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# Experimental Study on Combustion Characteristics of Transformer Oil Pool Fire with Different Scales

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## Abstract

*To study the combustion characteristics of transformer oil pool fire with different sizes, transformer oil pool fire experiments with diameters of 40cm, 50cm, and 60cm are carried out to analyze the evolution laws of flame height, fire plume temperature, and oil temperature of oil pool fire with different diameters. The results show that the ignition process of the transformer oil pool can be divided into three typical stages: initial growth stage, full development stage, and extinguished stage. According to the characteristics of combustion rate and flame height, the full development stage is subdivided into the stable combustion stage and boiling combustion stage. The flame height of the boiling combustion stage is about 1.1 times higher than that of the stable combustion stage. With the increase of diameter, the range of intermittent flame area of oil pool fire with three diameters increases by 1.2 times. The heat transfer analysis of the full development stage shows that the oil temperature presents the phenomenon of temperature stratification. There is a boiling layer below the liquid level. Its temperature is about 330 °C and its thickness is about 2.3 mm. The oil temperature under the boiling layer decreases in a gradient, and the boiling layer thickness and temperature have no significant correlation with the oil pool diameter.*

## Keywords

*Transformer oil; Oil pool scale; Flame height; Boiling layer.*

## 1. Introduction

As an indispensable and important energy source in human life, petroleum is widely used in all fields of our production and life. However, the effective use of oil not only promotes the economic and cultural progress of human society but also increases the potential risk of liquid fuel fire and explosion accidents. Transformer insulating oil is a fractionation product of petroleum and is the main cooling and insulation medium of the oil-immersed transformer. Oil-immersed transformer body and top oil pillow are filled with a large amount of combustible transformer oil. Fire under failure and high temperature will often cause damage to oil-immersed transformer body and adjacent equipment, seriously damage the substation, and affect the safe operation of the power grid [1, 2]. The burning area of transformer oil after an accident determines the final scale of substation fire spread and development [3]. Research on the combustion performance of transformer oil itself, including combustion rate, flame height, temperature distribution at the centerline of the fire source, can provide a theoretical basis for intelligent early warning and early prevention and control of oil-immersed transformer fire.

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In recent years, scholars at home and abroad have carried out relevant research on transformer oil. For example, Fan Minghao et al. [4] measured the heat release rate of transformer oil in three oil pan diameters of 25cm, 30cm, and 40cm, and found that the heat release rate would increase with the increase of oil pan diameter. Zhang Bosi et al. [5] carried out a small-scale transformer oil pool fire experiment with a conical calorimeter and found that the peak of heat release rate and CO generation rate would increase with the increase of oil temperature. Zhang et al. [6] proposed the difference in combustion characteristics of different types of transformer oils and found that the ignition time and combustion rate of 10 # and 25 # transformer oils were like those of combustion gas, and the fire risk of 45 # transformer oils was greater than that of 10 # and 25 # transformer oils. Chen Peng et al. [7] carried out the normal temperature transformer oil pool fire experiment with different diameters and oil thicknesses and obtained the burning rate and radiation characteristics of transformer oil at different combustion scales. Wang Yalong et al. [8] found that the thickness of oil and fuel in uHV transformers has a significant impact on the combustion rate and proposed a linear equation for the axial average temperature distribution.

At present, the research on the combustion characteristics of transformer oil pool fire is still very limited, and the research on the flame height, fire plume temperature, and oil temperature of transformer oil pool fire is less. Transformer fire often leads to many transformers oil leakage, forming transformer oil pool fire of different scales. Therefore, this paper carries out oil pool fire combustion experiments with different diameters and specifically analyzes the evolution law of parameters such as transformer oil fire process, flame height, and fire plume temperature at different scales. It provides strong technical support for correctly understanding the occurrence and development of transformer fire and intelligent monitoring and firefighting of transformer substations.

## 2. Experimental method

### 2.1. Experimental device

Figure 1 is a schematic diagram of the experimental system. Three kinds of steel oil pools with different diameters were used in the experiment, with diameters of 40cm, 50cm, and 60cm respectively, and the lateral wall height of oil pools was 10cm. The fuel used in the experiment was Kunlun 25# transformer oil. The basic parameters are shown in Table 1. Because transformer oil belongs to heavy oil and is not easy to ignite directly, 50ml n-heptane is injected into the center of the oil pool. for. ignition.

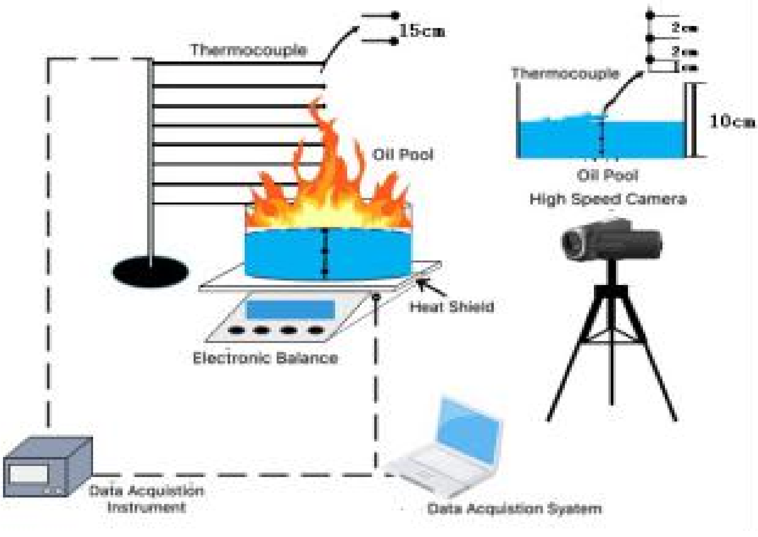


Fig.1 Schematic diagram of the experimental platform

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In the experiment, wrMK-191 K type armored thermocouple was used to collect the fire plume temperature and oil temperature, with a diameter of 1mm and a temperature measurement range of 0-1100℃. Three oil-temperature thermocouples were arranged in the oil pool with a height of 1cm, 3cm, and 5cm from the bottom of the oil pool, and one thermocouple was arranged every 15cm from 5cm above the center of the oil pool to measure the temperature of the fire plume. In the experiment, the Japanese AND type precision electronic balance was used to record the change of oil quality in real-time. The maximum weighing value of the balance was 60kg, AND the accuracy was 0.01g. A SONY NEX-fs700 high-speed camera was used to capture flame images with a frame rate of 60fps. It was placed 10m in front of the test stand.

Table 1 Basic parameters of Kulun 25# transformer oil

| Density/(kg/m$^3$) | Flash point / ℃ | 40℃ Kinematic viscosities/(mm2/s) |
|---|---|---|
| 882.8 | 155 | 7.412 |

Table 2 The specifications of experiments

| The serial number | Diameter (cm) | Oil thickness (cm) |
|---|---|---|
| T1 | 40 | 5 |
| T2 | | |
| T3 | | |
| T4 | 50 | 5 |
| T5 | | |
| T6 | | |
| T7 | 60 | 5 |
| T8 | | |
| T9 | | |

### 2.2. Test conditions

The experiment was carried out in a full-sized tunnel with a length of 100m, a width of 12.75m, and a height of 6.7m. The whole experiment environment can be regarded as open and windless space. Experimental conditions are shown in Table 2. To ensure the accuracy of the experiment, three groups of conditions are repeated respectively.

## 3. Experimental results and discussion

### 3.1. Combustion Process

The combustion process of an oil pool fire with a diameter of 40cm is shown in Figure 2. Adding 50ml n-heptane ignition transformer oil, the combustible steam vaporized by heat moves upward due to buoyancy, enters the combustion zone, and is ignited after mixing with air. Figure 2 (1~2) shows the initial growth stage of the oil pool fire. The combustion rate increases rapidly, and the flame height increases continuously. Meanwhile, the thermal feedback of the flame to the oil is gradually enhanced, and the two promote each other. With the development of fire, the combustion rate tends to be stable and enters the stable combustion stage, where the combustion rate and flame height fluctuate up and down within a certain range. Typical images of the stable combustion stage are shown in Figure 2 (3-4). With the development of combustion, the heat transfer between the oil pool wall and the fuel

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tends to be stable. Due to the rising temperature of the wall, many bubbles appear on the inner wall of the oil pool, and the combustion rate and flame height increase significantly, and the oil pool enters the boiling combustion stage, as shown in Figure 2 (5-6). When the fuel in the oil pool evaporates, the pool fire enters the extinguished stage, and the combustion rate and flame height decrease rapidly until the flame goes out, as shown in Figure 2 (7~8). Previous research results usually divide the combustion process of oil pool fire into the initial growth stage, full development stage, and extinction stage [7, 9-11]. Considering the characteristics of combustion rate, flame height, and oil temperature stratification, the fully developed stage is subdivided into the stable combustion stage and boiling combustion stage.

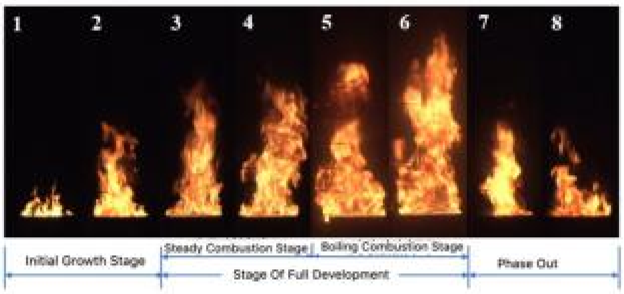


Fig. 2 Diagram of the development process of pool fire

## 3.2. Flame height

MATLAB is used for binarization processing of flame images [12] to obtain characteristic parameters such as flame height, which is the most used processing method for flame images at present [13]. The processing results are shown in Figure 3

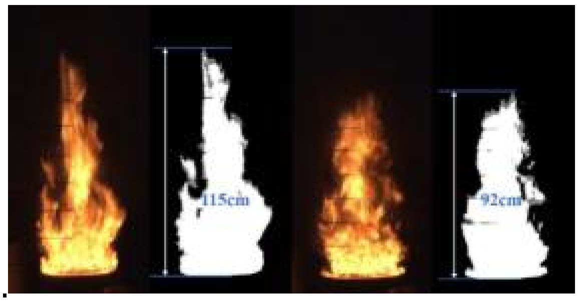


Fig. 3 Flame feature extraction map

The combustion process of oil pool fire in various working conditions was processed and flame height characteristics were extracted. The results are shown in Figure 4. To compare and analyze the various characteristics of flame height over time in the combustion process of pool fires at different scales, the adjacent averaging method was adopted to smooth the flame height curve, as shown in FIG. 4 (d). The flame height of the oil tank with a diameter of 40cm, 50cm, and 60cm is basically stable at the stage of stable combustion, with an average of 73.3cm, 98.8cm, and 128.1cm, respectively. Into the boiling combustion stage, the height of the flame increases, reaches the maximum after plummeting, into the extinguishing stage, until the combustion stops. The average flame height of the three-diameter oil pool fire boiling combustion stages is 80.3cm, 106.2cm, 146.1cm, which is about 1.1 times the flame height of the stable combustion stage.

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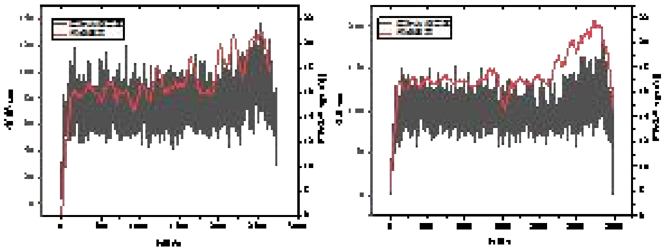
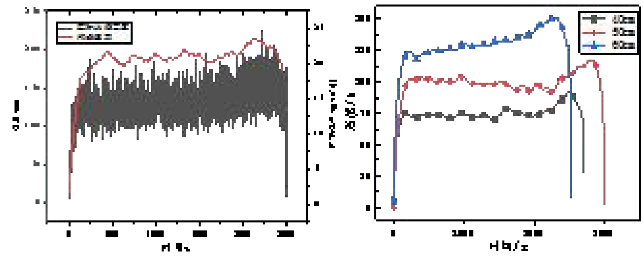


(a) Diameter of 40cm (b) diameter of 50cm



(c) Diameter 60cm (d) flame height after smoothing

Fig. 4 Flame height changes over time curves at different diameters

Flame intermittent rate I (H) refers to the proportion of time when flame height is greater than H [14]. Zukoski[15] defined three flame heights according to the relationship between flame height and intermittent rate: average flame height Have (I=0.5), maximum flame height Hmax (I=0.05) minimum flame height Hmin (I=0.95). Figure 5 shows the flame intermittent rate distribution of transformer oil pool fire with the diameter of 40cm. It can be seen from the figure that the minimum flame height, average flame height, and maximum flame height are 1.35d, 1.84d, and 2.46d respectively.

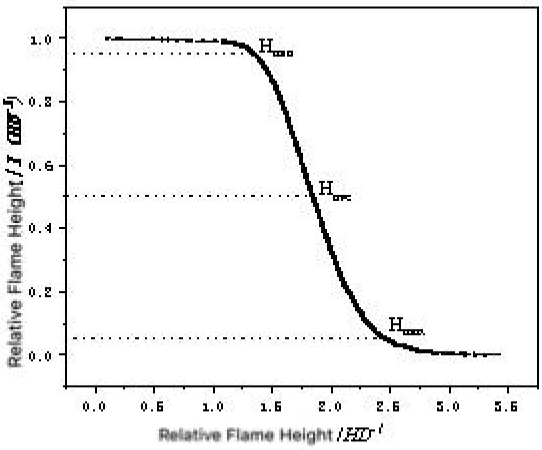


Fig. 5 Flame intermittent rate of nondimensional flame height for transformer oil pool fire （D=40cm）

Table 3 shows the three flame heights and the range of intermittent flame zones of transformer oil pool fires with different diameters. With the increase of the size of oil pool fires, the three flame heights all increase and the fire plume zones change significantly. The diameter of 40cm, 50cm, 60cm oil pool fire, intermittent flame range is 44.4cm, 57cm, 68.4cm respectively. As the diameter increases, the intermittent flame area of the three diameters increases by 1.2 times.

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Table 3 Three flame heights

| Diameter /cm | Minimum flame height | Mean flame height | Maximum flame height | Intermittent flame zone range /cm |
|---|---|---|---|---|
| 40 | 1.35D | 1.84D | 2.46D | 54-98.4 |
| 50 | 1.44D | 1.97D | 2.58D | 72-129 |
| 60 | 1.64D | 2.14D | 2.78D | 98.4-166.8 |

## 3.3. Flame temperature

In the process of pool fire combustion, the burning area is stretched under the drive of thermal buoyancy, and the flame moves upward [16]. According to flame height, axisymmetric flames can be divided into a continuous flame zone, intermittent flame zone, and smoke plume zone [14, 17, 18]. There is a positive correlation between flame height and oil pool diameter, which results in different temperature distribution characteristics of fire plume over oil pool with different diameters.

The temperature distribution curve of the centerline of flame plume area in the combustion process of transformer oil pool fire is shown in FIG. 6. Z is the vertical height from the center of the liquid level. The flame temperature shows an overall trend of rapid rise first, then steady, and then rapid decline, and there is an obvious temperature gradient in space at the stage of full development of fire plume temperature. Taking a 40cm diameter oil pool fire as an example, the flame temperature at 20cm above the oil pool is about 642℃, and the flame temperature at 50cm and 80cm above the oil pool are reduced to 413℃ and 203℃ respectively. The analysis of the plume temperature curve in the boiling combustion stage (3) shows that the temperature in the continuous flame zone remains unchanged while that in the intermittent flame zone increases significantly. This is due to the increase of combustion rate and flame height in the boiling combustion stage, the increase of continuous flame zone and intermittent flame zone, and the increase of flame temperature in the upper region.

Figure 6 (d) shows the average temperature distribution on the centerline of the oil pool fire plume with different diameters. The flame temperature of the oil pool with a diameter of 40cm was the highest at 5cm above the liquid level, reaching 653℃, and gradually decreased with the increase of the height from the liquid level. It can be considered that the oil pool with a diameter of 40cm is in a position 5cm above the liquid level where combustible steam and air are evenly mixed and the combustion is the most complete. The maximum flame temperature of 50cm and 60cm oil pools were 701℃ and 809℃, respectively, 20cm above the liquid level. The fire diameter of oil pools increased from 40cm to 60cm, and the maximum temperature of the fire plume increased by 156℃. There is also a great difference in the temperature of the centerline of the fire plume at different scales. The average temperature of the center line of the plume at 50cm above the liquid level of the oil pool with a diameter of 40cm is 413℃, and the average temperature of the plume at 60cm is 683℃, with a difference of 270℃. By comparing the temperature of the plume center line at the same height with

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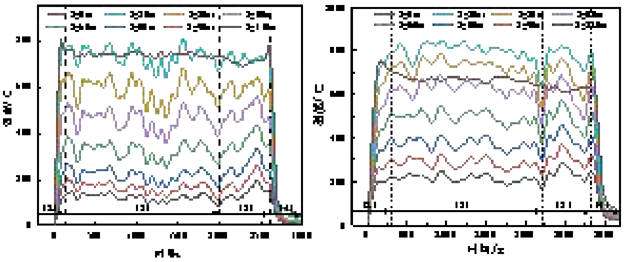
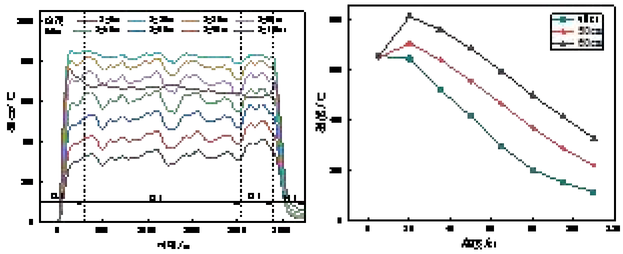
different diameters, the average temperature of the plume center line at the same height increases with the increase of the diameter of the oil pool, which is the same as the result of the KL50X transformer oil pool fire experiment conducted by Wang Yalong et al. This is due to the increase of oil pool diameter, combustion rate, flame radiation and convection effect, flame height increases with the increase of diameter, the fire plume of each zone also changed.



(a) Diameter of 40cm (b) diameter of 50cm



(c) 60cm diameter (d) plume centerline temperature

Fig. 6 Temperature distribution curve of fire plume

### 3.4. Heat transfer Analysis

The combustion process of transformer oil pool fire is closely related to the heat transfer process, and there is a strong correlation between oil temperature and combustion rate [19]. To study the mechanism and law of transformer oil pool fire combustion, it is necessary to analyze the temperature change and heat transfer mechanism of the combustion system. According to the research results of Hamins[19], the energy change of radiation master pool fire can be expressed as:

$$\dot{m}\Delta h_g = q_r + q_{conv} + q_{cond} - q_{heat} - q_{rr}$$

Where: $\Delta h_g$ is the heat of vaporization of fuel; $q_r$ , $q_{conv}$ and $q_{cond}$ are radiation heat absorbed by oil pool, convection heat and heat conduction from side wall to fuel respectively. $q_{heat}$ and $q_{rr}$ are heat transfer from high temperature oil layer to low temperature oil layer and pool surface reradiate heat loss respectively. And $q_{rr}$ is usually too small to be considered.

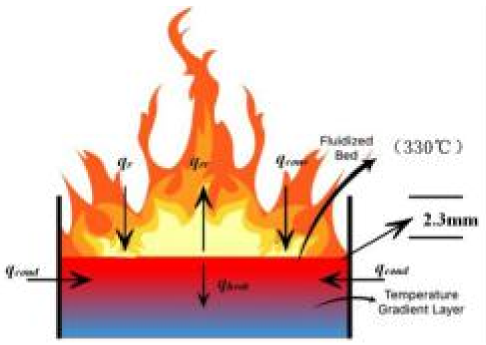



Fig. 7 Heat transfer process of oil

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FIG. 8 shows the change of oil temperature over time in a 40cm diameter oil pool. The temperature at 5cm from the bottom of the oil pool responds quickly after ignition, rising to 380℃, and then the temperature remains unchanged. This is because in the initial stage of pool fire ignition, the liquid surface fuel is heated and evaporates into combustible steam, and the thermocouple is exposed to the combustible steam area, so the temperature of transformer oil vapor is about 380℃. With the continuous accumulation of heat, the oil temperature at 1cm and 3cm away from the bottom of the oil pool gradually rises, and successively goes through the temperature gradient layer, boiling layer, and steam layer, and finally, the fuel burns out and enters the flame region.

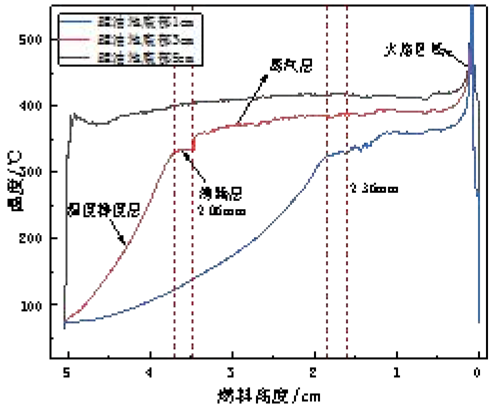


Fig. 8 Oil temperature change curve in diameter

Table 4 Different diameters of oil pools fire boiling layer thickness

| Diameter/cm | Distance from bottom of oil pool /mm | | |
|---|---|---|---|
| | 1 | 3 | 5 |
| 40 | 2.06 | 2.36 | - |
| 50 | 2.29 | 2.41 | - |
| 60 | 2.36 | 2.23 | - |

By analyzing the oil temperature variation curves at different locations, it can be found that the combustion heat fed back to the oil pool is not only used for evaporation on the liquid surface, but also part of the heat is transferred to the depth of the oil pool, and the oil temperature is stored in an obvious stratification phenomenon. In the process of oil pool combustion, there is a boiling layer with a certain temperature below the liquid surface. Table 4 shows the thickness of the boiling layer with different diameters. It can be seen that in the combustion process of transformer oil, a boiling layer about 2.3mm thick is formed below the liquid level, and the temperature is about 330℃, which has little relationship with diameter.

## 4. Conclusion

(1) The combustion process of transformer oil pool fire can be divided into the initial growth stage, full development stage, and extinction stage. Considering the characteristics of combustion rate, flame height, and oil temperature stratification, the fully developed stage is subdivided into the stable combustion stage and boiling combustion stage.

(2) The flame height of the transformer oil pool increases with the increase of the diameter of the oil pool. The flame height in the boiling combustion stage is 1.1 times higher than that in the stable combustion stage. With the increase of the diameter of the oil pool, the fire plume changes obviously, and the intermittent flame area increases by 1.2 times.

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(3) The temperature of the fire plume in the fully developed stage presents an obvious temperature gradient in space, and the temperature in the continuous flame zone does not change much in the boiling combustion stage, but the temperature of the fire plume in the intermittent flame zone increases significantly. The range of continuous flame zone and intermittent flame zone of oil pool fires with different diameters is different, and the average temperature of plume centerline at the same height increases with the increase of pool diameter.

(4) In the combustion process of the oil pool, the combustion heat fed back to the oil pool is used for evaporation on the liquid surface, and part of the heat is transferred to the depth of the oil pool, and the oil temperature is stored in an obvious stratification phenomenon. At the same time, it is found that during the combustion process of transformer oil pool fire, a boiling layer about 2.3mm thick is formed below the liquid level, and the temperature is about 330℃, which has nothing to do with the diameter of the oil pool.

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