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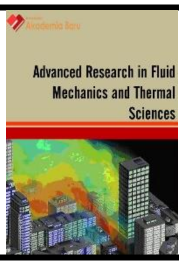


# Effects of Moisture Content and Temperature on the Dielectric Strength of Transformer Insulating Oil

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**ABSTRACT**

The primary function of insulating oils is to dissipate heat and provide electrical insulation for turn-to-turn windings in power transformers. These oils also serve as a means to monitor the health status of power transformers. At present, most transformer failures are due to the presence of moisture as well as heat, oxidation, and electrical stresses. The main objective of this research was to study the effects of moisture content and temperature on the dielectric strength of transformer insulating oil, which is known be the factors that lead to transformer failures. The effect of moisture content was investigated by varying the amount of distilled water added into the insulating oil samples from 1 mL to 5 mL with 1-mL increments. The effect of temperature was investigated by increasing the oil temperature from 40°C to 120°C with 20°C increments. The dielectric strength of each insulating oil sample was assessed by performing AC breakdown voltage tests according to the MS IEC 60156:2012 standard. With the assistance of FTIR spectra revealed that the chemical compounds of transformer insulating oil were also affected (based on absorption band) due to the presence of moisture and temperature. Based on the results, it can be concluded that moisture and temperature have a significant effect on the dielectric strength and chemical compounds of transformer insulating oil.

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## 1. Introduction

The objective of this research is to study the electrical and chemical properties of transformer insulating oils with the aim to understand the basics of the power transformer function and insulating oil. Power transformer is essentially a device in static conditions. As the name implies, power transformers transform electrical energy from one circuit to another while maintaining the same frequency. This frequency is 50 Hz in Malaysia. In addition, power transformers are essential equipment in power networks to convert voltage levels and maintain power flow. The transformer steps up or steps down the voltage level, depending on the requirements. The transformer consists

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of many parts from which the main ones are primary windings, secondary windings, and magnetic core. Transformer failures are caused by various factors such as overloading, short circuit, switching surges and etc. According to the statistics of transformer failures given by the respondents from International Council on Large Electric Systems (Cigre), the most common cause of transformer failures is insulation failure [1]. Figure 1 shows the statistics of the causes of transformer failures based on 964 major failures. The insulation system plays a significant role in influencing the lifetime of a power transformer [2]. The primary and secondary windings as well as the magnetic core of the transformer are insulated and cooled by solid and liquid insulations [3]. Solid insulation comprises pressboard, wood and unbleached softwood pulp [4]. "Kraft paper", which is a widely used solid insulation, is made from unbleached softwood pulp, which flows into the sulfate process. Liquid insulation plays a dual role in high-voltage transformers [5]: (1) as a coolant for heat dissipation and (2) as an electrical insulator. In this paper, liquid insulation refers to petroleum-derived mineral oils. It is evident that insulation failure makes up the highest percentage of transformer failure causes. Insulation system plays a vital role in influencing the lifetime of the transformer because it insulates and cools the transformer. Similar to the other high-voltage systems, transformers require insulating materials (solid and liquid insulations) to dissipate excessive heat [6]. The main objective of this research is to investigate the electrical and chemical properties of a petroleum-derived mineral oil. These properties were assessed according to the MS IEC 60156:2012 and ASTM D2144 -07(2013) standard to ensure reliability of the experimental results [7]. This research is focused on the effects of moisture content and temperature on the properties of the mineral insulating oil.

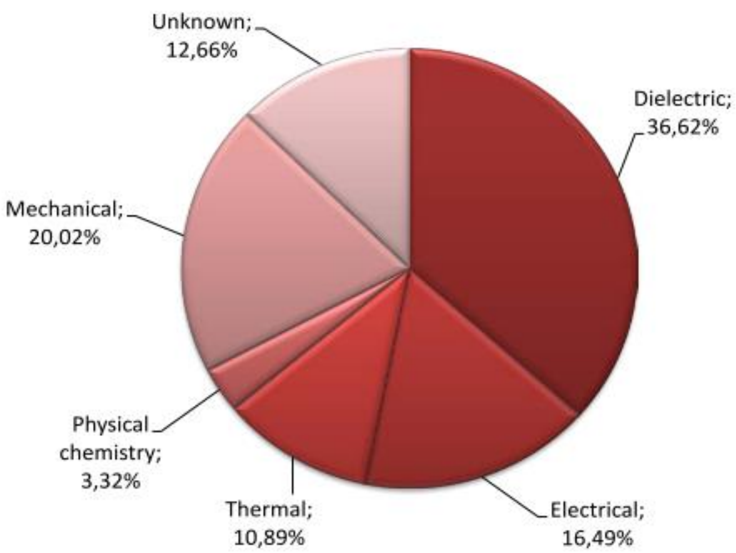


**Fig. 1.** Causes of transformer failures based on 964 major failures according to the Cigre respondents [1]

As the name implies, liquid dielectric is a dielectric in liquid state. The main purpose of liquid dielectric (liquid insulation) is to prevent electrical discharge. In general, a good liquid dielectric is nonflammable and has high dielectric strength, good chemical stability, and good thermal properties [8]. In addition, a good liquid dielectric is capable of preventing breakdowns under electrical stresses. The electric capacitance per unit of volume of the liquid dielectric is determined by its dielectric constant, which is dependent on the operating temperature of the liquid dielectric and frequency or structure of its constituent molecules. Even though solid insulations are important in the electrical industry, liquid insulations are generally used in many electrical devices and equipment such as transformers, circuit breakers, capacitors, and cables. The properties of the liquid dielectric need to be assessed to determine whether the liquid dielectric is favorable to be used for transformer applications.

The distillation of crude petroleum produces a fraction of hydrocarbons, which are used to produce transformer insulating oils by refining. The boiling range of the collected fraction and degree of refining are predefined prior to the process. The resultant product possesses properties that are suitable for transformer applications. Many international refining companies produce transformer insulating oils from crude petroleum. The physical, chemical, and electrical properties of the transformer insulating oils are determined to ensure that they conform with the specifications stipulated in transformer insulating oil standards [9, 10]. Each property was compared with the specifications of the standard, which have been agreed between the insulating oil manufacturers and crude oil refiners. The amount of insulating oil contained in a transformer varies depending on the loading capacity and physical size of the transformer. For example, a 100-kVA rated distribution transformer contains ~140 liters of insulating oil. The viscosity of the insulating oil is particularly important for heat transfer by natural convection and it is a principal parameter in design calculations. When the transformer is in operation, the insulating oil is subjected to electrical and mechanical stresses. The interactions between the insulating oil and windings can lead to contamination, which will accelerate chemical reactions at high operating temperatures and alter the original properties of the insulating oil [11]. The electrical, physical, and chemical properties of the insulating oil need to be periodically tested to assess whether the oil is fit for service. In this research, the following electrical property (AC breakdown voltage or flashover point) was investigated whilst the chemical property examined was the functional groups. In general, it is crucial to determine the chemical compounds present in transformer insulating oils. The transformer insulating oil consists of various hydrocarbon compounds, each of which comes from different sources. The variations in chemical compounds reflect the behavior of different classes of hydrocarbons. The hydrocarbon compounds present in transformer insulating oil can be generally classified as naphthenes, aromatic hydrocarbons, and alkanes. The chemical formula of transformer oils is $C_{12}H_{10-x}Cl_x$, where $x$ is polychlorinated biphenyl, with a value of 1–10 [5].

In this research, the effects on moisture content and temperature on the dielectric strength and chemical compounds of mineral insulating oil were analyzed. The dielectric strength (i.e., breakdown voltage) is the minimum voltage at which the liquid dielectric has lost some of its insulating property such that it becomes conductive. Breakdown occurs when the insulating oil reaches the stage where there is spark between the electrodes. The properties of the insulating oil at the atomic and molecular scale may play a role in influencing the breakdown voltage; however, in high-voltage breakdown tests, the electrode material, moisture content, gassing tendency, and temperature may also increase or decrease the breakdown voltage [12]. According to the MS IEC 60156:2012, the minimum breakdown voltage of transformer insulating oils is 30 kV [6]. In this research, the changes in the chemical compounds present in the insulating oils were analyzed using Fourier transform infrared (FTIR) spectroscopy, which is one of the most widely used analytical techniques. It is known that the presence of moisture has a significant effect on the insulating property of transformer insulating oils. Hence, ideally, the insulating oil should be free from moisture. In terms of the electrical properties, moisture can reduce the breakdown voltage of the insulating oil. The presence of moisture breaks down the molecular chains of the insulating oil [13], [14]. In terms of the chemical properties, the presence of moisture ($H_2O$) can be detected within a wavenumber range of 3600–3400 1/cm in the FTIR spectra, such that the insulating oil becomes conductive [15, 16] . A higher insulating oil temperature can also affect the breakdown voltage and chemical makeup of the insulating oil. A higher temperature will increase the breakdown voltage of the insulating oil whereas the aliphatic (C–H) compound will decrease. The decrease in aliphatic compound appears as a strong absorption band within a wavenumber range of 3000–2850 1/cm, which is ascribed to C–H stretching [17].

## 2. Methodology

The methodology adopted in this research is described briefly in this section. A portable oil dielectric strength tester (Model: OTS60PB, Megger Ltd., UK) equipped with semi-spherical electrodes was used to conduct the breakdown voltage tests. The instrument can be used to test an insulating oil sample with a volume of 500 mL. An FTIR spectrometer (Model: FT/IR-6100, Jasco Inc., USA) was used to measure the FTIR spectra of the oil samples within a wavenumber range of 4000–400 1/cm. The instrument is equipped with an IR analyzer, which is a software package that enables one to search and access the reference IR spectra and analyze the chemical structures of the sample under investigation. The effects of moisture content were investigated by varying the amount of distilled water added into the oil sample from 1 mL to 5 mL with 1-mL increments whereas the effect of temperature was investigated by increasing the temperature of the oil sample from 40°C to 120°C with 20°C increments using a hot plate magnetic stirrer. Figure 2 shows the flow chart of the research methodology. The insulating oil used in the experiments was Hyrax Hypertrans uninhibited mineral oil, sourced from Hyrax Oil Sdn. Bhd.

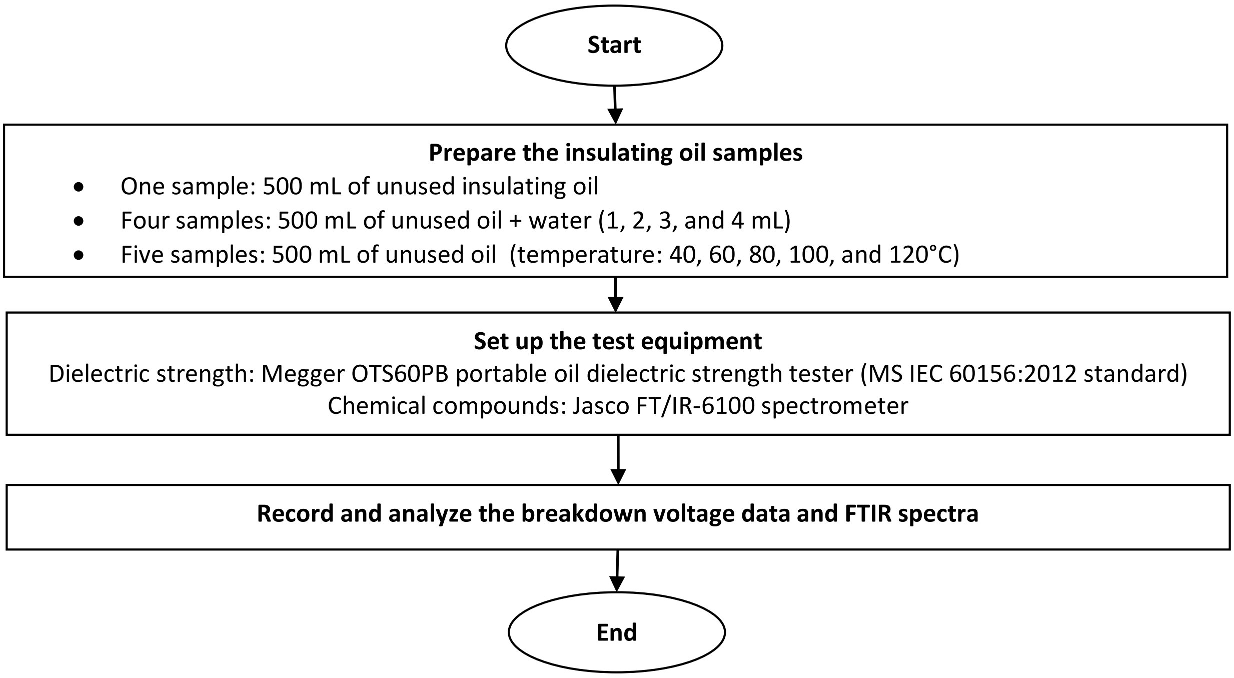


**Fig. 2.** Flow chart of the research methodology

## 3. Results and Discussion

### *3.1 Effect of Moisture on Breakdown Voltage of Insulating Oil Samples*

Table 1 shows the results of the breakdown voltage tests of the fresh insulating oil samples with different moisture content. The volume of each sample was 500 mL. Each sample was stirred thoroughly using a hot plate magnetic stirrer upon the addition of water and then poured into the test cell of the portable oil dielectric strength tester. For each experiment, six readings were taken and the average breakdown voltage was determined, following the procedure outlined in the MS IEC 60156:2012 standard. It can be seen from Table 1 that the average breakdown voltage was 60 kV for the insulating oil with moisture content of 0 mL. When 1 mL of water was added, the average breakdown voltage decreased to 18 kV, which does not fulfill the minimum breakdown voltage requirement for transformer insulating oils. The average breakdown voltage further decreased to 14 kV after 2 mL of water was added. The average breakdown voltage further decreased to 10 kV after 3 and 4 mL of water was added into the insulating oil samples.

**Table 1**
Effect of moisture content on the breakdown voltage of the insulating oil samples

| Moisture content (mL) | Breakdown voltage (kV) | | | | | | |
|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 | Average |
| 0 | 60 | 60 | 60 | 60 | 60 | 60 | 60 |
| 1 | 20 | 10 | 16 | 13 | 12 | 34 | 18 |
| 2 | 11 | 11 | 15 | 14 | 11 | 19 | 14 |
| 3 | 10 | 10 | 10 | 9 | 10 | 11 | 10 |
| 4 | 9 | 10 | 10 | 12 | 9 | 9 | 10 |

Breakdown occurs when the insulating oil reaches a state where there is a spark between the electrodes. The properties of the insulating oil on the atomic and molecular scale play a role in influencing the breakdown voltage. It shall be noted that the Megger OTS60PB portable oil dielectric strength tester is fully automatic to record the data or implement the standard. It is expected that the fresh insulating oil will have the highest breakdown voltage value compared with those in which breakdown has occurred because the fresh insulating oil is free from contaminants. Based on the results, the addition of 1 mL of water (≈ 2000 ppm of water) reduced the breakdown voltage of the insulating oil with a maximum difference of 42 kV. This is expected because the presence of moisture delivers charge carriers, which will reduce the dielectric strength of the insulating oil. The addition of 2–4 mL of water into the insulating oil reduces the breakdown voltage to 10–14 kV. The results conform with the theory of breakdown in insulating oils (bubble theory), where the breakdown voltage decreases with an increase in the moisture content of the insulating oil [18].

### *3.2 Effect of Moisture Content on Chemical Compounds of Insulating Oil Samples*

The characteristics of chemical compounds reflect the behavior of the broad classes of hydrocarbons. The hydrocarbon compounds of insulating oils can be classified into three classes: (1) naphthenes, (2) aromatic hydrocarbons, and (3) alkanes. The chemical formula of transformer insulating oils is $C_{12}H_{10-x}Cl_x$, where $x$ is polychlorinated biphenyl, with a value of 1–10. Figure 3 shows the FTIR spectra of the insulating oil samples with and without moisture. It is apparent that there are changes in the chemical compounds of the insulating oil owing to the presence of moisture.

It is crucial to monitor the presence of moisture (water) in insulating oils. It can be seen from Figure 3 that the absorption band at 3400 1/cm can be attributed to O–H stretching, which is a direct measure of the moisture concentration. The area of this absorption band is linearly correlated to the moisture concentration. It can be observed from Figure 4 that there is water vapor phase within a wavenumber range of 3600–3400 1/cm. The presence of moisture reduces the dielectric strength of the insulating oil because the moisture will break down the molecular chains of the insulating oil, making the oil more conductive.

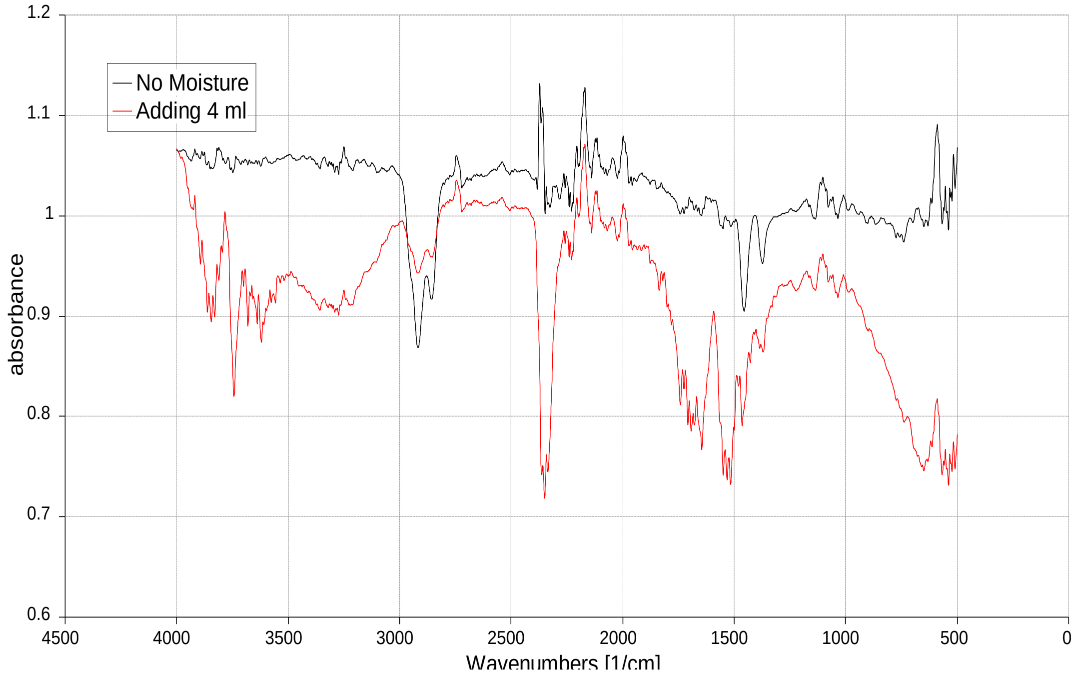


**Fig. 3.** FTIR spectra of the insulating oil samples with and without moisture

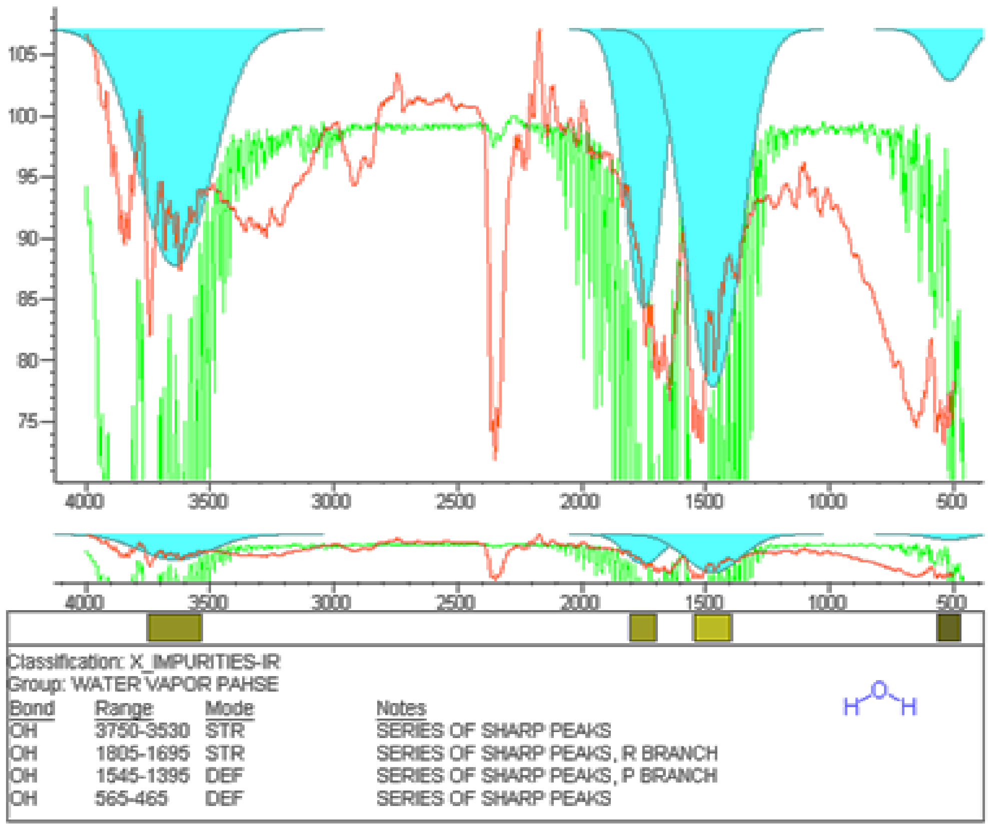


**Fig. 4.** Analysis of chemical compounds of the insulating oil sample with 4 mL of water

### 3.3 Effect of Temperature on Breakdown Voltage of Insulating Oil Samples

Table 2 shows the effect of temperature on the breakdown voltage of the insulating oil samples. The average breakdown voltage was 60 kV for the insulating oil at ambient temperature (22°C). The average breakdown voltage decreased to 44 kV when the temperature reached 40°C and further decreased to 41 kV when the temperature was increased to 60°C. In contrast, the average breakdown voltage increased to 55, 60, and 59 kV when the temperature was increased to 80, 100, and 120°C, respectively.

**Table 2**
Effect of Temperature on the breakdown voltage of the insulating oil samples

| Temperature (°C) | Breakdown voltage (kV) | | | | | | |
|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 | Average |
| 22 (ambient temperature) | 60 | 60 | 60 | 60 | 60 | 60 | 60 |
| 40 | 43 | 50 | 54 | 39 | 36 | 43 | 44 |
| 60 | 51 | 42 | 43 | 40 | 34 | 34 | 41 |
| 80 | 60 | 53 | 53 | 51 | 55 | 58 | 55 |
| 100 | 59 | 60 | 60 | 60 | 60 | 60 | 60 |
| 120 | 57 | 59 | 60 | 60 | 60 | 60 | 59 |

It is indeed expected that the fresh insulating oil sample will have the highest breakdown voltage compared with those in which breakdown has occurred because the sample is free from contaminants. When the temperature was increased to 40°C, the average breakdown voltage decreased to 44 kV. The average breakdown voltage slightly decreased to 41 kV when the temperature was increased to 60°C. However, the result is still considered acceptable. According to the MS IEC 60156:2012 standard, the minimum passing breakdown voltage is 30 kV. The results can be attributed to the presence of moisture in the test cell. In this research, the insulating oil was first heated in the beaker at a preset temperature and then poured into the test cell for the breakdown voltage tests. When the insulating oil sample was heated at a temperature of 80°C, the water began to vaporize and the breakdown voltage increased to 55 kV. The breakdown voltage increased to 60 kV when the insulating oil was heated at 100°C. The results conform well to the expectation that the breakdown voltage will increase with an increase in temperature.

### 3.4 Effect of Temperature on Chemical Compounds of Insulating Oil Samples

Figure 5 shows the FTIR spectra (absorbance versus the wavenumber) of the insulating oil samples at different temperatures. The black, red, green, blue, and light blue lines represent the FTIR spectra of the insulating oil samples preheated at 40, 80, 120, 160, and 180°C, respectively. The FTIR spectra within a wavenumber range of 3000–2800 1/cm were analyzed and it can be seen that there were significant differences in the carbon region. The characteristics of the chemical substances reflect the behavior of the broad classes of hydrocarbons. In general, the hydrocarbon compounds of insulating oils can be classified as naphthenes, aromatic hydrocarbons, and alkanes. The chemical formula of transformer insulating oils is $C_{12}H_{10-x}Cl_x$, where $x$ is polychlorinated biphenyl, with a value of 1–10. The results indicate that temperature indeed plays a significant role in influencing the molecular bonds of the insulating oil. Figure 6 shows the FTIR spectra of the insulating oils at different temperatures (22 and 180°C). There was a strong absorption peak within a wavenumber range of 3000–2850 1/cm, which can be ascribed to C–H stretching. In general, a higher temperature can alter the molecular structure of the insulating oil. Figure 7 shows that the aforementioned region is indicative of alkanes and aliphatic compound. The high transmittance in this region indicates a significant reduction in the C–H content. The breakdown of the C–H bond results in the appearance of combustible gases, particularly ethylene ($C_2H_4$) and acetylene ($C_2H_2$). This region is full of carbon compounds, which can lead to insulation failure.

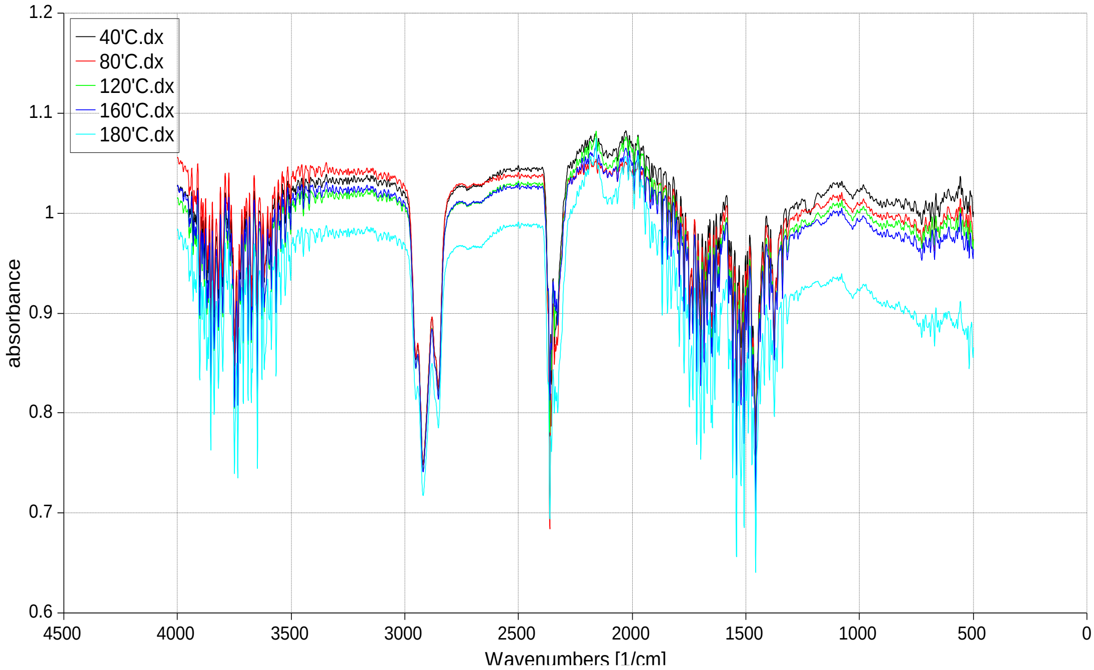


**Fig. 5.** FTIR spectra of the insulating oil samples preheated at different temperatures

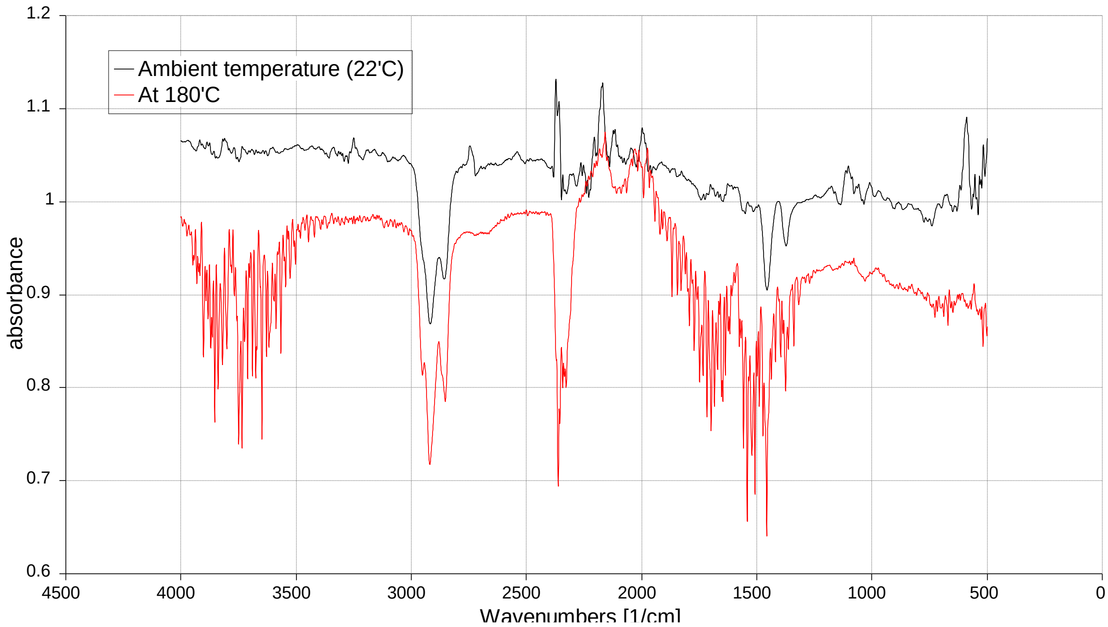


**Fig. 6.** FTIR spectra of the insulating oil samples at 22 and 180°C

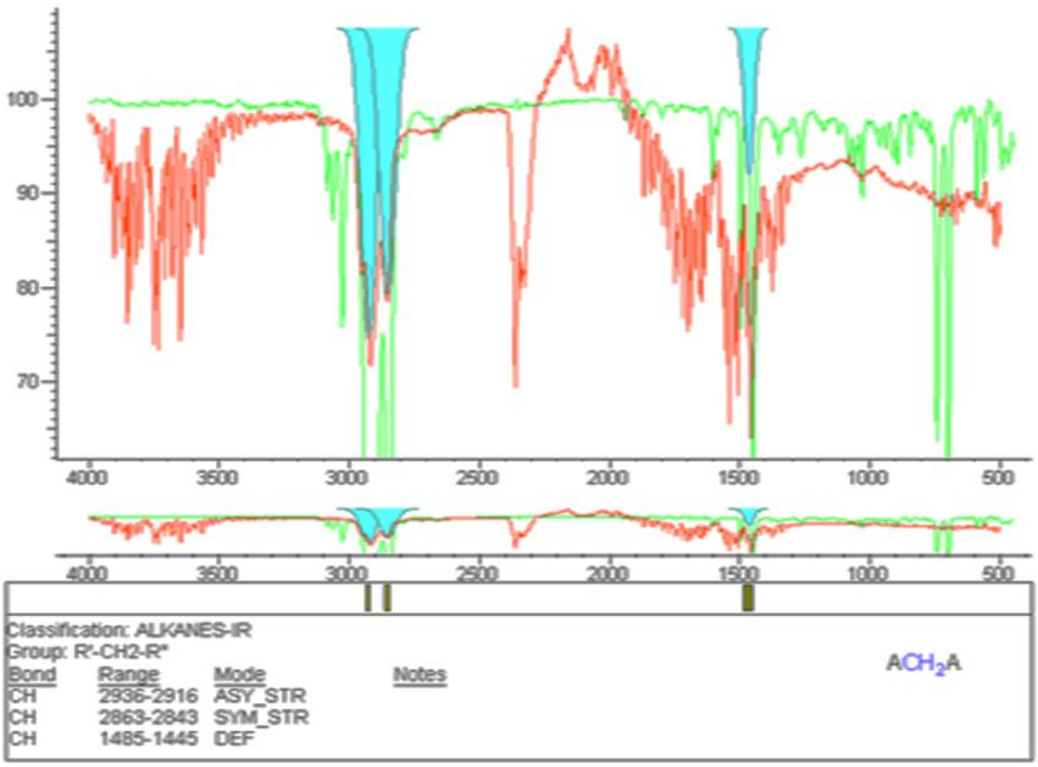


**Fig. 7.** FTIR spectra of the insulating oil samples at 180°C

## 4. Conclusions

In this research, the electrical and chemical properties of mineral insulating oils with different moisture content and preheated at different temperatures were investigated by experiments. Based on the results, it can be concluded that the moisture content and temperature have a significant effect on the breakdown voltage and chemical compounds of the insulating oil. The FTIR spectra revealed that the moisture content of the insulating oil affects the absorbance and wavenumber at which the peak of the absorption band occurs, indicating that there are changes in the chemical compounds of the insulating oil. This is indeed expected because the presence of moisture breaks down the molecular bonds in the insulating oil. Likewise, temperature affects the FTIR spectra because as the oil is heated, the molecules absorb the energy and become much more active, as indicated by the fluctuations in the waveforms.

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