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Effect of Temperature on Space Charge Distribution in Two Layers of Transformer Oil and Impregnated Pressboard Under DC Voltage

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ABSTRACT The space charge accumulation is an important factor to design the oil-pressboard composite insulation of convertor transformer, which is greatly affected by the temperature. In this paper, the space charge accumulation and attenuation in the two layers and single layer under DC voltage were studied by the Pulsed Electro-Acoustic Method from 20°C to 60°C, and the electric field distribution was calculated by the space charge distribution. The studied results have indicated that the distributions of space charge and electric field in the test results do not follow the Maxwell-Wagner polarization. The space charge distribution is affected by the surface trap, bulk trap, charge migration and electric field. The temperature affected the polarity and amount of the charge at oil-pressboard interface. The space charge accumulation of the two layers is more complex than that of the single layer, and the space charge accumulation and attenuation of two layers need longer time to reach the stable stage. The space charge accumulation in the single layer is largest at 40°C, whereas the space charge accumulation in the two layers is largest at 20°C. Moreover, the increase in the temperature increases the attenuation amplitude and speed of space charge.

INDEX TERMS Space charge, two layers, oil-pressboard insulation, temperature.

I. INTRODUCTION

The oil-paper insulation is the main insulation of the converter transformer, which is the core equipment for AC-DC conversion in the HVDC system. The valve side winding of the converter transformer works under AC-DC combined electric field during the operation [1], [2]. The space charge is easy to accumulate in the solid insulators under DC electric field [3]. Moreover, the interface charge will accumulate at the interface between the oil gap and the impregnated pressboard, which is affected by many factors, such as conductivity, interface barrier, space charge distribution and so on [4]. The interface charge and the space charge will distort the electric field distribution.

Until to now, most of the research focus on the single layer of oil-impregnated Kraft paper or pressboard. With the increase in the temperature and the moisture, the amount and mobility of space charge increase under DC electric field, and the space charge decay faster during short circuit test [5]–[7]. Moreover, the increase in electric field and aging period will increase the space charge amount [8]–[10]. However, the published works on the space charge characters in the two layers of oil gap and impregnated pressboard are very few, and most of them are studied under room temperature [11]. Many test results show that the electric field and charge distribution in the multi-layer may not followed the Maxwell-Wagner polarization theory [12], [13]. Wu studied the space charge characters in the two layers of thin paper and oil gap, and concluded that the polarity of the interface charge was same with the polarity of the electrode near the oil gap, and the interface charge decreased with the increase in the thickness of the oil gap [14]. Chen studied the space charge characters in the two layers of the aging oil gap and the pressboard, and concluded that the aging oil gap decreased

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the interface barrier, increasing the space charge amount in the pressboard [15]. During voltage-on and voltage-off test, the time to reach the steady state of the aging oil gap was much shorter than that of the fresh oil gap. Moreover, the electric field in the oil gap would be enhanced after the voltage polarity reversal, because of the slow decay speed of space charge and interface charge [16]. Huang studied the effect of temperature gradient on the space charge distribution of the oil and pressboard, and concluded that the electric field in the oil gap increased under temperature gradient [17]. Hao used the bipolar charge transport model to simulate the distribution of space charge and interface charge of multi-layer oil gap and oil impregnated pressboard [18]. The above studies do not consider the effect of temperature on the space charge distribution in the oil gap and impregnated pressboard, whereas the converter transformer works at high temperatures during actual operation.

In this paper, the Pulsed Electro Acoustic (PEA) method was used to measure the space charge distribution in oil gap and impregnated pressboard under high temperature. The electric field distribution in the two-layer sample at different temperatures is analyzed based on the space charge distribution.

II. EXPERIMENTAL SETUP

A. SAMPLE PREPARATION

The pressboard (thickness of 1 mm) was used for the test. Before the test, the transformer oil (Karamay 50#) is filtered through the oil filter to remove impurities such as moisture and bubbles. Unimpregnated pressboard was dried in vacuum at 105°C for 48 hours, then the pressboard was impregnated by the dry oil at 90°C. Finally, the oil-impregnated pressboard was storage in vacuum. The moisture content of transformer oil and pressboard are 7.3mg/kg and 0.34%, respectively.

B. MEASUREMENT DEVICE

The Pulsed Electro Acoustic method (PEA) was used to measure the space charge distribution [19]. The pulse width and amplitude of the pulse source was 10ns and 500V. The materials of lower electrode is aluminum, which has less attenuation to acoustic wave. The materials of upper electrode is semiconductor material, which is used for acoustic matching with the sample. The temperature of the upper and lower electrode was controlled by oil bath circulation. The test temperature was set at 20°C, 40°C and 60°C. The test voltage was set to: first apply +10kV for 2h, then apply +20kV for 2h, and short circuit test for 2h finally. The ambient temperature and humidity are 23°C and 40%, respectively.

Fig.1 shows the schematic diagram of measuring electrode structure. The samples were two layers of oil gap and impregnated pressboard, and the thickness of the oil gap and pressboard are 0.5 mm and 1 mm respectively. Acoustic wave propagation in oil-impregnated pressboard has a large attenuation, so that the waveform at the upper electrode has wider width and less amplitude. As the space

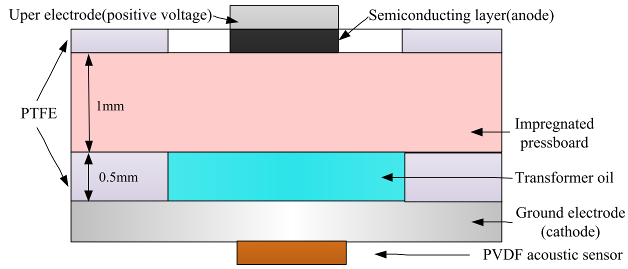

FIGURE 1. Schematic diagram of measuring electrode structure.

charge dynamic is not affected by the acoustic attenuation, the acoustic attenuation is not recovered in this paper [15]. The acoustic impedance of transformer oil is lower than that of oil-impregnated pressboard, causing the refractions and reflections when the acoustic waves propagated at the oil-pressboard interface. The acoustic velocity of transformer oil and oil-impregnated pressboard is affected by the temperature, shown as Fig. 2. The acoustic velocity of oil-impregnated pressboard and transformer oil decrease with the increase in the temperature. The horizontal axis recovery is according to the acoustic velocity at the corresponding temperature, and the acoustic impedance is also affected by the temperature. Moreover, the relative permittivity of transformer oil and oil-impregnated pressboard are different, so that the pulsed electric fields are different in the two. Thus, the stress waves generated by space charges and electric field were different in the oil and pressboard. In this paper, the signal recovery of the above two parts were according to [14].

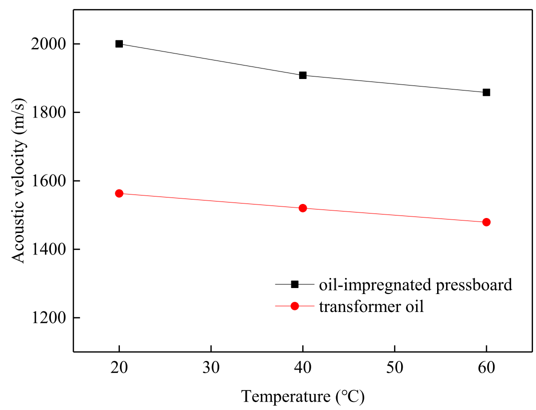

FIGURE 2. Acoustic velocity of transformer oil and oil-impregnated pressboard.

III. EXPERIMENTAL RESULTS

A. SPACE CHARGE DISTRIBUTION OF SINGLE LAYER PRESSBOARD UNDER DC VOLTAGE

In order to study the effect of oil gap on the space charge distribution in the two layers of oil and pressboard, the space charge distribution of single layer pressboard at different temperature under +10kV and +20kV are shown in Fig. 3(a) and Fig. 3(b) respectively. The increase of the temperature

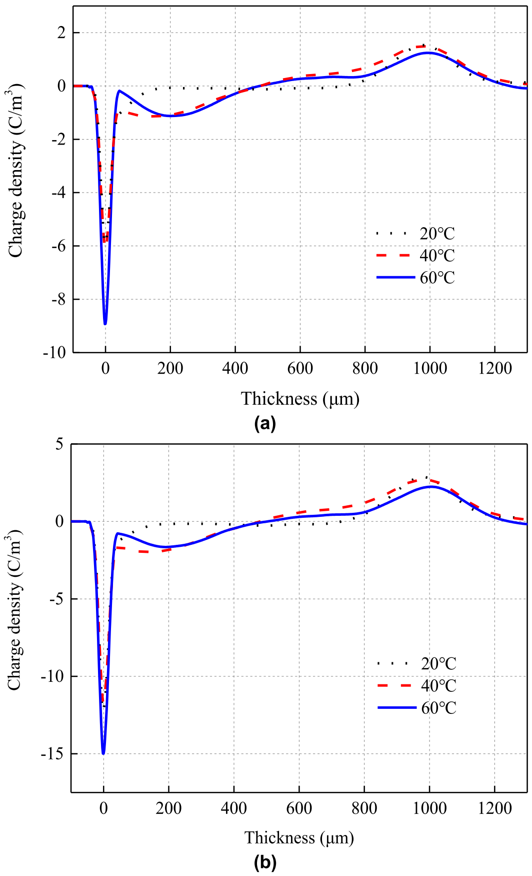

FIGURE 3. **Space charge distribution of the oil-impregnated pressboard. (a) 10kV. (b) 20kV.**

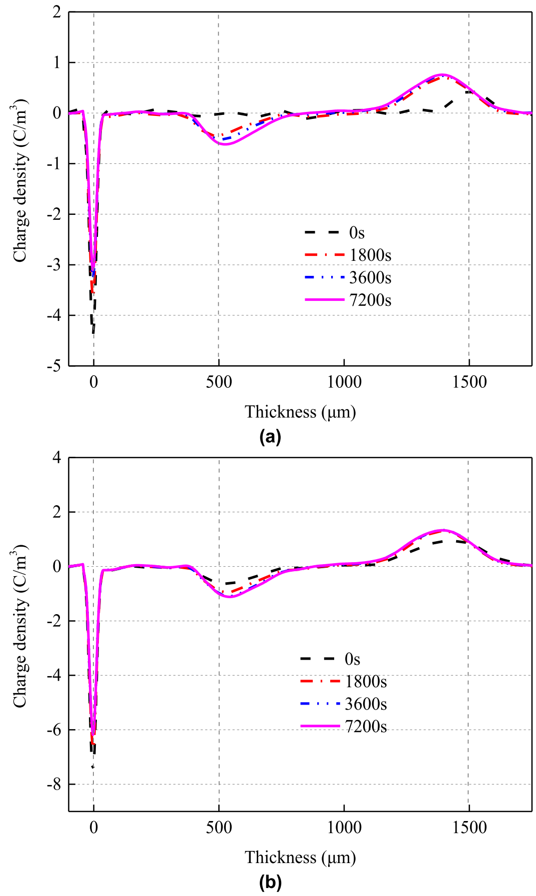

FIGURE 4. **Space charge distribution in two layers of oil gap and impregnated pressboard at 20°C. (a) 10kV. (b) 20kV.**

increases the charge migration, and the distribution range of space charge increase. The space charge amount is largest at 40°C, and the space charge at 60°C is larger than that at 20°C. The space charge packet occurs near the cathode at high temperature. However, the space charge packet does not appear near the anode due to the large acoustic attenuation. The space charge distribution is affected by the progress of the charge injection, migration, trapping, detrapping, and recombination. With the increase in the temperature, the injection and migration of charge increase, and the charge is easier to escape from the trap. At high temperature, the impurity molecules in oil-impregnated pressboard are easier to dissociate to form positive and negative ions, which migrate to both ends of the sample to form the heterocharge, causing the space charge packet. At 60°C, the trapped charge is easier to escape and the heterocharge increase, causing the space charge at 60°C is less than that at 40°C.

B. SPACE CHARGE DISTRIBUTION OF TWO LAYERS OF OIL AND PRESSBOARD UNDER DC VOLTAGE

Fig. 4(a) and 4(b) show the space charge distribution in oil gap and impregnated pressboard under 10kV and 20kV at 20°C respectively. During the test, the charge at the ground electrode decreases, whereas the charge at the oil-pressboard interface and the space charge inside the pressboard increase gradually. The homocharge accumulates in the pressboard. However, there is no charge accumulation in transformer oil. The space charge increases with the increase in the electric field. The negative charge accumulated at the oil-pressboard interface, and the charge density of oil-pressboard interface are -0.599C/m^3 and -1.006 C/m^3 under 10kV and 20kV respectively. The polarity of the interface charge is same with the polarity of the electrode near the oil gap, which is consistent with conclusions of [15]. Space charge changes rapidly in the initial stage, and it tends to be stable in the later period.

Fig. 5(a) and 5(b) show the space charge distribution in oil gap and impregnated pressboard under 10kV and 20kV at 40°C, and Fig. 5(c) and 5(d) show the space charge distribution under 10kV and 20kV at 60°C. The homocharge mainly accumulated inside the oil-impregnated pressboard, which is consistent with the test results at 20°C. At 40°C, the charge density at the ground electrode decreases during the test, and the negative charge accumulates at the oil-pressboard interface. The charge density of oil-pressboard interface is -0.264C/m^3 and -0.451C/m^3 under 10kV and 20kV respectively, which is less than that at 20°C. However, the positive

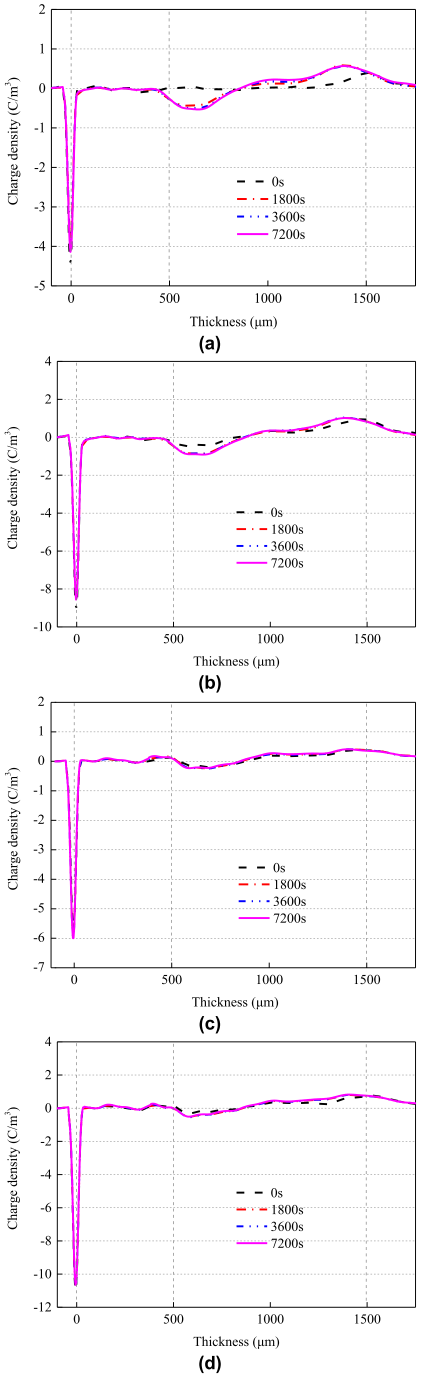

FIGURE 5. Space charge distribution of two layers under high temperature. (a) 40°C/10kV. (b) 40°C/20kV. (c) 60°C/10kV. (d) 60°C/20kV.

charge accumulates at the oil-pressboard interface at 60°C, and the charge at the ground electrode increases during the test. The space charge packet occurs at high temperature, indicating that heterocharge accumulates at the ends of the pressboard under high temperature. At the end of the test, the space charge accumulated inside the pressboard at 40°C is larger than that at 60°C. However, the space charge inside the pressboard of two layers at 60°C is less than that at 20°C, which is different from the test results of single layer pressboard. The space charge distribution is faster to be stable stage with the increase in the temperature, and the distribution range of space charge increases.

C. SPACE CHARGE DISTRIBUTION DURING SHORT CIRCUIT TEST

Fig. 6 shows the space charge distribution in two layers of oil gap and impregnated pressboard during short circuit test. At the beginning of the short circuit test, the charge polarity at the oil-pressboard interface and inside the pressboard are same with the polarity during the voltage-on test. Fig. 6(a) and Fig. 6(b) show that the negative charge accumulates at the oil-pressboard interface at 20°C and 40°C. In Fig. 6(c), positive charge accumulates at the left of the oil-pressboard interface, and the negative charge accumulates at the interface, which is different from the charge polarity under DC electric field. The reason is that the pulse width of the pulse source limits the resolution of the measurement results. The induced charge at the ground electrode was positive charge at 20°C and

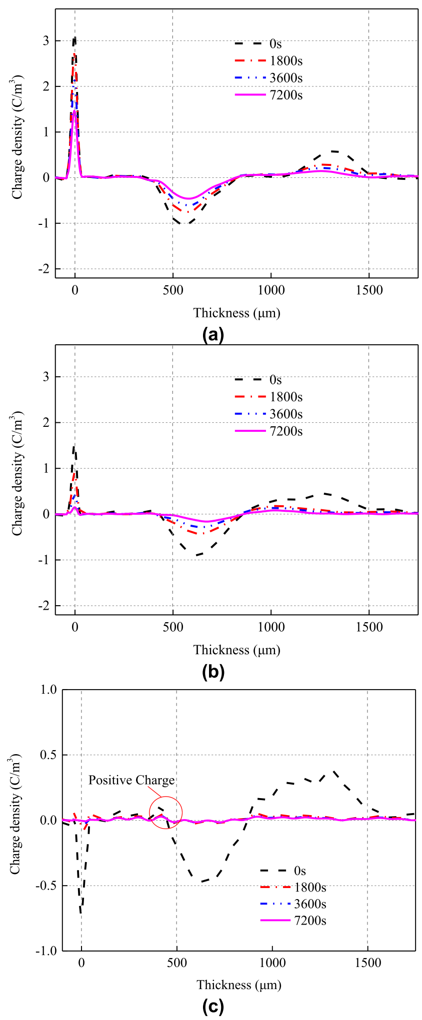

FIGURE 6. Space charge distribution during short circuit. (a) 20°C. (b) 40°C. (c) 60°C.

40°C, whereas the induced charge at the ground electrode is negative charge at 60°C. The induced charge density at 20°C is larger than that at 40°C. The induced charge density at ground electrode is affected by the amount and distribution of space charge, and the space charge accumulating closer to the electrode has greater effect on the induced charge. Fig. 6 shows that the space charge distribution at 20°C is closer to ground electrode compared with that at 40°C, so that the induced charge at 20°C is larger. Moreover, the space charge decays faster in the initial stage, and it decays slower in the late stage. The decay speed of space charge increases with the increase in the temperature.

IV. DISCUSSION

The mean volume density is used to further analyze the space charge characters, and its calculation formula is shown as follow.

$$Q(t) = \frac{1}{L}\int_0^d |\rho(x)|dx \tag{1}$$

where: $Q(t)$ is the mean volume density, $\rho(x, t)$ is the space charge density, L is the thickness of the two layers sample. 0 and d is the position of the ground electrode and upper electrode, respectively.

Fig. 7(a) and Fig. 7(b) show the mean volume density of two layers and single layer pressboard under different temperature. The mean volume density of space charge increases faster in initial stage, and it increases slowly in the late stage. The mean volume density is faster to reach the stable stage with the increase in the temperature. Moreover, the mean volume density of two layers needs longer time to reach the stable stage. Fig. 7(a) shows that the mean volume density of two layers (7200s) is largest at 20°C, and it is lest at 60°C in steady stage. Fig. 7(b) shows that the mean volume density of two layers (7200s) is largest at 40°C, and it at 60°C is larger than it at 20°C.

A. EFFECT OF TEMPERATURE ON SPACE CHARGE ACCUMULATION

Without considering space charge, the two layers polarization satisfies Maxwell-Wagner polarization. The electric field in the two dielectrics is distributed according to the capacitance in the initial stage, and it is distributed according to the resistance in the steady state. According to Maxwell-Wagner polarization, the difference of conductivity and relative permittivity of the two dielectrics causes the interface charge at the interface between the two dielectrics, shown as follow.

$$\sigma = \frac{\varepsilon_o\gamma_p - \varepsilon_p\gamma_o}{d_o\gamma_p + d_p\gamma_o}U(1 - e^{-t/\tau}) \tag{2}$$

where: ε, γ and d are the relative permittivity, conductivity and thickness. The subscripts of o and p represent the transformer oil and impregnated pressboard respectively. U is the applied voltage. τ is the time constant, shown as follow.

$$\tau = \frac{d_o\varepsilon_p + d_p\varepsilon_o}{d_o\gamma_p + d_p\gamma_o} \tag{3}$$

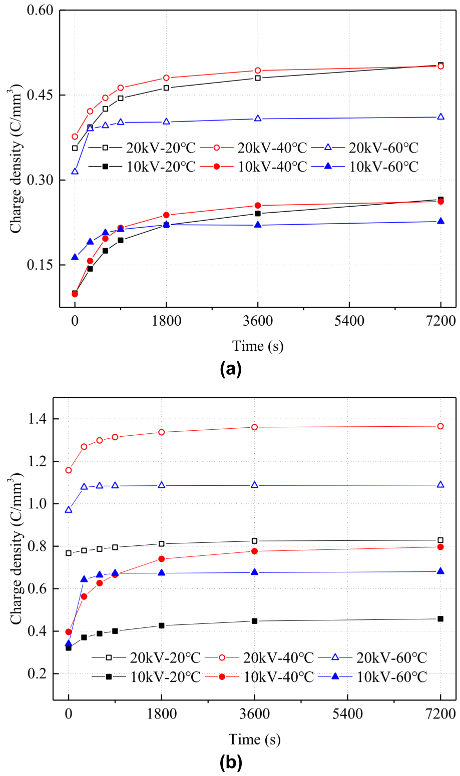

FIGURE 7. Mean volume density of space charge under different temperature. (a) two layers of oil and pressboard. (b) single layer pressboard.

The polarity and amount of interface charge is affected by the relative permittivity, resistivity and thickness. The relative permittivity of the impregnated pressboard is about twice that of oil, and they are less affected by temperature [20]. However, the conductivity is greatly affected by the temperature, which will affect the interface charge greatly. Fig. 8 shows the conductivity of the transformer oil and impregnated pressboard under different temperature. Both two increase with the increase in the temperature, but the increase in the conductivity of impregnated pressboard is more obvious. Refer to Equation (2), the interface charge between the oil gap and impregnated pressboard decrease with the increase in the temperature, and its polarity is

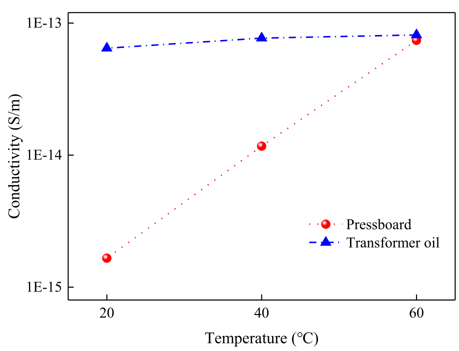

FIGURE 8. Conductivity of the transformer oil and impregnated pressboard under different temperature.

negative under different temperature. Refer to Equation (3), the time constant decreases with the increase in the temperature, indicating that charge distribution is faster to reach the stable stage, which is consistent with the test results.

Compared with the Maxwell-Wagner polarization, the interface charge at the oil-pressboard interface in the test results is smaller. In the actual, the space charge distribution in the two layers of oil-pressboard is more complex, which affected by the charge mobility, charge trapping, interface barrier, relative permittivity, and so on. Moreover, the above factors are affected by the temperature. The broken bond and chain folds existing at the interface of dielectrics provide the trap, trapping the migrate charge to form the space charge and interface charge. The charge in the surface trap will escape under the action of thermal vibration, then it will migrate into the pressboard to form the bulk space charge. The increase of temperature increases thermal vibration, causing the trapped charge easier to escape and the interface charge decreases [21]. Moreover, due to the porous structure of the oil-impregnated pressboard, there are many oil holes at the surface. The charge migrating in the oil will enter the pressboard along the oil hole, which also decrease the interface charge. The charge polarity in the pressboard of the two layers is same with that in the single layer. Homocharge accumulates inside the pressboard at 20°C and 40°C. Moreover, Fig. 3 shows that the heterocharge are generated by ionization of impurity ions at high temperature, and the heterocharge is largest at 60°C. Thus, the positive charge accumulates at the in interface between the oil gap and pressboard at 60°C, which is different from the polarity of interface charge at 40°C and 20°C. At high temperature, the progress of migration, trapping, detrapping and recombination of charge is faster to get dynamic balance, causing that the space charge distribution is faster to reach the stable stage.

The distribution and amount of space charge can affect the induced charge at the electrode interface, which affect the electric field at the electrode interface. The closer the space charge is to the electrode, the more induced charge. Fig 9 (a) and (c) show the schematic diagram of charge distribution under 20°C and 60°C at the stable stage according to the Maxwell-Wagner polarization. The negative charge only accumulates at the oil-pressboard interface, causing the generation of positive induced charge at the ground electrode and negative induced charge at upper electrode. The positive induced charge reduces the charge density at the ground electrode. According to the Equation (2), the difference of conductivity between the oil and pressboard becomes smaller with the increase in the temperature, causing that the oil-pressboard interface charge decreases and the charge at ground electrode increases. Fig 9 (b) and (d) show the schematic diagram of charge distribution under 20°C and 60°C at the steady stage according to the test results. The charge accumulates mainly inside the pressboard, which is far from the ground electrode. Thus, the positive induced charge at ground electrode decreases, and the charge density at ground electrode is larger than that in the Maxwell-Wagner

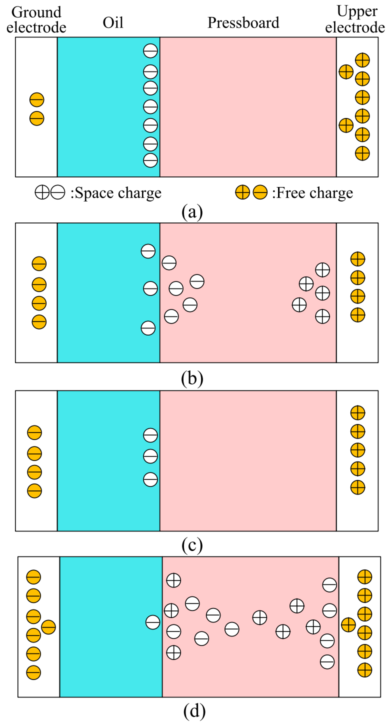

FIGURE 9. Schematic diagram of charge distribution. (a) Maxwell-Wagner polarization at 20°C. (b) test results at 20°C. (c) Maxwell-Wagner polarization at 60°C. (d) test results at 60°C.

polarization. Fig 3 shows that heterocharge accumulates inside the oil-impregnated pressboard at 60°C, so that the positive charge accumulating at the oil-pressboard interface causes that the negative induced charge increases at the ground electrode.

The space charge affects the electric field distribution in the two layers of the oil gap and pressboard. The electric field in the oil gap and impregnated pressboard is calculated by the space charge in the test results, shown as follow.

$$E(x) = \frac{1}{\varepsilon_0 \varepsilon_r} \int_0^x \rho(x) dx \tag{4}$$

where: E is the electric field, ρ is the space charge density. ε_0 is the vacuum permittivity. The relative permittivity of transformer oil and impregnated pressboard are 2.1 and 4.3, respectively.

Fig. 10 shows the Electric field distribution in the oil gap and impregnated pressboard at the end of voltage-on test under 20kV. The electric field distribution according Maxwell-Wagner polarization is shown in Fig. 10(a). At high temperature, the difference in conductivity between the pressboard and oil becomes smaller, causing that the electric field in the oil gap increases and the electric field in the impregnated pressboard decreases. Fig. 10(b) shows the electric field distribution calculated by the space charge distribution of the test results, which is quite different from the electric field according the Maxwell-Wagner polarization. The electric field inside the oil gap also increases with the increase in the temperature, whereas the electric field of the oil gap

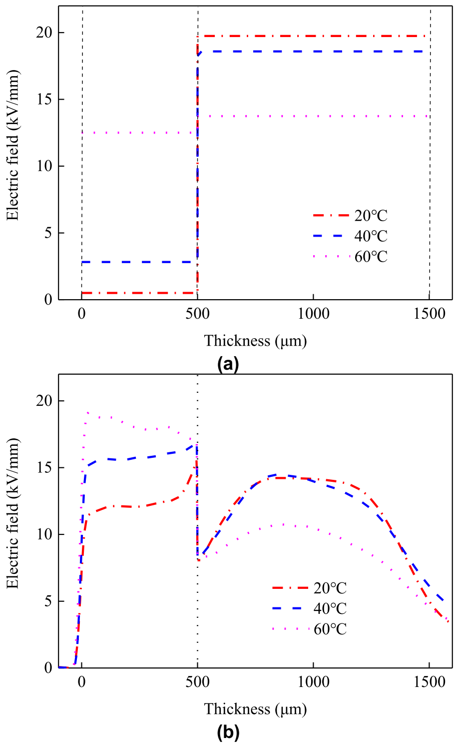

FIGURE 10. Electric field distribution in the two layers of oil gap and impregnated pressboard. (a) Maxwell-Wagner polarization under 20kV. (b) calculated by the test results under 20kV.

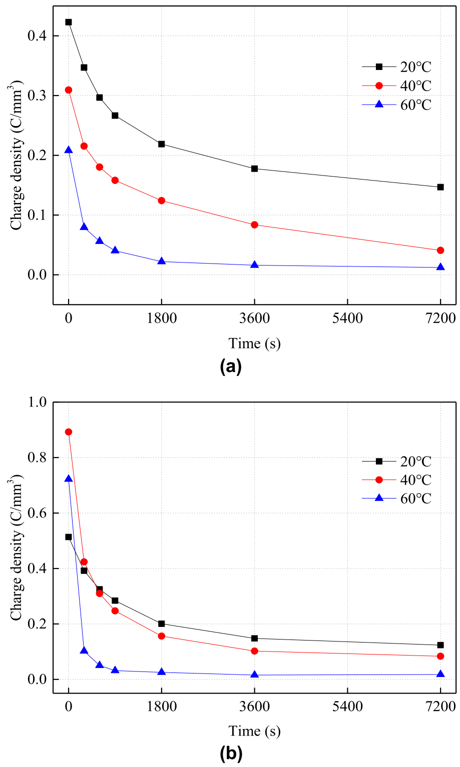

FIGURE 11. Mean volume density of space charge during short circuit test. (a) two layers. (b) single layer.

in the Fig 10 (b) is much larger than that in the Fig. 10 (a). There are very few charges in the oil gap, so the electric field of oil is mainly affected by the charge density at the ground electrode according to the Poisson Equation. In the test results, the charge at ground electrode is larger than that in the Maxwell-Wagner polarization, so that the electric field of the transformer oil is larger. The homocharge mainly accumulates inside the pressboard, which affect the electric field distribution in the pressboard. The electric field at both ends of pressboard is less than that in the middle.

The electric field distribution in the two layers is affected by the space charge distribution, and the space charge is also affected by the electric field distribution. This dynamic process is very complex, so it takes longer time for the two layers to reach stable state, compared to a single layer. Fig. 7 shows that the space charge in the single layer pressboard at 40°C is largest, and the space charge at 60°C is larger than that at 20°C. However, Fig 10 (b) shows that the electric field of the pressboard at 60°C is less than that at 20°C. Thus, the space charge in the pressboard of the two layers at 60°C is less than that at 20°C, and the mean volume density at 60°C is less than that at 20°C.

B. EFFECT OF TEMPERATURE ON SPACE CHARGE ATTENUATION

Fig. 11(a) and Fig. 11(b) show the mean volume density of space charge in the two layers and single layer during short circuit test. The variation tendency of single layer and double layer are same. At the beginning of the test, the mean volume densities of the two-layer are largest at 20°C, and that of single-layer is largest at 40°C, which is consisted with the test results during the voltage-on test. The mean volume density decreases gradually during the test, and it decrease faster with the increase in the temperature. The attenuation amplitude of the two layers is slower than that of the single layers.

The curve slope according to the charge density point is shown in Fig. 12. The slope value of charge density increases with the increase in the temperature, and slope value of single layer is larger than that of two layers. The test results

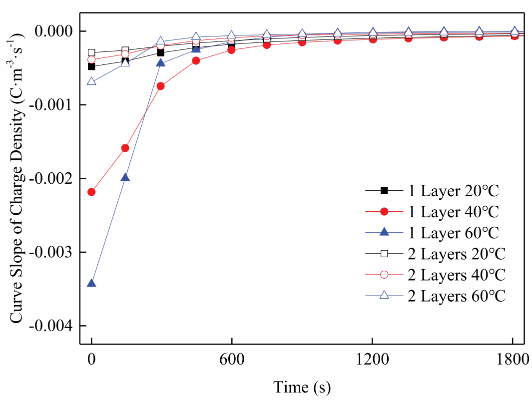

FIGURE 12. Curve slope of charge density.

show that the space charge mainly accumulate inside the impregnated pressboard, whereas the space charge inside the transformer is very few. During the short circuit test, the space charge in the trap of the pressboard will escape to form the free charge under the action of thermal vibration, and the detrapping progress of space charge increase with the increase in the temperature. Under the depolarization electric field, some free charges recombine with opposite polar charges. Moreover, some of the free charge moves to the electrode. Firstly, the charge inside the pressboard of two layers moves to the oil-pressboard interface, and it needs to escape from surface trap to enter the oil. Secondly, it takes a certain time for the charge in the oil to migrate to the ground electrode. Finally, the charge needs to overcome the barrier between the transformer oil and the electrode to get into the electrode. Compared to the single layer pressboard, the charge in the two layers migrating from the pressboard to the ground electrode needs a long time during the short circuit test.

V. CONCLUSON

The space charge distribution in the two layers of oil gap and impregnated pressboard is measured under DC voltage and under different temperature. The specific conclusions are shown as follows.

1) The distributions of electric field and space charge in the test results do not follow the Maxwell-Wagner polarization. The charge can escape from the surface trap of the pressboard to injected into the pressboard, and the porous structure of the pressboard surface makes it easier for charge to pass through the oil-pressboard interface. Moreover, the space charge accumulated in the pressboard also affects the induced charge at the electrode interface and the electric field.
2) The increase in the temperature makes the charge easier to escape from the trap, causing the interface charge decrease. At 60°C, the positive heterocharge accumulates in the negative end of pressboard, causing the polarity of oil-pressboard interface charge change from negative to positive.
3) In the single layer, the space charge accumulation is largest at 40°C, and the space charge accumulation at 60°C is larger than that at 20°C. In the two layers, the space chare accumulation decreases with the increase in the temperature.
4) During the short circuit test, the attenuation amplitude and speed of the space charge in the two layers of oil gap and pressboard increase with the increase in the temperature, which are less than those of the single layer pressboard.

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