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Effects of Temperature on Partial Discharges and Streamers in an Ester Liquid under AC Stress

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ABSTRACT

Insulating liquids in transformers experience the transformer operational temperature rather than the ambient temperature that is often used in discharge studies in laboratories. This paper presents the effects of temperature on partial discharge (PD) and streamer characteristics of a synthetic ester liquid under AC stress. A needle-to-plane electrode configuration was employed to perform the PD and streamer measurements. The PD pattern, streamer images, current signals were chosen to explore the PD and streamer characteristics at temperatures of 20, 40, 60 and 80 °C. It was found that both PD and streamer characteristics of the synthetic ester are temperature dependent. As the temperature increased, the magnitude and repetition rate of positive PDs increased slightly, but both the magnitude and repetition rate of negative PDs dropped dramatically. In addition, it was observed that when the temperature increased, the stopping length of positive streamers did not change appreciably while a significant reduction of negative streamer length and area was witnessed. A mechanism based on the electrohydrodynamics (EHD) phenomenon and the space charge theory has been used to explain the different effects of temperature on positive and negative PDs.

Index Terms — ester liquid, partial discharge (PD), streamer, electrohydrodynamics (EHD), transformer, temperature

1 INTRODUCTION

POWER transformers play an extremely important role in power networks. Their failures could result in a significant risk to the power network and a high cost for recovery. Hence, it is of great significance to ensure their reliable operations. At present, the liquid/solid combined insulation system is widely used in power transformers. During the practical operation, the insulation system is under multi-stresses and degraded gradually overtime, which could increase the risk of partial discharge (PD) and threaten the safe operation of power transformers.

Up to now, the pre-breakdown phenomenon in transformer liquids has been extensively studied [1-9], and a large portion of the research has been carried out to better understand the partial discharge phenomenon under AC stress. Concerning this subject, research efforts can generally be categorized into streamer investigation and PD patterns. The former is more concerned on the physical nature of partial discharges while the latter is more related to the industry application [1].

Previous studies have shown that the PD and streamer characteristics of insulating liquids are meaningfully influenced by many different factors such as moisture, floating particles, ageing and so on [2, 3, 8, 9]. It was reported that applying high AC electric fields with needle to plane electrode would produce space charges around the needle tip and cause the movement of the insulating liquid, which is also known as the electrohydrodynamics (EHD) [10]. Previous research has revealed that the space charges play a significant role on the PD activities at higher PD rates and applied voltages [11]. In addition, space charges generated in the previous AC half cycle would affect the electric field distribution close to the needle tip and further influence the initiation of PDs in the following half cycle [12-14]. Nevertheless, most of these studies were carried out at room temperature. In practice, the insulating liquids are not only used as the insulation material but also act as the coolant to dissipate the heat generated by the windings in power transformers. Meanwhile, due to the operating condition, the transformer oil is generally working at an elevated temperature rather than the ambient temperature.

As for the effect of temperature on the pre-breakdown phenomenon in insulating liquids, only very limited efforts were paid [15-17]. PD characteristics in the transformer oil at

various temperatures under the uniform AC stress with different defects were studied in [15]. It was found that the increasing temperature could improve the PDIV and result in a lower PD magnitude and PD repetition rate. PD and breakdown voltages in a biodegradable oil at different temperatures were investigated in [16]. As the temperature increased, both the PDIV and the breakdown voltage increased. The effect of temperature on PD characteristics in the moving transformer oil contaminated by metallic particles was studied under uniform AC stress [17]. The PD magnitude and frequency first increased and then decreased when the temperature was increased from 40 to 80 °C.

In the power transformer industry, the mineral oil has been widely used for decades based on its low cost, excellent dielectric strength and good cooling performance. However, as a petroleum-based product, the mineral oil also has its limitations in terms of high flammability and low degradability. With the development of the transformer industry, the concerns of environmental impacts have become more and more important. To answer these concerns, the ester liquids have become a promising alternative of the conventional mineral oil due to its higher fire point and lower environmental impact [18]. With the increasing application of ester liquids in large power transformers, it is essential to have a comprehensive understanding of its dielectric behaviors including PD and streamer characteristics at different temperatures.

In this study, the PD and streamers characteristics of a synthetic ester liquid have been experimentally investigated at different temperatures under various applied voltages. The PD pattern, PD magnitude and PD repetition rate were characterised while the streamer stopping length, streamer area and discharge current were also presented for further analysis. Then, discussions were carried out in terms of the space charge distribution at different temperatures in order to explain the experimental results.

2 EXPERIMENTAL DESCRIPTIONS

As shown in Figure 1, the experimental setup was basically composed of three parts: high voltage supply unit, oil heating/circulation system and measurement unit.

The oil heating/circulation system mainly consisted of a buffer chamber, a needle valve, a test cell, a flow meter and a centrifugal pump. The stainless steel made buffer chamber with a volume of 20 L was grounded for charge relaxation. A heating tape was wrapped on the chamber for the heating function. The pump was used to force the oil to circulate in the system and the needle valve could help to control the oil flow rate. The circulation direction is shown in Figure 1 and the flow rate was obtained from the flow meter.

During the heating process, the oil flow rate was controlled below 1 L/min. Hence, the oil could stay in the buffer chamber for more than 20 mins before flowing into the test cell again, which is long enough for extra charges to dissipate. Thus, the effect of streaming electrification could be ignored. Two thermocouples were placed at the entrance and exit of test cell to indicate the temperature inside the cell. The pump was switched off after the temperature in the test cell reached the desired value, and a one-minute standby was implemented to

ensure all the formal tests were carried out in a static oil condition. The test cell was made of Nylon and had two transparent Perspex windows for the streamer observation.

In this study, the needle-to-plane electrode configuration was employed to generate a local high electric field for the PD and streamer initiation. The needle tip had a radius of around 10 μm , and the gap distance between the needle tip and the plane electrode was fixed at 25 mm. The plane electrode was made of copper and had a diameter of 50 mm.

The arrangement of the high voltage supply unit and the measurement unit was based on the standard IEC 60270 [19]. The power supply was an AC transformer which could provide up to 70 kV (all the voltage levels are RMS values in this paper). A 1 M Ω water current-limit resistor was connected between the test cell and the high voltage supply to limit the current arc during the breakdowns. In order to record the applied voltage across the test cell, a capacitive high voltage divider was connected in parallel with the test cell and the voltage signal was obtained from an oscilloscope.

A commercial PD detector Omicron MPD 600 was connected in series with a 500 pF coupling capacitor to perform the PD measurement. The IEC 60270 mode of the detector was used, where the centre frequency is 250 kHz and bandwidth is in the range of 100 to 400 kHz. The data obtained from the detector was further processed to obtain maximum PD magnitude and repetition rate by using a self-developed MATLAB code. The noise level was controlled below 10 pC, and hence 20 pC was selected as the threshold for valid PD signals. To obtain the corresponding current signal, a low-inductance 50 Ω resistor was connected in series with the plane electrode.

In order to capture the streamer image, a high-speed camera and the shadowgraph technique were used. Once the current signal detected from the measurement resistor was recorded by the oscilloscope, a TTL signal would be sent to the camera simultaneously. Then the camera would be triggered to capture the corresponding images. In this study, the camera was working in a central trigger mode, which enabled the camera to continuously record a certain number of frames before and after the initiation of a streamer.

Figure 1. Experimental setup.

In this paper, the tested oil sample was a synthetic ester liquid: MIDEI 7131. The oil samples were directly taken from the sealed barrel without further filtering. The particle content was measured and the contamination level was defined as ‘Nil’ according to [20]. Before the formal test, all the oil samples were degassed and dehydrated at 85 °C in a vacuum oven below 500 Pa for 72 hours. After the process, the relative humidity of the liquid was below 10%.

The test temperature was ranged from 20 to 80 °C with a step of 20 °C. For the PD measurement, the applied voltage was maintained for 1 minute for each recording. Every PD measurement was performed for three times to observe repeatability. To avoid potential changes of the needle tip, a new needle would be used when the applied voltage was changed to another level. In other words, each needle was only used for three PD measurements. Ten streamers were captured under each applied voltage level at the four different temperatures.

3 RESULTS

3.1 PDIV AND TYPICAL PD PATTERN

The PD inception voltage (PDIV) at different temperatures was determined according to the procedure detailed in our previous study [21]. The threshold for determining the PDIV was taken as 20 pC. Table 1 summaries the PDIV and standard deviation (SD) at different temperatures. It is shown that the PDIVs at the four temperatures are very close to each other, with an average of 12.7 kV. In other words, it means temperature does not affect the observed PDIVs in this study.

Table 1. PDIVs at different temperatures, kV.

Temperature	20 °C	40 °C	60 °C	80 °C
PDIV	12.7	12.8	12.4	12.9
SD	0.21	0.22	0.16	0.26

PD patterns under voltages above the PDIV were investigated at various temperatures. The applied voltage was increased step by step from 16 to 26 kV with a step of 2 kV. The maximum applied voltage for 60 and 80 °C was set to only 24 kV as breakdowns might occur during the PD measurement at a higher voltage. Typical PD patterns at different temperatures under 24 kV are shown in Figure 2. It is noted that the peak magnitude of positive and negative PDs generally occurred around the vicinity of the peaks of the applied voltage waveform. What is important is that the increased temperature resulted in a flatter and more compressed PD pattern in the negative half voltage cycle, especially when the temperature was raised from 20 to 40 °C. Moreover, from 40 to 80 °C, no further evident change of negative PD patterns was observed.

3.2 PD CHARACTERISTICS

Figure 3 and Figure 4 show the PD magnitude of positive PDs (those occurring in the positive half cycle) and negative PDs (those occurring in the negative half cycle) under different voltages at different temperatures. By increasing the applied voltage, both the positive and negative PD magnitude increased continuously at the same temperature level. As for the impact of temperature on the PD magnitude, it was found

that the increased temperature gradually induced a higher positive PD magnitude under the same voltage level, and this influence was more obvious under higher applied voltages. However, the negative PD magnitude decreased substantially with the increasing temperature.

Figure 2. Typical PD patterns at four temperatures under 24 kV.

Figure 3. Positive PD magnitude under various voltages at different temperatures.

Figure 4. Negative PD magnitude under various voltages at different temperatures.

The total number of PDs occurring in one minute is defined as the PD repetition rate. The variations of the total PD

repetition rate and corresponding frequency (in Hz) under different voltages at various temperatures are presented in Figure 5. At the same temperature level, the total PD repetition rate was continuously increased with the applied voltage. From 16 to 20 kV, the effect of temperature on the PD repetition rate was not obvious. However, along with the applied voltage increased from 22 to 26 kV, it was interesting to witness a dramatic reduction of the total PD repetition rate caused by the rise of temperature.

Figure 5. Total repetition rate and frequency under different voltages at different temperatures.

Figure 6. PD repetition rate and frequency under different voltages at different temperatures of (a) positive PDs and (b) negative PDs.

To further investigate the large reduction of the total repetition rate resulted from the increasing temperature, the repetition rate of positive and negative PDs, are presented in

Figure 6a and Figure 6b, respectively. From Figure 6a, the positive PD repetition rate increased slightly with the increasing temperature. On the other hand, Figure 6b indicates that the negative PD repetition rate dropped substantially when the temperature was raised from 20 to 80 °C. The slight increment of positive PD repetition rate could not offset the dramatic drop of the negative PD repetition rate, which resulted in the eventual decrease of the total PD repetition rate at a higher temperature shown in Figure 5.

3.3 STREAMER CHARACTERISTICS

The same as the PD measurement, the maximum applied voltage of streamer investigations was only 24 kV for 60 °C and 80 °C to prevent breakdowns during the streamer measurement. The stopping length, propagation velocity and streamer area were used to study the characteristics of streamers under various conditions. In this paper, the stopping length is defined as the straight distance from the needle tip to the furthest streamer tip. The streamer propagation time is defined as the duration of corresponding current signals.

Typical shapes of positive streamers (those occurred during the positive half AC cycle) under various applied voltages at different temperatures are shown in Figure 7. It can be seen that by increasing the voltage, the positive streamer propagated further, and with more main branches. Meanwhile, under the same voltage level, the number of branches was decreased with the increase of temperature.

The stopping length of positive streamers under various voltages at different temperatures is summarized in Figure 8. It is indicated that the stopping length increased with applied voltage but the effect of temperature on the stopping length was no obvious. Only under 24 and 26 kV, a slight increase of stopping length with increasing temperature was noticeable.

Figure 7. Typical positive streamers under different voltages at different temperatures.

The average propagation velocity of the streamer was calculated as the ratio between the stopping length and the duration measured from the current signal. Figure 9 compares the average streamer propagation velocity of positive streamers under different voltages at various temperatures. It was revealed that the average propagation velocity was around

1.5 km/s which is classified as the 2nd mode streamer [22]. The average propagation velocity remained stable in the investigated range of the applied voltage at different temperatures.

Figure 8. The stopping length of positive streamers under different voltages at various temperatures.

Figure 9. The average propagation velocity of positive streamers under different voltages at various temperatures.

Figure 10. Comparison of streamer areas at various temperatures.

The area of streamers was measured by a self-developed MATLAB code which could convert the streamer image to a binary image and count the total number of pixels which were covered by all streamer branches. Figure 10 shows the relationship between the average stopping length and the average streamer area at different temperatures. The shape and branch characteristics of streamers can be studied by comparing the area of streamers with the same stopping length

length. According to Figure 10, it can be concluded that positive streamers at lower temperature level tend to have a larger streamer area or more branches compared to those at a higher temperature.

Typical negative streamers (those occurred during the negative half AC cycle) under various voltage levels with increasing temperature are presented in Figure 11. At 20 °C, the rising voltage generally resulted in a longer stopping length and more branches of the negative streamer. However, from 40 to 80 °C, negative streamers became much smaller compared to those at 20 °C and no obvious shape change was observed with the increase of applied voltages.

Figure 11. Typical negative streamers under different voltages at various temperatures.

Considering the fact that negative streamers at higher temperatures were too small for the accurate measurement of stopping lengths, the streamer area was used to evaluate the effect of temperature on negative streamers and the results are summarized in Figure 12. As the temperature was increased from 20 to 40 °C, a sharp decrease of the streamer area was observed while the decreasing tendency became less evident when the temperature was further increased from 40 to 80 °C. This trend is in accord with previous results that the rising temperature decreases the negative PD magnitude shown in Figure 4.

Figure 12. The negative streamer areas under different voltages at various temperatures.

The reduction impact of temperature on the negative streamer area can also be evidenced by studying the measured negative discharge current signals. Four typical current signals of negative streamers under 24 kV at different temperatures are presented in Figure 13. The negative streamer current signal was composed of a train of high-frequency discrete pulses with an increasing magnitude at 20 °C. As the temperature was increased, it was revealed that the peak value of the negative current was reduced significantly. In addition, the total number of pulses of a negative PD current signal also decreased when the temperature was raised.

Figure 13. Typical negative current signals under 24 kV at different temperatures.

4 DISCUSSION

4.1 SPACE CHARGE EFFECT ON STREAMERS IN ONE AC VOLTAGE CYCLE

Under AC stress, more than one streamer may occur in the same AC cycle. For these successive streamers that happening closely in time, the preceding streamer could leave some ‘by-product’ for subsequent streamers. These ‘by-product’ could be either charges or gaseous channels or both. Before the occurrence of the subsequent streamer, the residual charges or gaseous channels may not have enough time to be dissipated. As a result, the electrical field around the needle tip could be distorted and further affect the initiation and propagation of subsequent streamers.

It was observed that a positive streamer occurring close to 90° was generally followed by a negative streamer occurring close to 270°, which agrees with previous findings about correlations between positive and negative PDs [13]. Figure 14 presents a pair of typical positive and negative streamers that occurring in one voltage cycle at four different temperatures under 24 kV. Their corresponding phase angles are also indicated. According to Figure 14a, the two streamers occurred close to the positive and negative voltage peaks respectively. Based on the space charge theory, after the occurrence of the positive streamer, some positive charges were left around the needle tip. Then, after the applied voltage

of the needle tip was reversed to negative, the electric field between the needle tip and the positive charges was enhanced, which promoted the initiation and propagation of the subsequent negative streamer.

However, as shown in Figure 14b, c and d, at higher temperatures, the stopping length of the subsequent negatives were significantly decreased compared to the negative streamer in Figure 14a. It can be concluded that the space charge effect from the proceeding positive streamer to facilitate the successive negative streamer was reduced owing to the increase of temperature.

Figure 14. Space charge effect on negative streamers at different temperatures (a) 20 °C, (b) 40 °C, (c) 60 °C, (d) 80 °C.

4.2 STREAMER DISSIPATION PROCESS UNDER AC STRESS

With the help of the high-speed camera, the dissipation process of the positive streamer can be clearly observed. The investigation of the dissipation process can help us to have a better understanding of the space charge distribution and dissipation around the needle tip. Figure 15 presents a typical positive streamer dissipation process at 20 °C under 24 kV. It is shown that, when the positive streamer began to dissipate, the branches of the streamer would expand and fade in a very short time. In addition, instead of dissipating around the needle tip, the ‘root’ of the streamer was pushed away from the needle tip and moved forwards to the plane electrode. After 10 ms from the occurrence of the positive streamer, before the ‘black’ channels were totally dissipated, the subsequent negative streamer occurred. As the ‘black’ channels were the results from the change of the density in the liquid [23], the movement of the channels could indicate the local movement of the liquid around the needle tip under AC stress, which is also known as the EHD phenomenon [10].

By tracking the trajectories of the ‘black’ channels, the velocity of the corresponding liquid movement can be estimated. Figure 16 summarizes the instantaneous distance from the moving ‘root’ of the positive streamer to the needle tip at different temperatures under 24 kV during the

dissipation process. Ten streamers were analyzed at each temperature. According to Figure 16, the liquid flowing velocity close to the needle tip (within 2 mm) was about 0.4 m/s. It did not change with the increase of temperature probably because electric field is dominating the liquid movement in this region. Nevertheless, in the areas further away from the needle tip, the rising temperature resulted in an increased liquid velocity, especially when the temperature was increased from 20 to 40 °C. This may be caused by the decrease of the viscosity of MIDEI 7131 when the temperature was increased from 20 to 80 °C [24]. The viscosity of MIDEI 7131 dropped dramatically when the temperature increased from 20 to 40 °C, and then the decreasing trend became much slower when the temperature was further increased to 80 °C. The nonlinear reduction of the viscosity with increasing temperature agreed with the change of liquid flowing velocity indicated in Figure 16.

Figure 15. Typical dissipation process of a positive streamer under 24 kV at 20 °C.

Figure 16. The moving distance from the 'root' to the needle tip with time at different temperatures.

4.3 ASSUMPTION OF SPACE CHARGE DISTRIBUTION AT DIFFERENT TEMPERATURES

Based on previous discussions and available literatures, an assumption of space charge distribution at different temperatures was made to explain the effects of temperature

on PD and streamer characteristics. As reported in previous studies [11-13, 25], charge injection from the needle electrode and ionic dissociation in the liquid contribute to space charge phenomena in the liquid. Under the positive half cycle, as the mobility of electrons is much higher than that of positive charges, some positive charges are left close to the needle tip while most electrons have been attracted by the needle electrode and neutralized. It is assumed that those residual positive charges will move towards the plane electrode with the oil flow resulted from the EHD phenomenon, while the effect of liquid motion on electrons is ignored considering their high mobility.

Figure 17 is a conceptual sketch to show how the temperature influences the space charge distribution and further affect the PD and streamers under AC stress. As shown in Figure 17a, at the low temperature level, under the positive half cycle, the homocharges around the needle tip reduce the internal electric field. Hence, it becomes more difficult for the successive positive streamer to occur and propagate. When the polarity of the needle tip is reversed to negative, these heterocharges enhance the internal electrical field, E_{sc} , and promote the initiation and propagation of negative streamers.

Figure 17. Sketch showing the influence of temperature on the space charge distribution under AC stress.

As shown in Figure 17b, when the temperature is increased, the significant drop of the liquid viscosity enhances the EHD motion and those residual positive charges move further from the needle tip before the next streamer occurs. As a result, the space charge distribution is changed and the negative effect of the homocharges on following positive streamers is weakened. Therefore, it becomes more likely for subsequent positive streamers to initiate, and the magnitude and repetition rate of positive PDs increase correspondingly, which are supported by Figure 3 and Figure 6a. On the other hand, under the negative half cycle, the enhancement of the internal electric resulted from the heterocharges is decreased, which makes it more difficult for negative streamers to occur and propagate. In addition, the magnitude and repetition rate of negative PDs decrease consequently, which are supported by Figure 4 and Figure 6b.

5 CONCLUSIONS

In this paper, the effects of temperature on partial discharges and streamers in a synthetic ester were experimentally studied. It was found that the increased temperature increases the magnitude and repetition rate of positive PDs. In contrast, the rise of the temperature had a greater opposite impact on

negative PDs. Both the magnitude and repetition rate of negative PDs dropped dramatically with the increasing temperature. These influences were also verified by the investigation of streamers at different temperatures. It was also observed that the increasing temperature increases the liquid flowing velocity around the needle tip due to the decreasing viscosity of the liquid. An assumption based on the space charge theory was made to explain the different effects of temperature on positive and negative PDs.

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