Flammability properties of typical aviation functional oils

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Abstract. A sequence of experiments were conducted in a cone calorimeter to measure the flammability properties of 4050# lubricating oil and 15# hydraulic oil. Meanwhile, the heat release rate, mass loss rate and ignition time were used to investigate the combustion characteristics of the two kinds of oil with varying external radiant heat fluxes. The results show that the 15# oil is easier to be ignited than the 4050# oil and -0.55 power of the ignition time is linear with the external radiant heat flux, which agrees with the previous studies.

1. Introduction

Lubricating and hydraulic fluids are two typical functional oils, which are widely used in transportations: vehicles, vessels and aircraft. The lubricating oil is commonly employed as a liquid lubricant to protect machines and components, comprising base oil, additives and other chemical components [1]. The hydraulic oil is used as a medium for power transfer and control, heat transfer or sealing. However, the flammability of the two kinds of oil could lead to a potential fire hazard. Meanwhile, a main hazard is the accidental leakage near to a source of ignition [2]. In particular, the fire risk in aviation safety is paid more attention. Hence, it is significant to investigate the flammability properties of aviation lubricating and hydraulic fluids.

The cone calorimeter based on oxygen consumption principle is a standard apparatus to measure the flammability properties of materials in fire tests [3]. Iwata et al. [4] conducted a sequence of pool fire tests in a cone calorimeter to study the combustion characteristics of crude oils and the results showed that heat release rate (HRR), mass loss rate (MLR) and smoke yield are dependent on its density. Chen et al. [1] employed the same instrument to investigate the influence of radiant heat flux on ignition and combustion behaviour of lubricating oils. Generally, a combustible fluid is easier to be ignited in the presence of an external radiation by a pilot such as spark, flame and hot surface. Thus, although the heat release rate is the single most important variable to determine the flammability of materials in fire hazard [5], the ignition time is also an essential parameter to understand the combustion characteristics of liquid fuels because it can be used to predict fire initiation.

The objective of this study is to measure the flammability properties of two typical aviation lubricating and hydraulic oils including heat release rate, mass loss rate and ignition time using a cone calorimeter. On this basis, a quantitative analysis for HRR and ignition time with varying radiant heat fluxes was carried out.

2. Experimental set-up

The experiments were conducted in a cone calorimeter, which consists mainly of a combustion chamber, load cell and gas analyser [3]. Two typical aviation functional oils: 4050# lubricating oil and
15# hydraulic oil were chose as the test samples. The fluid samples of 50 mL for each test were loaded by a square pan with the length of 100 mm. The liquid fuel was exposed to the radiant cone with a high temperature and the distance of the liquid-level was 60 mm away from the bottom of the cone radiant source. Considering there existing a high flash point for the lubricating oil [6], 3 radiant heat fluxes: 25, 35 and 50 kW/m² were used to heat the fluid sample so that it was faster to be ignited by an electric spark. It should be noted that the flash point of 15# is appropriate 82 °C. Some typical specifications of 4050# lubricating oil and 15# hydraulic oil are summarized in Table 1.

Table 1. Specifications of 4050# and 15# oils.

| Specifications          | 4050#       | 15#       |
|-------------------------|-------------|-----------|
| Appearance              | clear and colorless | red       |
| Viscosity at 100 °C (mm²/s) | 4.9 – 5.4 | 4.9       |
| Flash point (°C, open cup) | 246       | 82        |
| Work Temperature (°C)   | –40 – 200   | –54 – 135 |

In total, 16 experiments were conducted. The experimental conditions are shown in Table 2. Except the minor variations in ambient temperature and humidity, every experiment was repeated at least twice at the same radiant heat flux. Meanwhile, several parameters including HRR, MLR, ignition time and flame temperature were measured in real time during the experiments. Note that the ignition time was determined by the flame temperature histories combined with observing the experimental phenomena, for the reason that there was an abrupt change in temperature at occurring a flame.

Table 2. Summary of the experimental conditions.

| Experiment No. | Sample | Heat flux (kW/m²) | Ambient temperature (°C) | Humidity (%) |
|----------------|--------|-------------------|--------------------------|--------------|
| 1-2            | 4050#  | 25                | 24                       | 39.5         |
| 3-5            | 4050#  | 35                | 23.5                     | 42           |
| 6-8            | 4050#  | 50                | 23.7                     | 44           |
| 9-11           | 15#    | 25                | 24.5                     | 51           |
| 12-13          | 15#    | 35                | 24.8                     | 52           |
| 14-16          | 15#    | 50                | 24.8                     | 51           |

3. Results and discussion

3.1. Heat release rate

HRR is the single most important parameter because it can indicate the size of fire and the growth rate of fire [7]. Consequently, these predicted values contribute to knowing the time available for safe evacuation or suppression in a real fire scenario. In the current study, the HRR was measured in a cone calorimeter based on the oxygen consumption principle, which assumes the heat released per unit of oxygen consumed is approximately the same value of 13.1 kJ/g with ±5% accuracy [8]. The heat release rates of the samples with varying radiant heat flux are shown in figure 1 and it are used to analyse the influence of external heat flux on HRR. Note that the initiation point is the ignition instant. This means the horizontal axis is a relative time but not beginning with heating fuels in figure 1. Figure 1(a) shows the HRR histories of 4050# lubricating oil exposed to 3 different radiant heat fluxes. An obvious feature is the maximum HRR increases with the increase of the external heat flux. In addition, the variation of HRR under the condition of 25 kW/m² is more stable than others, which can be divided into three typical stages: (1) ascending stage; (2) steady stage and (3) descending stage. However, the steady stage gradually fades away with increasing of the heat flux. This indicates a higher radiant flux can enhance the burning intensity of oils. Likewise, this phenomenon can be observed in figure 1(b). However, a distinct steady burning for 15# hydraulic oil is not to occur. Furthermore, the average maximum HRR of 15# is 3 – 4 times greater than that of 4050# at the same radiant flux. This result is consistent with a lower flash point of 15#, which means the ignition time of 15# is earlier than 4050#.
3.2 Mass loss rate

The average depth of oils in the current study is 5 mm that belongs to the range of the thin-layer fuel. However, the burning process for a thin-layer fuel is more complicated in comparison with that of pool fire with infinite depth due to the involvement of the boiling phenomenon [9]. According to previous study [10], this process can be divided into four stage: (1) pre-burning stage; (2) quasi-steady burning stage; (3) boiling stage and (4) decay stage. Compared with the simplified partition based on HRR, above four stages are more significant to understand the burning process of fluid fuels in the presence of external radiant heat flux.

The mass loss rates of the samples at 50 kW/m\(^2\) are shown in figure 2, where three repeated experiments for the same condition are all plotted. The 4050# lubricating oil and 15# hydraulic oil are corresponding to figures 2(a) and 2(b), respectively. As figure 2 (a) shows, four typical stages can be observed. For 4050# samples, the quasi-steady burning stage occurs after 50 s of the pre-burning stage and lasts about 60 s, but the first two stages are not presented distinctly in figure 2(b). During this stage, the heat feedback from flame to fuel surface is approximately equivalent to the convective heat loss and the heat loss from gasification of the fuel. Subsequently, an abrupt increase in burning rate occurs with the consumption of fuel until reaching to peak, which is called the boiling stage. This is because the residual fuel has already been heated to the boiling temperature by the flame and hot oil pan.

Meanwhile, as figure 2(b) shows, an interesting phenomenon is noticed that a longer quasi-steady burning happens in the decay stage, which corresponds to a relatively stable flame. The reason for this is unknown, but one could speculate that the low boiling point for 15# hydraulic oil, resulting in a fast boiling before reaching heat equilibrium.
3.3. Ignition time
In the current work, the temperature histories were used to determine the ignition time associated with occurring flame. There exists an abrupt increase in temperature at a certain instant, which corresponds to the ignition time. For typical oils including diesel and aviation kerosene, Chen et al. [1] verified that the -0.55 power of the ignition time is linear with the external radiant heat flux. Figure 3 shows the ignition time of 4050# and 15# with varying heat fluxes. As a result, the experimental data agrees well with the correlation $t^{-0.55} \sim \dot{q}_e^*$. 

![Figure 3](image)

**Figure 3.** (a) Ignition time of 4050#; (b) ignition time of 15# with varying radiant heat fluxes.

4. Conclusions
The major results and observations are summarized as follows:

1. It is easier to ignite 15# hydraulic oil at the same radiant heat flux than 4050# lubricating oil. In addition, although there exist four typical burning stages for the two kinds of oil, a longer quasi-steady burning happens in the decay stage for 15# but not following after pre-burning stage.

2. The relationship between the ignition time of the two kinds of oil and the radiant heat flux is consistent with the linear correlation $t^{-0.55} \sim \dot{q}_e^*$. 

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