion efficiency. This not only enriched the study of combustion characteristics under the cross wind, but also the oscillation frequency characteristics applied to diagnosis the combustion process. Fig.10 shows a flame-oscillation frequency and combustion efficiency diagram, which were put together for ease comparison.

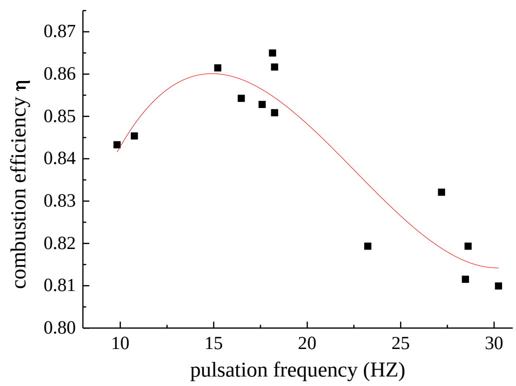

Fig.10 Relationship between combustion efficiency and flame oscillation frequency

Fig.10 shows that high combustion efficiency concentrated in a range whose flame-oscillation frequency is in 15 Hz - 18 Hz, and relating to the mixing combustion stage, *i.e.*, 0.1 $\leq \mathrm{Re}_\mathrm{w}^2/\mathrm{Gr}_\mathrm{f} \leq 10$; the efficiency value was not below 85% in this case. A possible reason is that the shear layer vortex formed by the interaction between gas and the flame make the fuel and air has been fully mixed, thus intensifying the combustion and increasing combustion efficiency. When the wind speed was small, the excess air coefficient was not sufficient to support complete combustion. When forced convection dominated, even if the amount of oxygen was sufficient, a large amount of cold air would remove the heat to reduce the flame burning temperature, which will lead to lower combustion efficiency. According to the experimental image of Fig. 2, it becomes clear that the visible area of the flame image increased and the combustion efficiency increased during the mixing stage ($0.44 < u_w < 1.68$ m/s), which can also be proven the high combustion efficiency is in a certain oscillation frequency range. Only keep the flame-oscillation frequency in 15 Hz-18 Hz, it may ensure combustion efficiency in right way.

4. Conclusions

Turbulent flame-oscillation frequency and combustion efficiency are the important parameters in combustion. Based on the results of wind tunnel experiment and combined the flame sequence image using a high-speed video and the treatment of MATLAB, the flame-oscillation frequency and combustion efficiency of 120 mm ×50 mm ×50 mm oil pool flames under the action of cross wind were studied. The following conclusions were drawn:

(1) For wind speed of $0 < u_w < 0.44$ m/s, $\mathrm{Re}_\mathrm{w}^2/\mathrm{Gr}_\mathrm{f} < 0.1$, the flame was mainly affected by the buoyancy in the vertical direction. The influence of cross sweeping wind on the flame was dominated by $u_w > 1.68$ m/s, $\mathrm{Re}_\mathrm{w}^2/\mathrm{Gr}_\mathrm{f} > 10$ and the mid interval was a mixed phase. In the experimental wind speed range, with the increase of wind speed, flame-oscillation frequency first increased, then decreased, and then increased again.

(2) With increasing lateral wind speed, the trend of combustion efficiency first increased and then decreases, reaching a maximum at $u_w = 0.64$ m/s. When 0.1 $\leq \mathrm{Re}_\mathrm{w}^2/\mathrm{Gr}_\mathrm{f} \leq 10$, the combustion was in a mixed convection stage where the combustion efficiency fluctuated, but the values are higher.it was possible to judge the combustion efficiency by observing the fluctuation characteristics of the flame image.

(3) During the mixing stage, the combustion efficiency was higher in the range of turbulent oscillation frequency of 15 Hz-18 Hz, the combustion efficiency may ensure not below 85% in this case.

Acknowledgments

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Nomenclature

g –gravitational acceleration, m/s^2

Gr_f –Grashof number of flame(=$g\alpha_v\Delta T l_w^3/v_f^2$)

l_w –equivalent diameter of the cross section of the wind tunnel, m

l_f –equivalent diameter of the oil sump, m

R –jet-to crossflow momentum flux ratio(=$\rho_j u_j^2/\rho_w u_w^2$)

Re_w –crosswind Reynolds number(=$u_w l_w/\nu_w$)

T_f –average temperature of the flame plume, K

T_∞ – ambient temperature, K

u_w –crossflow velocity, m/s

ν_f –kinematic viscosity of flame plume at average temperature, m^2/s

ν_w –kinematic viscosity of air, m^2/s

α_v –volume expansion coefficient

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