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Gas Production by Monoester of Saturated Fatty Acids under Electrical Fault

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ABSTRACT

This paper deals with the gas production by monoester oil intended to be used as insulating oil under an electrical discharge of low energy. The monoester contains only saturated fatty acids in its hydrocarbon chain. The electrical fault was realized by implementing an AC high voltage to hemispherical shaped electrode pairs with the gap of 2.5 mm immersed in the oil sample. The voltage application was paused when the breakdown occurred in oil and re-applied repeatedly up to 50 and 75 times to allow a high concentration of gasses produced by the oil sample. The resulting gasses were extracted from the oil sample using the headspace method and then analyzed using gas chromatography (GC). Fault identification methods, like DGA status, Key Gas, Duval Triangle, and IEC Ratio, were performed to predict the fault causing the production of such gasses. The results are compared with those of the monoester of unsaturated type. It is found that the Key Gas method is applicable for both oils under electrical discharge. The Duval Triangle and the IEC Ratio methods diagnose the electrical discharge in both monoesters but overestimate them as high energy discharge.

INTRODUCTION

Biodegradable insulating liquid derived from a natural ester of vegetable oil has been commercially available. These liquids are mainly in the original form of triglyceride or tri-ester. Since the structure is tri-ester, the liquids typically have a higher viscosity and pour point. The viscosity of the liquids, measured based on ASTM Standard, is about 33 $\mathrm{mm^2/s}$ at 40 ^{o}C. This value is much higher than mineral oil, whose viscosity is about 9.2 $\mathrm{mm^2/s}$ under the same condition [1].

Researchers have made some Attempts to obtain biodegradable oil having a lower viscosity. One of the attempts is to change the structure of the natural ester from tri-ester to monoester. Japan Company, Lion Corporation, produced monoester type insulating oil from fatty acids of palm oil called PFAE. The viscosity of the oil is about 5.1 $\mathrm{mm^2/s}$ at 40 ^{o}C. This value is even lower than the viscosity value of mineral oil at the same temperature, 40 ^{o}C [2]. Another attempt was conducted by mixing the original tri-ester oil with the monoester resulted from the transesterification of the oil [3]

The PFAE has been implemented in oil filled-distribution transformer [4]. The oil is undergoing intensive research to be implemented in a power transformer that typically utilizes a high voltage. Other researchers developed monoester type insulating oil from vegetable oil, such as methyl ester and isopropyl ester [5-7]. The need for a diagnosis method to assess their performance is essential [8]. For this reason, the research on generated gases by monoester under thermal and electrical stresses is essential.

Under thermal fault, especially the fault with temperature below 300 ^{o}C, it was found that the type of gasses generated by monoester containing only saturated fatty acids is more similar to those produced by the mineral oil than by the monoester containing unsaturated fatty acids [9]. This is the motivation of the work presented in this paper. The gas generation of monoester containing only saturated fatty acids due to the electrical fault of low energy discharge was investigated. Fault interpretation methods, such as the DGA status, the Key Gas, the IEC Ratio, and the Duval Triangle, are applied to the dissolved gas analysis data to evaluate the applicability of the methods to the oil. The comparison with the monoester containing unsaturated fatty acids is made and discussed.

METHOD

A. Sample

The oil sample used for the investigation was monoester containing only saturated fatty acids. The current results are compared with the previous results on the monoester containing unsaturated fatty acids.

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B. Experiment

B.1. Oil Chamber and Oil Filling process

The oil chamber used for simulating electrical fault of discharge of low energy discharge is depicted in Figure 1. The chamber's main body was made of a glass tube with a thickness of 10 mm having an inner diameter of 120 mm. The base and the cover are made of acrylic. The chamber can be completely dismantled for cleaning, as in [10]. The air inside the chamber was vacuumed before the oil filling process to prevent the air from contaminating the oil. Then, the oil sample of about 1000 mL was filled into the chamber using the vacuum pump. The chamber contains electrode pairs having a hemispherical shape in a vertical arrangement. The electrode gap is 2.5 mm, and the hemispherical pair electrode is immersed in the oil sample.

Figure 1. The oil chamber used for simulating the electrical fault in the oil sample

B.2. Application of the Electrical Stress

The low energy discharge in the oil sample was simulated by stressing the oil sample with the breakdown voltage test based on the IEC 156 standard [11]. The test was repeated many times to generate enough concentration of the gasses. The breakdown tests were conducted 50 and 75 times for each oil sample.

B.3. Oil Sampling and Gas Extraction

The oil for gas analysis was taken from the bottom of the chamber. The extraction of the gasses from the oil sample was conducted using the headspace method, and it was conducted in a syringe, as shown in Figure 2. The oil sample of about 50 mL was inserted into the syringe. Nitrogen and Oxygen were introduced into the syringe through a CO_2 trap to avoid other gases entering the syringe. The syringe containing oil was shaken for about 30 seconds to extract gasses in oil.

Figure 2. The syringe and CO_2 trap for gas in oil extraction using the headspace method

B.4. Dissolved Gas in Oil Analysis

Dissolved gas in oil analysis was conducted using gas chromatography. The extracted gas was injected into the gas chromatography for analysis by connecting the syringe to the GC through an oil trap to avoid the oil entering the gas chromatography. The computer-based analysis system performed the analysis of the type and the concentration of gasses.

RESULTS AND DISCUSSION

A. Distribution of Gasses

The distribution of gasses produced by monoester oil under electrical breakdown 50 and 75 times, respectively, are shown in Figure 3 and Figure 4. The gasses produced by both monoesters are similar, both in type, but a bit different in the amount of generated gas. Under 50 times breakdowns, the unsaturated oil produces a lower concentration of gasses except for ethane and carbon monoxide. Under 75 times breakdowns, the unsaturated oil produces a higher concentration of all gasses than the saturated one. Both oils produce all kinds of combustible gasses, usually detected in the mineral oil experiencing electrical discharge of low energy. However, the amount of generated gasses in monoesters is higher than in mineral oil. These are in line with the results reported in [12].

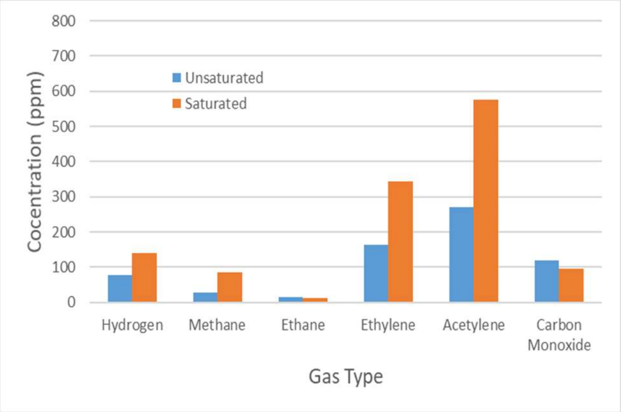


Figure 2. Gas composition in oil samples after 50 times electrical breakdown

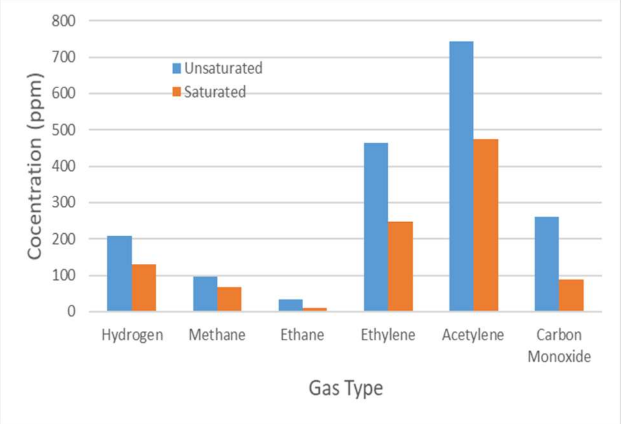


Figure 3. Gas composition in oil samples after 75 times electrical breakdown

The dominant gas observed in both oils is also similar. The gas is acetylene. This behavior will be discussed further in the fault interpretation section. These tendencies apply to both treatments, namely 50 and 75 times breakdown.

B. DGA Status

The DGA status was determined based on the IEEE C57.104-2019 standard to predict the possible presence of a fault in a mineral oil-filled transformer [13]. The DGA Status is used to estimate the transformer operation conditions. Status 1 means the transformer works under a normal operating condition. Status 2 indicates the presence of an abnormal condition, and the transformer needs further monitoring. In contrast, status 3 indicates the presence of a fault, and the transformer needs fault interpretation and more assessment.

The resulting DGA status of monoester oils stressed 50 and 75 times are illustrated in Table 1 and Table 2, respectively. Both oils result in a similar DGA status for both conditions, 50 and 75 times breakdowns. The resulted status is status 3. The final DGA status refers to the highest status reached by any individual gas, acetylene.

Table 1. The DGA Status of Saturated and unsaturated oils subjected to the electrical breakdown 50 times

Gas	Saturated Monoester		Unsaturated Monoester	
	Connect. (ppm)	Status	Connect. (ppm)	Status
Hydrogen	78	Status 2	17	Status 1
Methane	29	Status 2	11	Status 1
Ethane	14	Status 1	3	Status 1
Ethylene	164	Status 3	44	Status 1
Acetylene	270	Status 3	215	Status 3
Carbon Monoxide	118	Status 1	18	Status 1
Carbon Dioxide	76	Status 1	122	Status 1
Final Status		Status 3		Status 3

Table 2. The DGA Status of Saturated and unsaturated oil subjected to the electrical breakdown 70 times

Gas	Saturated Monoester		Unsaturated Monoester	
	Connect. (ppm)	Status	Connect. (ppm)	Status
Hydrogen	208	Status 3	69	Status 2
Methane	97	Status 3	35	Status 2
Ethane	34	Status 2	6	Status 1
Ethylene	464	Status 3	110	Status 3
Acetylene	742	Status 3	575	Status 3
Carbon Monoxide	260	Status 1	122	Status 1
Carbon Dioxide	76	Status 1	917	Status 1
Final Status		Status 3		Status 3

C. Key Gas Method

Fault interpretation by the Key Gas method uses a dominant gas to predict the fault. Acetylene of equal or higher than 30 % is considered due to the arcing fault. The hydrogen of equal or higher than 85% is considered caused by the partial discharge. Ethylene of more than 63% and hydrogen of about 20% are considered overheating of oil [14]. Carbon monoxide up to 92% is considered as overheating of cellulose [15, 16].

Figure 5 and Figure 6 show the relative percentage of each gas to the total combustible gasses in saturated and unsaturated monoesters, respectively. Both oils result in the percentage of the acetylene greater than 30 % in both stresses conditions, indicating the presence of electrical discharge in oil. The results suggest that the Key Gas method applies to both monoesters under arcing conditions. The correct interpretation of electrical breakdown fault in ester oils by the Key Gas method is also reported in [17]. However, the Key Gas cannot distinguish the low and high energy discharges. Thus, it requires other interpretation methods.

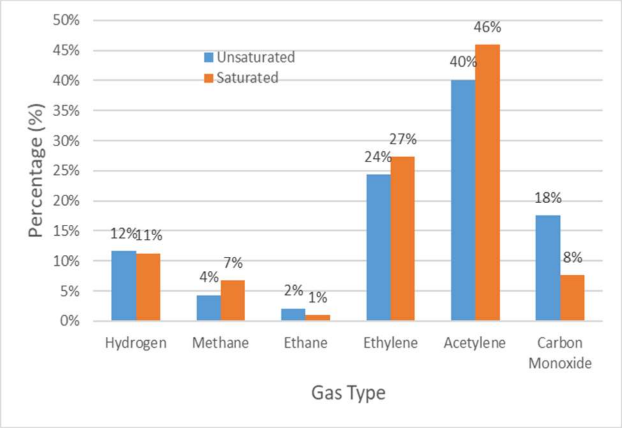


Figure 4. The relative percentage of individual gas to the total combustible gasses in saturated and unsaturated monoesters after 50 times electrical breakdown

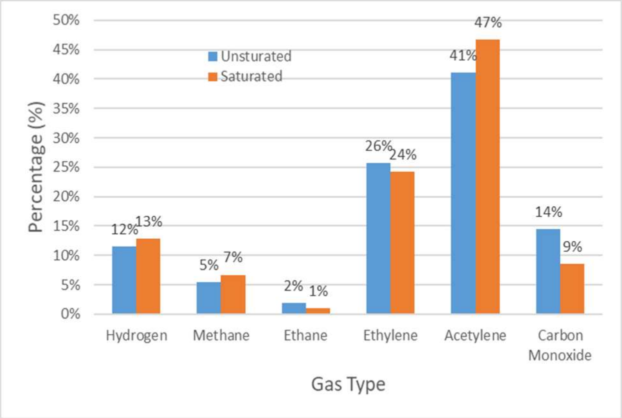
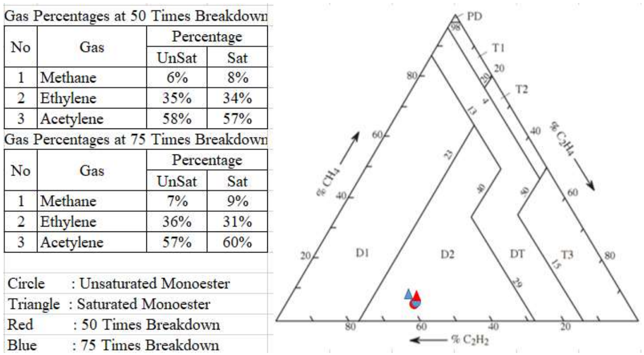


Figure 5. The relative percentage of individual gas to the total combustible gasses in saturated and unsaturated monoesters after 75 times electrical breakdown

D. Duval Triangle Method

This method uses the relative percentage of three kinds of gasses, namely, methane (CH_4), ethylene (C_2H_4), and acetylene (C_2H_2), to estimate fault [18]. For instance, the percentage of methane, ethylene, and acetylene concentrations are 6, 35, and 58%, respectively. The resulted interpretation is represented by the red circle mark in the triangle shown in Figure 7. Other results are calculated and determined similarly and plotted in Figure 7. Both monoesters are located in the D_2 region of the Duval Triangle, indicating the fault of high energy discharge.



Gas Percentages at 50 Times Breakdown

No	Gas	Percentage	
		UnSat	Sat
1	Methane	6%	8%
2	Ethylene	35%	34%
3	Acetylene	58%	57%

Gas Percentages at 75 Times Breakdown

No	Gas	Percentage	
		UnSat	Sat
1	Methane	7%	9%
2	Ethylene	36%	31%
3	Acetylene	57%	60%

Circle : Unsaturated Monoester
Triangle : Saturated Monoester
Red : 50 Times Breakdown
Blue : 75 Times Breakdown

Figure 5. The Duval Triangle and the fault identification of saturated and unsaturated monoesters after 50 and 75 times electrical breakdowns.

E. IEC Ratio Method

In this method, the ratios are C_2H_2/ C_2H_4, CH_4/H_2, and C_2H_2/ C_2H_4 are calculated, and the results are compared to the corresponding ratios listed in Table 3 to obtain the fault interpretation result [19]. NS in Table 3 is an abbreviation of not significant, which means that the ratio does not affect the diagnosis result. The fault interpretation results are listed in Table 4. The method overestimates the fault in both oils by estimating them as high energy discharge (D_2). These results slightly differ from [20], where the electrical breakdown in tri-ester oil was estimated by the IEC Ratio method as the electrical discharge of low energy. It should be noticed that the oil in [20] was subjected to the electrical breakdown 12 times, whereas, in the current investigation, the number of breakdowns is 50 and 75 times.

Table 3. Fault identification according to IEC 559 Ratio method

Nature of fault	C_2H_2/ C_2H_4	CH_4/ H_2	C_2H_4/ C_2H_6
Partial discharge (PD)	NS	<0.1	<0.2
Discharge of low energy (D_1)	>1	0.1-0.5	>1
Discharge of high energy (D_2)	0.6–2.5	0.1 – 1	>2
The thermal fault of low temp. (T_1)	NS	>1	<1
The thermal fault of medium temp. (T_2)	<0.1	>1	1 – 4
The thermal fault of high temp. (T_3)	0.2	>1	>4

Table 4. The results of fault identification based on the IEC 559 Ratio method

Oil Sample	Ratio of Concentration			Identified Fault
	C_2H_2/ C_2H_4	CH_4 /H_2	C_2H_4/ C_2H_6	
Unsaturated monoester, 50 times	1.6	0.4	11.7	D_2
Unsaturated monoester, 75 times	1.6	0.5	13.6	D_2
saturated monoester, 50 times	4.9	0.6	14.7	D_2
saturated monoester, 75 times	5.2	0.5	18.3	D_2

CONCLUSIONS

Both saturated and unsaturated monoesters produced similar gasses under the fault of the low energy fault discharge. The Key gas method applies for both oils under 50 and 75 times breakdown, which is indicated by acetylene production of at least 40% of total combustible gasses. The Duval Triangle and the IEC Ratio methods correctly identify the electrical discharge in both monoesters. However, as indicated by the D_2 code in their interpretation results, they overestimate them as high energy discharge.

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REFERENCES

[1] C. P. McShane, "Vegetable Oil-Based Dielectric Coolant," *IEEE Industry Applications Magazine,* vol. 8, no. 3, pp. 34-41, 2002.

[2] T. kanoh, H. Ibawuchi, Y. Hoshida, J. Yamada, T. Hikosako, A. Yamazaki, Y. Hatta and H. Koide, "Analyses of Electro-Chemical Characteristics of Palm Fatty Acid Esters as Insulating Oil," in *ICDL*, 2008.

[3] Y. Bertrand, and P. Lauzeviz, Development of A Low Viscosity Insulating Liquid Based on Natural Esters for Distribution Transformers, 22nd International Conference on Electricity Distribution, 2013.

[4] Y. Ohki, "Development of High-Performance Environmentally Friendly Palm Fatty Acid Ester Insulating Oil for Transformer," *IEEE Electrical Insulation Magazine,* vol. 27, no. 3, pp. 55-57, 2011.

[5] Suwarno, Y. E. Sari, and T. I. D. K. Dewi, “The Making Processes of Natural Ester from Palm Oil through Transesterification Reaction for Transformer Application,” *ICHVEPS* 2019, pp. 5–9, 2019.

[6] A. Rajab et al., “Filtration and water reduction of methyl ester for insulation purpose,” *Telkomnika*, vol. 17, no. 6, pp. 3183–3190, 2019.

[7] A. Rajab, J. Ramadhani, R. Kurniawan, K. Qibran, M. Latief, and M. I. Hamid, “Preliminary Study on the Basic Characteristics of Isopropyl Esters Used As Insulating Liquid,” *2nd Conference on Innovation in Technology* (CITES), 2020.

[8] C. Perrier, M.-L. Coulibaly and M. Marugan, "Efficiency of ageing markers for different transformer insulation systems," in *IEEE International Conference on Dielectric*, Montpellier, 2016.

[9] A. Rajab, M. Tsuchie, M. Kozako, M. Hikita and T. Suzuki, "Comparison of Low Thermal Fault Gases of Various Fatty Acid Mono esters," in *ICPADM*, Sydney, 2015.

[10] A. Rajab, M. Tsuchie, M. Kozako, M. Hikita, and T. Suzuki, “Low thermal fault gases of various natural monoesters and comparison with mineral oil,” IEEE Trans. Dielectr. Electr. Insul., vol. 23, no. 6, pp. 3421–3428, 2016.

[11] IEC 60156, Insulating Liquids – Determination of the Breakdown Voltage at Power Frequency – Test Method, 2018.

[12] Z. Wang, X. Wang, X. Yi, and S. Li, “Gas Generation in Natural ester and Mineral Oil under Partial Discharge and

https://doi.org/10.25077/jnte.v11n2.968.2022

Spark Faults," *IEEE Electr. Insul. Mag.,* vol. 29, no. 5, pp. 62–70, 2013.

[13] T. Committee, I. Power, and E. Society, IEEE Guide for the interpretation, vol. 2019. 2019.

[14] Imad-U-Khan, Z. Wang, and I. Cotton, "Dissolved Gas Analysis of Alternative Fluids for Power Transformer," *IEEE Electr. Insul. Mag*., vol. 23, no. 5, pp. 5–14, 2007.

[15] I. A. Hohlein and R Frotscher, "Carbon Oxides in the Interpretation of Dissolved Gas Analysis in Transformers and Tap Changers," *IEEE Electrical Insulation Magazine,* vol. 26, no. 6, pp. 22-26, 2010.

[16] N. Abu Bakar, A. Abu-Siada, and S. Islam, "A Review of Dissolved Gas," *Deis Featur. Artic*., vol. 30, no. 3, pp. 39–49, 2014.

[17] C. Xiang, Q. Zhou, J. Li, Q. Huang, H. Song, and Z. Zhang, "Comparison of Dissolved Gases in Mineral and Vegetable Insulating Oils under Typical Electrical and Thermal Faults, *Energies*, Vol. 9, No. 312, 2016.

[18] M. Duval, "A review of faults detectable by gas-in-oil analysis in transformers," *IEEE Electr. Insul. Mag.*, vol. 18, no. 3, pp. 8–17, 2002.

[19] IEC 60599, "International Standard Mineral oil-filled electrical equipment in service," *Guidance on the interpretation of dissolved and free gases analysis*, vol. 2003.

[20] N. A. Gómez, H. M. Wilhelm, C. C. Santos, and G. B. Stocco, "Dissolved Gas Analysis (DGA) of Natural Ester Insulating Fluids with Different Chemical Compositions," *IEEE Transactions on Dielectrics and Electrical Insulation* Vol. 21, No. 3, June 2014.

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