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Research Article

Fire Risk Assessment and Experimental Study of Transformer Insulating Oil

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Most previous works concentrated on burning characteristics of pool fire using common fuels such as heptane, propane, biodiesel, and diesel, whereas burning characteristics for transformer oil are barely involved, although transformer oil is arguable of more practical importance in power system. This study performed a series of pool fire experiments using transformer oil to study the burning characteristics in open and confined spaces. Three fuel thicknesses and five initial temperatures are changed in open space. The essential parameters of mass loss rate, flame height, and fire plume temperature are obtained and analyzed. Moreover, three oil pool diameters are varied in a chamber. The main conclusions are summarized as follows: the variations of mass loss rate, flame height, and fire plume temperature not only obviously increase as the fuel thickness increases from 0.5 cm to 1.0 cm, but also insignificantly increase as the fuel thickness changes from 1.0 cm to 2.0 cm. The mass loss rate is less sensitive to the initial temperature of transformer oil, but the flame height and fire plume temperature significantly rise with the initial temperature. Moreover, the modified models to predict the flame height and fire plume temperature for 25°C initial temperature conditions are proposed, but the fitting coefficients are obviously different from that for common liquid fuels. The flame height in confined space is higher and will rapidly increase to the maximum, then decreases, and tends to be stable, which is obviously different from the oil pool fire burning in open space. In addition, the phenomenon of burning blast and the ignition of the adjacent oil pool will be observed with a high-temperature ignition source and a certain high temperature in a chamber under 30 cm oil pool diameter, which will not be recorded in 15 cm and 20 cm.

1. Introduction

As an important part of the electric power transmission system, the normal operation of transformers is an increasingly prerequisite for daily life and industrial production. The transformer oil, as an electrical insulation and heat transfer fluid, is widely used in oil-immersed transformers [1]. However, the accidental leakages of transformer oil into surrounding space can form a hazardous pool fire once an ignition source is available [2], which may result in serious economic losses and human casualties. On November 11, 2019, the transformer fire occurred in Jinan, Shandong Province, China, causing one death, two injuries, and significant economic losses. On December 13, 2021, Taiwan's Wanlong Transformer No. 5 distribution substation failed and then the transformer oil caught fire, causing the insulation to fail and forcing the power supply system to shut down. The fire safety issues of transformer oil have attracted increasing attention because it is characterized by flammability and highly calorific. Therefore, it is very necessary to investigate the burning characteristics of pool fire for transformer oil in order to evaluate the fire risks.

In recent years, the burning characteristics of pool fires, such as burning rate [3–7], flame height [4, 6, 8–12], fire plume temperature [9, 13–15], and pulsation frequency [16, 17], have been widely investigated as an important issue. Previous investigations mainly focused on the combustion behaviors of pool fire using common fuels such as heptane, propane, biodiesel, and diesel. However, there are only a limited number of studies addressing the burning characteristics of transformer oil pool fire although transformer oil is arguable of more practical importance in power systems. Heskestad and Dobson [18] performed the pool fires of transformer oil over a rock bed in a 1.2 m diameter pan to study the effects of oil drainage on heat release rate. The burning tests conducted by Zhu et al. [19] studied the suppression of transformer oil pool fire by water mist. Zhang et al. [20] carried out a series of experiments to study the burning characteristics of different types of transformer oils using a cone calorimeter and found that the mass loss rate, heat release rate, and smoke production rate of 10# and 25# transformer oils were basically similar, whereas the corresponding values are smaller than that for 45# transformer oils. Zhao et al. [21] experimentally studied the burning behaviors of thin-layer transformer oil on a water layer considering the effects of initial fuel thickness and demonstrated the insignificant effects of initial fuel thickness on the steady burning rate. Moreover, it is worth noting that oil pool fires occurred in confined space are extremely different from open space. The burning characteristics are influenced by the heat feedback, the radiation of the space, and the ventilation condition. Compared with open space, confined space oil pool fires have a greater fire risk and may cause flashover. There have been some studies on burning characteristics of confined space oil pool fire [23, 24], but at present, there is still a lack of reports on transformer oil in confined space. As a basic and important issue in the research of transformer oil, Chen et al. [24] studied the influence of the amount of transformer oil and the volume of iron core on the formation and development of fire in a confined space. Based on the previous work mentioned above, researchers have attempted to reveal the burning behaviors of transformer oil pool fires, but the comprehensive information on combustion characteristics of transformer oil, such as flame shape, mass loss rate, flame height, and fire plume temperature, was barely involved, in particular, in confined space. In particular, in the process of transformer fire development, the phenomenon that the transformer upper oil pillow, the transformer lower oil collection pit, and flowing fire together constituted a multiscale transformer fire [25] will be emphatically studied by setting multiple fire sources in the chamber in this experiment.

In order to ensure the safety of the substation, the fire requirements for the transformers are specified. The "Code for fire protection design of buildings GB 50016-2014 (2018)" divides the total oil of transformers into three classes and makes requests for the fire separation distance under each of the three classes. Meanwhile, the "Code for design of 20 kV and below substation GB50053-2013" defines the fire protection of the transformer. According to "Operation specification for power transformer DL/T572-2010," the working temperature of the top-layer transformer oil in oil-immersed transformers can be as high as 70°C~95°C. Li et al. [26] experimentally reported that an increase in initial fuel temperature could enhance the fuel evaporation rate and consequently lead to an increase in flame spread using spilling aviation kerosene. Ji et al. [27] also found that the initial temperature could affect the flame spread characteristics of diesel and gasoline-diesel blends. However, the studies mentioned above related to transformer oil pool fires were carried out at fixed initial temperature without considering different initial temperatures. Hence, it is very important to understand the effects of initial temperature on the burning characteristics of pool fire for transformer oil. In addition, the essential parameters of fuel thickness are directly related to the burning behaviors of pool fires [21, 28]. Zhao et al. [21] studied the effects of fuel thickness on the combustion characteristics of pool fire for transformer oil, but only focused on the burning process, and did not quantitatively analyze the flame height and flame temperature. Therefore, it is necessary to carry out further studies on the burning characteristics of transformer oil pool fire taking the effects of initial temperature and fuel thickness into account.

In this study, a series of comparative laboratory-scale experiments are conducted to investigate the effects of fuel thickness and initial temperature on the burning behaviors of pool fire using transformer oil in open space and the difference between transformer oil between open and confined spaces. The essential parameters of mass loss rate, flame height, and fire plume temperature are obtained and compared. The results are not only helpful in a better understanding of the burning characteristics of transformer oil pool fires but also provide some basic data for the prevention and control of transformer oil fires.

2. Materials and Methods

As concluded above, the burning characteristics of transformer oil are different in open space and confined space. Therefore, two experimental apparatus were designed in the experiments reported, which were illustrated in Figures 1(a) and 1(b), respectively. The chamber used in confined space experiments is 1.2 m (length) × 1.2 m (width) × 1.2 m (height). The front side of the chamber is fireproof glass, and the other side is a stainless steel plate with a fireproof board. A circular pool with a diameter of 20.0 cm and 10.0 cm side wall is used as a burning project in open space, while the diameters of the pools used in confined space are 15 cm, 20 cm, and 30 cm. The diameters of the oil pool applied in this study have been widely used in previous studies [21, 29, 30]. Kunlun transformer oil labeled by KI25X is selected as the test oil, which is widely used as insulation in electrical equipment, such as transformers. The detailed thermophysical parameters of transformer oil are shown in Table 1.

The data acquisition systems used in open space are mainly composed of electronic balance, high-definition

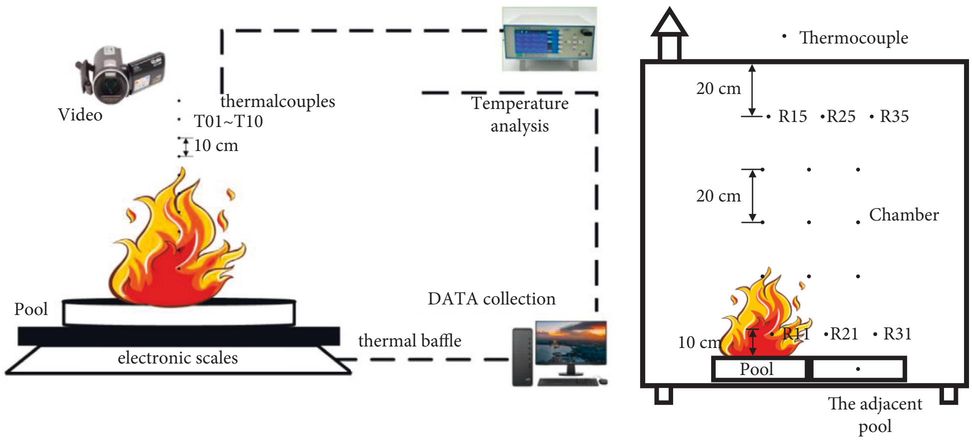


Figure 1: Schematic diagrams of the experimental setup. (a) For open space. (b) For confined space.

Table 1: Thermophysical parameters of Kunlun transformer oil KI25X.

Pour point	Density, 20°C	Flashpoint (°C)	Viscosity, 40°C
−45°C	885 kg/m	143	9.9 mm^2/s

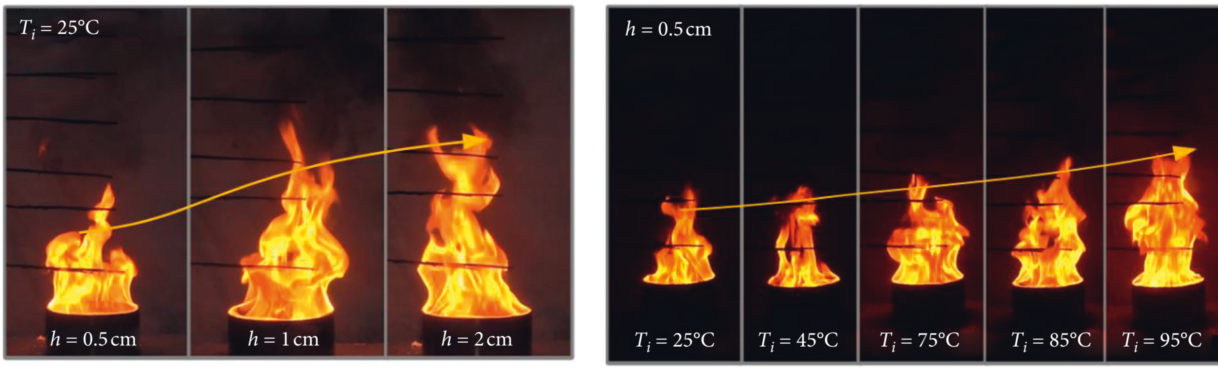
(HD) camera, heat flux meter, and thermocouple tree. However, considering the high temperature will cause damage to equipment, only thermocouples and high-definition (HD) camera are used for data acquisition in confined space experiments. The electronic balance with an accuracy of 0.01 g is placed under the burning project to record the mass loss rate at an interval of 1.0 s during the combustion process. A Sony 4K HD camera with a resolution of 1920 × 1080 and a frame rate of 25 frames per second is set at the side to monitor the flame geometry. A flame image processing software is applied to process the video-captured images frame by frame to obtain the flame height. The thermocouple tree of open space consisting of 10 K thermocouples with the first and the last thermocouples at 0.2 m and 1.1 m from the burning pool at 0.1 m interval is arranged to monitor the flame temperature. Three thermocouple trees are arranged above the two pools along the central axis of each pool and the centerline of two pools in the chamber. Each thermocouple tree consists of 5 K thermocouples with the first and the last thermocouples at 0.1 m and 0.9 m from the pool at 0.2 m interval. All the thermocouples used in this work have a temperature range and date collection interval of 0~1 100°C and 1.0 s, respectively. The use of K-type thermocouples to measure the temperature above the pool of a transformer oil fire has been successfully adopted in previous studies [21].

In order to investigate the effects of fuel thickness and initial temperature on pool fire of transformer oil, the variables of three fuel thickness and five initial temperatures are considered in open space in this study. The initial fuel thicknesses of 0.5 cm~3.0 cm for heptane pool fires and 1.0 cm for transformer oil fires were applied in previous work [20, 31]. Therefore, a total of three popular fuel thicknesses (h) used in oil pool fire of 0.5 cm, 1.0 cm, and 2.0 cm are designed, which can be achieved by controlling the volume of the test transformer oil. As is well known, the maximum working temperature of transformer oil in the oil-immersed transformer can be as high as 70°C~95°C. Five initial temperatures (T_i) of 25°C, 45°C, 75°C, 85°C, and 95°C are considered in this study, and the transformer oil is heated to the desired initial temperature by a heating device before each experiment. To investigate the combustion characteristics of transformer oil in a confined space and whether the adjacent transformer oil pool can be ignited, two oil pools of the same size are placed next to each other in the chamber. All the experiments are carried out in a test hall with the environmental conditions of 26°C ± 4°C ambient temperature and 70 ± 5% relative humidity. Generally, each burning test with the same condition is repeated at least three times to reduce the experimental uncertainty.

3. Results

3.1. Burning Characteristics in Open Space

3.1.1. Burning Behavior. Figure 2 represents the typical flame images in the steady stage under different fuel thickness and initial temperature conditions, respectively. According to the video analysis, the pool fire of transformer oil rapidly reaches a steady stage after a short initial period. Hence, the typical flame images in the steady stage under different fuel thickness and initial temperature conditions are selected to compare and analyze in this study. Obviously, the flame of the pool fire is basically perpendicular to the fuel surface and the flame geometry is generally conical in still-air conditions. It can be seen from Figure 2(a) that the flame height apparently increases when the fuel thickness increases from 0.5 cm to 1.0 cm, while the flame height does not significantly change as the fuel thickness increases from 1.0 cm to 2.0 cm. The previous work by Suo-Anttila et al. [32] and Vali et al. [33] reported that when the pool fire of liquid fuel burned, about 3.0 mm isothermal layer would be formed below the fuel surface, which would absorb the majority of the heat generated by combustion. When the fuel thickness



(a) (b)

Figure 2: Typical flame images in steady stage under different experimental conditions. (a) Different fuel thickness conditions. (b) Different initial temperature conditions.

increases beyond a critical value, the fuel can be regarded as infinitely deep; consequently, the insignificant influence of fuel thickness on the combustion process of pool fire was observed. In this study, as the fuel thickness increases beyond 1.0 cm, the flame height and geometry cannot be significantly affected by the fuel thickness, which coincides well with the previous work.

Moreover, it is noted from Figure 2(b) that the flame height obviously increases with the increase in the initial temperature of transformer oil fuel. This may be caused by the fact that the enhancement of initial temperature will promote the combustion reaction activity of transformer oil, and subsequently, the combustion efficiency of transformer oil would be strengthened, which results in an increase in flame height.

3.1.2. Mass Loss Rate. Figure 3 plots the variations of mass loss rate as a function of time for various fuel thickness and initial temperature conditions, respectively. Generally, the mass loss rate of the pool fire drops slowly in the initial time, and then shows a steady and rapid decrease until the pool fire begins to decay and extinguish. It can be found from Figure 3(a) that the deeper the fuel depth and the larger the volume of transformer oil, the longer the burning duration time. In order to the study effects of fuel thickness and initial temperature on mass loss rate, the average value of mass loss rate in the steady stage is taken as a characteristic value to compare and analyze, as summarized in Table 2.

It is worth noting that the mass loss rate in the steady stage increases when the fuel thickness increases from 0.5 cm to 1.0 cm, whereas the values of mass loss rate in the steady stage do not significantly change as the fuel thickness is beyond 1.0 cm. This is mainly due to that when the fuel thickness is less than 1.0 cm, the pool fire can be recognized as a small-thickness pool fire and consequently the heat loss by side wall conduction should be considered, while with the fuel thickness increases beyond 1.0 cm, the oil pool gradually turns to a deep pool, and then, the heat loss by side wall conduction can be gradually neglected [34]. In addition, the variation of mass loss rate with fuel thickness is similar to the results in a previous work by Chen et al. [34]. Moreover, the mass loss rate in the steady stage is less sensitive to the initial temperature of transformer oil. This observation is similar to results in previous work by Chen et al., which demonstrated that the burning rate in the stabilization stage did not significantly vary with initial fuel temperature for n-heptane [35]. To the best of our knowledge, the heat release rate of fire during the combustion process can be determined by mass loss rate, combustion heat, and combustion efficiency, which can be expressed by the following formula:

$$Q = \varphi \dot{m} \Delta H, \quad (1)$$

where Q denotes the heat release rate, φ is the combustion efficiency, $\dot{m}$ is the mass loss rate, and ΔH is combustion heat. Therefore, as the fuel thickness increases from 0.5 cm to 1.0 cm, the mass loss rate rises and then the heat release rate increases, while when the fuel thickness increases from 1.0 cm to 2.0 cm, the mass loss rate and consequently heat release rate do not vary significantly. In addition, although the mass loss rate is found to be independent of the initial temperature of transformer oil, the combustion efficiency φ and the heat release rate may change with the initial fuel temperature.

3.1.3. Flame Height. Figure 4 shows the variations of flame height versus time for various fuel thickness and initial temperature conditions, which are obtained from the video analyzed frame by frame. It can be noted that after the transformer oil is ignited, the flame height rapidly rises for a period of time and then pool fires reach a relatively steady stage, and the flame frequently fluctuates but remains changing around a stable value. Appreciably, the deeper the fuel thickness, the larger the flame height, but the effects of fuel thickness on the flame height significantly reduce when the fuel thickness is greater than 1.0 cm. Moreover, as the initial temperature of the transformer oil rises, the flame height shows a significant increase. As mentioned above, the initial temperature had a small effect on mass loss rate, but the flame height increases as the initial temperature increases. This can be attributed to the fact that the increase in

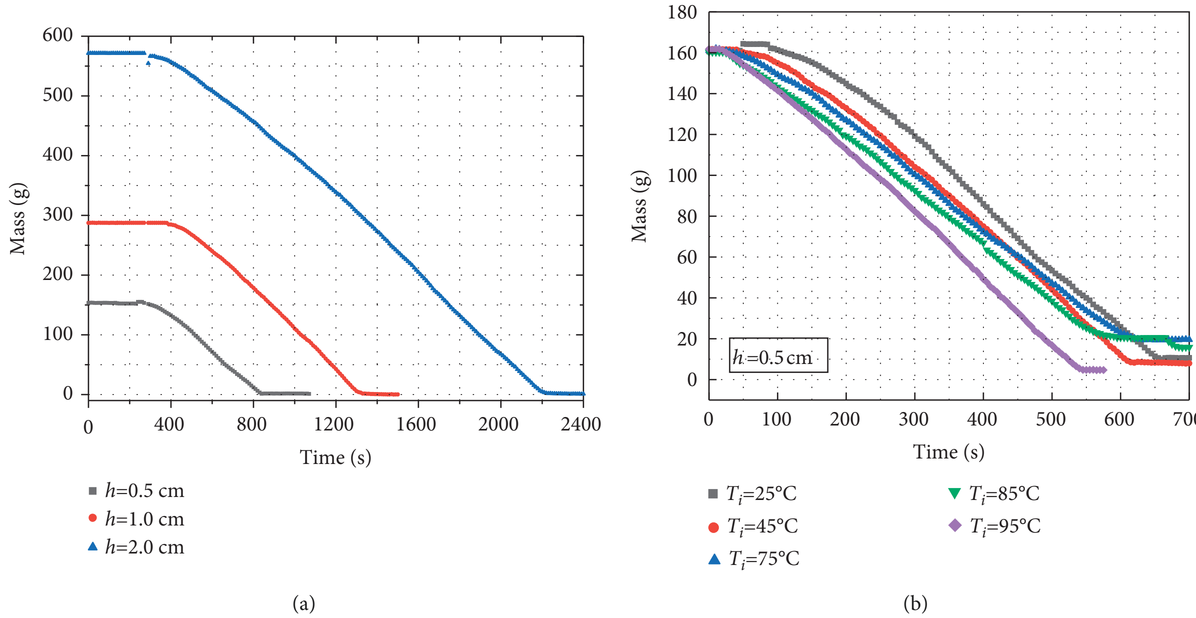


Figure 3: Variations of mass loss rate as a function of time under different experimental conditions, (a) different fuel thicknesses, and (b) different initial temperatures.

Table 2: Average values of mass loss rate for different experimental conditions.

Fuel thickness (cm)	Initial temperature (°C)	Mass loss rate (g/s)
0.5	25	0.291
1.0	25	0.314
2.0	25	0.315
0.5	45	0.280
0.5	75	0.285
0.5	85	0.283
0.5	95	0.295

initial temperature may enhance the reaction activation energy and combustion efficiency, which results in the rise in the flame height. At present, some investigations have been performed to propose a prediction model to describe the flame height of pool fire. For circular pool fire, a modified model for predicting the flame height was established by Heskestad [36], which is shown as follows:

$$\frac{Z_f}{D} = 3.7\dot{Q}^{*2/5} - 1.02, \quad (2)$$

where Z_f is the flame height of the pool fire, D is the diameter of the circular pool, and $\dot{Q}^*$ is the dimensionless heat release rate, which can be calculated by the following equation [4]:

$$\dot{Q}^* = \frac{\dot{Q}}{\rho_\infty c_p T_\infty g^{1/2} D^{5/2}} = \frac{\varphi \dot{m} \Delta H}{\rho_\infty c_p T_\infty g^{1/2} D^{5/2}}, \quad (3)$$

where ρ_∞, c_p, and T_∞ are the density, specific heat, and temperature of the ambient air, respectively, and g is the gravity acceleration. Subsequently, equation (2) can be further simplified as follows:

$$Z_f \propto (\varphi \dot{m})^{2/5}. \quad (4)$$

Based on equation (4), the flame height of the pool fire as a function of $\dot{m}^{2/5}$ is plotted in Figure 5, in which the red dotted line presents the linear fitting between the flame height and $\dot{m}^{2/5}$ for 25°C initial temperature conditions. The value of Adj. R-Square is more than 0.94, and the residual sum of squares is only 0.85, which demonstrates that the flame height linearly increases with the increase in $\dot{m}^{2/5}$ for 25°C initial temperature conditions. However, as the initial temperature increases, the flame height is significantly larger than the predictions of 25°C initial temperature conditions. This indicates that the increase in initial temperature will promote the combustion efficiency of the transformer oil, which is consistent with the analysis mentioned above.

3.1.4. Fire Plume Temperature. Figure 6 shows the fire plume temperature at different heights as a function of time for various fuel thicknesses and initial temperature conditions. It can be seen that the temperature at different heights rapidly increases, then remains basically stable for a period of time, and eventually begins to decay. Obviously, as the height rises from the fuel surface, the fire plume temperature drops. Moreover, it can be noted that the temperature of the fire plume is different as the fuel thickness and initial temperature varying. Hence, the average temperature of fire plume at different heights in a steady stage for different experimental conditions is plotted in Figure 7.

It can be noted that the fire plume temperature at a fixed height shows an increase with fuel thickness and initial temperature. Heskestad [8] carried out a series of pool fire

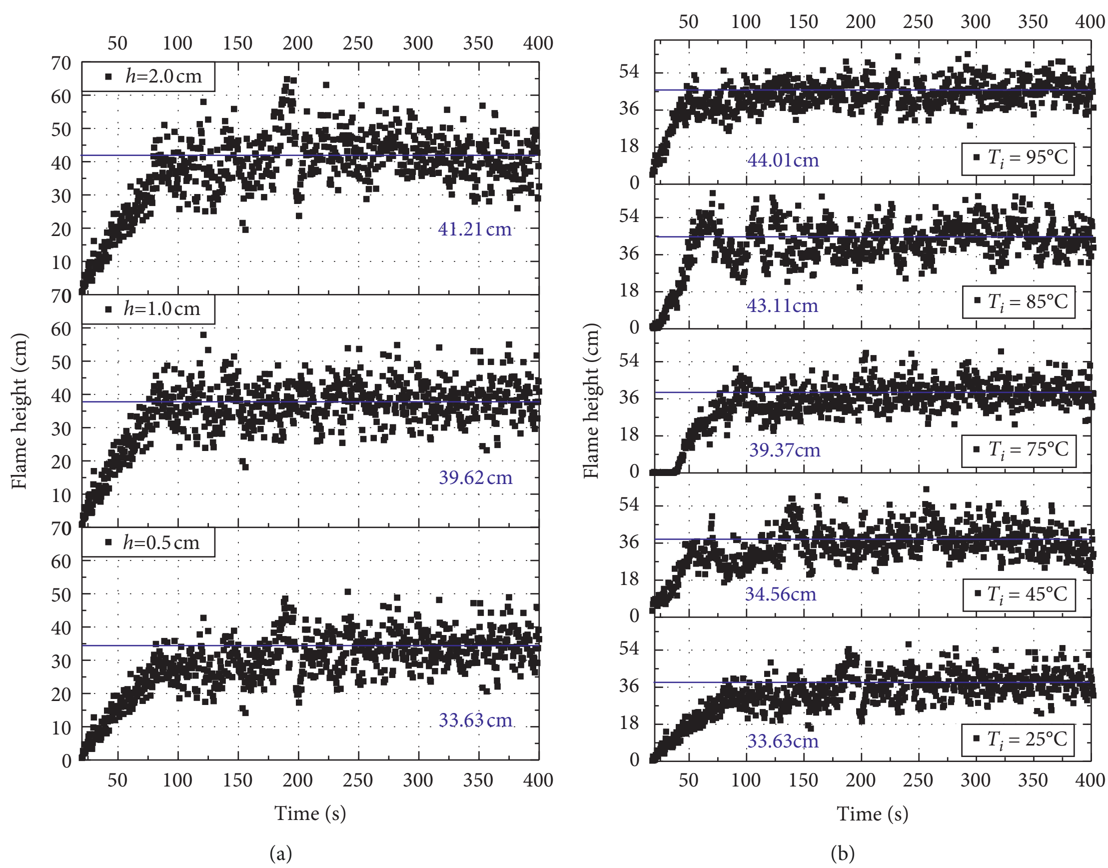


Figure 4: Variations of flame height as a function of time under different experimental conditions, (a) different fuel thicknesses, and (b) different initial temperatures.

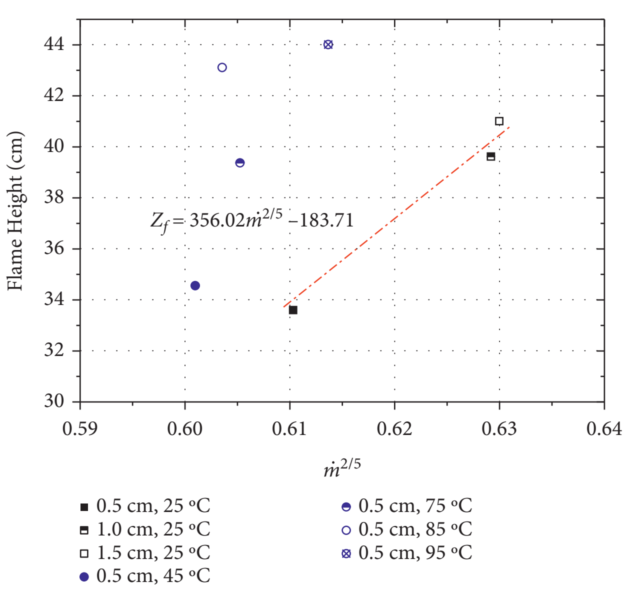


Figure 5: Flame height as a function of $\dot{m}^{2/5}$ for different experimental conditions.

experiments and established a modified equation to describe the axial fire plume temperature rise, which can be calculated by the following:

$$\Delta T_0 = 9.1\left(\frac{T_\infty}{g c_p^2 \rho_\infty^2}\right)^{1/3} \dot{Q}_c^{(2/3)} (Z - Z_0)^{-(5/3)}, \quad (5)$$

where ΔT_0 is the axial fire plume temperature rise, $\dot{Q}_c$ is the convective heat release, which can be determined by approximately $0.7\dot{Q}$ [13], Z is the height from the fuel surface, and Z_0 is the height of virtual origin, which can be expressed by the following formula (8):

$$Z_0 = 0.083\dot{Q}^{2/5} - 1.02\ D. \quad (6)$$

According to equation (5), the axial temperature profile of the fire plume can be simplified as follows:

$$\frac{(\Delta T_0/T_\infty)}{\dot{Q}^{*2/3}} \propto \left(\frac{Z - Z_0}{D}\right)^{-5/3}. \quad (7)$$

Then, equation (7) above can be converted to [14] the following:

$$\left(\frac{\dot{Q}^{*2/3}}{\Delta T_0/T_\infty}\right) \propto \frac{Z}{D}. \quad (8)$$

Figure 8 represents the dimensionless temperature profile of the fire plume as a function of normalized vertical height Z/D. Notably, the values of $(\dot{Q}^{*2/3}/(\Delta T_0/T_\infty))$

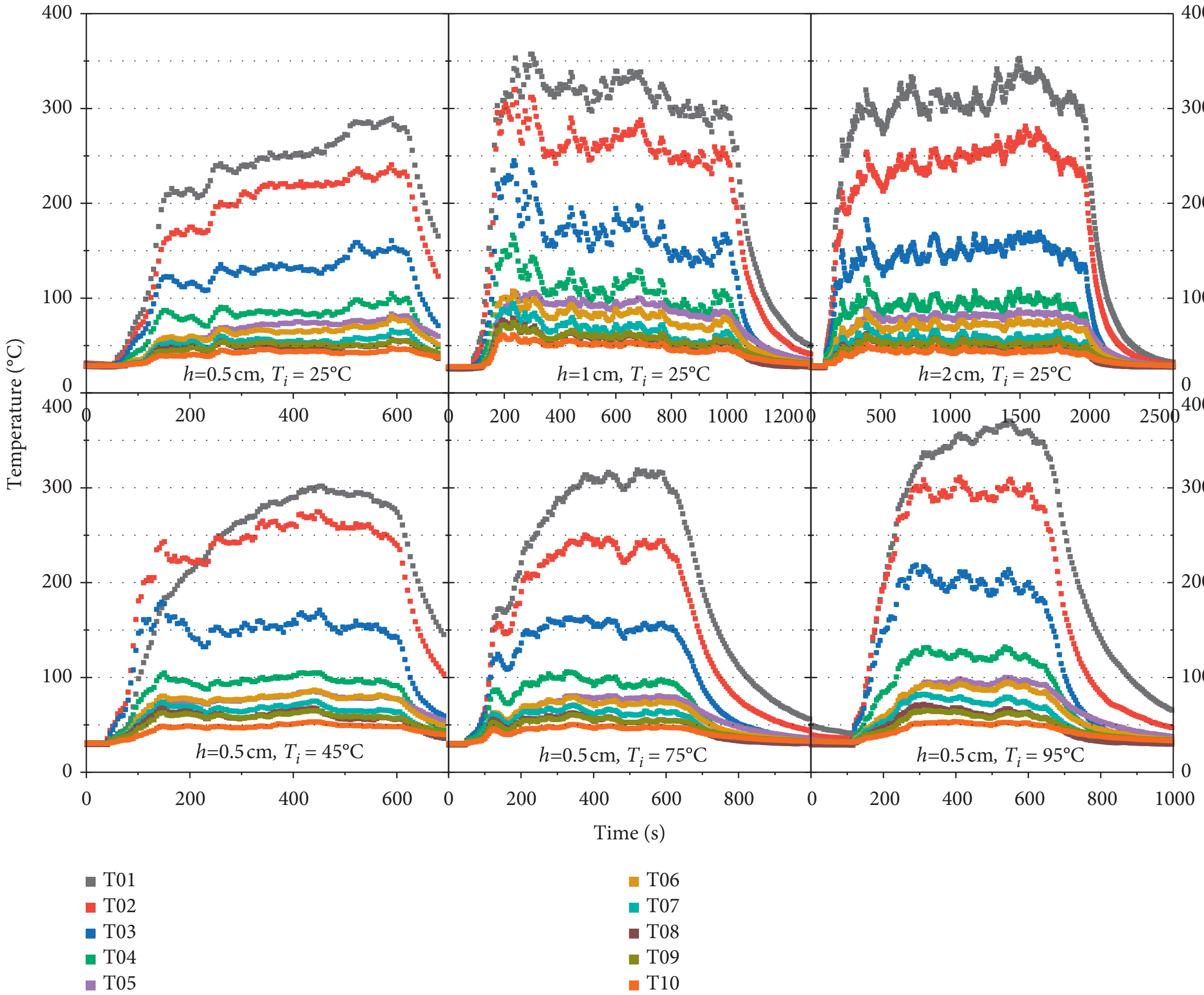


Figure 6: Fire plume temperature as a function of time under different experimental conditions.

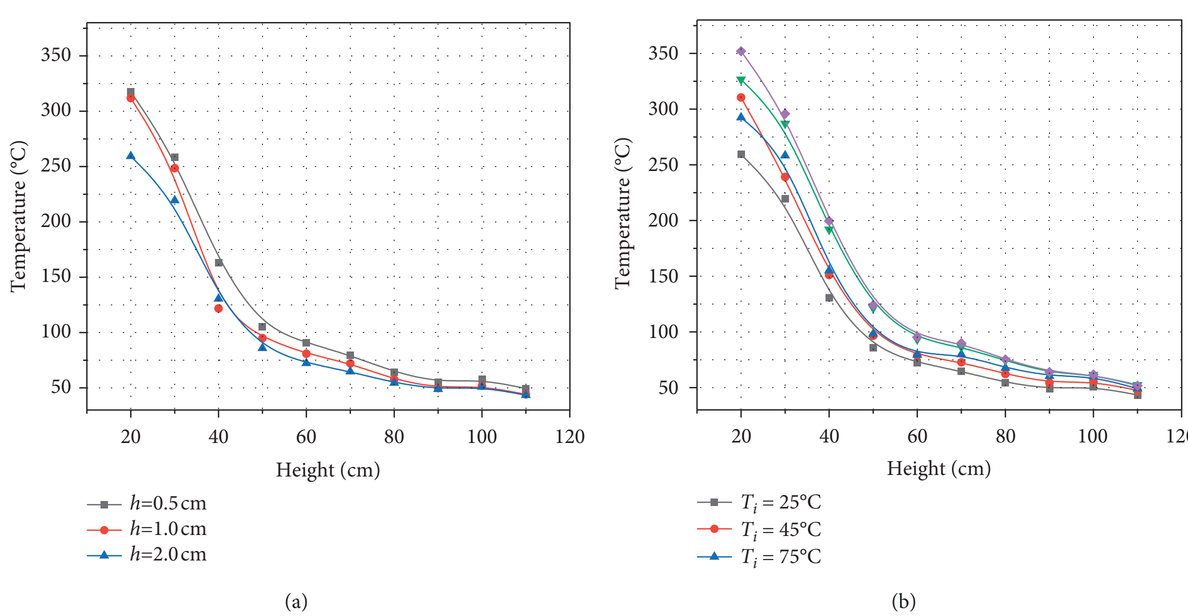


Figure 7: Fire plume temperature as a function of height for different experimental conditions, (a) different fuel thicknesses, and (b) different initial temperatures.

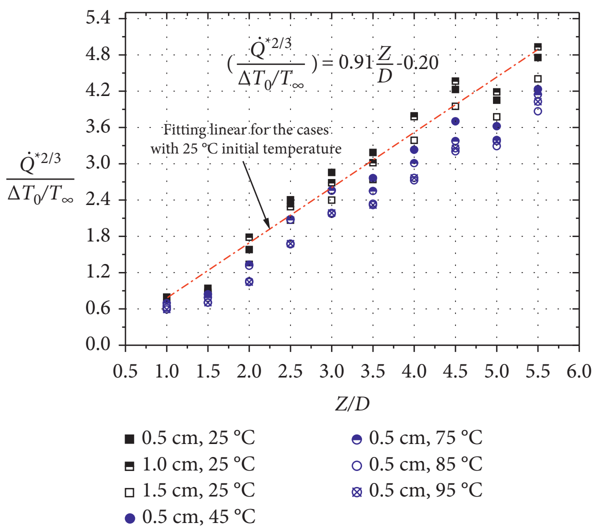


Figure 8: Dimensionless temperature profile of the fire plume as a function of normalized vertical height Z/D.

linearly increase with the increase in normalized height Z/D. Equation (8) is applied to describe the axial temperature profile of the fire plume for the cases with 25°C initial temperature, as shown by the red dot solid line in Figure 8, which can be expressed as follows:

$$\left(\frac{\dot{Q}^{*2/3}}{\Delta T_0/T_\infty}\right) = 0.91\frac{Z}{D} - 0.20. \quad (9)$$

The value of Adj. R-Square is well above 0.98, and the residual sum of squares is less than 1.23, which demonstrates that the experimental results match the predicated data reasonably well. The fitting coefficient of 0.91 is obviously different from the corresponding result of 0.44 for biodiesel pool fire reported by Fan et al. [10]. Tang et al. [15] and Hayasaka [37] also pointed out that the combustion characteristics of a pool fire are essentially related to the properties of the fuel. In addition, since the combustion efficiency φ is not considered in the data processing of $\dot{Q}^*$, the experimental data of $(\dot{Q}^{*2/3}/(\Delta T_0/T_\infty))$ for cases with larger initial temperatures are lower than the predicted value, which also shows that the initial temperature of transformer oil has a significant effect on combustion efficiency φ.

3.2. Burning Characteristics in Confined Space

3.2.1. Burning Behavior. Flame shapes of oil pools with diameters of 15 cm and 20 cm burning in the chamber at typical times are displayed in Figure 9. As can be seen, after being ignited, the flame height rapidly increases to the maximum, and then decreases and becomes stable. The stabilization phase will last for a long time until extinction. In addition, when the diameter of the oil pool is 15 cm or 20 cm, another adjacent oil pool is not ignited. However, when the diameter of the oil pool is 30 cm, the adjacent oil pool is ignited and the burning blast phenomenon occurs, which will be discussed later. Compared with open space, the fire flame in confined space is darker and the particles generated by combustion will adhere to the glass that will affect the observation.

3.2.2. Flame Height. The camera could not shoot through the fireproof glass when the combustion and burning blast characteristics of the oil pool with a diameter of 30 cm are tested in the chamber. Therefore, only the flame height of oil pools with diameters of 15 cm and 20 cm in the chamber is analyzed, as shown in Figure 10.

The fire growth in the chamber is similar to the development of compartment fire, which can be regarded as the initial stage, rapid growth stage, stable stage, and decay stage. In the beginning, the flame height rapidly increases over time in a trend similar to t2 fires. Subsequently, as more and more combustible pyrolysis gas is accumulated in the chamber, the flame height will rapidly increase to the maximum. Accordingly, a large amount of accumulated combustible pyrolysis gas is rapidly consumed, oxygen content in the chamber decreases, and the flame height gradually begins to decline. The flame height then stabilizes due to the opening of smoke exhaust and air-supply holes in the side wall of the chamber. The average flame height is 33.63 cm in an open space of 20 cm oil pool, which is a little lower than the flame height in the confined space. The results suggest that due to the restriction of oxygen supply, the flame needs to be extended longer in the vertical to entrainment air, making the flame of confined space higher than in open space.

3.2.3. Fire Plume Temperature. The temperature of each measuring point in the chamber under different conditions is plotted in Figure 11. For $D = 15$ cm and 20 cm, the temperature variation above the burning pool (R11~R15) can be divided into three stages: rapid temperature growth stage, temperature stability stage, and temperature attenuation stage, while the temperature stability stage is replaced by the temperature steady growth stage when focusing on the temperature of the centerline of two pools (R21~R25) and temperature above the unburning pool (R31~R35). As a result, the temperature in the chamber is discussed by taking the average of the temperature in the temperature stability stage or temperature steady growth stage as shown in Figure 12. The temperatures in the chamber found an obvious increase with the oil pool diameter, and R1 is much higher than R2 and R3. It can be noted that the temperature of R1 decays with increasing height, which is consistent with the variation trend of flame temperature in open space. According to the analysis in section 3.1, the dimensionless temperature profile of the fire plume is proportional to the normalized vertical height, as shown in Figure 13. The relationship between the dimensionless temperature profile of the fire plume and normalized vertical height can be expressed by the following:

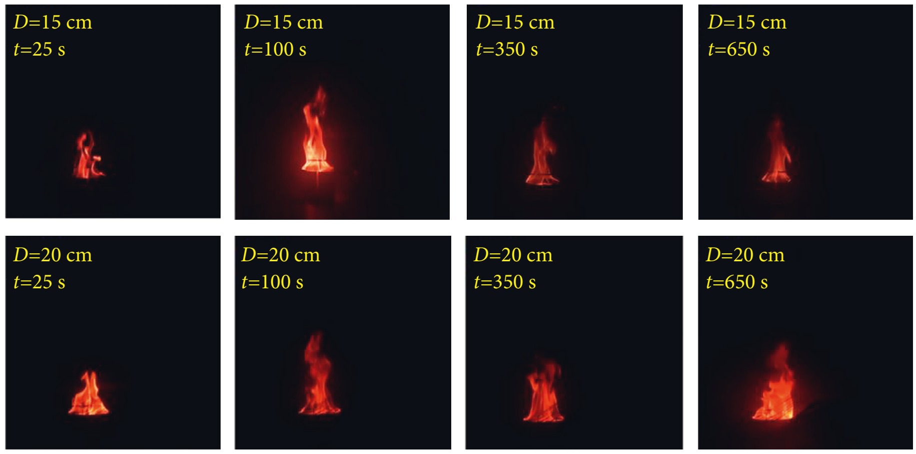


FIGURE 9: Sequence diagram of flame shape at a typical time in the chamber.

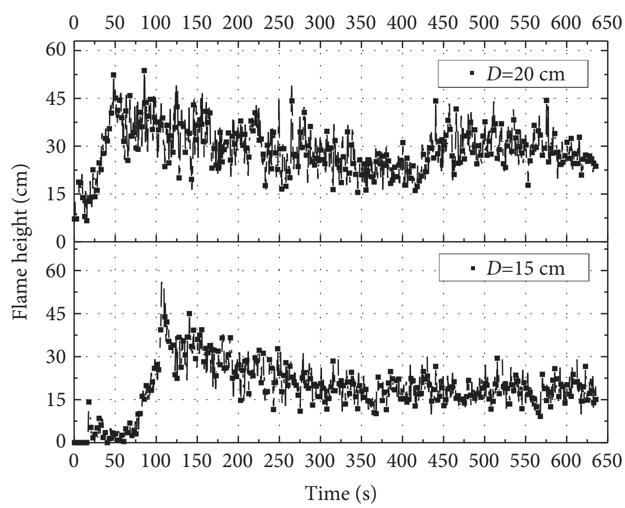
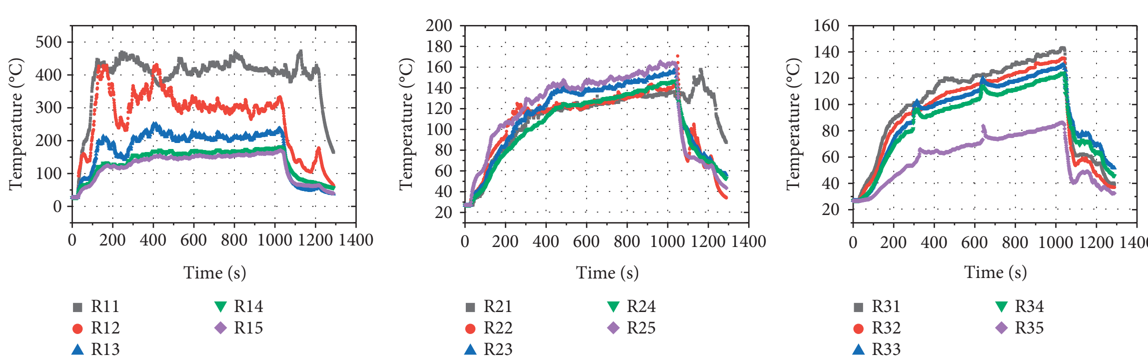


FIGURE 10: Flame height in the chamber varies with time.



(a)

FIGURE 11: Continued.

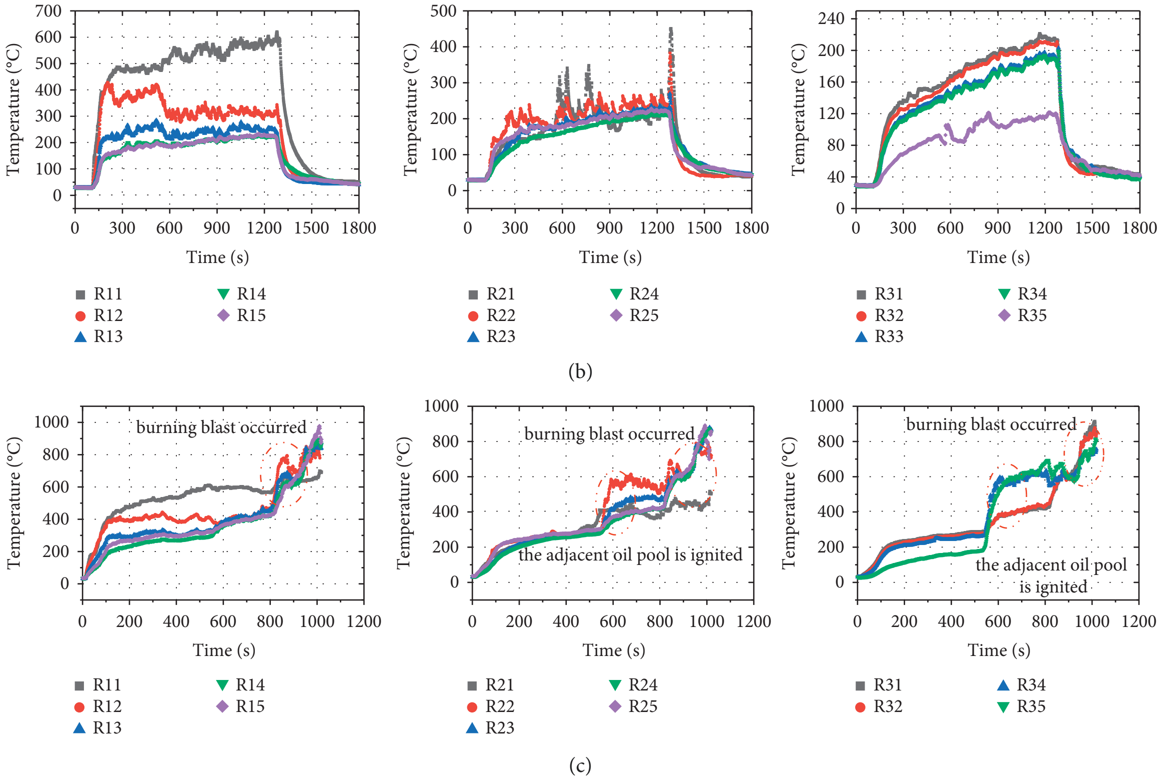


Figure 11: Temperature of each measuring point in the chamber of different conditions. (a) $D = 15$ cm. (b) $D = 20$ cm. (c) $D = 30$ cm.

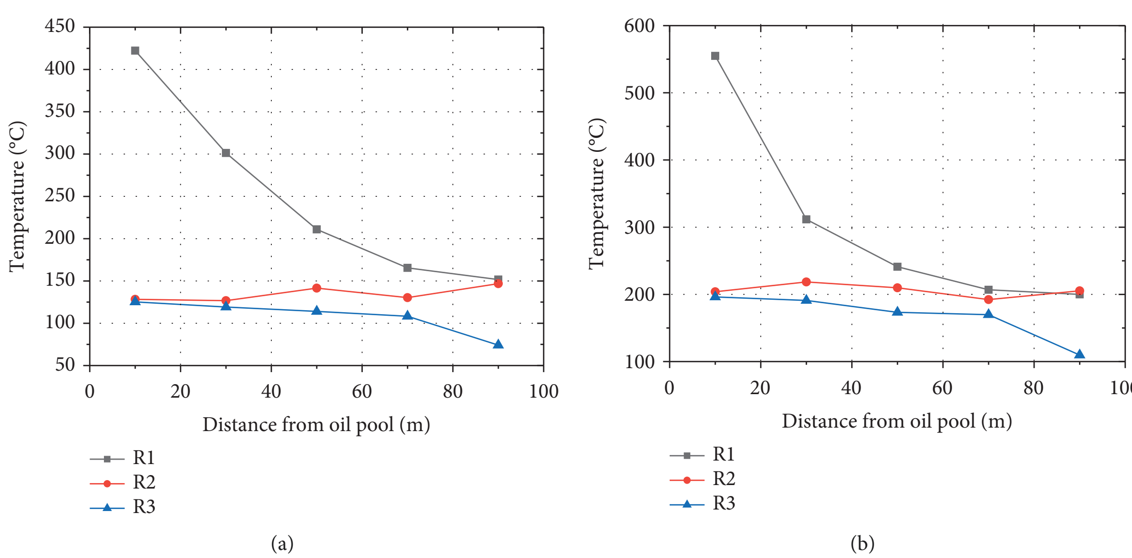


Figure 12: Average temperatures in different diameters vary with distance. (a) $D = 15$ cm. (b) $D = 20$ cm.

$$\left(\frac{\dot{Q}^{*2/3}}{\Delta T_0/T_\infty}\right) = 0.25\frac{Z}{D} + 0.31. \quad (10)$$

The value of Adj. R-Square is well above 0.95, and the residual sum of squares is only 1.94, which demonstrates that the experimental results coincide well with the predicted data. The fitting coefficient differs from the corresponding result of in open space, which may be due to the difference in experimental configuration.

The phenomenon of burning blast and the ignition of the adjacent oil pool are observed when the combustion experiment of oil pool fire with a diameter of 30 cm is carried out in the chamber, which will be analyzed by considering the temperature in the chamber displayed in Figure 11(c). At the beginning of 550 s, the temperature

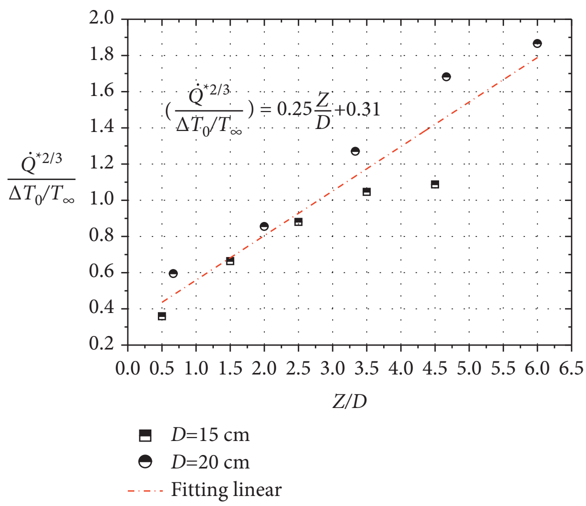


Figure 13: Dimensionless temperature profile of the fire plume as a function of normalized vertical height Z/D.

variation trend is similar to that of oil pool fire with diameters of 15 cm and 20 cm, which rapidly increases to a certain value and maintains for a long time. But at this time, the temperature of the chamber is about 270°C, which is much higher than the oil pool fire with diameters of 15 cm and 20 cm. When it comes to 580 s, the adjacent oil pool is ignited by a high-temperature ignition source, the temperature of R2 and R3 thermocouple trees rapidly increases and exceeds 400°C, and the temperature of the upper part of the chamber even reaches 600°C. Between 600 s and 800 s, the two oil pools burn at the same time, and the temperature in the chamber reaches a relatively stable stage again. Finally, at 800 s, due to the continuous high temperature, the chamber door deforms, which leads to a certain gap between the door and the chamber. Immediately, fresh air is filled into the chamber, and the burning blast happens. It can be inferred from the experiment that when the temperature in the chamber reaches 270°C, the adjacent oil pool can be ignited only under the condition of the high-temperature ignition source. Moreover, the temperature of the chamber exceeds 400°C, and the temperature of the upper part of the chamber reaches 600°C. Only when fresh air is added, the phenomenon of a burning blast can occur.

4. Conclusions

In this study, a series of comparative experiments were carried out using transformer oil to investigate the effects of fuel thickness and initial temperature on the burning characteristics of pool fires in open space and the difference between transformer oil between open and confined spaces. The variables of three fuel thickness and five initial temperatures are considered in open space, and the characteristics of mass loss rate, flame height, and fire plume temperature are quantitatively analyzed and compared. The variations of mass loss rate, flame height, and fire plume temperature apparently increase as the fuel thickness increases from 0.5 cm to 1.0 cm, whereas the insignificant influence of fuel thickness on the corresponding burning characteristics as the fuel thickness increases from 1.0 cm to 2.0 cm. The mass loss rate is less sensitive to the initial temperature of transformer oil, but the flame height and fire plume temperature significantly rise with the initial temperature. Moreover, the modified models to predict the flame height and fire plume temperature for 25°C initial temperature conditions are proposed. For cases that burning in the chamber, the flame height is higher and will rapidly increase to the maximum, then decreases, and tends to be stable, which is obviously different from the oil pool fire burning in an open space. In addition, when the diameter of the oil pool is 30 cm and the temperature in the chamber reaches 270°C, the adjacent oil pool can be ignited by a high-temperature ignition source. At the time the temperature of the upper part of the chamber comes to 600°C, fresh air added to the chamber will cause a burning blast.

Based on the results of this study, the quality of transformer oil and the size of pool fire formed by flowing transformer oil have a significant influence on the scale of fires. In addition, despite its high flash point, the transformer oil has the potential to be ignited by a nearby large enough fire source. Therefore, in the process of use, transportation, and storage of transformer oil, the total amount of transformer oil should be fully considered and it should be kept away from other dangerous combustibles. A further study is in progress to investigate the effects of spacing and size on the ignition and combustion characteristics of multiple oil pools in a confined space. Moreover, the characteristics of large-scale fires for transformer oil will be also studied.

Data Availability

The data used to support the findings of the study can be obtained from the corresponding author upon request.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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