ABSTRACT: Transformer oil jet fire is one of the most dangerous types of fires in substations. The combustion behavior of transformer oil jet fire produces uncontrollable hazards to personnel and equipment and even triggers a domino effect. However, the jet fire combustion behavior of such materials as transformer oil has not been revealed before. Investigation of the combustion behavior of transformer oil jet fire has positive implications for the prevention and control of substation fires. In this paper, KI25X transformer oil was used as fuel. A series of transformer oil jet fire experiments were conducted with variable orifice diameters (5, 10, and 15 mm) with heat release rates ranging from 200 to 659.2 kW. The results showed that the entrainment coefficient of transformer oil jet fire was greater than that of pure gas phase jet fire. The entrainment coefficient of transformer oil jet fire was 0.029. Using dimensionless theory, it was proposed that the imaginary point source was proportional to the 0.317 power of Froude number. Based on the point source model, a dimensional analysis model with Reynolds number was developed. The radiation fraction of transformer oil jet fire was proportional to the $-0.133$ power of Reynolds number. This study played an important role in improving the jet combustion behavior of transformer oil.

1. INTRODUCTION

1.1. Background and Literature Review. A substation is an important carrier of power transmission. Transformer oil is widely used as an insulating material in substations. However, jet fire accidents often occur due to the thermal runaway of transformer oil. Many scholars have been puzzled by substation safety problems. Gómez-Mares et al. investigated 84 jet fire events and found that 50% of the events induced a domino effect. A typical example is the substation fire accident in Xi’an, China, in 2016. Transformer oil jet fire occurred and caused serious equipment damage. Therefore, quantification of transformer oil jet combustion behavior is of great significance to substation fire safety.

When transformer oil jet fire occurs in a substation, the fire hazard degree is directly determined by fire characteristic parameters such as flame height, flame temperature, and flame radiant heat flux. In previous studies, scholars have carried out a lot of research on flame height. Based on the Heskestad flame height model, Bradley et al. studied the flame height of six kinds of gas fuel jet fires. Based on the Suris flame height model, Gopalaswami et al. studied the propane jet flame height at exit velocities varying from 25 to 210 m/s. Imamura et al. studied the flame height characteristics of hydrogen jet. Labourer et al. studied the characteristics of LPG jet flame height. Hu et al. studied the change of propane flame height with different environment pressures. The correlation between the entrainment coefficient and the flame Froude number was also developed. For the study of flame temperature, Heskestad introduced a virtual point source to study the correlation between the flame temperature and the flame height. Gómez-Mares et al. carried out the propane jet flame experiment and proposed the quadratic polynomial between flame temperature and flame height. Hu et al. found that under different ambient pressures, the virtual point source of propane jet fire was dimensionless in correlation with the flame Froude number by $2/5$ power law function. About the study of flame radiation heat flux, based on the hydrogen jet fire experiment, Lowesmith et al. proposed a multipoint source radiation model. Zhou et al. proposed a line source model to improve the radiation model. In addition, Zhou et al. studied the correlation between the propane jet fire radiation fraction and the Froude number. Hu et al. established a correlation between the radiation fraction and the Reynolds number based on the propane jet fire experiment.
It can be seen that all this literature considered the flame height, flame temperature, and flame radiation heat flux of gas fuel jet fire in detail. However, another typical liquid fuel jet fire exists in actual production and life. The oil filling equipment in a substation is subjected to external thermal load, and the transformer oil in the oil filling equipment sprays out, which means that a jet fire characterized by liquid fuel is formed. The flame color of transformer oil jet fire is brighter than that of gas jet fire. Transformer oil jet fire generates more carbon black. The flame height generated by transformer oil jet fire is higher. The jet fire combustion behavior of transformer oil has not been revealed. Therefore, it is necessary to reveal the combustion behavior of transformer oil jet fire.

1.2. The Aim of This Study. The above studies focus on the combustion characteristics of jet fire caused by gas fuels. However, the jet flame generated by thermal runaway in a substation cannot be directly applied to the classical gas jet flame combustion model. Therefore, it is extremely important to reveal the combustion behavior of transformer oil jet fire. Research on these problems is conducive to the current substation fire prevention.

In this paper, first, the background and purpose of this study were expounded. Then, a series of transformer oil jet combustion experiments were carried out to study jet fire combustion characteristics. Finally, the combustion behavior of transformer oil jet fire was analyzed and discussed. On the basis of theoretical analysis and scaling analysis, three new correlations describing the combustion behavior of transformer oil jet are further developed.

2. EXPERIMENTAL SETUP

2.1. Experimental System. The schematic of the experimental setup is shown in Figure 1. The jet fire experiment was carried out in a cylindrical vessel. The top three orifice diameters were 5, 10, and 15 mm, respectively. A circular oil tank with a diameter of 30 cm was placed under the vessel. The vessel sidewall was 10 cm high. A load cell (AND GP-61ks; range: 0–60 kg) was placed underneath the vessel to collect fuel mass loss rates. A fireproof board was placed between the oil vessel and the load cell to protect the load cell. A CCD camera (SONY NEX-FS700; frame rate: 25 fps) and an infrared thermal imager camera (DALI TECHNOLOGY DL700; frame rate: 25 fps) were used to collect flame images. An 8K-type thermocouple (OMEGA; diameter, 1 mm) was used to measure the axial centerline temperature of flame. The bottom of the thermocouple was at the orifice of the vessel. The thermocouple spacing was 0.3 m. A water-cooled radiometer (OMEGA; maximum range: 50 kW/m²) was used to measure the incident radiation heat feedback on the flame surface. The radiometer was 1 m away from the vessel. Before measuring the incident radiation flux, the radiation blocking effect was calibrated. KI25X transformer oil was used as fuel in the experiment. All experiments were completed in a closed hall to eliminate the influence of the environment on flame combustion. Three experiments were conducted in each group. The experimental conditions are shown in Table 1.

2.2. Experimental Method. The flame image processing method is shown in Figure 2. First, the original image was obtained by processing the original flame video frame (Figure 2a). Then, the original flame image color was removed to

Table 1. Test Conditions

| group number | vessel diameter (cm) | orifice diameter (mm) | heat release rate (kW) |
|--------------|----------------------|-----------------------|------------------------|
| 1            | 5                    | 5                     | 200                    |
| 2            | 5                    | 10                    | 235.2                  |
| 3            | 5                    | 15                    | 250                    |
| 4            | 8                    | 5                     | 212                    |
| 5            | 8                    | 10                    | 289.2                  |
| 6            | 8                    | 15                    | 405.6                  |
| 7            | 10                   | 5                     | 214                    |
| 8            | 10                   | 10                    | 468                    |
| 9            | 10                   | 15                    | 659.2                  |
obtain a grayscale image (Figure 2b). Subsequently, the appropriate threshold is selected based on the Otsu method to transform the gray image into a binary image (Figure 2c). The flame average image (Figure 2d) was obtained by removing the nonflame zone interference. Finally, the Tecplot was used to convert the flame average image into the probability cloud image (Figure 2e). As shown in Figure 3, the flame height was defined as the axial distance between the orifice and the intermittent distribution of 0.5.

The calculation method of flame radiation fraction is shown in Figure 4. The flame center could be obtained from the flame intermittent contour shown in Figure 3. Based on the point source model, the flame radiation fraction was calculated as follows:

$$\chi_R = \frac{4\pi R_f^2 I_R}{Q}$$  \hspace{1cm} (1)

where $\chi_R$ is the flame radiation fraction, $R_f$ is the distance from the vertical flame midpoint height to the radiometer position (m), $I_R$ is the radiation flux (kW/m²), and $Q$ is the heat release rate (kW).

$$R_f = \sqrt{R^2 + \left(\frac{h}{2} - H_R\right)^2}$$  \hspace{1cm} (2)

where $R_f$ is the distance from the vertical flame midpoint height to the radiometer position (m), $R$ is the horizontal radiometer-nozzle distance (m), $h$ is the flame height (m), and $H_R$ is the radiometer height (m).

3. RESULTS AND DISCUSSION

3.1. Flame Height Evolution Behavior. Figure 5a shows the height evolution of jet flame with a heat release rate of 235.2 kW and an orifice diameter of 10 mm. With the development of flame, the trend of flame height increased first and then decreased. As a large amount of transformer oil was sprayed from the vessel, the entrainment around the flame was enhanced. It can be seen that the flame height increased significantly from 225 to 255 s.

Figure 5b shows variation of flame height at different heat release rates. The following was observed: (1) With the increase in heat release rate, the flame height increased. (2) With the increase in orifice diameter, the flame height increased significantly. This can be attributed to the enhance-
ment of flame turbulence with the increase in orifice diameter. The enhancement of turbulence would improve the mixing degree of fuel and the surrounding air. The increase in orifice diameter increased the degree of air entrainment, resulting in a significantly enhanced flame height. Therefore, for jet diffusion flame, the flame height was closely related to the entrainment mechanism.

To quantify the flame entrainment coefficient, Hu et al. established a generalized flame entrainment coefficient solution model, as follows:

$$Q^* = \frac{Q}{\rho_0 c_0 T_0 g^{1/2} D^{5/2}}$$  \hspace{1cm} (4)

where $\dot{Q}^*$ is the dimensionless heat release rate, $\Delta T_z$ is the temperature rise at height $z$ ($^\circ$C), $\Delta T_f$ is the temperature rise at the flame tip ($^\circ$C), $\alpha$ is the entrainment coefficient, $Z$ is the vertical height above the orifice (m), $h$ is the flame height (m), and $D$ is the orifice diameter (m).

As shown in Figure 6, the entrainment coefficient of transformer oil jet fire was significantly greater than that of gas jet fire. It can be seen that there were significant differences between the entrainment mechanism of gas jet fire and that of transformer oil jet fire. This can be attributed to Rayleigh–Taylor instability and Kelvin–Helmholtz instability. Due to the presence of droplets, fuel mass flow increased. Therefore, the heat release rate of liquid jet fire was greater than that of gas jet fire. With the increase in heat release rate, Rayleigh–Taylor instability occurred at the boundary between fuel and the surrounding environment. In addition, the momentum difference between fuel and the surrounding environment resulted in Kelvin–Helmholtz instability. The combined effect of the two led to the enhancement of flame entrainment.

### 3.2. Flame Radiation

The flame radiation of hydrocarbons was mainly generated by carbon black particles. Radiation fraction ($\chi_R$) was the key parameter to characterize flame radiation. The radiation fraction was greatly affected by the fuel flow state. Figure 7a shows the variation of jet fire radiation fraction with different flow rates. It can be seen that the radiation fraction decreased with the increase in flow velocity. With the increase in flow velocity, the flame turbulence was intensified. This led to the flame bottom fuel and surrounding oxygen mixing more fully. Therefore, the radiation fraction decreased with the increase in flow velocity. In addition, the radiation fraction decreased with the increase in nozzle diameter.

Obviously, the flame radiation fraction was obviously affected by the degree of flame turbulence. Therefore, Hu et

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Figure 5. (a) Height evolution of jet flame with a heat release rate of 235.2 kW and an orifice diameter of 10 mm. (b) Variation of flame height at different heat release rates.

Figure 6. Calculation of flame entrainment coefficient.
al.43 used the Reynolds number to characterize radiation fraction, as follows:

$$\chi_R \sim R_e^{0.32}$$ (5)

where \(\chi_R\) is the flame radiation fraction, and \(R_e\) is the Reynolds number.

$$R_e = \frac{\rho UD}{\mu}$$ (6)

where \(R_e\) is the Reynolds number, \(\mu\) is the coefficient of viscosity (Pa s), \(\rho\) is the fuel density (kg/m\(^3\)), \(U\) is the flow rate of fuel (m/s), and \(D\) is the orifice diameter (m).

As shown in Figure 7b, based on the Hu model, the correlation between the radiation fraction of transformer oil jet fire and the Reynolds number was established, as follows:

$$\chi_R = 1.79R_e^{-0.133}$$ (7)

where \(\chi_R\) is the flame radiation fraction, and \(R_e\) is the Reynolds number.

The radiation fraction fluctuated in the range of 0.28–0.4. The radiation fraction decreased with the increase in Reynolds number. Flame radiation was affected by the fuel retention time and carbon black formation time. On the one hand, liquid fuels increased the shear stress between fuel and the surrounding air, leading to enhanced turbulence. Turbulence made the fuel ejection speed significantly increase. Therefore, the fuel retention time was shortened. On the other hand, turbulence strengthened fuel entrainment. The increased mixing of fuel and air led to a more adequate combustion reaction. Therefore, the spatial concentration of carbon black decreased. In addition, it can be seen that the fitting line of Hu was significantly different from that of this study. This can be attributed to the fuel state. The radiation fraction of gas jet fire was significantly affected by turbulence. The radiation fraction of the Hu model decreased significantly in a small Reynolds number range. However, the combustion efficiency of liquid fuel was lower than that of gas fuel because the droplet participates in combustion after evaporation. The performance of the transformer oil model was less obvious than that of the Hu model.

### 3.3. Flame Temperature

The thermal buoyancy of flame was determined by the heat release rate. The initial height of the fire source varied with thermal buoyancy. To correct the initial flame height, Heskestad33 introduced the concept of a virtual point source to reveal the thermal buoyancy of the flame. Based on the plume equation,35 the virtual point source was substituted, as follows:

$$\Theta = \frac{\Delta T_z/T_0}{Q^{2/3}} = f(Z, Z_0, D)$$ (8)

where \(\Delta T_z\) is the dimensionless heat release rate, \(\Delta T_z\) is the temperature rise at height \(z\) (°C), \(T_0\) is the ambient temperature (°C), \(Z\) is the vertical height above the orifice (m), \(Z_0\) is the virtual origin (m), and \(D\) is the orifice diameter (m).

The axial centerline temperature and height of the axisymmetric fire source were as follows:

$$\phi = \Theta^{3/5} = \left(\frac{Q^{2/3}}{\Delta T_z/T_0}\right)^{3/5} \propto (Z - Z_0)$$ (9)

Figure 8 shows the location of the virtual point source with different heat release rates. It can be seen that for the same orifice diameter, with the increase in heat release rate, the thermal buoyancy of the flame increased. Correspondingly, the virtual point source location rose.

To further explore the dimensionless model of the virtual point source, Heskestad33 established the correlation between the virtual point source and the dimensionless heat release rate. Hu et al.35 established the correlation between the virtual point source and the flame Froude number.

This study introduced the Froude number to explore the correlation between the virtual point source and the Froude number, as follows:

$$\frac{Z_0}{D} \sim F_e$$ (10)

where \(F_e\) is the Froude number, \(Z_0\) is the virtual origin (m), and \(D\) is the orifice diameter (m).

$$F_e = \frac{U^2}{gD}$$ (11)

where \(F_e\) is the Froude number, \(U\) is the flow rate of fuel (m/s), \(g\) is the gravitational acceleration (m/s\(^2\)), and \(D\) is the orifice diameter (m).
where $Q$ is the heat release rate (kW), $m'$ is the mass loss rate (g/s), $\Delta H_c$ is the effective heat of combustion (MJ kg$^{-1}$), $U$ is the flow rate of fuel (m/s), $\rho_i$ is the fuel density (kg/m$^3$), and $D$ is the orifice diameter (m).

$$\frac{Z_0}{D} = 0.36F_r^{0.317}$$  \hspace{1cm} (14)$$

where $F_r$ is the Froude number, $Z_0$ is the virtual origin (m), and $D$ is the orifice diameter (m).

Figure 9 shows the dimensionless correlation between the Froude number and the virtual point source. It can be seen that for the same orifice diameter, with the increase in Froude number, the position of the virtual point source increased. However, the upward trend gradually slowed down. This can be attributed to the change in buoyancy acting on the flame. When the Froude number was small, buoyancy dominated. Therefore, as the Froude number increased, the thermal buoyancy of the flame increased. Correspondingly, the location of the virtual point source rose significantly. With the increase in Froude number, the buoyancy drive gradually lost its dominant position. Therefore, the rising trend of virtual point source location gradually slowed down.
4. CONCLUSIONS

Substations played an important role in global power transmission. Transformer oil jet fire posed great harm to substations. However, the combustion behavior of transformer oil jet fire was still unclear. To reveal the combustion behavior of transformer oil jet fire, a series of combustion experiments of transformer oil jet fire with different heat release rates were carried out. The flame height, flame temperature, and flame radiation heat flux with different orifice diameters were analyzed. This paper investigated the dimensionless correlation between a series of dimensionless parameters and flame characteristic parameters. The major research results include the following:

(1) The flame height of transformer oil jet increased with the increase in heat release rate. The entrainment coefficient of transformer oil jet fire was 0.029. It can be seen that the entrainment coefficient of transformer oil jet fire was significantly greater than that of gas jet fire. This can be attributed to Rayleigh–Taylor instability and Kelvin–Helmholtz instability.

(2) The radiation fraction of transformer oil jet fire decreased with the increase in flow velocity, which was consistent with the feedback of gas jet fire. The radiation fraction fluctuated in the range of 0.28–0.4. Based on the dimensionless theoretical analysis, the dimensionless correlation between the Reynolds number and the radiation fraction was proposed: \( F_r = 1.79 R_e^{0.133} \). In this study, the radiation fraction model well described the radiation fraction of transformer oil jet combustion, and the correlation coefficient was 0.9. However, it was not applicable to gas jet fire.

(3) For the same orifice diameter, with the increase in heat release rate, the virtual point source location rose. The dimensionless correlations between the virtual point source and the dimensionless heat release rate and flame Froude number had been proposed. In this study, we propose a dimensionless correlation between the virtual point source and the Froude number: \( Z_0/D = 0.36 F_r^{0.117} \). When the Froude number was small, as the Froude number increased, the location of the virtual point source rose significantly. With the increase in Froude number, the rising trend of virtual point source location gradually slowed down.

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Notes

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