Effect of Moisture Content on Temperature Characteristics of Dielectric Breakdown Strength of Biodegradable Ester Oils

Takahiro Okamoto
Department of Electrical and Energy Engineering,
Kyushu Institute of Technology, Fukuoka, Japan
okamoto.takahiro732@mail.kyutech.jp

Daigo Okumura
Department of Electrical and Energy Engineering,
Kyushu Institute of Technology, Fukuoka, Japan
okumura.daigo794@mail.kyutech.jp

Kyouhei Hamasuna
Department of Electrical and Energy Engineering,Kyushu Institute of Technology, Fukuoka, Japan
hamasuna.kyouhei346@mail.kyutech.jp

Motoo Tsuchie
Department of Electrical and Energy Engineering, Kyushu Institute of Technology, Fukuoka, Japan
santa1949@outlook.jp

Masahiro Kozako
Department of Electrical and Energy Engineering, Kyushu Institute of Technology, Fukuoka, Japan
kozako@ele.kyutech.ac.jp

Masayuki Hikita
Department of Electrical and Energy Engineering, Kyushu Institute of Technology, Fukuoka, Japan
masahikita@gmail.com

Mrutyunjay Maharana
School of Electrical Engineering, Xi'an Jiaotong University
m.maharana979@gmail.com

Cristian Olmo
Department of Electrical and Energy Engineering University of Cantabria, Santander, Spain
cristian.olmo@unican.es

***Abstract*—The authors showed in previous report that the relative moisture content of biodegradable ester oil increases with increasing temperature, which affects the AC breakdown voltage (BDV). This paper presents the dependence of BDV on moisture content and temperature under conditions of high moisture content in biodegradable ester oil (EO). AC BDV of the three biodegradable ester oils, PFAE (monoester), FR3 (tri-ester), and MIDEL (tetra-ester), with different ester linkages, was measured at different oil temperatures and relative water contents using sphere electrodes. Results showed that BDV decreased with increasing moisture content (MC) in all kinds of the ester oils. The BDV of PFAE and FR3 decreased from room temperature to 50 °C, but then increased in the temperature range from 50 °C to 80 °C. The decrease and increase in insulation properties are attributed to an increase in water content in the oil and to the viscosity decrease resulting in suppression of streamer discharge propagation, respectively. On the other hand, BDV of tetra-ester continued to decrease with increasing temperature. This result can be attributed to the larger number of ester bonds, unlike monoesters and tri-ester. The ester linkages in the material are a weak point in the insulating properties, which can easily lead to a decrease in BDV at all the measuring temperatures.**

Keywords— Saturation moisture content, breakdown voltage, insulating oil, biodegradable oils

I. INTRODUCTION

Mineral oil (MO) produced from crude oil has excellent thermal conductivity and insulation performance, and has been used as electrical insulating oil in oil-filled transformers. Recently, there has been a growing interest in the use of environmentally friendly ester oil-based insulating oils with excellent dielectric strength and high biodegradability for the realization of a sustainable society, as represented by the SDGs, and a shift is underway. There have been many reports on BDV of ester oils (EO) when subjected to AC voltage. It is known that ester oils, when dehydrated, have the same insulating properties as mineral oil (MO). In addition, the presence of particles and water content in the ester oil decreases its insulating properties[1]. In addition, it has been reported that the BDV by impulse voltage application increases with increasing temperature [2]. The insulating properties of a composite insulating system consisting of EO impregnated paper/pressboard (EO/PB) were reported to be higher than those of MO/PB, and this phenomenon is explained by the matching effect of the relative permittivity of oil and PB[3]. The BDV of EO in extremely non-uniform electric fields at a negative polarity DC voltage to the needle electrode is higher than that at the positive polarity. This result of the polarity different BDV is interpreted in terms of the difference in streamer stop length [4]. P.Rozga *et.al.* also showed that BDV of insulating oil with large kinematic viscosity is lower than that with small kinematic viscosity. The result is explained by more rapid streamer propagation in the oil with high viscosity[5][6].

On the other hand, there has been few report on the temperature dependence of AC BDV in ester oil on relative moisture content (RMC) to saturation moisture content (SMC). In a previous report, the authors showed that increasing the temperature of ester oil (FR3, PFAE) increased moisture content (MC) in the oil, resulting in a lower BDV [7]. This paper presents the effect of the moisture content on the insulation properties of three kinds of ester oils with controlled moisture content at 30 %, 40 %, and 50 % RMC at different temperatures. Three kinds of EOs; PFAE, FR3, and MIDEL were prepared by varying both oil temperature and moisture content parameters, and AC breakdown voltage BDV was investigated. The temperature dependence of RMC was evaluated and the moisture content dependence of BDV at each oil temperature was measured with varying 30 %~ 50 % RMC [9] .

II. EXPERIMENTAL

Table 1 lists main specifications of the three kinds of EOs used in this experiment: monoester (Lion Co., PFAE), tri-ester (Cargill, FR3), and tetra-ester (M&I Material, MIDEL7131).

TABLE1. TYPICAL PARAMETERS OF INSULATING OILS

	FR3	PFAE	MIDEL
Density[kg/L]	0.923	0.8632	0.9735
Viscosity[mm^2/s]	32.19	5.062	31.07
Fire point[°C]	356	206	314
Volume resistivity [GΩ*m]	85	76	192
Relative permittivity	2.92	2.54	2.92

Oils with 30 %, 40 %, and 50 % RMC to saturated moisture content SMC at each oil temperature were used in the BDV test. Table 2 lists the moisture content MC corresponding to the oil temperatures of the various ester oils [8]; Natural Ester represents FR3 and PFAE, while Synthetic Ester does MIDEL7131.

TABLE2. MOISUTURE CONTENT

MOISTURE CONTENT[ppm]							
		Natural Ester			Synthetic Ester		
		20 °C	50 °C	80 °C	20 °C	50 °C	80 °C
RMC	30 %	300	540	750	750	1200	1800
	40 %	400	720	1000	1000	1600	2400
	50 %	500	900	1250	1250	2000	3000

- **Sample preparation**

Water steam was added to each oil to adjust MC of the sample. Figure 1 shows the sample preparation method: nitrogen gas extracted from a N_2 bomb A is introduced into a chamber B. Water vapor is generated by the nitrogen gas and water in chamber B. The generated water vapor is added to EO in an oil cup in a chamber C. Use of nitrogen gas provides high purity water vapor. Adding the water vapor allows each EO to be adjusted to a given RMC. Figure 2 shows a device (Kyoto Electronics Corporation, MKC-710) employed for measuring MC in oil using the Karl Fisher method. MC was monitored while controlling the oil temperature. Immediately after a given MC was reached, BDV measurement was performed.

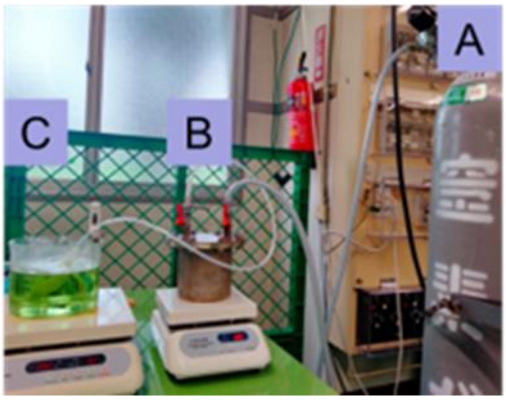

Fig. 1. Equipment for moistening and heating process of ester oils. Symbol A represents nitrogen gas bomb, B chamber with a heater to keep inside temperature at 70 to 80 °C, and C is an oil cap with a heater to control the temperature.

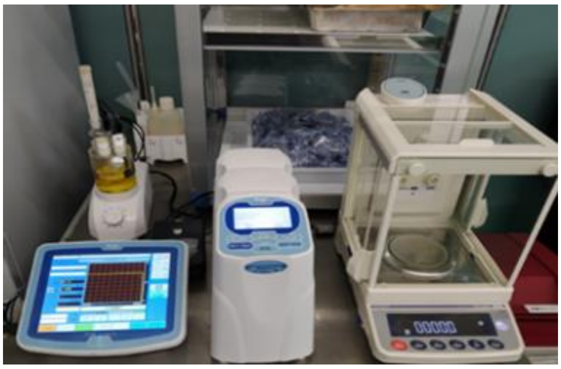

Fig. 2. Moisture content measurement device.

- **Breakdown measurement**

Figure 3 depicts AC BDV measurement electrode and test circuit. BDV of different ester oils was measured by applying an AC voltage (frequency: 60 Hz, step-up rate: 3 kV/s) to sphere to sphere electrodes with a gap length of 1 mm. Measurements were repeated six times to evaluate BDV at a given condition.

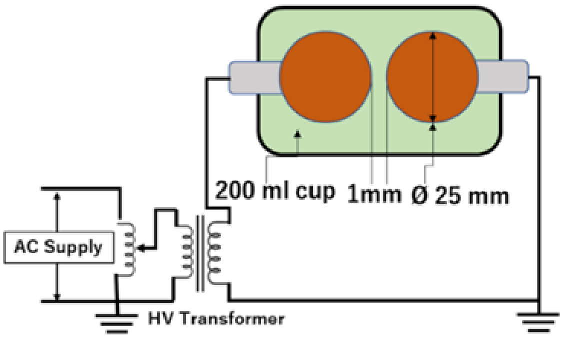

Fig. 3. AC BDV measurement circuit and test equipment

III. PESULTS AND DISCUSSION

Figures 4 through 6 show Weibull distribution of BDV for various temperatures and RMC in FR3, PFAE, and MIDEL, respectively. Table 3 lists scaling parameters evaluated from the Weibull distributions, together with the shape parameters *m* for each condition. The scale parameter is hereafter referred to as BDV.

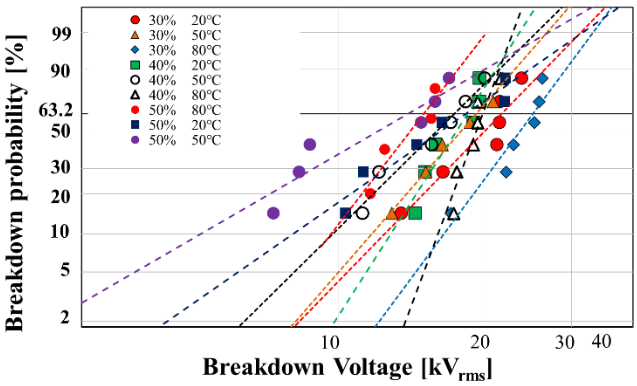

Fig. 4. Weibull distribution of the breakdown voltage of FR3 at different RMC and temperatures

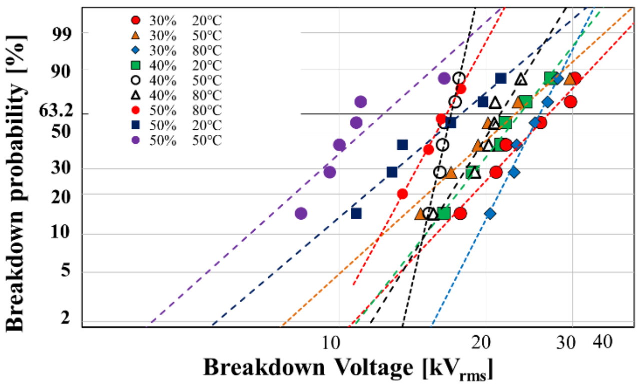

Fig. 5. Weibull distribution of the breakdown voltage of PFAE at different RMC and temperatures

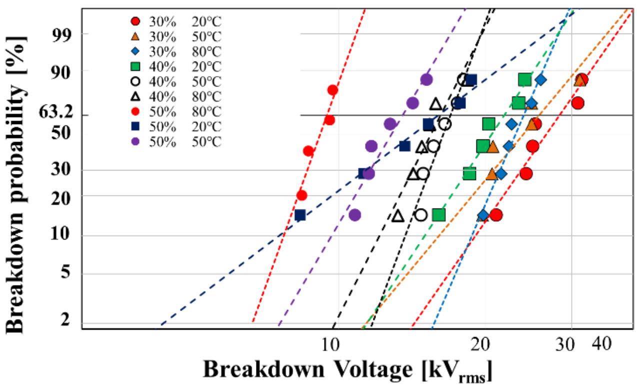

Fig.6 Weibull distribution of the breakdown voltage of MIDEL at different RMC and temperatures

TABLE3. Shape Parameters at different RMC and Temperatures

		Shape Parameters : *m*								
		FR3			PFAE			MIDEL		
		20°C	50°C	80°C	20°C	50°C	80°C	20°C	50°C	80°C
RMC[%]	30	4.1	4.59	5.39	4.26	3.64	7.83	5.71	4.79	9.26
	40	6.25	3.95	10.74	5.11	17.48	6.45	6.03	10.62	7.86
	50	2.78	2.31	4.34	3.4	3.59	4.87	3.01	6.76	6.8

It is found from the table that the shape parameter *m* increases with increasing oil temperature. The results arise from the fact that the slope of the Weibull distribution curves shown in Figures 4 to 6 become sharper with temperature. This increase in *m* with temperature is considered to be due to the trade-off between the increase in water content and the decrease in viscosity with increasing the temperature. Further investigation is needed on the results shown in the Weibull distribution.

A. RMC dependence of BDV

Figures 7 to 9 show RMC dependence of BDV of FR3, PFAE and MIDEL at various oil temperatures, respectively.

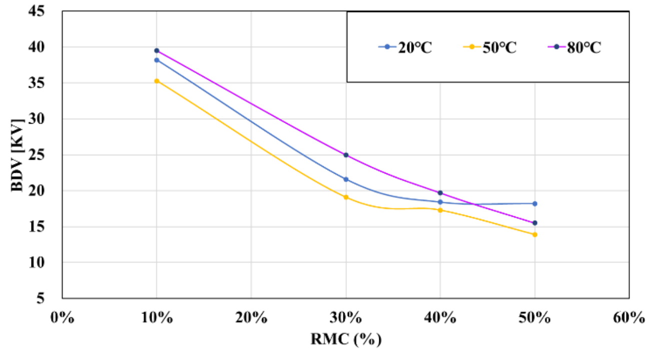

Fig.7 RMC dependence of BDV of FR3 at different temperatures

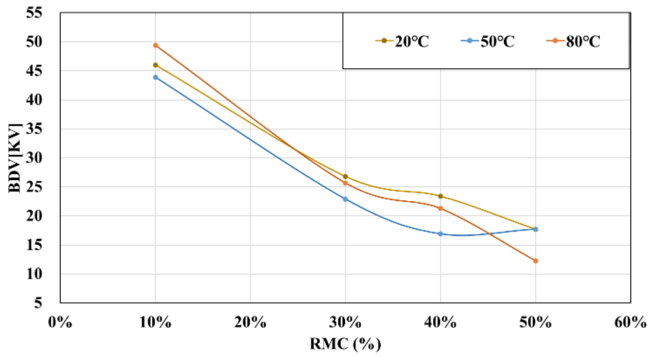

Fig.8 RMC dependence of BDV of PFAE at different temperatures

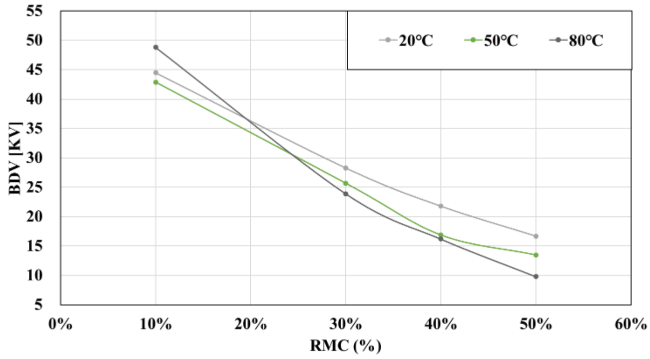

Fig.9 RMC dependence of BDV of MIDEL at different temperatures

It can be seen from Figures 7 to 9 that BDV decreases with increasing RMC at a given temperature for all ester oils.

B. Temperature dependence of BDV

Figures 10 to 12 show the temperature dependence of BDV of FR3, PFAE and MIDEL at various RMC, respectively. As can be seen in Figures 10 and 11, BDV decreases for monoester and tri-ester kept at a fixed RMC as temperature increases from 20 °C to 50 °C (Region I) and then increases at 80 °C (Region II). These temperature dependences of BDV can be interpreted as follows: As the oil temperature increases, (1) SMC also increases, and MC increases accordingly. On the other hand, as the temperature increases, (2) the kinematic viscosity of the oil decreases. Considering (1) and (2) with the increase in oil temperature, the decrease in BDV in Region I is attributed to the increase in MC of the water content in the oil. While in Region II, the decrease in the kinematic viscosity of EO suppresses streamer discharge development, resulting in BDV increase. On the other hand, the tetra-ester (MIDEL) has about twice SMC compared to the monoester (PFAE) and tri-ester (FR3), and thus has a larger MC at each oil temperature. Accordingly, the tetra-ester includes larger amount of MC than the monoester and tri-ester even at the same RMC in the high temperature region. As a result, the tetra-ester is more likely to suffer from the moisture in the oil on the degradation of the insulation performance.

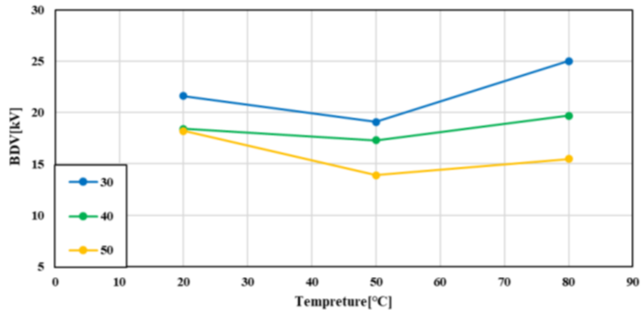

Fig.10 Temperature dependence of the breakdown voltage of FR3 at different RMC

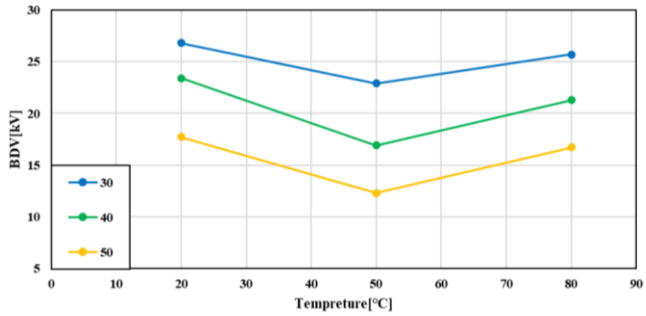

Fig.11 Temperature dependence of the breakdown voltage of PFAE at different RMC

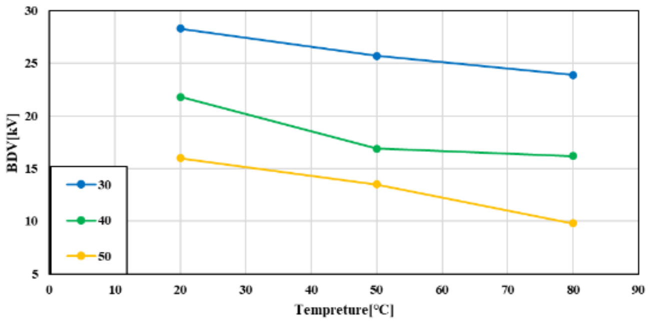

Fig.12 Temperature dependence of the breakdown voltage of MIDEL at different RMC

IV. CONCLUSION

In this paper, the dielectric breakdown tests of monoester, tri-ester, and tetra-ester were conducted under high moisture content conditions with RMC at 30 %, 40 %, and 50 % of SMC to investigate their dielectric properties. Scaling parameters were evaluated from Weibull distributions and their values were used as BDV.

From the results, the dependence on moisture content was evaluated, and it was found that an increase in moisture content in the insulating oil contributed to a decrease in insulating properties. In addition, the temperature dependence was also evaluated from the same test, and it was found that the decrease in BDV due to the increase in MC in the oil as the temperature rises and the increase in BDV due to the suppression of streamer discharge propagation by the decrease in kinematic viscosity with temperature rise were mutually working. For monoester and tri-ester, either the moisture content or kinematic viscosity in the oil is dominant at each oil temperature, contributing to the change in BDV. On the other hand, in the case of tetra-ester, the effect of moisture content dominates at each oil temperature due to the high moisture content in the oil, and contributes to the change in BDV.

These results indicate that the insulating properties of EOs are complicated by the factors of RMC, temperature, and viscosity. In the future, we plan to obtain PD characteristics and investigate the dielectric breakdown mechanism and degradation tendency of the EOs, as well as the insulating properties in a composite insulating system with solid insulating materials.

ACKNOWLEDGMENT

We sincerely thank the BIOTRAFO project and LION Corporation, Japan for providing PFAE for analysis.

REFERENCES

[1] X.Wang, Z.D.Wang, “Study of Dielectric Behavior of Ester Transformer Liquids under ac Voltage”, IEEE Transactions on Dielectric and Electrical Insulation, Vol.19, No.6, December 2012, pp.1916-1925 (2012)

[2] S.Arazoe, K.Yasuda, S.Okabe, G.Ueta, S.Yanabu "Breakdown Characteristics and Streaming Electrification Characteristics of Flame Retardant Silicone Oil" IEEJ Trans. PE, Vol.130, No.6, pp603-611 (2010)

[3] S.Arazoe, D.Saruhashi, Y.Sato, S.Yanabu, G.Ueta, S.Okabe, ” Electrical Characteristics of Natural and Synthetic Insulating Fluids”2011 IEEE Transactions on Dielectrics and Insulation,vol.18,pp.506-512 (2011).

[4] Y.Zhao, H.Li, Y.Qian, C.Zhang, L.Zhong, Q. Wang, “Breakdown Characteristics of Ester Liquids under DC Voltage” 2022 IEEE 21st International Conference on Dielectric Liquids (ICDL),pp.311-314 (2022).

[5] Rozga, P.; Stanek, Marcin. “Characteristics of streamers developing at inception voltage in small gaps of natural ester, synthetic ester and mineral oil under lightning impulse”. IET Science Measurement & Technology. 2016, 10, 50-57 (2016).

[6] V. -H. Dang, A. Beroual and C. Perrier, "Investigations on streamers phenomena in mineral, synthetic and natural ester oils under lightning impulse voltage," in *IEEE Transactions on Dielectrics and Electrical Insulation*, vol. 19, no. 5, pp. 1521-1527, October (2012).

[7] M. Maharana, K. Hamasuna, M. Kozako, M. Hikita, M. Tsuchie,K. Wu, “InVestigation of saturation moisuture in the PD behavior in the biodegradable ester oil”,9th International Conference on Condition Monitoring and Diagnosis 2022,P4-12,pp.763-766 (CMD 2022)

[8] CIGRE Brochure 436 “Experience in Service with New Insulating Liquid.” (2010).

[9] C. Perrier and A. Beroual, "Experimental investigations on insulating liquids for power transformers: Mineral, ester, and silicone oils," in *IEEE Electrical Insulation Magazine*, vol. 25, no. 6, pp. 6-13, November-December (2009)