Effects of ambient humidity and thermal aging on properties of Nomex insulation in mining dry-type transformer

Lu Li¹ | Jiancheng Song¹ | Zhipeng Lei¹ | Ailiang Kang¹ | Zhengyu Wang² | Rujia Men¹ | Yun Ma³

¹Shanxi Key Laboratory of Mining Electrical Equipment and Intelligent Control, College of Electrical and Power Engineering, Taiyuan University of Technology, Taiyuan, Shanxi, China
²Zhengzhou Power Supply Company, State Grid Henan Electric Power Company, Zhengzhou, Henan, China
³Jinzhong Power Supply Company, State Grid Shanxi Electric Power Company, Jinzhong, Shanxi, China

Abstract
Temperature and humidity are the main factors that cause the decomposition of Nomex paper widely used as turn-to-turn insulation material of mining dry-type transformers. In this study, for understanding the effect of ambient humidity and thermal aging on the properties of Nomex paper, specimens with the initial moisture content of 7% were aged in the oven for 168, 504, 672 h at 180°C, respectively. After thermal aging, corona discharge experiments of unaged and aged specimens with different aging degrees were carried out at different relative humidity (RH) levels from 10 to 70%. The characteristic parameters of corona discharge, such as the average discharge amplitude and the number of discharges, were measured. Then, the surface conductivity and the surface potential decay rate were measured. The morphology and attenuated total internal reflectance Fourier transform infrared spectroscopy were also analysed for explaining the difference of properties between unaged and aged specimens. The experiment results indicate that the average discharge amplitude decreases with the increase of RH or the deepening of the aging degree of specimens, but the number of discharges shows the reversal tendency. The changes in the physical structure and chemical composition, which is induced by the hydrolysis reaction of Nomex paper, accelerate the surface potential decay and increase the surface conductivity.

1 | INTRODUCTION
Mining dry-type transformers are the core equipment in the underground power supply system, and their safety directly affects the reliability and stability of electricity supply. The lifetime of a dry-type transformer mainly depends on the condition of insulation material, because the insulation system is one of the weakest parts in the transformer. In mining dry-type transformers, the turn-to-turn insulation is composed of varnished Nomex paper and air, which is a typical two-phase composite insulation structure. Under the environment of an underground coal mine, the Nomex insulation structure is inevitably subjected to electrical, thermal, mechanical stresses and ambient factors, which will cause the gradual deterioration of insulation and ultimately lead to a variety of insulation failure. One of the major problems causing serious damage to Nomex insulation is the appearance of the hottest spot where the local temperature can rise to about 180°C [1,2]. Under a dry air condition, Nomex paper, even exposed at 220°C, can always maintain excellent electrical and mechanical properties for at least 10 years [3]. However, it has been reported by Fofana et al. [4] that the decomposition temperature of the insulation paper would evidently decrease in the moisture environment. Due to the high humidity in the underground coal mine, Nomex paper is extremely easy to be hydrolysed at high temperature in the presence of moisture, which results in molecular chain scission and the production of new molecules and moisture, and further accelerates the degradation of Nomex paper. Therefore, the combination of humidity and temperature not only affects the electrical and mechanical properties of Nomex paper, but also
affects physicochemical properties, and finally causes the irreversible damage of insulation paper.

Some researchers had researched the properties of insulation paper. It had been verified that during the operation of the transformer, the insulation varnish would be damaged by thermal aging gradually and replaced by air, which has a much lower dielectric strength than that of the insulation varnish. It had also been found that the weak parts restricting the insulation performance of solid materials are often located at the gas-solid interface [5], such as the edge of the winding or protrusion from the winding conductor, where corona discharge can deteriorate and damage the insulation. The characteristics of corona discharge are affected by many factors, such as ambient humidity, temperature [6] and intrinsic properties of the material. Wang et al. have performed the experimental measurements of the corona discharge characteristic at different RH, and analysed the influence of humidity and trapezoidal voltage waveform on discharge characteristics [7]. Li et al. [8] have studied the effect of vapour with different chemical properties on corona discharge of stator windings. They had concluded that the amplitude of discharge decreased when the RH was higher than 60%. At present, considerable research works have also been done in the area of the partial discharge (PD) characteristics of transformer insulation paper, especially in oil-immersed cellulose paper [9,10]. Yadav and Sarathi [11] measured the corona discharge characteristics of oil-impregnated pressboard with different thermal aging degrees, and discussed the influence of thermal aging on phase-resolved PD (PRPD) pattern, corona inception voltage and the number of PDs. However, very little research has been published on the properties of Nomex insulation of mining dry-type transformers, especially on the thermal aged Nomex insulation at the different ambient humidity.

Due to the humid ambient in the underground coal mine and the poor heat dissipation of mining dry-type transformer, Nomex insulation is easy to be thermally aged. For understanding the effects of ambient humidity and thermal aging on properties of Nomex insulation, in this paper, the corona discharge of unaged and thermally aged Nomex paper specimens has been measured at different RH levels from 10 to 70%, and the effects of ambient humidity and thermal aging on average discharge amplitude and a number of discharges have been analysed. The changes in surface conductivity and surface potential decay rate of Nomex paper with RH and thermal aging have been measured to explain the changes in corona discharge properties. Also, the microstructure and physicochemical properties of Nomex paper during the thermal aging process have also been characterised by scanning electron microscopy (SEM) and attenuated total internal reflectance Fourier transform infrared spectroscopy (ATR-FTIR).

2 EXPERIMENTAL SETUP

2.1 Thermal aging test

DuPont Nomex® type 410 paper with a thickness of 0.05 mm was used as specimens. The Nomex paper was cut into the disc with a diameter of 90 mm, as shown in Figure 1. In a thermal aging test, Nomex paper specimens were placed in the hydrothermal autoclave reactor to simulate the environment of the mining dry-type transformer with an explosion-proof shell, as shown in Figure 1. The shell of the autoclave is made of 304 stainless steel. Both steel reactor and a para polyphenyl (PPL) container with a volume of 300 ml can withstand the pressure of no >3 MPa and the temperature ranging from −200 to +260°C.

According to the actual operation of mining dry-type transformer, the aging temperature is selected firstly. The previous research found that the average temperature is about 80°C inside mining dry-type transformers with good sealing, and poor heat dissipation after a long-term running. The hottest spot temperature of transformers’ coil during the normal operation is about 180°C [1,12]. Therefore, the aging temperature referring to a great deal of experimental research, is set at 180°C.

The pretreatment and aging process of Nomex paper specimens was set as follows [13]. Firstly, the specimens were dried in a vacuum oven under the temperature of 120°C and 50 Pa for 24 h. Then all specimens’ weight, which was considered as the weight without moisture, was measured on an electronic precision balance. Secondly, the dried specimens were placed in the constant temperature and humidity chamber until the moisture content of specimens reached 7%. Thirdly, the specimens with the initial moisture content of 7% were put into the autoclave reactors and sealed. Then reactors were placed into a thermal oven at 180°C. The corona discharge, surface potential decay, surface conductivity, SEM and ATR-FTIR of specimens were measured periodically during the thermal aging.

It should be noted that 7% of initial moisture content was determined depending on the earlier research results. After Nomex paper with initial moisture content <7%, such as 3 or 5%, was aged for >600 h at 180°C, the degree of polymerisation of Nomex paper >50% of the initial value, which means that Nomex paper still maintain relative good properties, and one will expend a long time to totally degrade Nomex paper. When Nomex paper with initial moisture content was higher than 7%, such as 9%, it will be aged too fast. After aged about 500 h, Nomex paper becomes brittle. In this case, it will be difficult to clearly know how the aging process of Nomex paper is. All in all, for making the aging process of Nomex paper measurable, the initial moisture content of Nomex paper was determined as 7%.
2.2 | Corona discharge measurement

The experimental schematic diagram of the corona discharge measurement system is shown in Figure 2. A needle to plane electrode configuration was used according to the standard IEC 60243-1. The tip angle of the high voltage needle electrode was 30° and the bottom plane ground electrode was 75 mm in diameter. Both electrodes were brass electrodes. Because the weight of Nomex paper is low and paper can be bent easily, the air gap between the Nomex paper and ground electrode is difficult to be removed when Nomex paper is placed on the ground electrode. A double-sided carbon conductive tape adhered to the backside of the Nomex specimen, which was in contact with the bottom plane ground electrode, to avoid the occurrence of discharge between the specimen and the plane electrode. The air gap between the specimen and the HV electrode is about 4 mm. Corona discharge pulses were measured using a high-frequency current sensor (IPEC HFCT 100/50, frequency range from 50 kHz to 200 MHz). Both the corona discharge pulse signal and the applied voltage signal from the coupling capacitor \( C_k \) were displayed and stored by the LECROY HD06104 oscilloscope.

The electrode configuration and specimens were placed in a climatic chamber, with a volume of 100 × 60 × 60 cm, which can control the RH and temperature. The climate chamber was placed in the electromagnetic shielding room for effectively blocking the interference of external noise signals. Before the measurement, the climatic chamber was dried with silica gel desiccant and the RH was controlled at 10% for 4 h. Then the RH was adjusted to the test value (RH = 10, 30, 50, 70%) at room temperature (about 25°C) for 6 h in order to reach the steady state. During the measurement, the applied voltage was increased gradually from the discharge inception voltage with a gradient of 0.2 kV. Each voltage level was kept for 10 min, and the corona discharge signal was continually collected until the specimen was broken down. In order to ensure the uniformity of statistical characteristic data, the discharge signals at each voltage level were recorded no <5 s.

2.3 | Surface potential decay measurement

The surface potential decay of unaged and aged Nomex papers with the variations of the ambient humidity was carried out.

2.4 | Surface conductivity measurement

In order to evaluate the effect of humidity on the surface conductivity of Nomex paper, the surface conductivity of specimens was also tested at room temperature and the different RH levels in the electromagnetic shielding room. Figure 4 shows the surface conductivity measurement system. The KEITHLEY-6517B electrometer was used to measure the surface current. According to the standard IEC 60093:1980, the three-electrode system was used. In order to make sure the testing environment in a steady state, all specimens were short-circuited in the climatic chamber for at least 6 h before measurement. During the measurement, the HV electrode was applied 500 V DC voltage for 1 min. The surface current was automatically recorded.

2.5 | Surface physical and chemical properties

The surface morphology of unaged and aged specimens was observed by SEM, TESCAN VEGA3SB. The surface chemical composition and structure of specimens were analysed with ATR-FTIR. Each specimen was scanned 32 times, and the range of wavenumber is 400–4000 cm\(^{-1}\).
3 | EXPERIMENTAL RESULTS

3.1 | Appearance of specimens

Figure 5 shows the appearance change of Nomex paper specimens with the initial moisture content of 7% aged at 180°C for 0, 168, 504, 672 h. It can be seen that the colour of a specimen with thermal aging changes from white, light yellow to yellowish-brown and dark brown due to the hydrolysis of Nomex paper. Decomposition products of thermal aging accumulate on the surface of specimens and lead to obvious changes in colour under the macroscopic.

3.2 | Result of corona discharge properties

Average discharge amplitude $U_{avg}$ of unaged Nomex paper specimens in the positive half-cycle depends on the applied voltage at different RH, as shown in Figure 6a. It can be seen that the $U_{avg}$ reduces to a low value with the increase of ambient RH. When the RH is 10%, the $U_{avg}$ is about 6.2–8.6 V, which is obviously higher than that at the other three RH levels. The $U_{avg}$ at 50% is very close to value at 70% RH. From the results, it is clear that under the condition of low RH, PD varies obviously with the increase of RH, and the effect of humidity on average discharge amplitude tends to a stable state when the RH increases to a certain extent.

The number of discharges $N$ of unaged Nomex paper specimens in positive voltage half-cycle with the applied voltage at different RH is shown in Figure 6b. It can be found that at different RH, the $N$ of the insulation paper specimens increases with the increase of the applied voltage. When the applied voltage reaches close to the breakdown voltage, about 4.5 kV at 10% RH, 30% RH, 50% RH, and 4.3 kV at 70% RH, the $N$ is increased fast. In addition, at the same voltage, the higher the ambient RH, the higher the $N$. The $N$ at high RH is 1.5–2 times higher than that at low RH. The $N$ at high RH of 50 and 70% RH is similar, showing a similar tendency with $U_{avg}$. The results now provide evidence that RH has a great influence on both $U_{avg}$ and $N$ of Nomex paper.

Figure 7 indicates the $U_{avg}$ of unaged and aged Nomex paper specimens at 10 and 50% RH, respectively. It can be seen that at 10 and 50% RH, the $U_{avg}$ decreases with specimens aging. For example, when the applied voltage is 4.3 kV, the $U_{avg}$ of the unaged specimens are 8.3 and 2.7 V at 10% RH and 50% RH, respectively. The $U_{avg}$ of the specimen aged for 168 h is 4.6 and 2.0 V, whereas those of the specimen aged for 672 h is about 3.4 and 1.3 V. In addition, by comparing Figures 7a and 8, it can be observed that the $U_{avg}$ of the aged Nomex paper specimens decreases with the increase of RH, which is consistent with that of the unaged specimens.

The number of discharges $N$ of unaged and aged Nomex paper at 10 and 50% RH is shown in Figure 8, respectively. It can be seen that the $N$ increases with the aging. For instance, the $N$ of the specimens aged for 0, 168 and 672 h at 10% RH are about 50–70, 55–90 and 86–130 num./s, respectively,
whereas which at 50% RH are about 95–126, 98–210 and 105–300 num./s. The \( N \) at 50% RH is about twice as much as that at 10% RH. The effect of humidity on the \( N \) of aged specimens is consistent with that of unaged specimens, i.e. the \( N \) increases with the humidity increasing.

The evident differences of the corona discharge properties, both average discharge amplitude and number of discharges, at different aging stages are mainly due to the hydrolysis reaction of Nomex paper during the thermal aging process, i.e. the scission of macromolecular chains and significant changes in the microstructures of the specimens.

### 3.3 Result of surface potential decay

The surface potential decay measurement of the specimens can show information about the surface accumulated charge, which has been widely used to characterise the electrical properties of various insulation materials. In this paper, the surface potential measured immediately after the corona charging is called the maximum surface potential \( U_{\text{max}} \) of Nomex paper [18,19]. \( t_{10\%} \) is the decay time when the maximum surface potential reduces to 10%, and the decay time constant \( \tau \) is used to describe the dependence of surface potential on time and the surface charge dissipation characteristics of Nomex paper. The decay time constant \( \tau \) was obtained via the exponential curve fitting method according to the exponential function

\[
U(t) = U_0 + Ae^{-t/\tau}
\]

where \( U_0 \) and \( A \) are constants, \( \tau \) is the decay time constant.

Figure 9 represents the curves of surface potential decay of unaged and aged Nomex paper at room temperature and different RH levels. It can be observed that the surface potential of the unaged specimen decays relatively slowly at 10% RH and 30% RH, but at 50% RH, the decay rate of surface potential accelerates, especially at 70% RH, the decay rate is significantly increased. At the same time, it can be seen that at the lower humidity levels, about 10% RH or 30% RH, the \( U_{\text{max}} \) of unaged specimens has a smaller
FIGURE 9  Surface potential decay curves of unaged and aged Nomex paper at room temperature and 10% RH, 30%RH, 50% RH and 70% RH (a) 10% RH, (b) 30% RH, (c) 50% RH, (d) 70% RH

decrease, which is about 1826 and 1393 V, respectively. However, at a higher humidity level, the \( U_{\text{max}} \) of unaged specimens significantly reduces to about 941 V at 50% RH and 673 V at 70% RH.

Compared with the unaged specimens, the aged specimens show very different surface potential decay characteristics. The surface potential of the specimens with longer aging time decays faster at the same given ambient humidity level. It is particularly noteworthy that the \( U_{\text{max}} \) of specimens aged for 504 and 672 h is about 563 and 375 V at 50% RH, respectively, whereas those at 70% RH are reduced to 392 and 233 V, respectively. The lower \( U_{\text{max}} \) of the aged specimens at high humidity is due to the higher charge leakage through the specimens in the corona charging stage.

The \( t_{10\%} \) and \( \tau \) of the unaged and aged Nomex paper at different RH levels are shown in Figure 10. The \( t_{10\%} \) and \( \tau \) of specimens decreased with the increase of ambient humidity. For example, the \( t_{10\%} \) and \( \tau \) of specimens at 70% RH are evidently lower than that at 10 and 30% RH. In addition, at the same humidity level, the aged specimens show smaller \( t_{10\%} \) and \( \tau \) than the unaged specimens. The longer the aging time, the smaller the \( t_{10\%} \) and \( \tau \). For instance, the \( t_{10\%} \) and \( \tau \) of the unaged specimens are about 26,871 and 5239 s at 70% RH, which of specimens aged for 672 h reduce to 8322 and 1698 s.

Both ambient humidity and thermal aging can accelerate the surface potential decay of Nomex paper. Wang et al. [7] mention that moisture can significantly change the surface conductivity of insulation by forming a conductive layer on the insulation surface. At higher RH levels, the significant decrease of the surface potential of Nomex paper should be mainly attributed to the surface transfer of the deposited charges introduced by water adsorption. In addition, thermal aging can change the surface structure of Nomex paper and affect the water adsorption rate on the surface, which also causes the conduction of charges accumulating on the surface. Therefore, in order to evaluate the effect of ambient humidity and thermal aging on the surface conductivity of Nomex paper, the surface conductivity of unaged and aged specimens at different RH levels is tested too. The results are shown in Figure 11. It can be seen that the surface conductivity increases with the increase of ambient humidity and the aging time. Especially in the case of high humidity, the conductivity of specimens aged for 672 h is twice higher than that of
unaged specimens at 70% RH. There is also a positive correlation between the surface potential decay rate and the surface conductivity.

**FIGURE 10** $t_{90\%}$ and $\tau$ of the unaged and aged Nomex paper at different RH levels (a) $t_{90\%}$, (b) $\tau$

**FIGURE 11** Surface conductivity of unaged and aged Nomex paper

4 | DISCUSSION

During the corona discharge, the charges, depositing or accumulating on the surface of Nomex paper, can cause an opposite electric field, weaken the applied electric field and extinguish the discharge. Therefore, the occurrence and development of discharge depend not only on the applied voltage, but also on the charge distribution on the surface of Nomex paper. The surface properties of Nomex paper, especially the surface conductivity and surface potential decay rate, have a strong relationship with the charge distribution. As mentioned above, both ambient RH and thermal aging can change the surface conductivity and surface potential decay rate of Nomex paper. Therefore, RH and thermal aging have important effects on the discharge process too.

4.1 | Effect of relative humidity

Ambient humidity has a complex effect on corona discharge. The electronegativity of water molecules in the air enhances the electron attachment and reduces the number of effective free electrons during the discharge [20]. When free electrons are captured by water molecules, they form more stable clusters, which means that it will be difficult for electrons separated from these clusters during molecular collisions [21]. Moreover, the charge mobility decreases due to the increase in mass and volume of the clusters, and their lifetime increases because the attached water molecules form a protective barrier around the charge carriers. In addition, water molecules can also weaken photoionisation in the air by absorbing radiated photons [22]. All of these humidity effects will have an impact on corona discharge activity in the air, but there is a quite difference between the effects in the higher electric field and the lower electric field [21].

Ambient humidity not only changes the nature of the air, but also affects the surface condition of Nomex paper. It has been verified that the surface conductivity of insulation materials depends on the ambient humidity and the absorbing water vapour. With the increase of ambient RH, the surface conductivity of Nomex paper with the same aging degree rises, so the acceleration of the surface potential decay, as shown in Figure 10 is mainly caused by electric conduction along the surface of the insulation paper [23]. At a higher RH level, a higher surface potential decay rate causes that the deposited charges, which is from the previous corona activity, on the surface of insulation paper spread to larger surface area at a faster rate. It is mentioned in [24] that the discharge intensity is closely related to the surface area of the deposited charges on the surface of insulation materials. At 50% RH and 70% RH, due to the spread of deposited charge, the opposite electric field is generated at more spots on the surface of insulation paper. Therefore, the lower overvoltage on a larger area of the insulation paper surface will generate a large number of smaller amplitude discharge pulses, as shown in Figure 6. In addition, because of the rapid decay of deposited charges, the local...
electric field strength does not show the evident decrease. The high enough local field can separate the clusters into electrons, which actively participate in the formation of the avalanche, and accelerate the breakdown of the discharge track. However, under dry conditions (10% RH), the surface conductivity of insulation paper is relatively low, as shown in Figure 11, and the surface potential decay rate is also slower, as shown in Figure 10, which will hinder the migration of deposited charges, and cause that the deposited charges on the surface of insulation paper will be limited in a very small area. Therefore, the overvoltage at other locations will be large, and several discharges with the larger amplitude will be generated, such as $U_{\text{avg}}$ and $N$ of 10% RH, as shown in Figure 6.

### 4.2 Effect of thermal aging on the physical structure

Morphology of unaged and aged specimens provides more evidence, as shown in Figure 12. It can be seen that under the effect of thermal aging, the fibre structure and surface morphology of Nomex paper specimens change dramatically. The pulps of unaged specimens are tightly wrapped on the surface of chopped fibres, and the effective bonding area between fibres is large, which makes the interface between chopped fibres and pulps very close and smooths the surface of insulation paper, as shown in Figure 12a. After 168 h of aging treatment, there are some microgaps between the chopped fibres and the pulps, and dents are found on the chopped fibres, but the surface of the insulation paper was still smooth, as shown in Figure 12b. With the prolongation of aging time, the pulps lap on the surface of the chopped fibres like silk, and a large number of gaps form between the chopped fibres and the pulps, resulting in the reduction of the effective contact area. At this time, the dents on the chopped fibres are further deepened and the surface of insulation paper becomes rough, as shown in Figure 12c. After aging for 672 h, the pulps scattered around the chopped fibres gradually become thinner and looser, and the gaps between the chopped fibres and the pulps become larger, resulting in poor interfacial bonding between the chopped fibres and the pulps, and the loose surface of the paper. The dents on the chopped fibres become very deep and even exhibit signs of cracking, as shown in Figure 12d.

Therefore, compared with chopped fibres, the degradation of pulps in Nomex paper is more obvious during thermal aging, because the pulps are flocculent, and have a larger surface area and more surface polar component. Finally, under the long-term effect of high temperature and humidity, the hydrolysis reaction starts from the pulps, and then the chopped fibres are also decomposed.

### 4.3 Effect of thermal aging on the chemical composition

The main chemical composition of Nomex paper is poly(m-phenylene isophthalamide) (PMLA) [25], and its chemical structure is shown in Figure 13. The chemical decomposition of Nomex paper is caused by hydrolysis and pyrolysis, and the decomposition products depend on the degradation environment and the aging time. Hydrolysis is one of the main decomposition forms of Nomex paper during the operation of mining dry-type transformers, because the hydrolysis temperature of Nomex paper is lower than its pyrolysis temperature, especially in an environment with sufficient moisture content. There are three kinds of hydrolysis forms for the Nomex
paper, as shown in Figure 13. The continuous hydrolysis reaction of the Nomex paper can cause a continuous scission of molecular chains and the decrease of degree of polymerisation (DP), which affects the insulation properties of the Nomex paper. In a thermal aging test, the physicochemical properties of Nomex insulation paper will change significantly, which will affect the electrical properties of the insulation surface, and then affect the corona discharge activity.

For further analysing the chemical properties, the ATR-FTIR spectrum of unaged and aged Nomex paper specimens was tested. It can be seen from Figure 14 that the intensity and width of the peaks in the range of 3100–3500 cm⁻¹ are relatively large. In the range of 1000–1700 cm⁻¹, the number of the peak is larger and the distribution is close. This is because the main chain of Nomex macromolecule is composed of m-diphenyl and amide groups. The peak at a wavenumber of 3280 cm⁻¹ corresponds to the N–H stretching vibrations with a bonded hydrogen, where the waveform is relatively wide due to the formation of a large number of hydrogen bonds between amide groups of adjacent macromolecule chain or between amide groups and crystalline water in Nomex paper [25]. The absorption peak at 1643 cm⁻¹ is ascribed to the amid C = O stretching (amide I band) for hydrogen bond amide groups and aromatic C = O stretching vibrations without any bonding. The coupling peaks of N–H in the plane bending vibration and C–N stretching vibration in the C–N–H group in the amide II band and the amide III band are in 1524 cm⁻¹ and the range from 1403 to 1232 cm⁻¹, respectively. In addition, the observed peaks at 1598 and 1473 cm⁻¹ are assigned to C = C stretching vibrations and C–N stretching vibrations of an aromatic ring.

It can be found in Figure 14 that the position and number of absorption peaks of specimens in the ATR-FTIR spectrum at different aging times do not show significantly change, which indicates that the main functional groups of insulation paper have not changed much during thermal aging.

During the thermal aging process, hydrogen bonds between the molecules are destroyed, crystalline water is released, and the transition from crystalline to amorphous region occurs, resulting in the reduction of N–H with a bonded hydrogen. However, the released crystal water and the water in the environment, which penetrate specimens, cause a hydrolysis reaction, destroy the amide bond and form a large amount of hydroxyl groups (3200–3650 cm⁻¹ for O–H stretching) and amino groups (3300–3500 cm⁻¹ for free N–H stretching). Both of them and unreacted N–H with a bonded hydrogen are present in the specimens, giving rise to a mixed band. This can

**FIGURE 13** Decomposition process caused by hydrolysis (a) First hydrolysis form, (b) Second hydrolysis form, (c) Third hydrolysis form

**FIGURE 14** ATR-FTIR spectrum of unaged and aged Nomex paper specimens
explain why the absorption peak strength around 3280 cm$^{-1}$ increases with thermal aging. With the association degree of hydrogen bond decreasing during thermal aging, the absorption strength of the aged specimen comparing with the unaged specimen increases in the range of 1000–1700 cm$^{-1}$, which means that the change degree of the dipole moment of the groups increases with aging, that is to say, the restriction for groups is weakened.

It can be concluded that during the thermal aging process, the surface chemical composition and microstructure of Nomex paper have changed significantly, which is the reason for the difference of surface electrical properties between unaged and aged specimens after the thermal aging. According to the three kinds of the hydrolysis reactions of Nomex and the ATR-FTIR results, the insulation papers will undergo hydrolysis reaction and form hydrophilic groups during the thermal aging, such as hydroxyl groups and amino groups. These polar groups are easily combined with water molecules to form hydrogen bonds. With the thermal aging, the hydrolysis reaction intensifies, and the number of hydroxyl and amino groups increases, leading to an increase of surface polarity. The results of SEM verify that the surface of aged Nomex specimens is rougher than that of the unaged specimen. The increase of surface roughness will reduce the water contact angle over the surface of the insulation paper [26]. The increase of the number of surface polar groups, as well as surface roughness, can enhance the surface wettability, which rises the content of water molecules adsorbed on the surface, so the surface conductivity and the rate of charge dissipation along with the surface increase. In addition, compared with the unaged specimens, the number and size of microgaps between the chopped fibres and the pulps in the aged specimens increase, resulting in the rising of specific surface area which denotes that a lot of polar groups forms on the surface, conductive tracks appears, and the decay of surface potential is accelerated [27]. In non-dry condition, i.e. relative humidity is higher than about 10%, the surface conductivity and surface potential decay rate of Nomex paper with different aging degrees finally depend on surface physicochemical properties of Nomex paper. Moreover, during the corona discharge experiment, because the surface conductivity of the aged specimens is higher than that of the unaged specimens, and the surface deposited charges can decay faster, a few discharge pulses with larger amplitude will change to a large number of smaller amplitude discharge pulses.

The surface potential also has a strong relationship with leakage current flowing on the material surface [28]. As shown in Figure 9a, the surface potential decay rate of the aged specimens is faster than that of the unaged specimen, even in the dry condition (10% RH). On the one hand, it can be attributed to the formation of polar groups such as hydroxyl and amino groups in Nomex paper during thermal aging. The appearance of polar groups can introduce shallower traps, which increases the de-trapping opportunity of trapped charges and accelerates the dissipation of surface charges [29,30]. On the other hand, the physical defects of Nomex paper caused by chain scission, i.e. hydrolysis reaction, during thermal aging can affect the viscosity of insulation paper, which will increase the charge carrier's mobility. All in all, during corona discharge test in dry air (10% RH), the increase of surface conductivity of aged specimens will rise the mobility of deposited charges, so deposited charges will not only remain at the bottom of the discharge channel, but will spread to a larger area. Compared with the unaged specimens, the partial electric field at other locations will decrease, resulting in the change of the amplitude and number of discharge pulses.

5 | CONCLUSIONS

The effects of ambient humidity and thermal aging on the corona discharge characteristics of unaged and aged Nomex paper specimens were investigated and explained based on the changes of surface conductivity, surface potential decay rate and the surface physicochemical properties in this paper. The experimental results show that the physical and chemical properties and electrical properties of Nomex paper used in mining dry-type transformers have a specific relationship with the aging, which can provide an experimental basis for the establishment of an aging database and promotes the development of insulation monitoring and fault diagnosis system for mining dry-type transformers. The conclusions are summarised as follows:

(i) With the increase of ambient RH or the deepening of the aging degree of specimens, the average discharge amplitude of Nomex paper decreases gradually. On the contrary, the number of discharges increases. In the humidity ambient or after thermal aging, because of the increase of the surface conductivity and the acceleration of surface potential decay, a small amount of large amplitude discharge pulses is possible to become a large number of small amplitude discharge pulses.

(ii) Both ambient humidity and thermal aging can affect the surface properties of Nomex paper, such as surface conductivity and surface potential decay rate, but the mechanism is completely different. The effect of humidity can be explained by the transfer of deposited charges on the surface of Nomex paper caused by water adsorption in humid ambient. However, the effect of thermal aging is mainly due to the hydrolysis reaction of Nomex paper during aging, which further results in the changes in microstructure and chemical composition of the Nomex paper surface.

(iii) The hydrolysis reaction of Nomex paper during thermal aging can break the molecular chain, form polar groups, enlarge the micro gaps between short fibres and pulps, and rough the surface of Nomex paper.

ACKNOWLEDGMENTS

Project supported by the National Natural Science Foundation of China (51577123).

REFERENCES

1. Pierce, L.W.: Thermal considerations in specifying dry type transformers. IEEE Trans. Ind. Appl. 30(4), 1090–1098 (1994)
2. IEEE Std C57.134: IEEE guide for determination of hottest-spot temperature in dry-type transformers, (2006)

3. Ul-Haq, S.: Influence of moisture on dielectric strength in polyamide (aramid) paper. Conf. Electrical Insulation and Dielectric Phenomena, Albuquerque, USA 325–328 (October 2003)

4. Fofana, I., Wasserberg, V., Borsi H.: Challenge of mixed insulating liquids for use in high-voltage transformers.1. Investigation of mixed liquids, IEEE. Electr. Insul. Mag. 18(3), 18–31 (2002)

5. Li, C., Lin, C., Chen, G.: Field-dependent charging phenomenon of HVDC spacers based on dominant charge behaviors, Appl. Phys. Lett. 114(20), 202904 (2019)

6. Nawawi, Z., Muramoto, Y., Hozumi, N.: Effect of humidity on partial discharge characteristics. Conf. Properties and Applications of Dielectric Materials, Nagoya, Japan 307–310 (June 2003)

7. Wang, X., Taylor, N., Eden, H.: Effect of humidity on partial discharge in a metal-dielectric air gap on machine insulation at trapezoidal testing voltages J. Electrostat. 83, 88–96 (2016)

8. Li, C., Song, J., Lin, L.: Effects of vapor with different chemical properties on corona partial discharges of stator windings, IEEE Trans. Dielectr. Electr. Insul. 21(3), 964–972 (2014)

9. Chen, W., Chen, X., Peng, S.: Canonical correlation between partial discharges and gas formation in transformer oil paper insulation, Energies 5(4), 1081–1097 (2012)

10. Liao, R., Duan, L., Wang, K.: Partial discharge characteristics of point-plane model in oil-paper insulation under AC voltage, High Volt. Eng. 40(3), 648–654. (in Chinese) (2014)

11. Yadav, K.S., Sarathi, R.: Influence of thermally aged barrier on corona discharge activity in transformer oil under AC voltages, IEEE. Trans. Dielectr. Electr. Insul. 22(5), 2415–2423 (2015)

12. Tian, M., Zhu, J., Song, J.: Temperature field simulation of coal dry-type transformer based on fluid-solid coupling analysis, High Volt. Eng. 42(12), 3972–3981. (in Chinese) (2016)

13. ANSI/IEEE C57.12.56: IEEE standard test procedure for thermal evaluation of insulation systems for ventilated dry-type power and distribution transformers. (1986)

14. Li, C., Lin, C., Hu, J.: Novel HVDC spacers by adaptively controlling surface charges – part I: charge transport and control strategy, IEEE. Trans. Dielectr. Electr. Insul. 25(4), 1238–1247 (2018)

15. Du, B., Li, Z.: Hydrophobicity, surface charge and DC flashover characteristics of direct-fluorinated RTV silicone rubber, IEEE. Trans. Dielectr. Electr. Insul. 22(2), 934–940 (2015)

16. Li, C., Lin, C., Zhang, B.: Understanding surface charge accumulation and surface flashover on spacers in compressed gas insulation, IEEE. Trans. Dielectr. Electr. Insul. 25(4), 1152–1166 (2018)

17. Men, R., Lei, Z., Han, T.: Effect of long-term fluorination on surface electrical performance of ethylene propylene rubber, High Volt. 4(4), 339–344 (2019)

18. Narvestad, H., Gregersen, O.W., Stenius, P.: Variables that affect surface potential decay of supercalendered paper, Nord. Pulp Pap. Res. J. 29(3), 484–498 (2014)

19. Liu, Y., An, Z., Yin, Q.: Rapid potential decay on surface fluorinated epoxy resin samples J. Appl. Phys. 113(16), p. 164105 (2013)

20. Kikuchi, Y., Murata, T., Uozumi, Y.: Effects of ambient humidity and temperature on partial discharge characteristics of conventional and nanocomposite enameled magnet wires, IEEE. Trans. Dielectr. Electr. Insul. 15(6), 1617–1625 (2008)

21. Levesque, M., David, E., Hudon, C.: Contribution of humidity to the evolution of slot partial discharges, IEEE. Trans. Dielectr. Electr. Insul. 19(1), 61–75 (2012)

22. Aints, M., Haljaste, A., Plank, T.: Absorption of photo-ionizing radiation of corona discharges in air, Plasma Process. Polym. 5(7), 672–680 (2008)

23. Lutz, B., Kindersberger, J.: Influence of relative humidity on surface charge decay on epoxy resin insulators. Int. Conf. Properties and Applications of Dielectric Materials, Harbin, China 883–886 (July 2009)

24. Villar-Rodil, S., Martinez-Alonso, A., Taseón, J.M. D.: Studies on pyrolysis of Nomex polyaramid fibers J. Anal. Appl. Pyrolysis 58, 105–115 (2001)

25. Ryan, B.J., Poduska, K.M.: Roughness effects on contact angle measurements, Am. J. Phys. 76(11), 1074–1077 (2008)

26. Nilsson, M., Stromme, M.: Electrodynamic investigations of conduction processes in humid microcrystalline cellulose tablets J. Phys. Chem. B 109(12), 5450–5455 (2005)

27. Boukezzi, L., Rondot, S., Jbara, O.: Thermal aging effects on the surface potential under electron beam irradiation (SEM) of XLPE insulation cables. Int. Conf. Electrical Engineering Boumerdes, Algeria 1–4 (December 2015)

28. Du, B., Li, J.: Surface charge coupling behavior of fluorinated polyimide film under DC and pulse voltage, IEEE. Trans. Dielectr. Electr. Insul. 24(1), 567–573 (2017)

29. Du, B., Huang, P., Xing, Y.: Surface charge and flashover characteristics of fluorinated PP under pulse voltage, IET Sci. Meas. Technol. 11(1), 18–24 (2017)

How to cite this article: Li I., Song J., Lei Z., et al. Effects of ambient humidity and thermal aging on properties of Nomex insulation in mining dry-type transformer. High Voltage. 2021;6:71–81. https://doi.org/10.1049/hve.2019.0293