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TRANSMITTANCE CHARACTERISTICS OF VARIOUS INSULATING OILS EVALUATED BY TERAHERTZ SPECTROSCOPY

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Abstract: A large number of aged power equipment such as transformers, power cables and capacitors is still in use. Therefore, it is important to establish diagnostics that identify necessary maintenance. This paper presents the terahertz transmittance spectra of various insulating oils such as mineral oil and synthetic oils described by the International Electrotechnical Commission standard. We found that each sample shows similar trends in the transmittance spectra. Oxidation, the major cause of oil aging, causes spectral changes in the terahertz region.

1 INTRODUCTION

At present in Japan, much of the power equipment installed during the earlier rapid economic growth and bubble remains in operation, for financial reasons. This equipment must be highly reliable, despite deterioration of the insulating material. Thus, it is important to assess the insulation characteristics, and establish diagnostics of its state [1].

Various solids, liquids and gases are used as insulating materials. Insulating oils, a liquid insulation material, are used in many types of equipment; mineral oil in particular has been used because of its desirable properties. Mineral oil is obtained by refining crude petroleum and contains various mixtures of oil hydrocarbons and various types of impurity. The mixing ratio depends on the origin of the crude oil and is known to have a major impact on the oil's oxidative stability and insulating properties. Synthetic oils such as alkylbenzene and alkylnaphthalene have recently been introduced in many fields because they contain fewer impurities than mineral oil.

Oxidation is the main cause of oil deterioration. Power equipment such as transformers and capacitors is sealed to prevent oil deterioration, but loose seals or corrosion of the packing material may allow oxidation to proceed. The resulting increase in moisture content, dielectric loss tangent, and electrostatic charging due to flow electrification increase the risk of failure. Therefore, it is important to determine the oxidation status of power equipment. Oil degradation phenomena have been studied; however, most of measurement instruments cannot observe molecular interactions associated with an oil's insulating characteristics, and few studies have examined molecular interactions in oils.

Terahertz waves have recently been applied in many types of research [2]. The terahertz band is located between light and radio waves and combines the characteristics of both, such as coherence and transparency. It allows easy observation of interactions between molecules and vibration of large molecules.

Interactions of molecules in oil have been studied using terahertz spectroscopy [3]. In this study, we applied terahertz spectroscopy to three types of insulating oil and one reference. We compared the transmittance spectra of new oils and oils subjected to accelerated aging and observed the changes in spectra. The observed characteristics depend on the type of oil.

2 SAMPLES

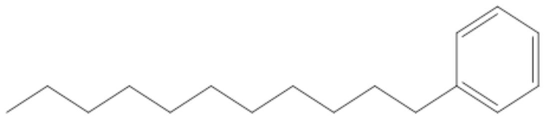
We examined samples of mineral oil, alkylbenzene, and alkylnaphthalene, which are used as electrical insulating oils. For comparison, we also examined dodecane. Table 1 lists the insulating oils described by Japanese Industrial Standard (JIS) and the International Electrotechnical Commission (IEC) standard [4].

The IEC standard classifies insulating oil into seven main types. Figure 1 shows the molecular structures of alkylbenzene, alkylnaphthalene, and dodecane. Mineral oil consists of many types of molecules and contains impurities. Alkylbenzene is a synthetic oil consisting of a straight chain of carbon atoms, 12 on average, and a benzene ring. Alkylnaphthalene is also synthetic and consists of a straight chain of carbon atoms, 18 on average, and a naphthalene ring. In both oils, the number of carbon atoms and the position of ring are not clear. Dodecane consists of a straight chain of 12 carbon atoms. It has been included to determine the effect of carbon chain behavior.

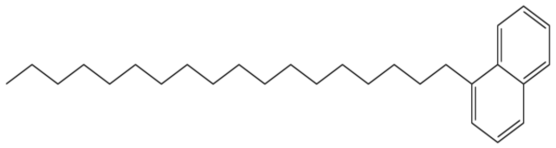
We heated these oil samples to simulate the aging process. Figure 2 shows the heating system.

Table 1: List of insulating oils in JIS C2320 and IEC standards

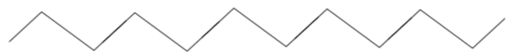
JIS C2320 Class	IEC standard	Components	Applications
1	IEC60465 IEC60296	Mineral oil	Transformer,Capacitor, Cable,Circuit breaker
2	IEC60867	Alkylbenzene	Capacitor, Cable
3	IEC60963	Polybutene	Capacitor, Cable
4	IEC60867	Alkylnaphthalene	Capacitor
5	IEC60867	Alkyldiphenylalkane	Capacitor
6	IEC60836	Silicone oil	Transformer
7	-	Mineral oil and Alkylbenzene	Transformer, Capacitor Cable, Circuit breaker



(a) Alkylbenzene



(b)Alkylnaphthalene



(c) Dodecane

Figure 1: Molecular structures of sample oils

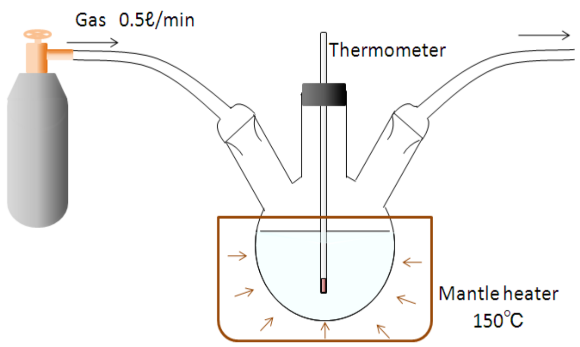


Figure 2: **Heating system**

These samples were heated in an oxygen-rich atmosphere using a three-neck flask. A thermometer was placed at the centre of the neck, and the gas flowed from one neck to the opposite neck. The oils were heated in oxygen for 2 hr. using mantle heater at 150°C.

3 MEASUREMENT METHOD

A Fourier transform (FT) terahertz spectrometer, (JASCO, type VIR-F; Figure 3) was used to measure the transmittance spectra of the samples at 3–18THz.

Polyethylene (PE) was used as the window material of the measurement cell for the terahertz band. The alkylnaphthalene sample was 2mm thick; the other samples were 3mm thick. The samples were placed in the PE cell.

Measurements were repeated 64 times for each sample, with a resolution of 0.06THz.

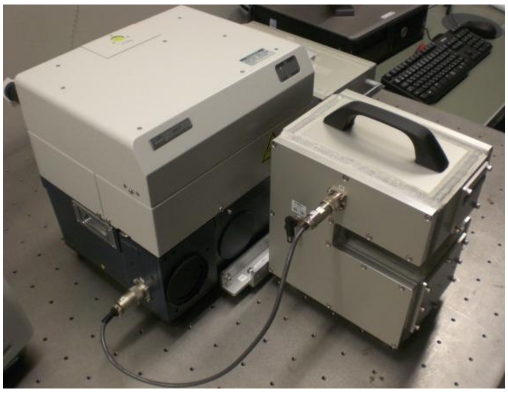


Figure 3: Terahertz spectrometer (JASCO VIR-F)

4 RESULTS OF MEASUREMENT AND OBSERVATION

4.1 Spectra of new samples

Figure 4 shows the transmittance spectra of the samples. Several overlapping peaks and a broad bottom were observed between 3 and 10 THz. Mineral oil, alkylbenzene, and alkylnaphthalene generally showed similar trends. Alkylnaphthalene has a sharp bottom at 5.5 THz. Since this bottom is observed only in alkylnaphthalene, it seems that it is caused by naphthalene ring. Other than this 5.5 THz bottom, the three oils have similar bottoms at 6–9 THz and 12–18 THz. A comparison with dodecane, which shows a drop at 9 THz, suggests that the drop at 6–9 THz for these three oils is due to the carbon chain. The strong high-frequency absorption band at 12–18 THz seems to be affected by the benzene or naphthalene ring.

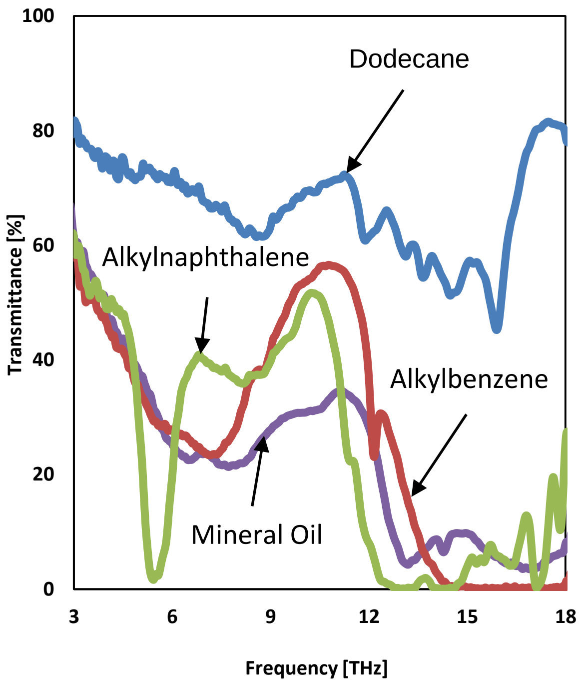


Figure 4: Transmittance spectra of sample oils

4.2 Spectra of accelerated aging samples

4.2.1 Mineral Oil

Figure 5 shows the spectra of mineral oil heated in oxygen. The oil's transmittance decreased slightly with heating; the difference seems greatest between 5 and 12 THz. However, its high-frequency side shows less spectral change.

4.2.2Alkylbenzene

Figure 6 shows the spectra of alkylbenzene heated in oxygen. The spectra changed more with heat than that for mineral oil, and the changes appear from the lower end up to 15 THz, which is a considerably wider frequency range than that for mineral oil. Moreover, the variation is larger at the beginning and tends to decrease gradually with time.

4.2.3 Alkylnaphthalene

Figure 7 shows the spectra of alkylnaphthalene heated in oxygen. Almost no changes in transmittance appear.

4.2.4 Dodecane

Figure 8 shows the spectra of dodecane heated in oxygen. The effect of oxidation appears more significantly and in a broader band than for the other samples. The variation is larger at the start of heating and tends to decrease gradually with time.

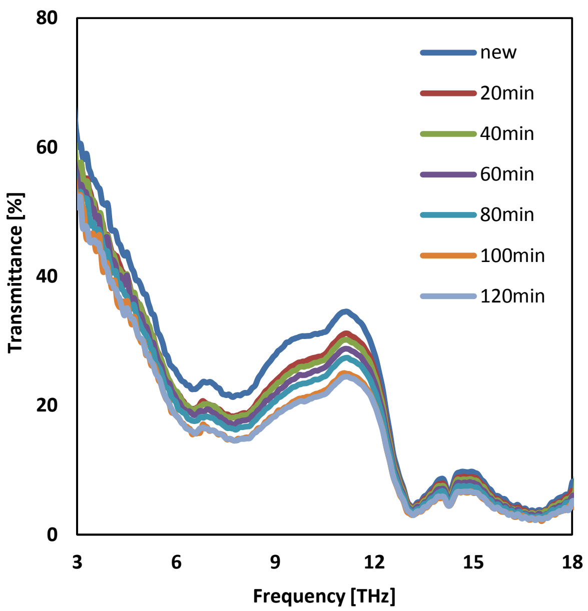


Figure 5: Spectra of mineral oil heated in oxygen

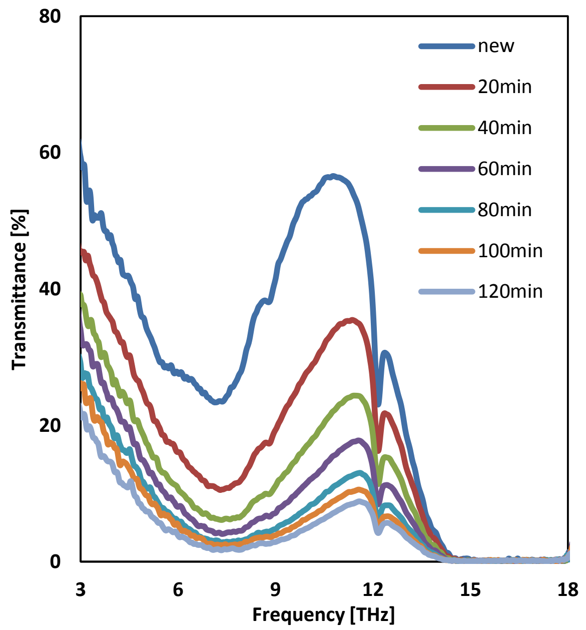


Figure 6: Spectra of alkylbenzene heated in oxygen

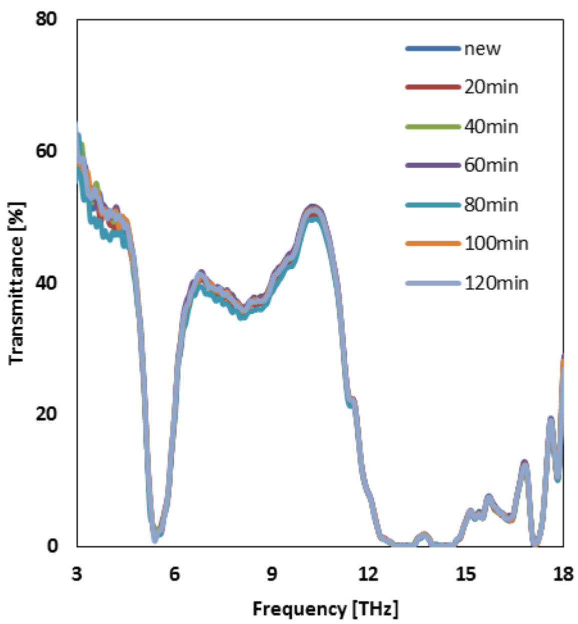


Figure 7: Spectra of alkylnaphthalene heated in oxygen

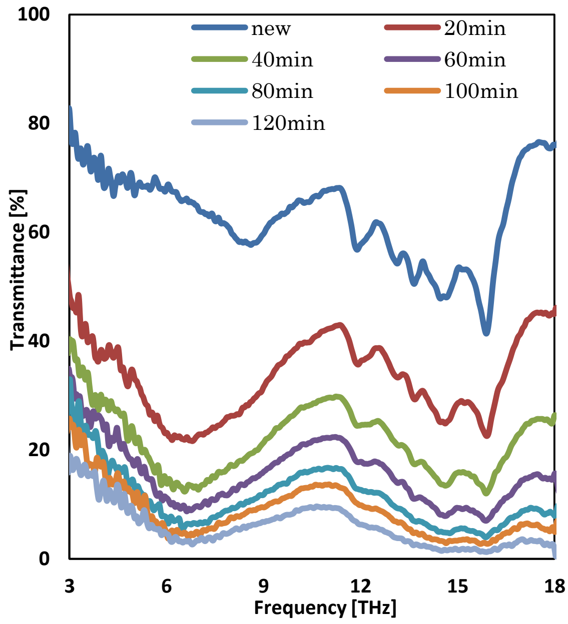


Figure 8: Spectra of dodecane heated in oxygen

4.2.5 Observations of transmittance changes on heating

Figure 9 shows the ratio of the samples' transmittance changes on heating. Each line shows the rate of transmittance at the frequency having the greatest drop below 12 THz compared with the new sample. The vertical axis represents the transmittance change ratio on a logarithmic scale. The transmittance change ratio is

$$\text{Transmittance Change Ratio [\%]} = \frac{T_n}{T_0} \times 100$$

Where T_n: transmittance of oil heated for n min

T_0: transmittance of new sample

The horizontal axis represents the heating time.

The figure shows that for dodecane, alkylbenzene and mineral oil, the transmittance decreases with heating time. Dodecane, which consists only of carbon chains, has the largest change, and that alkylbenzene shows a similar trend. The change for mineral oil is smaller than that for dodecane and alkylbenzene. In contrast, alkylnaphthalene shows no change in the transmittance. Thus, the spectral changes differ under the same heating conditions.

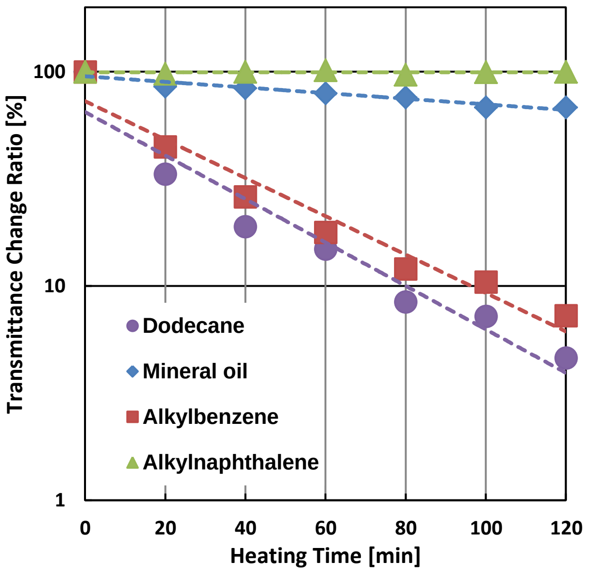


Figure 9: Transmittance changes of samples

Let us now consider the magnitude of the characteristic transmittance difference. Dodecane consists only of short carbon chains; alkylbenzene, for the most part, contains the same number of carbon chains. It seems to oxidize easily. Mineral oil, which contains many types of molecules and impurities, seems to show a smaller change in the transmittance spectra. Alkylnaphthalene, whose structure is similar to that of alkylbenzene, shows no change in transmittance spectra. This indicates that the difference in rings affects oxidation, or longer carbon chains result in chemical stability.

5 CONCLUSION

We examined new and heated samples of various insulating oils by terahertz spectrometer. The results are as follows.

New samples: Since the new samples have similar structures, the transmittance spectra also show a similar trend. A notable peak at 6–9 THz is common to all four samples. The peak seems to be caused by carbon chains. In addition, mineral oil, alkylbenzene, and alkylnaphthalene have strong absorption at 12–18 THz, which is due to presence of benzene or naphthalene rings.

Heated samples: The transmittance characteristics changed for each sample; Dodecane and alkylbenzene were clearly affected by heating; mineral oil changed by a small extent, and alkylnaphthalene showed no change.

From these results, we conclude that oxidation is affected by carbon chain length and ring type. Our future research will focus in more detail on the molecular interactions involved in oil aging.

6 REFERENCES

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