Thermal Aging Analyses of a Gearbox oil Used for Wind Turbine Nacelles

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Abstract. The original gearbox oil (typed CALTEXMEROPA 320) used for wind turbine was heated for 96 h at 155.0 °C in air to simulate the thermal aging process. By thermogravimetry (TG) experiments in air, the thermal stability of the gearbox oil and the oil heated after 96 h were compared. The Advanced Kinetics and Technology Solutions (AKTS) tool was used to explore related thermal aging effect. The results demonstrate that the thermal decomposition processes of the gearbox oils can be divided into three stages, with major mass loss occurring in the second stage. The maximum mass loss rates are -12.0 %/min (0 h) and -13.0 %/min (96 h). The S value (combustibility index) of original gearbox oil (7.35) is higher than that of preheated oil for 96 h (6.70). The thermal aging curve of gearbox oil presents an inverted L-shape, the thermal aging rate is faster in the first week and then gradually slows down. Practically, the fire risk of gearbox oil in the initial application stage is the highest to induce a potential burning process in an unwanted high temperature (say, higher than 270.0 °C based on TG results) environment.

Keywords: Gearbox oil, thermogravimetry analysis, AKTS analysis, pyrolysis characteristics, thermal aging effect

1. Introduction

Wind power generation has become a globally recognized and deep developed renewable energy, especially in China [1]. However, there are still inevitable challenges currently [2]. According to the statistics counted by Caithness Windfarm Information Forum (CWIF) [3], a total of 3033 wind turbine accidents have occurred worldwide until June 30, 2021, including 414 fire accidents that accounts for 13.6 % of the total accidents and is the second common cause. In fact, the number of fire accidents of wind turbines is far more than the statistics showed above [4].

Previously, there have been some researches on thermal aging properties of oils. Wei Sun et al. [5] used Thermogravimetric Analysis - Differential Scanning Calorimetry (TG-DSC) to analyze the pyrolysis characteristics and kinetics of typical oils of gearbox oil, hydraulic oil and transformer oil in the wind turbine nacelle, and obtained some basic data. Ping Li [6] used a small cone calorimeter (according to ISO5560-1) to analyze the reaction-to-fire characteristics of single oil (gearbox oil, hydraulic oil and transformer oil) and assessed their fire risks by evaluating parameters of heat release rate, total heat release and specific extinction area. Zhenhua Wang et al. [7] developed a complete method to evaluate the flammability of typical fuels (transformer oil, hydraulic oil, gear oil, and
lubricating grease) used in wind turbine nacelle. The oil varieties used in these studies were mainly gearbox oil and transformer oil.

The consumption of gearbox oil is the largest in the wind turbine nacelle and oil spills occur frequently [7]. Also, with increasing failures of the gearbox in recent years, the safety of the gearbox oil has been paid serious attentions [8]. The working environment of gearbox oil is not as safe as people think, especially when it is exposed in high temperature to cause a potential fire. Therefore, the thermal aging characteristics of gearbox oil at high temperatures and under long periods are required to be figured out.

In this work, the original gearbox oil in a G5X-850 kW wind turbine nacelle was collected and preheated for 96 h at constant temperature (155.0 ℃). Thereafter, the pyrolysis processes and characteristics of the original gearbox oil were explored by TG experiments. Finally, the thermal aging characteristics of unheated gearbox oil at five different heating rates (2, 4, 6, 8, 10 K/min) and 155.0 ℃ for a long time (1 year) were analyzed by AKTS tool.

2. Materials and Methods

2.1. Samples and Treatment Methods

CALTEXMEROPA 320 (Caltex industrial gearbox oil, supplied by Z Energy Ltd., New Zealand) typed gearbox oil were used. The original gearbox oil sample was heated at constant temperature (155.0 ℃) for 96 h in air (in an air ventilation climatic chamber typed LRHS-225-NHQ, Shanghai Linpin Instrument Stock Co., Ltd., China) to realize simulated thermal aging effect.

The main component of gearbox oil is polyalphaolefin, a typical long alkyl hydrocarbon chain.

2.2. Thermal Analyses of Gearbox Oils by TG

TG experiments were performed from 20.0 to 500.0 ℃ at five heating rates (2, 4, 6, 8, 10 K/min) in air atmosphere (an airflow rate of 20.0 mL/min) via STA7200RV (HITACHI Ltd., Japan) to provide basic data for thermal analyses. To analyze basic pyrolysis characteristics of original and preheated gearbox oils, the data at a heating rate of 10 K/min was taken as an example. Microgram of gearbox oil heated for 0 and 96 h were put into Al₂O₃ crucible. The oil samples were shaken uniformly before sampling and the middle parts were adopted with a syringe.

2.3. Thermodynamic Analyses of Gearbox Oils by AKTS Tool

In fact, due to the oxidation of gearbox oil, the viscosity of gearbox oil increases gradually, which will generate corrosive sludge products, generating dirt in the gearbox. The increase of viscosity will lead to the increase of internal friction, flow resistance and energy consumption. At the same time, the convection heat dissipation speed will be reduced, resulting in the increase of oil temperature and a fire risk [9].

TG experiments of original gearbox oil were heated from room temperature to 550.0 ℃ at five heating rates (2, 4, 6, 8, 10 K/min) in an air atmosphere. On this basis, AKTS is used to infer the long-term thermal aging characteristics and mechanism assessment

Arrhenius-type equations can be utilized to describe thermodynamic properties of gearbox oil samples. Their mass loss rates in TG experiments were applied in AKTS dynamic analysis software to establish the iso-conversional model and calculate the activation energy (E). According to the non-isothermal kinetic theory and Arrhenius equations, the kinetic equation of the thermal decomposition of matter can be written as follows:

\[
\frac{d\alpha}{dt} = Ae^{-\frac{E_a}{RT}}f(\alpha)
\]

\[
\frac{d\alpha}{d\bar{T}} = \frac{A}{\beta}e^{-\frac{E_a}{R\bar{T}}}f(\alpha)
\]
In this equation, $A$ is the pre-exponential factor ($\text{min}^{-1}$); $E_a$ is the apparent activation energy ($\text{kJ/mol}$); $\alpha$ is the conversion degree, $\alpha = \frac{m_0 - m_t}{m_0 - m_f}$ where $m_0$, $m_t$, $m_f$ are the mass of the sample when the reaction starts, ends and the time is $t$, respectively; $t$ is the time (s); $T$ is the temperature (K); $f(\alpha)$ is the liquefaction reaction model, the integral form is as follows (3); $\beta$ is the heating rate ($\text{K} \cdot \text{min}^{-1}$), $\frac{dT}{dt}$; $R$ is the molar gas constant, 8.314 $\text{J/(mol} \cdot \text{K})$. The physical meanings of two important parameters, $A$ and $E$, are explained by collision theory and activated-complex theory based on statistical mechanics, quantum mechanics and material structure respectively [10].

$$g(\alpha) = \int_0^{\alpha} \frac{d\alpha}{f(\alpha)}$$

Eq. (4) is obtained by integrating eq. (2) and (3).

$$G(\alpha) = \frac{A}{\beta} \int_0^{T} \exp \left(-\frac{E}{RT}\right) dT$$

$$= \frac{A}{\beta} \int_0^{T} \exp \left(-\frac{E}{RT}\right) dT = \frac{AE}{\beta R} P(u)$$

Where $u = E/RT$, taking logarithm, Eq. (5) is obtained.

$$\ln \beta = \ln \left(\frac{0.00484AE}{RG(\alpha)}\right) - \frac{1.0516E}{RT}$$

$$A'(\alpha) = A(\alpha) \times f(\alpha) = \frac{0.00484AE}{RG(\alpha)}$$

Eq. (5) is called Ozawa equation, according to which the curves of $\ln \beta$ and $1/T$ under the same conversion rates and different heating rates can be obtained.

3. Results and Discussions

3.1. Analyses of Pyrolysis Characteristics of the Gearbox Oil

Figure 1 show the TG and DTG curves of the original gearbox oil (unheated) and the artificial aging oil (heated for 96 h) at a heating rate of 10 K/min.

The temperature at which the DTG curve has its peak value and the corresponding slope to the intersection with respect to the TG curve is defined as the ignition temperature ($T_i$) [11]. The burnout temperature ($T_f$) is defined as a point where 98.0 % of total mass loss has occurred [12]. To learn comprehensive combustion characteristics of the gearbox oil, a combustibility index $S$ [11, 13] is defined, as presented in Eq. (7):

$$S = \frac{\left(\frac{d\alpha}{dt}\right)_{\text{max}} \left(\frac{d\alpha}{dt}\right)_{\text{mean}}}{T_i^2 T_f}$$

where $\left(\frac{d\alpha}{dt}\right)_{\text{max}}$ represents the maximum mass loss rate and $\left(\frac{d\alpha}{dt}\right)_{\text{mean}}$ represents the average mass loss rate. A high $S$ value indicates that the sample is most probably to undergo a violent combustion reaction [13]. All parameters of TG and DTG data at a heating rate of 10.0 K/min in air are listed in table 1.

In figure 1, the mass loss trend and phase division of the original sample oil and the oil preheated at 155.0 $^\circ\text{C}$ for 96 h are basically the same. The decomposition process of gearbox oil can be split into three main stages, marked as I, II and III. Stage I is the volatilization stage with no obvious mass loss. There is a slight increase in mass with oxygen inhalation. It is mainly due to the release of physical
adsorption of water and light volatiles. Stage II is the main mass loss stage, in which a large number of oxidative pyrolysis reactions take place and the mass loss is rapid. Stage III is the mass loss slowing down stage, which was due to the carbonization of the solid residues.

![Figure 1](image_url)

**Figure 1.** TG and DTG curves of gearbox oil samples: (a) 0 h, (b) preheated for 96 h.

**Table 1.** Pyrolysis parameters of the original (0 h) and aging gearbox oil preheated for 96 h.

| Sample          | Gearbox oil 0 h | 96 h |
|-----------------|-----------------|------|
| $T_{\text{onset}}$ (°C) | 279.0           | 275.1 |
| $T_{\text{peak}}$ (°C)  | 293.6           | 287.7 |
| $T_i$ (°C)       | 280.3           | 277.6 |
| $T_f$ (°C)       | 462.0           | 461.4 |
| DTG$_{\text{max}}$ (%/min) | -12.0          | -13.0 |
| $S$ ($10^{-7}$)  | 7.35            | 6.70  |
| Residual char rate (%) | 11.1           | 10.5  |

For the unheated oil sample, at 293.6 °C, the DTG curve shows the maximum mass loss rate of -12.0 %/min. For the gearbox oil sample preheated for 96 h, at 287.7 °C, the DTG curve shows the maximum mass loss rate of -13.0 %/min.

According to DTG curve in figure 1(b), in stage I, the mass loss rate of unheated sample is more severe at the beginning, and then slows down and slowly absorbs oxygen to gain mass. On the contrary, the gearbox oil preheated for 96 h shows steady oxygen absorption and mass gain (see figure 1). At this stage, after constant temperature heating treatment, the oil itself will have a lower content of physically adsorbed water and a certain degree of light matter will escape, leading to a certain degree of oxidation.

The $S$ value (see table 1) of unheated gearbox oil (7.35) is higher than that of preheated oil for 96 h (6.70), indicating that the combustion propensity of original gearbox oil is somewhat higher than that of the oil preheated for 96 h. Therefore, it is important to monitor the quality and status of the original gearbox oil in time.

### 3.2. Thermal Aging Characteristics and Thermal Kinetic Analyses of the Gearbox Oil

Figure 2 shows the reaction processes and reaction rates of gearbox oils by using AKTS software based on TG experiments under five heating rates. It can be seen that the mass loss rates of the gearbox oil (see figure 2(b)) are 97.052 % (2 K/min), 95.897 % (4 K/min), 95.966 % (6 K/min), 95.487 % (8 K/min) and 97.264 % (10 K/min), respectively. And all of them reach the maximum values at about 400.0 °C. The mass loss rates of the gearbox oil are on average 96.333 ± 0.778 % according to the results under five heating rates. These data are used to establish the iso-conversional
models and analyze the thermal aging reaction processes of the explored gearbox oil.

Figure 2. Reaction processes (a) and mass loss rates (b) of the gearbox oil derived from TG experiments.

Figure 2(a) shows the relationship between the experimental curves are in good agreement with the fitting curves with the correlation coefficient of -0.98591, indicating that the reaction processes can be truly simulated. The pyrolysis starts at around 250.0 °C and reaches the maximum conversion at 460.0 °C or so. This is consistent with the conclusion of the main pyrolysis stage of TGA (see figure 1). At the same pyrolysis temperature, the higher the heating rate, the lower the conversion rate, and the curve moves to the right gradually.

Figure 2(b) shows the curves of mass loss rates and temperatures of the gearbox oil. The reaction starts at around 250.0 °C. At the beginning of the reaction, the lower temperature cannot result in the breakage of the chemical bond with higher activation energy [14], also the reaction rate is slower. However, when the reaction temperatures reach 360.0 °C (see figure 2(a)), the mass loss rates are suddenly and apparently accelerated. When the heating rates gradually increase, the temperatures reaching the maximum mass loss rates are around 383.0 °C (2 K/min), 394.0 °C (4 K/min), 400.0 °C (6 K/min), 403.0 °C (8 K/min) and 406.0 °C (10 K/min), respectively.

Figure 3 shows the differential isoconversion curves of the gearbox oil at five heating rates. Connecting the points at the same conversion at five groups of heating rates, 15 straight lines are obtained. By calculating $\ln \beta$ vs $\frac{1}{T}$, the slope and intercept in each given transformation can be expressed as $E/R$ and $\ln (A'(\alpha))$, then Fig.6 is given. This method assumes that $E$ and $A'(\alpha)$ are variable functions without exact $T(\alpha)$.

As can be seen from figure 3, in the conversion rate $\alpha$ under the same conditions, the activation energy $E$ of different heating rates presents a linear distribution [15-18]. The overall trend of $\alpha$ is from low heating rate to high heating rate.
Figure 4 shows the apparent activation energy values of $E$ and $A'(\alpha)$ of the gearbox oil calculated by iso-conversional method.

From figure 4, under different conversion rates, the activation energy values of the gearbox oil are between 120.0-250.0 kJ/mol. It can be seen that the overall trend is rising, reaching the maximum value (250.0 kJ/mol) when the reaction process (conversion rate) reaches about 0.96, the upward trend during this period (0-0.96) can be regarded as a linear segment. When the reaction process (conversion rate) between 0.96-1.00, the activation energy ($E$) begins to fall down. After obtaining these two parameters ($E$ and $A'(\alpha)$), the conversion rates of five processes can be integrated, and the reaction processes can be predicted by presetting initial temperatures, heating rates and final temperatures. In the experiments, the gearbox oil samples were preheated at 155.0 ℃. In the simulation, the same environment was used, the initial temperature and final heating temperature were set 155.0 ℃, the heating rate was 0 K/min, and the simulation period was 1 year. Figure 5 shows the thermal aging process of gearbox oil under 155.0 ℃ in this case.

It can be seen from figure 5, the constant temperature thermal aging curve (in red) of gearbox oil present an inverted L-shape, and the initial thermal aging rate is fast. With the extension of time, the thermal aging rate (in black) gradually slows down. In the first week, the thermal reaction (in red) of
the gearbox oil is the most intense. Thereafter, the thermal aging rate decreases steadily. After one year, the overall reaction process of the gearbox oil reaches 25 %, and the reaction progress tends to stop.

The gearbox oil has the greatest fire risk in the early stage of high temperature heating, which is consistent with the result \((S)\) calculated in Section 3.1. High temperature environment often occurs in the confined wind turbine nacelle due to lightning strike, circuit fault, mechanical friction, etc. To remind the fire prevention of wind turbine, more attention should be paid to the fire risk of the first use and timely monitoring of original gearbox oil, and the proper period of aftermath replacement work.

4. Conclusion
(1) The TG and DTG curves of the gearbox oil after different preheated hours (0 h and 96 h) have obvious differences at the beginning of the reaction. The reason is that at this stage, the oil after constant temperature heating treatment has a lower content of physically adsorbed water and releases a certain degree of light volatiles, resulting in a certain degree of oxidation.

(2) The thermal reaction of original gearbox oil will decrease with the delay of thermal aging time. The overall reaction process of original gearbox oil reaches 25 % and the reaction progress tends to stop.

(3) The aging characteristics of gearbox oil are used to strengthen the monitoring of gearbox oil products. High temperature environments should be avoided to the greatest extent in which original gearbox oil may initiate potential thermal degradation steps. Gearbox oil in the oil box is better to be regularly replaced and cleaned in a proper period to avoid generate corrosive sludge products, generating dirt in the gearbox.

Notes
The authors declare no competing financial interest.

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