Dissolved Gases Analysis of Rice Bran Oil Under Thermal Fault for Transformer Application

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Abstract— **Dissolved gas analysis (DGA) of transformers can reveal electrical stresses encountered by oil-immersed power transformers. DGA can potentially avoid additional damage since it identifies incipient transformer failures. In this paper, a comparison of DGA under electrical breakdown between conventional transformer oil; Mineral Oil (MO) and Rice Bran Oil (RBO) has been discussed. The many approaches developed for analyzing these gases and interpreting their significance include Key Gas, Duval Triangle and Pentagon Method, Doernenburg Ratio, Rogers Ratio, and IEC Ratio. Based on the results, the diagnostic approaches were not completely reliable for identifying electrical faults in RBO. The findings suggest that present DGA interpretation procedures for RBO or vegetable oil shall be properly modified. In the case of MO, however, DGA analysis indicated that there is a thermal crack in the oil sample that must be addressed. Once the fault has been determined, test instruments are needed to help narrow the fault area and identify the problem component.**

Keywords—Dissolved Gas Analysis (DGA), mineral oil, rice bran oil, thermal, transformer

I. INTRODUCTION

Biodegradable oil (BIO) is a renewable resource obtained from natural crops such as rice, soybeans, rapeseed, sunflower, corn, and palm oil. Many researchers and industries have explored and developed BIO as a replacement for conventional transformer oil. Biodegradable oil feature qualities such as high biodegradability (> 95%), low toxicity, high flash points (>300 °C), fire points (>300 °C), lesser flammability, and is regarded more environmentally friendly fluid [1]. BIO is slightly different in properties compared to mineral oil (MO), which is the most commonly used insulating liquid in power transformers. Among the BIO under consideration, the Rice Bran Oil (RBO) are widely preferred due to its high potential and high rice production in the South-Asia country [2].

Rice oil, which is often referred to as rice bran oil (RBO), has seen significant consumption in a variety of Asian nations, including Malaysia, Japan, Korea, China, Taiwan, Thailand, and Pakistan [3]. Rice bran, which is the part of the paddy that can be found between the hull and the white rice grain, is where the RBO is taken from. Extraction of RBO from extrusion-stabilized bran using hexane results in a RBO that has a low total amount of free fatty acids [4]. RBO has a composition of 38% mono-unsaturated fatty acid, 37% of poly-unsaturated acid, and 25% of saturated fatty acid [5].

Hamid et al. [6] conducted research on the dielectric and electrical properties of RBO in 2022 for the purpose of applying it in transformers. According to the findings, RBO possesses a significantly higher amount of AC breakdown voltage when compared to standard transformer oil. This assertion is supported by the findings of Kumar et al. [7], who discovered that RBO has performance levels that are comparable to those of other natural ester oils when used as an alternative transformer oil. Hamid et al. [8] also discovered that RBO lightning impulse behaviour employing rising-voltage, up-and-down, and multiple level approach produce a comparable result under a uniform electric field. When compared to other natural ester oils, RBO possesses excellent oxidation stability and offers advantages in terms of both cost and availability [9].

Whenever a transformer undergoes abnormal thermal stresses, certain gases are produced due to the decomposition of transformer oil. The condition of the total internal healthiness of the transformer can be predicted by monitoring the number of different gasses contained in transformer oil. Hence, the study of Dissolved Gas Analysis (DGA) in insulating oil is important not only to monitor the operating condition but also to prevent failure. With the emergence of BIO, it is necessary to know how DGA can be applied. In this paper, the thermal fault gases produced by mineral oil (MO) and rice bran oil (RBO) were diagnosed, analysed and compared, respectively. When a thermal fault occurs in the transformer's active part, the energy breaks the C-C and C-H chemical bonding of oil, forming new molecules which including hydrocarbons (organic chemical compounds composed of hydrogen and carbon atoms). Hydrogen (H_2), methane (CH_4), ethane (C_2H_6), ethylene (C_2H_4), acetylene (C_2H_3), carbon monoxide (CO), carbon dioxide (CO_2), nitrogen (N_2), and oxygen are the most common gases found in used oil (O_2).

In this study, in the second section, the extraction methods of DGA are explained, and in the third section, the gases are analysed using the Key Gas Method, the Duval Triangle

Method, the Duval Pentagon Method, the Doernenburg Ratio Method, and the IEC Ratio Method.

II. EXTRACTION METHODS

In this study, two types of oil are involved, mineral oil (MO) and rice bran oil (RBO). Table I below list the detailed components of MO and RBO.

TABLE I. DETAIL COMPONENTS OF MINERAL OIL AND RICE BRAN OIL.

Types Of Oil	Mineral Oil	Rice Bran Oil
Brand	Hyrax Hypertrans	Green Love
Physical Appearance	Clear and Bright	Clear
Viscosity (cSt)	10.4	37 – 50
Saturated Fat (g)	-	22.0
Mono-unsaturated Fat (g)	-	36.3
Polyunsaturated Fat (g)	-	21.2
Vitamin E (mg)	-	7.5

A. Gas Extraction

The gases in oil are extracted and analysed to determine the number of gases in a specific amount of oil. The internal condition of a transformer can be predicted by observing the percentages of various gases present in the oil. Methods to analyse DGA are described in the IEC 60567 standard [10]. The dissolved gas in tested samples will be separated or extracted using the gas chromatography method. Gas chromatography (GC) was chosen because it is suitable for liquid samples and has been standardised by ASTM D3612 standard [11] for gas extraction in power transformer oil. This GC section offers several extraction sections, including single-cycle vacuum, multi-cycle vacuum, stripping, and head space methods. GC with stripping was chosen for this study because it is slightly faster than other extraction methods and chemically safe (no chemicals that harm researchers or the environment) and can be used for each sample. Table II shows the amount of gas content in parts-per-million (ppm) for H_2, CH_4, C_2H_6, C_2H_4, C_2H_2, and CO measured by a gas analyser. The H_2, O_2 and N_2 are classified as non-fault gases, while CO and CO_2 are categorized as carbon oxides gases and other gases known as hydrocarbon gases.

TABLE II. CONCENTRATION OF GASES IN MINERAL OIL AND RICE BRAN OIL

Types of Gases	Concentration of Gases (in ppm)	
	Mineral Oil	**Rice Bran Oil**
H_2 (Hydrogen)	41	49
CH_4 (Methane)	45	11
C_2H_6 (Ethane)	50	38
C_2H_4 (Ethylene)	1	2
C_2H_2 (Acetylene)	1	1
CO (Carbon Monoxide)	191	114
CO_2 (Carbon Dioxide)	1034	568
N_2 (Nitrogen)	29955	31131
O_2 (Oxygen)	5602	4986
Total	36919	36899

III. DGA INTERPRETATION

According to international DGA interpretation guides, IEEE C57.104 [12], the main methods applicable to MO are the Key Gas Method, the Duval Triangle Method, and Duval Pentagon Method. The Duval Pentagon Method uses five key gases at once rather than the Duval Triangle method's three. While IEC 60599 [13] recommended the Rogers Ratio Method, the Doernenburg Method, and the IEC Ratio Method.

A. Key Gas Method

The Key Gas Method detects faults by measuring individual gases rather than by calculating gas ratios. The significance and proportion of the gases are called "key gases". The Key Gas Method considers four general fault types; thermal fault due to overheated oil, thermal fault due to overheated cellulose, electrical fault due to corona and electrical fault due to arcing. In MO and RBO, CO is present as the key gas with 191 ppm and 114 ppm. However, both are considered in normal operating conditions due to below 350 ppm in accordance with the IEEE C57.104 standard [12]. The high amount of CO does not mean that any fault involving in insulation paper, but is directly related to the oxidation of the oil. The level of CO is commonly affected by the oil temperature absorption and desorption by paper insulation caused by the load.

B. Duval Triangle Method

The Duval Triangle method is a graphical method that utilizes the relative percentages of the three fault gases: CH_4, C_2H_4 and C_2H_2. Figure 1 shows the conventional Duval Triangle that has been subdivided into fault zones corresponding to the six basic IEC fault types; partial discharges of corona types (PD), discharges of low energy (D1), discharges of high energy (D2), thermal fault below 300°C (T1), thermal fault at 300°C (T2), thermal fault between 300°C to 700°C (T3) and combinations of thermal and electrical discharge fault (DT). The top vertex of the triangle corresponds to 100% methane (CH_4), the right bottom vertex corresponds to 100% ethylene (C_2H_4) and the left bottom corresponds to 100% acetylene (C_2H_2). The fault zone in which the spot is located shows the common types of faults that would be most likely to produce based on those three fault gases [14], [15].

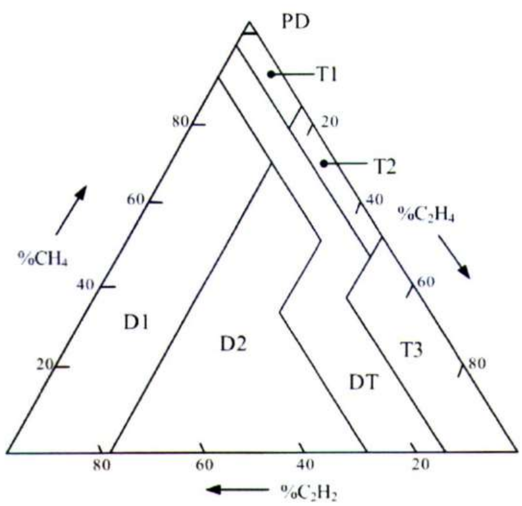

Fig. 1. Conventional Duval Triangle.

Figure 2(a) and Figure 2(b) show the indicated faults of MO and RBO using the Duval Triangle. The calculation of the relative proportion of three gases is listed as Equation (1) and Table III shows the relative proportion value of gases for MO and RBO. Using the Duval Triangle method, it was discovered that MO produces partial discharges of the cold plasma (corona) type in gas bubbles or voids, with the formation of X-wax in the paper, whereas RBO produced electrical and thermal faults. Inside the transformer, both thermal and electrical faults can occur. These faults expedite the breakdown of electric fluid and solid insulation.

$$C_T = CH_4 + C_2H_4 + C_2H_2 \quad (1)$$

$$\% CH_4 = 100 \times CH_4 / C_T$$
$$\% C_2H_4 = 100 \times C_2H_4 / C_T$$
$$\% C_2H_2 = 100 \times C_2H_2 / C_T$$

TABLE III. RELATIVE PROPORTION OF GASES IN MINERAL OIL AND RICE BRAN OIL

Types of Gases	Relative Proportion of Gases (%)	
	Mineral Oil	Rice Bran Oil
CH_4	95.74	78.57
C_2H_4	2.13	14.29
C_2H_2	2.13	7.14

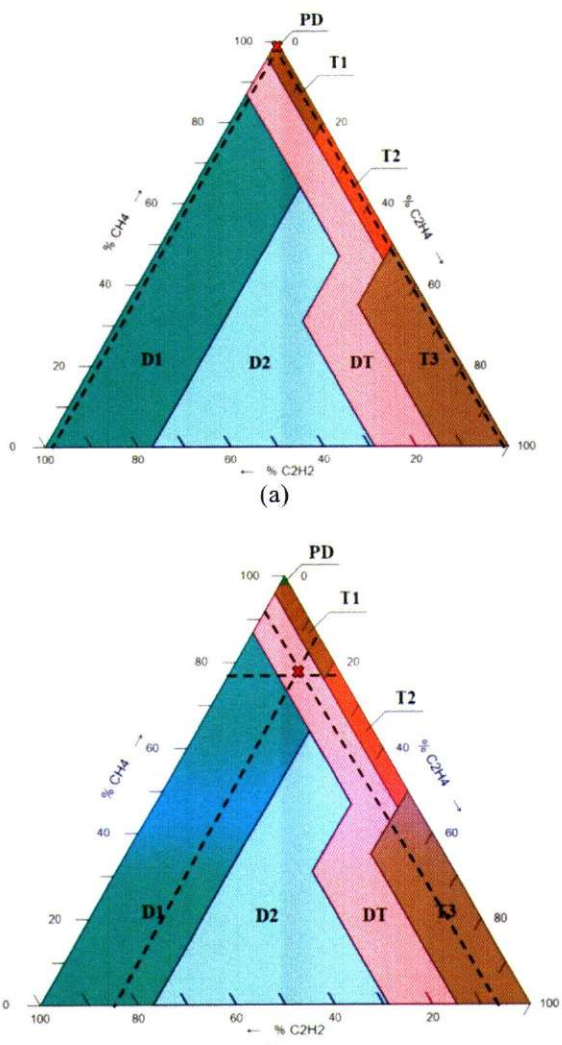

Fig. 2. Duval Triangle formed by the three axes that correspond to the relative proportion of CH_4, C_2H_2 and C_2H_4 gases in (a) Mineral Oil, and (b) Rice Bran Oil.

C. Duval Pentagon Method

The Duval Pentagon Method uses five gases to detect types of faults undergone by a transformer [16]. Figure 3 shows the representation of fault areas in the Duval Pentagon. The centre of pentagon corresponds to 0% gas concentration, while the summit corresponds to 100% of gas concentration. Each ax represents five points of the relative proportion of each gas. Each of these relative proportions is plotted in the corresponding gas axis, and then forms the generic irregular polygon of five sides. For the final classification of the DGA, the geometrical centroid coordinate will be determined.

To mathematically find the centroid of the irregular polygon, the coordinates of x and y need to be calculated for each gas as shown in Equation (2). In this study, the coordinates of MO for H_2, C_2H_6, CH_4, C_2H_4, and C_2H_2 are (0, 12.46), (-14.45, 4.69), (-8.04, -11.07), (0.18, -0.24), and (0.29, 0.09). For RBO, the coordinates are (0, 22.79), (-16.81, 5.46), (-3.01, -4.41), (0.55, -0.75) and (0.45, 0.15). Then, the geometrical centroid coordinate for MO and RBO of the Duval Pentagon that is computed using Equation (3) are (1.95, 1.56) and (-5.74, 7.60) [16]. Figure 4 illustrates the irregular polygon plotted according to the coordinates and their centroid location.

For MO, it was obvious that the Duval pentagon interpretation methods gave the discharges of high energy in paper or oil, resulting in extensive damage to paper insulation or large formation of carbon particles in the oil, metal fusion, tripping of the equipment and gas alarms. For RBO, the Duval pentagon has detected some stray gassing, primarily hydrogen, methane, and ethane heated at relatively low temperatures (90°C – 200°C).

$$x_{C_2H_6} = 15.20\% \times \cos \propto = 15.20 \times \cos 162^\circ = -14.45$$
$$x_{C_2H_6} = 15.20\% \times \sin \propto = 15.20 \times \sin 162^\circ = 4.69 \quad (2)$$

$$C_x = \frac{1}{6A}\sum_{i=0}^{4}(x_i + x_{i+1})((x_i \times y_{i+1}) - (x_{i+1} \times y_i)) \quad (3)$$
$$C_y = \frac{1}{6A}\sum_{i=0}^{4}(y_i + y_{i+1})((x_i \times y_{i+1}) - (x_{i+1} \times y_i))$$
$$A = \frac{1}{2}\sum_{i=0}^{4}(x_i \times y_{i+1} - x_{i+1} \times y_i)$$

where

x_i, y_i : coordinates of the five points of gases
C_x, C_y : coordinates of the centroid
A : surface of the polygon.

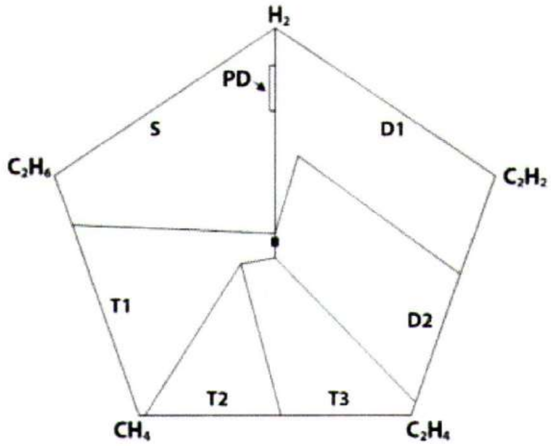

Fig. 3. Duval Pentagon for the six basic types of faults.

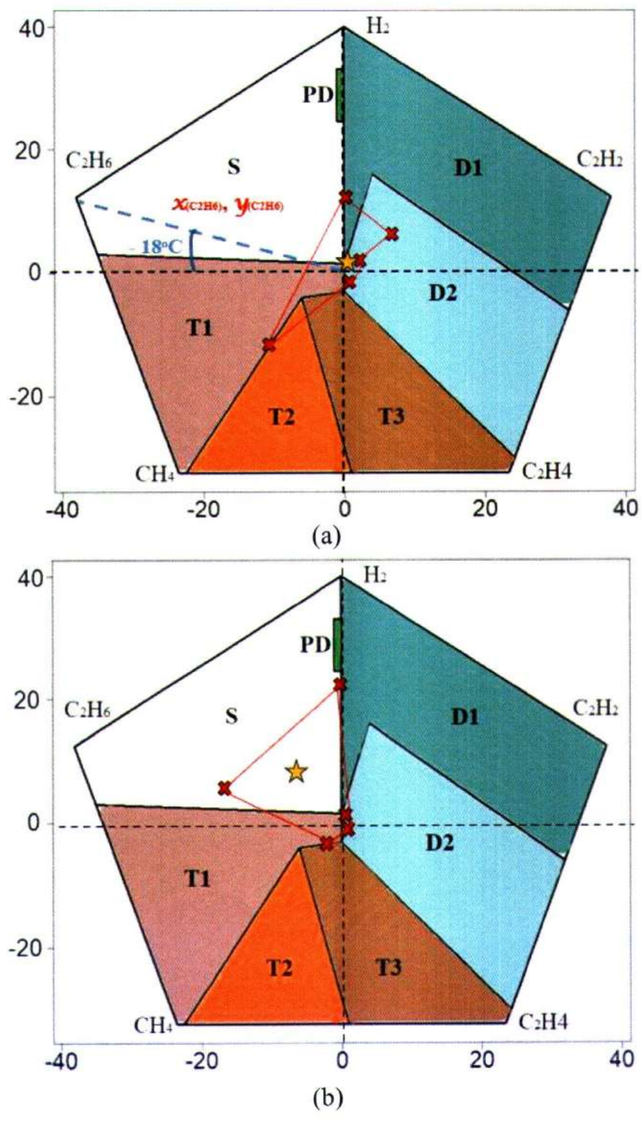

Fig. 4. The irregular polygon formed by five coordinates that calculated using relative proportion of H_2, C_2H_6, CH_4, C_2H_4, and C_2H_2 gases for (a) Mineral Oil and (b) Rice Bran Oil.

D. Doernenburg, Rogers Ratio and IEC Ratio Method

The Doernenburg Ratio method suggests the existence of three general types of faults; thermal decomposition, corona and arcing. This method identifies faults by analysing gas concentration ratio. To determine the validity of the four ratios, each successive ratio is then compared with certain values (Table IV). Table V lists the gas concentration ratio of MO and RBO.

Rogers Ratio Method or known as Basic Gas Ratio Method is similar to Doernenburg Ratio Method, which suggests five to six general fault types via three ratios from five fault gases. Table VI shows the recommended fault diagnosis using Rogers Ratio Method, while Table VII shows the tested results of gases ratio for MO and RBO.

The IEC Ratio Method uses the same three ratios as in Rogers Ratio Method but suggests different ratio ranges and interpretations. The International Electrotechnical Commission (IEC 60599) fault diagnosis scheme addresses four conditions: normal ageing, partial discharge of low and high energy density, thermal faults, and electrical faults of varying intensity. Table VIII lists the type of faults recommended by IEC ratio and Table IX shows the gas concentration ratio calculated, respectively.

From the results of gas concentration ratio using the Doernenburg Method and Rogers Ratio Method, it is figured out that both methods are inapplicable for diagnosing thermal faults in aged MO and RBO. However, IEC Ratio Method interprets MO and RBO produced thermal fault at low temperatures.

TABLE IV. DOERNENBURG RATIO FAULT DIAGNOSIS

Types of Faults	Gas Ratio			
	$\frac{CH_4}{H_2}$	$\frac{C_2H_2}{C_2H_4}$	$\frac{C_2H_2}{CH_4}$	$\frac{C_2H_6}{C_2H_2}$
Thermal Decomposition	> 1.0	< 0.75	< 0.3	> 0.4
Corona (low intensity PD)	< 0.1	-	< 0.3	> 0.4
Arcing (high intensity PD)	> 0.1	> 0.75	> 0.3	< 0.4

TABLE V. CONCENTRATION RATIO OF GASES IN MINERAL OIL AND RICE BRAN OIL BASED ON DOERNENBURG RATIO METHOD

Types of oil	Gas Ratio				Suggested Fault Diagnosis
	$\frac{CH_4}{H_2}$	$\frac{C_2H_2}{C_2H_4}$	$\frac{C_2H_2}{CH_4}$	$\frac{C_2H_6}{C_2H_2}$	
Mineral Oil	1.098	1.000	0.022	50	-
Rice Bran Oil	0.224	0.500	0.091	38	-

TABLE VI. ROGERS RATIO FAULT DIAGNOSIS

Types of Faults	Gas Ratio $\frac{C_2H_2}{C_2H_4}$	$\frac{CH_4}{H_2}$	$\frac{C_2H_4}{C_2H_6}$
Normal unit	< 0.1	> 0.1 – 1.0	< 1
Partial Discharge	< 0.1	< 1.0	< 1
Arcing	0.1 – 3.0	0.1 – 1.0	> 3.0
Low Thermal Temperature	< 0.1	> 0.1 – < 1.0	1.0 – 3.0
Thermal: < 700°C	< 0.1	> 1.0	1.0 – 3.0
Thermal: > 700°C	< 0.1	> 1.0	> 3.0

TABLE VII. CONCENTRATION RATIO OF GASES IN MINERAL OIL AND RICE BRAN OIL BASED ON ROGERS RATIO METHOD

Types of Oil	Gas Ratio $\frac{C_2H_2}{C_2H_4}$	$\frac{CH_4}{H_2}$	$\frac{C_2H_4}{C_2H_6}$	Suggested Fault Diagnosis
Mineral Oil	1.000	1.098	0.020	-
Rice Bran Oil	0.500	0.224	0.053	-

TABLE VIII. IEC RATIO FAULT DIAGNOSIS

Types of Faults	Gas Ratio $\frac{C_2H_2}{C_2H_4}$	$\frac{CH_4}{H_2}$	$\frac{C_2H_4}{C_2H_6}$
Partial Discharge	Insignificant	< 0.1	< 0.2
Discharge of Low Energy	> 1	0.1 – 0.5	> 1
Discharge of High Energy	0.6 – 2.5	0.1 – 1	> 2
Thermal: < 300°C	Insignificant	> 1 but insignificant	< 1
Thermal: 300°C < T < 700°C	< 0.1	> 1	1 – 4
Thermal: > 700°C	< 0.2	> 1	> 4

TABLE IX. CONCENTRATION RATIO OF GASES IN MINERAL OIL AND RICE BRAN OIL BASED ON IEC RATIO METHOD

Types of Oil	Gas Ratio $\frac{C_2H_2}{C_2H_4}$	$\frac{CH_4}{H_2}$	$\frac{C_2H_4}{C_2H_6}$	Suggested Fault Diagnosis
Mineral Oil	1.000	1.098	0.020	Thermal: < 300°C
Rice Bran Oil	0.500	0.224	0.053	Thermal: < 300°C

IV. CONCLUSION

Based on the findings, it is possible to conclude that the DGA analysis for MO is nearly consistent where heating is indicated. It is recommended to monitor the gassing condition on a regular basis. However, different DGA techniques are required for RBO to identify the types of faults. If the same fault gas interpretation techniques are used on the RBO, the fault prediction may be incorrect. Techniques for DGA interpretation that have been utilised for many decades in transformers immersed in mineral oil need to be modified so that they can be used with rice bran oil. In order to make a diagnosis, new criteria need to be defined. Additionally, supplementary research on the effects of ageing and the expected lifespan of transformers now in use (actual scale) is required.

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