Analysis of Gasses Generated by Electrical Discharges in Low Viscosity Silicone Oil

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***Abstract*—Silicone oil has merits of less flammability and excellent environment-friendliness. High-viscosity silicone oil of 50 cSt has been widely applied to power and distribution transformers. Recently, application of low-viscosity silicone oil of 20 cSt to transformers has been considered for its excellent cooling performance. Detection of incipient fault conditions in low-viscosity silicone oil immersed transformers becomes more important when they are operated in electric power systems.**

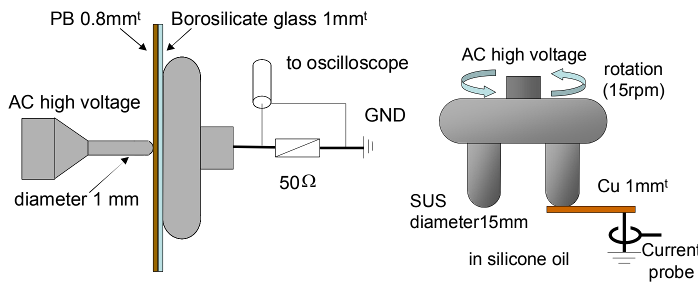
Detection of certain gases generated in a transformer is usually the useful indication of an abnormal condition. To clarify its applicability to a low-viscosity silicone oil immersed transformer, this paper described gas characteristics generated by electrical discharges in detail. It was clarified that the identification of abnormal conditions are possible by considering the amounts and types of generated gases. Finally, gas characteristics were compared with those in 50 cSt silicone oil and mineral oil.

***Index Terms*— Silicone oil, Transformer, Dissolved gas analysis (DGA), Diagnosis, Discharge.**

I. Introduction

Dissolved gas analysis (DGA) has been used as an effective and reliable diagnostic method to detect incipient faults in mineral oil immersed transformers for many years[1]. However, recently, from the viewpoint of fire prevention and low environmental impact, silicone oil of low viscosity (20 cSt)[2] has been expected as a substitute for mineral oil, because 20cSt silicone oil has high flash point, high chemical stability and hydrolysis in the natural surroundings. Transformers insulated with 20 cSt silicone oil have already been commercialized[2]. Today, it is important to clarify the dissolved gas characteristics and to establish the diagnostic method in 20cSt silicone oil-immersed transformers.

In this paper, the authors measured and analyzed dissolved gases in 20 cSt silicone oil generated by partial discharges (PD: 10^{-1}~10^{1}J) and arc discharges (10^{2}~10^{3}J). As a result, the relationship between injected energy and dissolved gas was clarified. Behaviors of key gases such as H_2, C_2H_2 etc. were discussed. Finally, the diagnostic method of 20 cSt silicone oil was discussed by comparing with dissolved gases of high viscosity silicone oil (50 cSt) and mineral oil.



(a) Partial discharge electrodes (b) Arc discharge electrodes

Fig. 1. Electrode configuration.

Table 1. Properties of insulating oil.

	Silicone oil (20cSt)	Silicone oil (50cSt)	Mineral oil
Specific gravity (g/cm^3) at 15°C	0.96	0.97	0.87
Kinematic viscosity (mm^2/sec) at 40°C	15	38.8	8.36
Flash point (°C)	264	330	145
Fire point (°C)	323	365	152
Relative permittivity at 80°C	2.7	2.7	2.2
Volume resistivity (Ω·cm) at 80°C	9.5×10^{15}	9.5×10^{15}	4.6×10^{14}

II. Experimental Setup

A. Electrodes for Partial Discharge Experiments

Rod (1 mm diameter)-plane electrodes were used for PD experiment. A 0.8 mm thick pressboard and a 1 mm thick borosilicate glass were inserted between electrodes (Fig. 1(a)). The electrodes were placed in a sealed chamber (diameter: 200 mm, height: 280 mm), which was filled with 20 cSt silicone oil of 4 liters. Properties of insulating oils including 20 cSt silicone oil are shown in Table 1. The space formed above silicone oil was filled with dry N_2. PD current was measured with the detecting resistor of 50 Ω and was recorded with an oscilloscope.

B. Electrodes for Arc Discharge Experiments

A rotating rod-plane electrode system was used to generate arc discharges (Fig.1 (b)). The system was placed in the same vessel mentioned above. Two rod electrodes (15 mm

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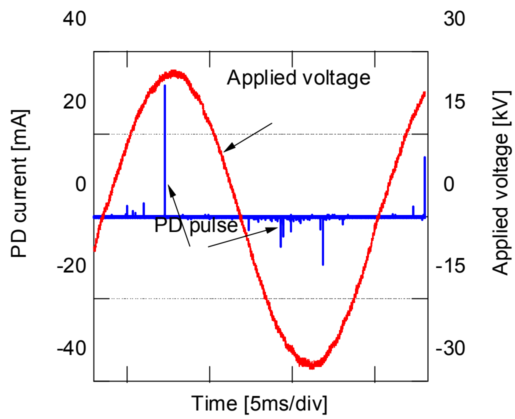

Fig. 2. PD current pulses and applied voltage.

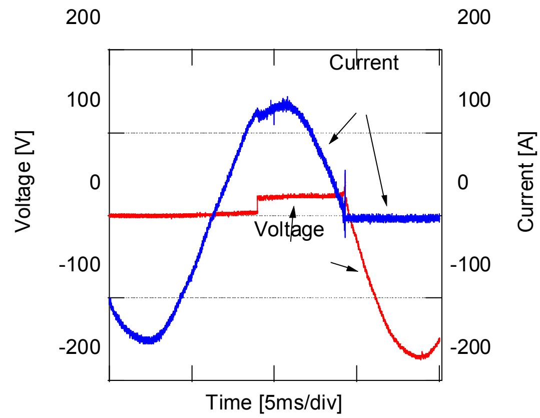

Fig. 4. Arc voltage and current.

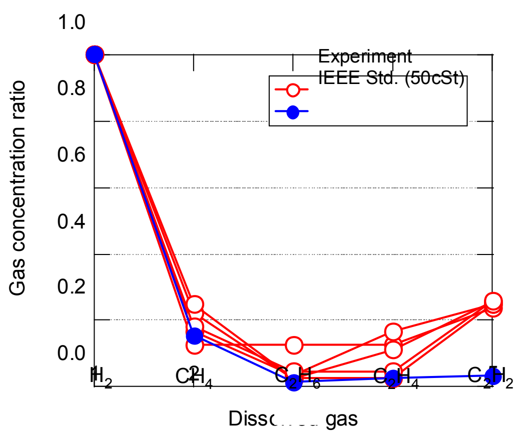

Fig. 3. Dissolved gas pattern of partial discharges.

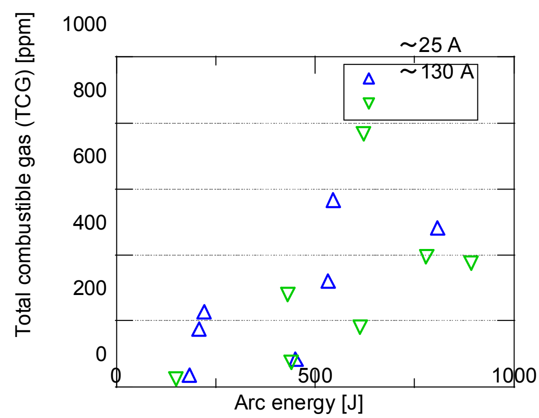

Fig. 5. Relationship between injected energy and total combustible gas of arc discharges.

diameter) rotated 15 times per minute. Arc discharges were generated at the moment when rod electrodes separated from a plane electrode. Arc current was measured with a current probe. Both arc current and arc voltage were recorded with an oscilloscope.

All experiments were carried out at room temperature. Electrical discharges were repeated until discharge energy reached the expected level. After that, silicone oil was extracted in an oil can. At the same time, N_2 gas in the space above silicone oil was extracted in another can. Dissolved gases in both cans were analyzed with a gas chromatography. Analyzed gas components were total combustible gas, CO, H_2, CH_4, C_2H_6, C_2H_4 and C_2H_2.

III. Experimental Results And Discussions

A. Partial Discharges

Figure 2 shows an example of partial discharges. Many PD current pulses appeared every cycle. Average PD charge and injected energy were 150-460 pC and 0.2-40 J, respectively.

Combustible gas was composed of carbon monoxide (CO), hydrogen (H_2), methane (CH_4), ethane (C_2H_6), ethylene (C_2H_4) and acetylene (C_2H_2). The amount of combustible gas increased from 8 ppm to 42 ppm when PD energy increased from 0.2 to 40 J. And about half quantity of combustible gas was H_2. The second dominant gas was C_2H_2 and CO. Each gas component was expressed as the ratio to the H_2 quantity, and was plotted in Fig. 3. The quantity of C_2H_2 (the feature gas of electrical discharges) was about 20 % of H_2 quantity. The quantity of C_2H_6 and C_2H_4 was very little. Solid symbols show the gas concentration ratio expressed in the IEEE standard[3] for 50 cSt silicone oil. The measured data in 20 cSt silicone oil were almost the same as the level in the IEEE standard except the C_2H_2 quantity. A molecular formula of silicone oil is $(H_3C)[SiO(CH_3)_2]_nSi(CH_3)$. The difference between two silicone oil was polymerization degree "n". Silicone oil of 20 cSt has the small value of n. Bonding energies of C-H and C-C were almost equal between two silicone oil. This means that the decomposition energy is nearly equal between two oils. Therefore, two silicone oils show similar dissolved gas patterns.

B. Arc Discharges

Rotating electrodes were connected to a 400/200 V 40 kVA transformer. Examined (arc current, arc voltage) were (about 25 A_{peak}, 19 V) and (about 130 A_{peak}, 25 V). Figure 4 shows

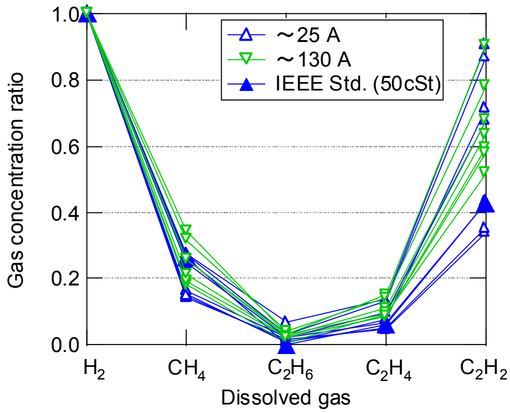

Fig. 6. Dissolved gas pattern of arc discharges.

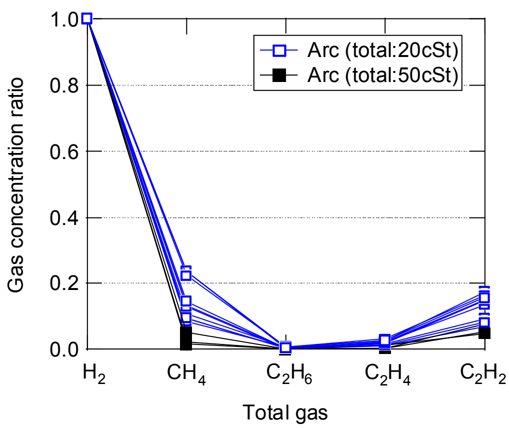

Fig. 7. Total gas pattern of arc discharges (in oil and in N_2 gas space)

Table 2. Solubility coefficients.

Gas	Silicone oil	Mineral oil
H_2	0.057	0.0429
N_2	0.143	0.0745
CO	0.096	0.102
O_2	0.175	0.138
CH_4	0.514	0.337
CO_2	1.401	0.9
C_2H_2	1.411	0.938
C_2H_4	1.018	1.35
C_2H_6	1.339	1.99

the typical arc current and arc voltage at 130 A_{peak}. Arc voltage was appeared at the moment of electrode separation, and sinusoidal arc current flowed between electrodes. Arc discharge was quenched at the time of the following current zero. Injected arc energy was calculated based on arc current and arc voltage, and its value was 150-900 J.

The relationship between the injected energy and the total combustible gas (TCG) quantity of arc discharge is shown in

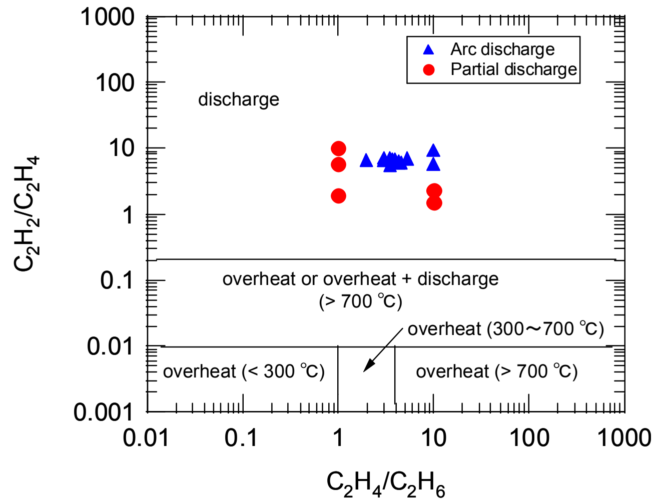

Fig. 8. Comparison of generated gases in 20 cSt silicone oil with diagnostic chart A for mineral oil [4].

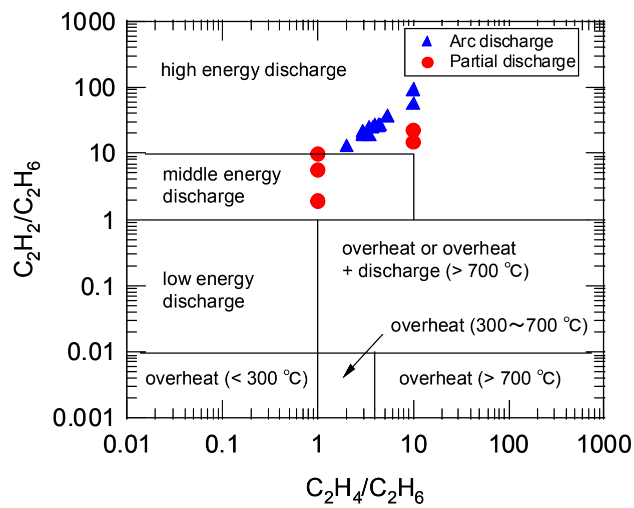

Fig. 9. Comparison of generated gases in 20 cSt silicone oil with diagnostic chart B for mineral oil [4].

Fig. 5. TCG increased when the injected energy was large. There was no significant difference between small and large arc discharges. This suggests that the TCG quantity can be estimated by the injected arc energy. The quantities of H_2 and C_2H_4 were about half and one fourth to one third of the TCG quantity, respectively. The CO quantity was about one third of the TCG one. The dominant gas was H_2, and the concentrations of other gas components were plotted as the relative ratio to the H_2 quantity in Fig. 6. The concentration ratio of C_2H_2 was extremely larger in arc discharges than in PD. And its dispersion was large. Solid triangles in Fig. 6 show the values expressed in the IEEE standard[3] for 50 cSt silicone oil. It is clear that the dissolved gas patterns of 20 cSt silicone oil was almost equal to that in IEEE standard.

The data in Fig. 6 was obtained by analyzing the dissolved gas in silicone oil. However, bubbles were generated by arc discharges, moved upward and run into the N_2 filled space above the silicone oil. As a result, most gas components were

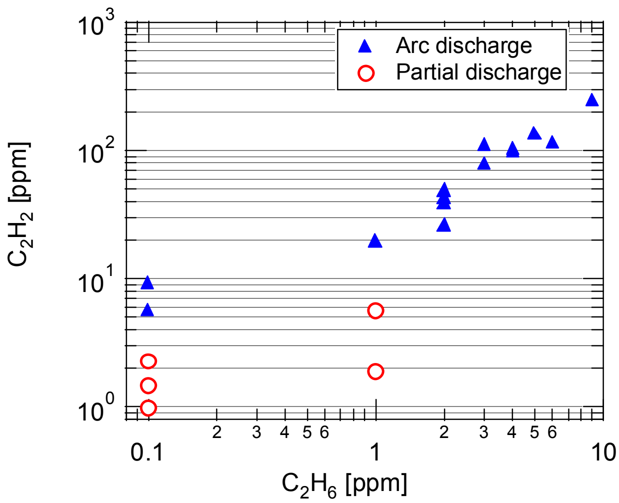

Fig. 10. Relationship between C_2H_2 and C_2H_6 quantities.

released in the N_2 filled space. Solubility is greatly different between gas components as shown in Table 2. Solubility of H_2 is much smaller than that of other gases, and is about 1/25 of that of C_2H_2. Therefore, the ratio of C_2H_2 in silicone oil becomes very large. This means that whole generated gases are different from gases dissolved in oil. Gas components were analyzed in both oil and N_2 space. And the whole gas components are plotted in Fig. 7. As the H_2 quantity in the N_2 gas space was extremely large, the whole H_2 quantity increased greatly. And the ratio of C_2H_2 decreased. Solid rectangles in Fig. 7 were characteristics in 50 cSt silicone oil[5]. Whole gas components both in silicone oil and in the N_2 gas space were plotted. Gas patterns were almost the same between two silicone oils.

C. Diagnostic method in 20 cSt silicone oil

Diagnostic charts of DGA were established in mineral oil by Electric Technology Research Association as shown in Fig. 8 and Fig. 9[4]. Chart A was composed of the field data and was consistent with the IEC criterion. Chart B was the detail classification of abnormalities, in which the discharge region of Chart A is divided into three discharge groups (high, middle and low energy discharge). Data in silicone oil were plotted in these charts.

In Fig. 8 (diagnostic chart A), all experimental results could be plotted into the discharge region. In Fig. 9 (diagnostic chart B), data of arc discharge exist in the high energy discharge region. However, data of PD extend from the middle energy discharge to the high energy discharge regions. In the chart B, it was difficult to identify PD clearly from arc discharges. To identify PD and arc discharges, relationship between several gases was examined.

Figure 10 shows the relationship between C_2H_6 and C_2H_2 quantities. At the same C_2H_6 quantity, the C_2H_2 gas was generated more at arc discharges than at PD. This is caused by the difference of the generation energy between two gases. As the generation energy of C_2H_2 is higher than that of C_2H_6, arc discharges can generate more C_2H_2 than PD. This relationship gives us a good index for discharge identification. Other gas components were compared with each other. But it was difficult to identify PD from arc discharges.

IV. Conclusions

A new type of a transformer insulated with low viscosity silicone oil (20 cSt) has been commercialized recently. To diagnose the transformer condition, dissolved gas characteristics by discharges were investigated, and were compared with the IEEE standard for 50 cSt silicone oil and the standard for mineral oil. Results are summarized as follows;

(1) Hydrogen (H_2) was a dominant dissolved component in both PD and arc discharge in 20 cSt silicone oil. And considerable quantity of acethylene (C_2H_2), which is a characteristic component at discharges, was also generated.

(2) In partial discharges and arc discharges, the dissolved gas pattern of 20 cSt silicone oil was almost similar to that of 50 cSt silicone oil.

(3) When large bubbles were generated by discharges, a large amount of generated gas escaped from silicone oil into the N_2 space above silicone oil. Moreover, solubility coefficients to silicone oil were different between gas components. Owing to these, the gas concentration ratio was different between the dissolved gas and the whole generated gas.

(4) Diagnostic charts for mineral oil are seemed to be applicable to 20 cSt silicone oil in a certain extent. For clear discrimination of PD from arc discharge, the relation of the gas quantity between C_2H_2 and C_2H_6 became a good index.

V. References

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