Fire resistance test of transformers filled with natural ester insulating liquid

Shengwei Cai, Cheng Chen, Huihao Guo, Shaobing Chen, Zandong Zhou, Zhaofeng Guo

1 State Key Laboratory of Power Grid Environmental Protection, China Electric Power Research Institute, Luoyu road 143, Wuhan, People’s Republic of China
2 State Grid Company of China, West Changan Avenue No. 86, Beijing, People’s Republic of China
3 Wuhan NARI Limited Liability Company of State Grid Electrical Power Research Institute, Wuhan, People’s Republic of China
4 State Grid Hubei Electric Power Company Limited, Xudong Road 175, Wuhan, People’s Republic of China

Abstract: Natural ester fluids, as a renewable, biodegradable liquid dielectric, its flash point is above 300°C, and the burning point exceeds 330°C, high flash point liquids known as ‘less flammable’ liquids. There is a possibility applying the natural ester fluid immersed transformer instead of dry type transformer in high fire resistance requirement occasion. In order to verify the fire resistance of natural ester insulating oil transformer, set forth a series of contrast test between natural ester insulating oil and mineral insulating oil, including flash point, burning point, explosion limits, metal hot surface test, and burning plate test. Through developing burning test platform of transformer to launch the burning test for 10 kV transformer of natural ester insulating oil. The results show that the transformer filled with natural ester fluid cannot burn for 30 min in the case of severe external fire, which provides a relatively abundant time for fire extinguishing and has certain fireproof performance. In addition, by improving the mechanical strength of transformer tank, install the specific pressure relief devices and using high temperature seal, bushing etc., which can improve the fire resistance of transformers filled with natural ester insulating fluids.

1 Introduction

The widely used mineral insulating oil is currently not renewable, with a poor biodegradability and it may easily lead to environmental pollution in case of any leakage, which will not help the construction of green power grid and environmental-friendly society [1]. In addition, a low burning point of mineral insulating oil cannot meet the design and manufacturing requirements of electrical equipment with a high fire resistance. Compared with the mineral insulating oil, the natural ester insulating oil (NEIO), as a renewable and biodegradable fluid insulating medium [2], can be used as a substitute for the mineral insulating oil [3]. The flash point of the NEIO exceeds 300°C and its ignition point exceeds 330°C [4]. In order to use the transformers filled with NEIO instead of dry-type transformers for high fire-resistance applications by making full use of the characteristics of high ignition point of the NEIO [5], it is required to carry out pilot studies on fire-resistance performance of NEIO transformers so as to eliminate people’s worry about the fire-resistance performance of NEIO transformers [6]. Here, the comparison of flash point, ignition point, and explosion limits and other fire safety parameters and the comparison of metal hot surface test and fire tray test between NEIO and mineral insulating oil were carried out. The burning test platform of NEIO transformers was developed and the burning test of 10 kV NEIO transformer was carried out. The site condition, temperature, pressure, heat radiation, and other characteristic parameters were monitored during the whole process of combustion test. According to the test results, the fire resistance performance of NEIO transformers was analysed and evaluated.

2 Fire resistance performance of NEIO

Fuel, air, and temperature are three elements for combustion. The combustion cannot happen so long as one of them is failed. Under the normal circumstances, oil-immersed transformer oil and other insulating systems are isolated from the air and the temperature is not high for normal operation (<105°C), so the combustion will not happen [7]. The combustion in transformer mainly refers to the combustion of oil ejected from the transformer in the air, so from the perspective of combustion and fire resistance, the combustion of oil-immersed transformer refers mainly to the combustion of transformer oil [8].

The biggest difference between the NEIO transformers and mineral insulating oil transformers is that the mineral insulating oil in the transformer is replaced by the NEIO. Under the circumstance of same insulating paper and insulating paperboard, the fire-resistance difference of a transformer is mainly determined by the fire resistance of the insulating oil. Therefore, it is necessary to research and test the fire-retardant property of the NEIO so as to determine its fire resistance.

Through the comparison of flash point, ignition point, explosion limit, and metal hot surface test and fire tray test between the NEIO (NET, soybean-based) and mineral insulating oil (SINOPEC), the fire resistance of the NEIO was assessed.

2.1 Conventional properties

A comparison of fire resistance parameters between two insulating oils can be seen in Table 1.

Table 1 Comparison of fire resistance parameters between two insulating oils

| Item                  | NEIO           | Mineral Insulating Oil | Reference Standard |
|-----------------------|----------------|------------------------|--------------------|
| flash point           | 318°C          | 156°C                  | GB/T3536           |
| ignition point        | 334°C          | 168°C                  | GB/T3536           |
| initial boiling point | 376°C          | 220°C                  | GB/T 616           |
| saturated vapor pressure (37.8°C) | 0.6 kPa          | 1.9 kPa (37.8°C)                  | GB/T8017           |
| KVIS (100°C)          | 9.2 mm²/s max. air intake is 0.3%, no burning and no explosion | 2.3 mm²/s max. air intake is 0.7%, no burning and no explosion | GB/T 265 | GB/T 12474 |
2.2 Metal hot surface test

The metal blocks at a temperature of over 800°C were immersed in constant temperature NEIO and mineral insulating oil to test the ignition capability of high-temperature metal block on the insulating oil. Fig. 1.

Test results show that, the NEIO was not ignited, which indicates that the NEIO can withstand the effects of short-term high-temperature and overheating.

2.3 Test of fire tray

The NEIO and mineral insulating oil were directly heated using the oxyacetylene flame to compare the combustion effect of two insulating oils in the open flame, as shown in Fig. 2.

The test results show that, mineral insulating oil was ignited approximately within 5 s and it burnt continuously after it was ignited; under the oxyacetylene flame, there is a smaller local flame for the NEIO, and the NEIO is self-extinguishing after the jet is stopped 5 min later. This test result shows that, compared with mineral insulating oil, the NEIO is not easily ignited by external fire sources and it has certain self-extinguishing function. This is associated with a high ignition point and boiling point and low saturated vapour pressure of the NEIO.

3 Fire-resistance test of NEIO transformers

In order to assess the fire resistance of the NEIO in case of an external fire, the test of prototype simulated external fire was carried out for the NEIO.

3.1 Test methods

3.1.1 Test platform: In order to simulate the effect of transformer room suffered with a fire, a semi-enclosed space was established. The test core area is 6 m (length) × 5 m (width). The core area contains sump, firewall, fire protection walls, ditches, and so on. The wood stacks of 1A standards were used in the combustion test, and its length, width and height were all 500 mm. Four wood stacks were arranged on the bottom of transformers, respectively. The tested transformer was NEIO transfers of 10 and 200 kA. The transformer tank was filled with 133 kg of NEIO, as shown in Fig. 3.

3.1.2 Test status monitoring:

i. Temperature monitoring: In order to monitor the temperature change inside and outside a transformer during the combustion test, the changes of inside and outside and dead-ahead temperature of the transformer was monitored in a real-time manner using K/J thermocouples of OMEGA Company. The temperature distribution gradient around the transformer was measured using the thermocouple tree during the combustion process of transformer. The thermocouple tree is composed of three measuring rods and nine thermocouples. The distance of three measuring away from the transformer is 1–3 m, respectively, and 3 K-type thermocouples are arranged on each measuring rod, as shown in Fig. 4.

ii. Heat radiation monitoring: In order to quantitatively monitor the heat flux density or heat flux during the transformer combustion process and evaluate the heat radiation performance, two TS-34C heat flux sensors of French CAPTEC Company were set up at 1 m away from the transformer, with a measuring range of ±200 kW/m² for each sensor. Its fast response time is 0.05 s and it outputs the voltage signals. The maximum measurable range is 150%F.S.

iii. Pressure monitoring: In order to monitor the changes of internal pressure of the transformer during the transformer combustion process, pressure sensor interface was set up at top cover of fuel tank of the transformer. The internal pressure of the transformer was monitored by connecting the internal pressure of fuel tank with the CY200-ZT high-precision digital pressure sensor through an impulse tubing. Fig. 5.

3.1.3 Test data acquisition system: The transformer internal/external thermocouples, the internal pressure sensor, heat flux sensor, and other monitoring sensors were collected with the TST6300 dynamic data acquisition system through signal lines to achieve the real-time monitoring of various states, as shown in Fig. 6.

3.1.4 Setting of camera pan tilt zoom device: The camera PTZ and wireless network remote monitoring system were set up to...
rotated for around 130° and 340° to observe the test situation from the insulating oil in the transformer was ejected out continuously. The wood stacks were all ignited after the thermocouple compensation lines were all burnt and the data monitoring stopped. The entire insulating oil was directly ejected to cause severe combustion for 8 min, and then the flame was reduced gradually. The entire combustion process lasted about 30 min. At about 30 min of the combustion, the heat radiation sensor, pressure sensor, thermocouple compensation lines were all burnt and the data acquisition was interrupted. The monitoring of combustion test of NEIO transformer is shown in Fig. 7.

### 3.2 Test process

i. First of all, the normal condition of test wiring and sensor monitoring state are checked. After the test conditions on the site were satisfied, an igniting stick was used to ignite the gasoline under the wood stack so as to ignite the wood stacks.

ii. The state variables and video during the whole process of combustion test were monitored to observe the combustion process, the escape of external gas from the transformer, the overflow of the NEIO, monitor the inside temperature rise and pressure change in the transformer, and judge whether there is a combustion-supporting phenomenon of the transformer as well as the actual state of the entire process of transformer combustion.

After the combustion test was started, various monitoring data were normal. The wood stacks were all ignited after the combustion test continued for 20 min; 30 min later, the pressure relief valve on top of fuel tank of the tested transformer acted and the insulating oil in the transformer was ejected out continuously at a frequency of once a second to lead to a violent fire, and the internal pressure of the transformer was released to <5 kPa. Afterwards, the fuel tank was heated to repeatedly eject the oil to support the combustion and the transformer casing was burnt. The insulating oil was directly ejected to cause severe combustion for 8 min, and then the flame was reduced gradually. The entire combustion lasted about 50 min. At about 30 min of the combustion, the heat radiation sensor, pressure sensor, thermocouple compensation lines were all burnt and the data acquisition was interrupted. The monitoring of combustion test of NEIO transformer is shown in Fig. 7.

### 3.3 Analysis of test results

i. **Analysis of transformer internal pressure**: Change of transformer internal pressure during combustion test shows that, within the first 15 min of the combustion test, the temperature rose more slowly. After about 20 min, the fire gradually increased and the internal pressure rose sharply. The pressure relief valve of the transformer acted at about 29 min, and the maximum measured pressure was 20 kPa. After the action of the pressure relief valve, the pressure dropped below 5 kPa.

ii. **Analysis of internal/external temperatures**: Figs. 8 and 9 show that, the inside temperature rise was relatively smooth in the combustion test of NEIO transformer, with a larger outside temperature jump. The inner upper part of the tested transformer enjoyed the maximum oil temperature, and the inner lower part enjoyed the minimum oil temperature. When the maximum external oil temperature was about 290°C, the maximum external temperature of the transformer was about 900°C.

iii. **Heat radiation monitoring**: Fig. 10 shows that, the heat flux was about 20 kW/m² when the upper heat radiation peak occurred in the first action of pressure relief valve, the maximum heat flux was about 22 kW/m² when the peak occurred in the second action of pressure relief valve; the maximum heat flux measured by the lower heat flux sensor was about 12 kW/m².

Table 2 shows that, the maximum heat flux at 1 m away from the tested NEIO transformer and at the height position of the transformer was up to 22 kW/m². It can cause the severe burns after an exposure time of 5 s, and it can cause second-degree burns after an exposure time of over 30 s, and the heat radiation can even burn the woods. Therefore, there will be a high risk if the NEIO transformer is ignited by a fire.

iv. **Thermocouple tree monitoring**: The monitoring temperature data of thermocouple tree show a similar overall trend of temperature changes for nine temperature-measuring points on the thermocouple tree with the change of time as Fig. 11. The wood stack fire temperature dropped sharply with the increase of distance, and the trend of temperature attenuation at three heights was similar. The maximum temperature attenuation with the distance increase occurred at the top (1.4 m), and the minimum temperature attenuation occurred at the bottom (0.4 m). At a distance of 1 m from the transformer, the maximum temperature during the combustion process reaches 195°C, and at a distance of 3 m, the maximum temperature is only 56°C. This shows that the heat resistance of the building or structure itself shall be considered when it is set up around the transformer. When the heat resistant temperature is lower than 60°C, the structure shall be kept at least 3 m away from the transformer to prevent the fire of the transformer from causing the thermal damage to the structures around it.

### 4 Conclusion

The flash point (ignition point), boiling point, fire diffusion characteristics, and explosion risk of the NEIO are all superior over those of the mineral insulating oil. The metal hot surface test shows that the plant insulating oil cannot be ignited after it withstand a certain fire resistance property. The monitoring results of internal/external temperatures show that the NEIO transformer is inflammable and not easy to explode.

In case of a harsh external fire, the NEIO transformer cannot be burnt for 30 min without explosion, which provides a relatively abundant time for the fire-fighting operation, and therefore, it has a certain fire resistance property. The monitoring results of temperature and pressure during the combustion test of NEIO transformer show that the internal pressure of NEIO transformer increased with the rise of temperature during the combustion. The existing 35 kPa mechanical pressure relief valve can meet the pressure relief requirements under fire conditions and it will not cause the transformer to explode. In order to improve the fire resistance of NEIO transformer, it is recommended to improve the fire resistance of the NEIO transformers using the fire-resistant high pressure casing and sealing materials, improving the structure and threshold value of pressure relief valve, improving the mechanical strength of fuel tank, and taking other measures.
Fig. 7 Monitoring chart of combustion test
(a) 5 min, (b) 20 min, (c) 25 min, (d) 30 min, (e) 35 min, (f) 50 min

Fig. 8 Change of inside oil temperature of the transformer

Fig. 9 Change of outside temperature of the transformer
Fig. 10 Heat radiation condition at 1 m away from the transformer

Table 2 Personal injury level by heat radiation

| Heat flux, kW/m² | Exposure time, s |
|-----------------|------------------|
|                 | 10               | 30            | 60            |
| death           | 32.73            | 14.36         | 8.54          |
| second-degree burn | 27.81        | 12.20         | 7.25          |
| first-degree burn | 12.22         | 5.36          | 3.19          |

Fig. 11 Relationship graph of temperature vs. time at temperature points

5 References

[1] Abdelmalik, A.A., Dodd, S.J., Dissado, L.A., et al.: ‘Charge transport in thermally aged paper impregnated with natural ester Oil’, IEEE Trans. Dielectr. Electr. Insul., 2014, 21, pp. 2318–2328

[2] Lukas, L., Jan, Z., Iraida, K., et al.: ‘Research of electrophysical properties of oil-paper insulation’. Proc. 2014 15th Int. Scientific Conf. on Electric Power Engineering (EPE), Brno, Czech Republic, 2014, pp. 403–406

[3] Shengwei, C., Jiangbo, C., Cuijuan, Z., et al.: ‘Study on thermal ageing characteristics of vegetable insulating Oil-paper compound insulations’, Insul. Mat., 2015, 48 (2), pp. 56–60

[4] Mazzaro, M., De Bartolomeo, D., Bemporad, E.: ‘Power transformer fire and environmental risk reduction by using natural esters’. 19th IEEE International Conference on Dielectric Liquids (ICDL), Manchester, United Kingdom, June 2017

[5] Pompili, M., Calcara, L., Sturchio, A.: ‘Natural esters distribution transformers: A solution for environmental and fire risk preventions’. 2016 AEIT Int. Annual Conf. (AEIT), Capri, Italy, April 2016

[6] Bingenheimer, D.: ‘Fire safety in transformer applications’. Proceeding of My Transfo 2016, Turin, Italy, 2016

[7] Frimpong, G.K., Oommen, T.V., Asano, R.: ‘A survey of aging characteristics of cellulose insulation in natural ester and mineral oils’, IEEE Electr. Insul. Mag., 2011, 27 (2), pp. 36–48

[8] Changxin, R., Jin, L., Xin, Z., et al.: ‘Discussion on safety of fire prevention of high ignition point vegetable insulating Oil transformers’, Transformer, 2009, 46 (6), pp. 26–28