Experimental Study on Double Jet Flames with Different Nozzle Diameters

Zilong Rui [1, a], Kuibin Zhou [1, b] *, Ruixing Dong [1 c] and Xia Shi [1, d]

[1] College of Safety Science and Engineering, Nanjing Tech University, Nanjing, Jiangsu, 211816, China;

[a] 1393507705@qq.com, [b] kbzhou@njtech.edu.cn, [c] 1140589683@qq.com, [d] 2311921259@qq.com

Abstract. Double jet flames are commonly observed in the energy industry. A facility consisting of a double jet flames apparatus, was designed to experimentally simulate the interaction of double jet fires with different spaces and nozzle diameters. It has been found that the exit momentum, nozzle diameters and nozzle spacing significantly affect the flame behavior. The experimental results show that the flame merging probability (Pm) of double jet fires with different nozzle diameters can be fitted with dimensionless parameters that couple the Froude number(Fr) and the distance between fire sources. Additionally, it has been observed that the difference in height between the two flames can be used as a parameter to determine the correlation between flame height and the distance to the nozzle center.

Keywords: Double flames; Merging behavior; Flame height.

1. Introduction

Energy is a crucial prerequisite for the rapid development of a nation. In recent years, the rapid economic growth and continuous urbanization in China have been facilitated by the ample supply of energy through pipelines. However, energy pipelines are inevitably subject to varying degrees of damage during installation, operation, and maintenance. The rupture of an energy pipeline can lead to jet fire incidents when exposed to an open flame. Extensive research has been conducted on jet fires, starting from early studies on vertically free jet fires in a stationary environment [1] Subsequent research expanded to investigate jet fires at different angles [2], in rotating flow fields [3], and under horizontal jet fire conditions in confined spaces [4]. Considerable progress has been made in understanding the geometric characteristics of single-source jet flames under various conditions, and relevant theories have matured.

When multiple ruptures occur in a pipeline, it can result in two or more flames. The interaction between two flames significantly alters their combustion characteristics compared to a single flame [5]. The distance between two flames affects the difference in air entrainment, influencing the tilt and merging state of the flames [6]. Early studies by Putnam and Speich [7] focused on the merging of jet flames from multiple sources, proposing that jet flames suddenly transition from individouble jet flames to large-scale flames when the critical spacing coefficient is approximately 2.

Flame height is a critical topic in fire science because the mutual restriction of air entrainment between two fire sources may render the flame height formula for a single source inadequate for double sources [8] Huang et al [9] found that a significant difference in heat release rates between two fire sources can lead to a small flame tilting towards a larger flame, establishing a critical criterion for the absence of correlation between merged flame height and fire source spacing. Shi et al [10] studied the flame merging probability and flame height of double jet flames with the same exit velocity in the Froude number range of 2×103 to 1.48×105, establishing relationships between flame merging probability and momentum control as well as buoyancy control, and correlating Froude number with flame height for double jet flames.

Therefore, this paper conducts experimental measurements of double jet flames with different nozzle diameters under flat wall constraint conditions. The study systematically investigates the influence of different nozzle Froude numbers and nozzle spacing on flame merging probability and flame height. A flame merging probability model for double jet flames with different nozzle diameters is established, and the height difference between the flames is used as a criterion for determining the correlation between double jet flame height and nozzle spacing.

2. Experimental

2.1 Experimental setup

The experimental setup for double jet flames with different nozzle diameters under flat wall constraint conditions mainly consists of a flat wall simulation system, a fuel control system, and a data acquisition system, as shown in Figure 1. The combustion control system includes two sets of identical gas cylinders, pressure regulators, gas supply pipelines, flow meters, flame arresters, and several nozzles with different nozzle diameters. The experiment uses 99% pure propane as fuel, and the pressure regulator is employed to control the pressure difference between the gas cylinders and the flow meters.

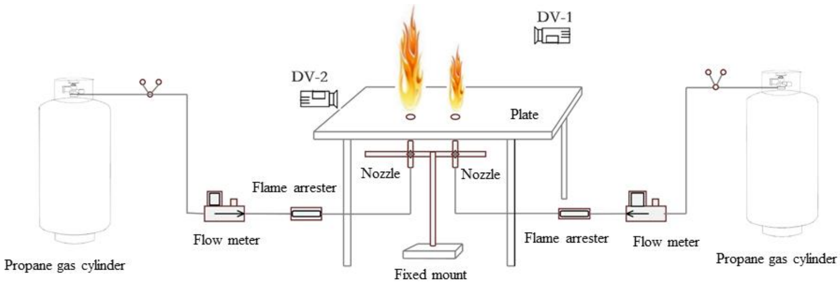


Fig. 1. Schematic for experimental setup.

The flat wall simulation system is composed of a fireproof board measuring 0.58 m in length, 0.58 m in width, and 0.01 m in thickness. It features a groove in the middle measuring 210 mm × 20 mm, allowing for flexible adjustment of the spacing between the two nozzles. Sealing treatment is applied to the gap between the fireproof board and the nozzles. The data acquisition system comprises flow meters and cameras. The flow meter (Alicat mass flow controller) was used to monitor the mass flow rate of propane with the accuracy of ±0.2% within the measurement range of 0–50 standard liter per minute. The nozzle exit velocity was the ratio of the mass flow rate to the exit area and propane density. Two digital video cameras (FDRAX60 of Sony) were used to record the flame geometrical features from the front and side views, respectively. The camera had the resolution of 3840 × 2160 pixels with a sampling frequency of 25 Hz. In actual leakage incidents, the internal and external environments of the two leakage points are consistent, and the gas release flow rate is the same. Therefore, the experimental design adjusts the flow meters to control the identical nozzle velocities of the two nozzles with different diameters. Here, dl and dr represent the nozzle diameters of the nozzles located on the left and right sides in the experiment. Table 1 presents the operating conditions for double jet flames with various nozzle diameters.

Table 1. Summary of experimental conditions

Numble	d (mm)	S (cm)	U_e (m/s)	Q (kW)	$Fr \cdot 10^{-4}$
1	d_l =3	2.5/6.5/10/12/15/17/18.5/20	9.44/18.87/28./42.4/56.62/61.34	5.65/11.3/16.95/25.42/33.89/39.5	0.3/1.21/2.72/6.13/10.89/12.78
	d_r =2.3			3.32/6.64/9.97/14.9/19.9/23.3	0.39/1.58/3.55/7.99/14.21/16.67
2	d_l =3	2.5/6.5/10/12/15/17/18.5/20	9.44/18.87/28./42.4/56.62/61.34	5.65/11.3/16.95/25.42	0.3/1.21/2.72/6.13
	d_r =4.2			11.07/22.02/33.21/49.81	0.21/0.86/1.94/4.4
3	d_l =3	2.5/6.5/10/12/15/17/18.5/20	9.44/18.87/28./42.4/56.62/61.34	5.65/11.3/16.95	0.3/1.21/2.72
	d_r =5			15.7/31.4/47.1	0.18/0.73/1.63

2.2 Data pretreatment and test repeatability.

To capture the flame morphology, a segment of the steady-state flame combustion video is first selected. The video is then converted into a series of consecutive flame images using a Matlab program. Subsequently, the Otsu method [13] is applied to process and obtain a contour map of the probability of flame appearance (Figure 2). A 50% intermittent probability is used to determine the geometric contour of the flame. The degree of merging for double flames is a crucial aspect of flame morphology research. To quantify the behavior of flame merging, we introduce the concept of flame merging probability (Pm). Through a probability density cloud map, the maximum value is selected from the contours of the two connected flames' gaps to determine the flame merging probability. As shown in Figure 3, with nozzle diameters dl=3 mm and dr=5 mm, nozzle center spacing S=15 cm, and exit velocity Ue=9.44 m/s, the flame merging probability is Pm=0.2. The range of variation for the flame merging probability Pm is from 0 to 1. When Pm=1, the double jet flames are in a fully merged state; when 0<Pm<1, the two flames are in an intermittent merged state; when Pm=0, the two flames are in an independent state.

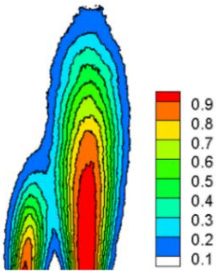


Fig. 2. Determination of the Pm value from the connected flame intermittency contour (Pm= 0.2 when dl=3 mm, dr=5 mm, S=15 cm and Ue=9.44 m/s)

For double jet flames with different nozzle diameters, when the merging probability Pm≥0.5, the flame height H is defined as the flame height after the merging of the double jet flames (Figure 3a). When the merging probability Pm<0.5, due to the small difference in height between the large flame and the merged flame height when Pm>0.5, the flame height of the double jet flames is defined as the height of the large flame (Figure 3b).

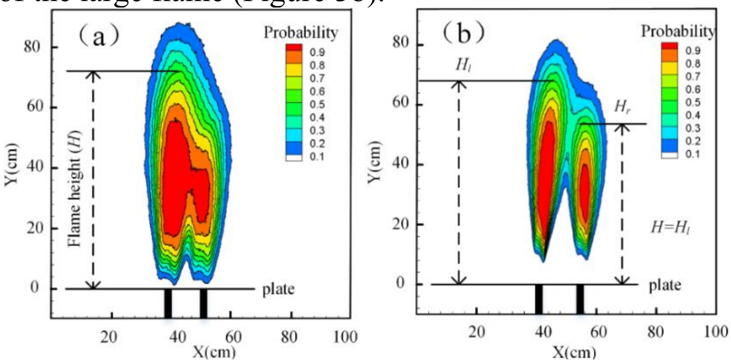


Fig. 3. Diagram of flame height with different nozzle diameters (dl=3 mm, dr=2.3 mm,): (a) Pm≥ 0.5 when S=15 cm and Ue=42.46 m/s, (b) Pm<0.5 when S=15 cm and Ue=28.31 m/s

3. Results and discussion

3.1 Phenomenon observation and flame merging

Figure 4 presents typical flame images of double jet flames with different nozzle diameters and nozzle center spacings. In Fig 4(a), it can be observed that, with nozzle diameters of dl=3 mm and dr=2.3 mm, the larger flame consistently tilts toward the smaller flame as the nozzle center spacing increases from 6.5 cm to 20 cm. In contrast, Figure 5(b) shows an opposite phenomenon for nozzle diameters dl=3 mm and dr=5 mm, where the smaller flame tilts towards the larger flame. This behavior is related to the Froude numbers (Fr) and heat release rates (Q) on both sides of the nozzle exits. Wu et al [12]. demonstrated through experiments that Fr=1×105 is a critical parameter distinguishing between buoyancy-controlled and momentum-controlled jet flames. In Figure 4(a), the Froude numbers at the nozzle exits on the left and right sides are Frl=3.03×103 and Frr=3.95×103, respectively, indicating buoyancy-controlled flames. Flames with smaller Froude numbers are more susceptible to the influence of air buoyancy. When both flames are burning simultaneously, the upper part of the larger flame on the left side, with a larger exit diameter, tends to tilt towards the smaller flame. In Fig 4(b), the maximum Froude numbers at the nozzle exits on both sides are Frl=3.03×103 and Frr=1.82×103, indicating that the flames are still controlled by buoyancy. When there is a significant disparity in heat release rates between the two flames, it leads to a substantial difference in height between them. In their investigation of double flames with identical burner sizes but varying heat release rates, Huang et al [9] observed that the smaller flame experiences significant hindrance in air entrainment when located close to the larger flame. This obstruction causes the smaller flame to tilt toward the larger flame. For the larger flame, it primarily draws in air through the feathered flow above the smaller flame. The greater the height difference between them, the less restricted the air entrainment becomes. The pressure drop between flames is a significant factor contributing to flame convergence [6]. In Fig 4(b), the upper part of the larger flame experiences almost no pressure drop, which causes the smaller flame on the left to tilt towards the larger flame.

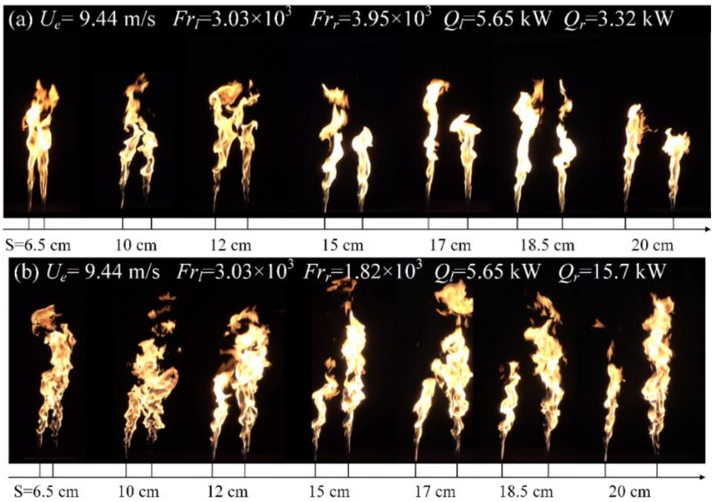
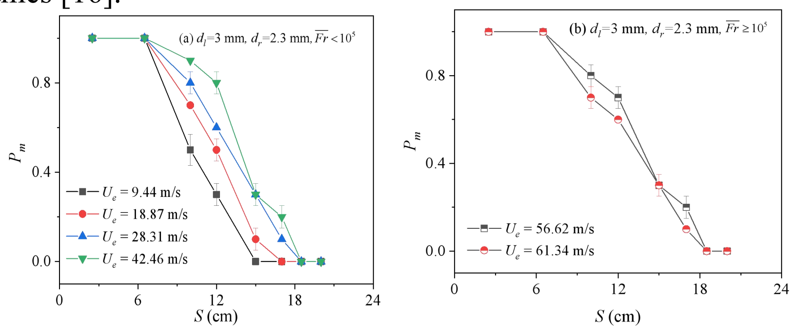


Fig .4. Typical photos of double jet fires: (a)dl=3 mm, dr=2.3 mm and (b)dl=3 mm, dr=5 mm.

The flame images processed using the method in Section 1.2 can yield the merging probability (Pm) of the two flames, thus quantifying the extent of flame merging. Figure 5 illustrates the change in flame merging probability with nozzle center spacing for double jet flames. The left diameter is 3 mm, and the right diameters are 2.3 mm, 4.2 mm, and 5 mm, respectively, at various exit velocities. Similar to double buoyancy-driven pool flames [15] and linear double flames [16], the flame merging behavior can be categorized into three states: fully merged state (Pm = 1), intermittent merging state (0 < Pm < 1), and independent state (Pm = 0). For double jet flames with different nozzle diameters, the probability of flame merging decreases as the spacing between the nozzle centers increases. This is consistent with the findings for double buoyancy-driven pool flames [15] and linear double flames [16].



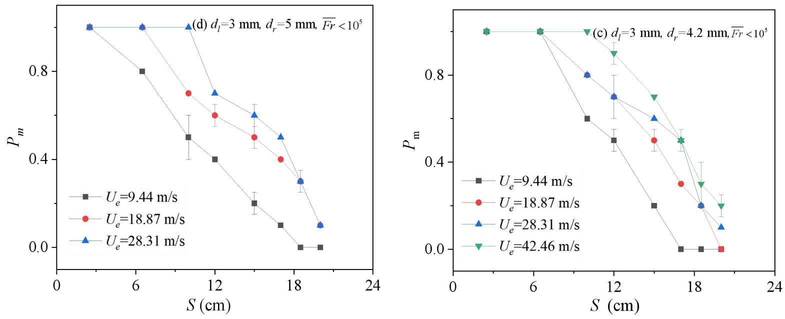


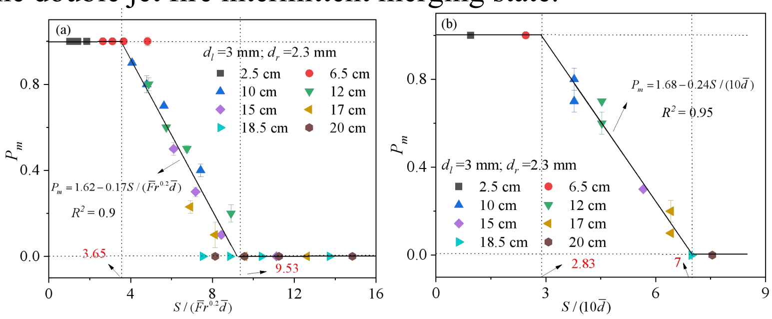
Fig. 5. Flame merging probability versus spacing

Many scholars often associate the nozzle Froude number with the flame height of the jet fire, and propose the critical Froude number ($Fr=1\times10^5$ for propane) that distinguishes the flame height controlled by momentum and buoyancy [14]. Shi et al [11] proposed $Fr=1\times10^5$ to distinguish the two modes of flame merger probability. The flame width of the double-jet fire has a significant influence on the flame merging behaviour [9], Therefore, in the analysis of double jet fires with different nozzle diameters, the average of the Froude number ($\overline{Fr}=1\times10^5$) on both sides of the nozzle is used to distinguish the two modes of flame merger probability. Since the flame width of a single jet fire is proportional to the flame height [17], the flame width of a single jet fire is used to normalize the flame spacing when studying the merging probability of double jet fires with different nozzle exit diameters. Within the range, the flame merging probabilities can be expressed as [10]:

$$P_m \sim \frac{S}{A\overline{Fr}^{0.2}\overline{d}/n_1} \tag{1}$$

$$P_m \sim \frac{S}{10A\overline{d}/n_2} \tag{2}$$

The formulas (1) and (2) can be simplified as: $P_m \sim S/\overline{Fr}^{0.2}\overline{d}$ and $P_m \sim S/10\overline{d}$. Figure. 8. presents the flame merging probability versus the dimensionless spacing under different nozzle diameters and exit velocities. By comparing Fig. 6 (a) and (b), it can be seen that the absolute value of the slope of the line in Fig 6 (a) is less than that of the slope in Fig 6 (b). That is to say, the intermittent merging state changes more rapidly in momentum control than in buoyancy control. Based on the analysis of Fig 6 (a, c, d), it can be observed that when the exit speed remains constant, the greater the difference in diameter between the two sides of the nozzle exit, the slower the Pm change trend of the intermittent merging state. This results in a larger critical dimensionless fire source spacing for the double jet fire intermittent merging state.



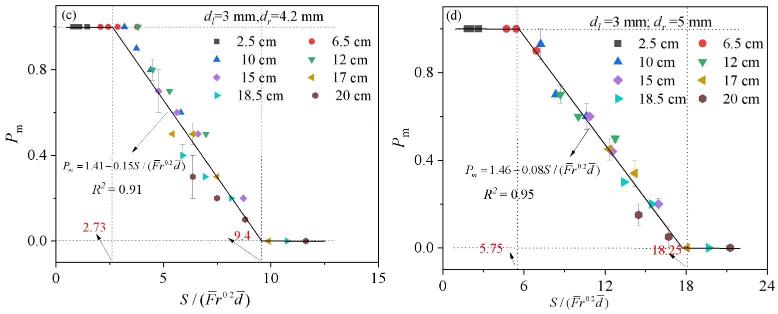


Fig. 6. Flame merging probability versus spacing normalized by width of single flame.(a), (c), (d) $\overline{Fr}<10^5$ and (b) $\overline{Fr}\geq 10^5$

3.2 Flame height

Figure 7(a)-(c) illustrate double jet flames with right nozzle diameters of 2.3 mm, 4.2 mm, and 5 mm, respectively. The variation in flame height with nozzle spacing for double jet flames at different exit velocities is shown. In Figure 7(a), the flame height gradually decreases with the increase of nozzle spacing, and the increase in nozzle spacing gradually reduces the interaction between the two jet flames, thereby lowering the restriction of air entrainment between them. In Figure 7(b), the flame height initially decreases as the nozzle spacing increases, and then stabilizes as the nozzle spacing further increases Figure 7(c) shows that the flame height remains relatively stable, indicating that the flame height of double jet flames with dl=3 mm and dr =5 mm is independent of the spacing.

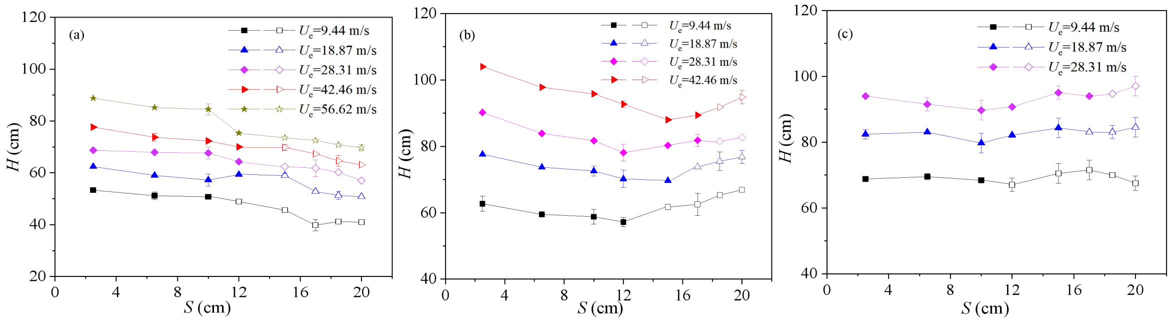


Fig 7. Flame height versus nozzle spacings for different exit velocity and diameters: (a) dr=2.3 mm, (b) dr=4.2 mm and (c) dr=5 mm. The solid point is the flame height when Pm≥0.5, and the modest point is the flame height when Pm<0.5.

The height difference Δh between the larger and smaller flames impacts the flame height of double jet flames with varying nozzle diameters. Figure 8 illustrates the correlation between the height difference of the larger and smaller flames and the nozzle spacing (S) for various right nozzle diameters. It is evident that when the exit velocity remains constant, the difference in flame height increases with a larger variance in the diameters of the left and right nozzles. Based on the flame height variation graph for double jet flames in Figure 7 and the flame height difference graph in Figure 8, it is noted that when the height difference between the two flames falls within the region of dl=3 mm, dr=5 mm and above in Figure 8, the flame height of double jet flames with different nozzle diameters is independent of the nozzle spacing. However, when the height difference falls within the region of dl =3 mm, dr =2.3 mm in Figure 8, the flame height of double jet flames is dependent on the nozzle spacing. This is evident from Figure 8(b) where the flame height initially decreases with the increase of nozzle spacing and then stabilizes. Combining this with the flame height difference region of dl =3 mm, dr =4.2 mm in Figure 8, it can be concluded that the region of dl =3 mm, dr =4.2 mm represents a transitional zone where the flame height of double jet flames is both dependent and independent of the nozzle spacing.

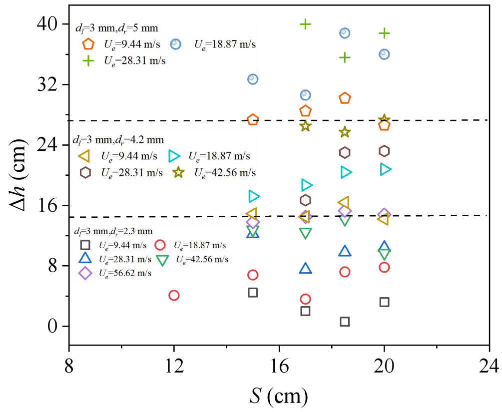


Fig. 8. Flame height difference (Δh) versus nozzle spacing under different right nozzle diameters

4. Summary

This paper systematically investigates the behavior of double jet flames with different nozzle diameters under wall conditions through experiments. The study provides a detailed analysis of the impact of varying nozzle diameters on the inclination of double jet flames, flame merging probability, and flame height. The main conclusions are as follows:

(1) The inclination of double jet flames with different nozzle diameters is related to the flame Froude number (Fr). When the difference in heat release rates between the two flames is small, the flame tends to incline from low Fr to high Fr.

(2) Similar to double jet flames with the same nozzle diameter, the concept of flame merging probability remains applicable for double jet flames with different nozzle diameters, allowing the distinction between two modes of flame merging.

(3) Three distinct regions of flame height difference are proposed to categorize the correlation between double jet flame height and nozzle spacing, offering a comprehensive understanding of their relationship.

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References

[1] Kalghatgi G T. Lift-off Heights and Visible Lengths of Vertical Turbulent Jet Diffusion Flames in Still Air. J. Combustion Science and Technology,1984, 41(1-2): 17-29.

[2] Tao Changfa, Shen Yan, Zong Ruowen. Experimental determination of flame length of buoyancy-controlled turbulent jet diffusion flames from inclined nozzles J. Applied Thermal Engineering,2016, 93: 884-7.

[3] Zhou Kuibin, Qin Xiaole, Zhang L. An experimental study of jet fires in rotating flow fields. Combustion and Flame, 2019, 210: 193-203.

[4] Zhou Kuibin, Zhou Mengya, Huang Mengyuan. An experimental study of jet fires in pits. Process Safety and Environmental Protection, 2022, 163: 131-143.

[5] Li Bo, Wan Huaxian, Gao Zihe, Experimental study on the characteristics of flame merging and tilt angle from twin propane burners under cross wind. Energy, 2019, 174: 1200-9.

[6] Weng W. G, Kamikawa D, Fukuda Y. Study on flame height of merged flame from multiple fire sources . Combustion science and Technology, 2004, 176(12): 2105-23.

[7] Thomas P H, Baldwin R, Heselden J M. Buoyant diffusion flames: Some measurements of air entrainment, heat transfer, and flame merging. Symposium (International) on Combustion, 1965 10(1): 983-96.

[8] Liu Naian, Liu Qiong, Lozano Jesse S, et al. Global burning rate of square fire arrays: Experimental correlation and interpretation. Proceedings of the Combustion Institute, 2009 32(2): 2519-26.

[9] Huang Yonglong, Wan Huaxian, Ding Long, et al. Research on the interaction between two line jet fires with unequal heat release rate at different burner distances. Fuel, 2019 258: 116016.

[10] Shi Xia, Zhou Kuibin. Geometrical features and global radiant heat of double turbulent jet flames. Fuel, 2023 350: 128789.

[11] Cha M S, Chung S H. Characteristics of lifted flames in nonpremixed turbulent confined jets. Symposium (International) on Combustion, 1996, 26(1): 121-8.

[12] Wu Yueqiong, Zhou Kuibin, Huang Mengyuan, Zhou mengya. Flame behavior of jet fire confined by the tank wall. Journal of chemical industry, 2021, 72(5):2896-2904.

[13] Otsu. A threshold selection method from gray-level histograms. IEEE Trans. Syst, 1979 9: 62–66.

[14] Wu Yueqiong, Zhou Kuibin, Zhou Mengya, et al Radiant heat feedback from a jet flame to the ruptured tank surface. International Journal of Thermal Sciences, 2022 172(72): 2896-904.

[15] Zhou Kuibin, Zhang Le, Huang Mengyuan, et al. Experimental study on flame interaction and geometrical features of two identical fires on a slope. Fire Safety Journal, 2021 126: 103463.

[16] Liu Naian, Zhang Shaojie, Luo Xisheng, et al. Interaction of two parallel rectangular fires. Proceedings of the Combustion Institute, 2018, 37: 3833-3841.

[17] Son J K, Hustad J. An experimental study of turbulent jet diffusion flames. Norwegian Maritime Research, 1984, 4(12): 2-11.