# Effect of Cellulose Impurities on Partial Discharges in Oil-pressboard Insulation under DC Voltage

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## ABSTRACT

**Previous studies indicate that cellulose bridges in oil-pressboard insulation are self-generating, and can influence the characteristics of partial discharges (PDs) under DC voltage. In this letter, further experiments based on an optical-electric experimental platform were conducted to determine the generating sequence between cellulose bridges and PDs, and to provide visual evidence of bridges' effects on PD process. The results show that the generation of cellulose bridges can be divided into three stages, which can be finished at a DC voltage lower than PD inception voltage ($U_{\mathrm{pdiv}}$). With the increase of the applied DC voltage, the generating time of the first bridge decreases. In addition, by using shadow photographic method, a bridge-triggered discharge in oil was observed. Further analysis indicates that cellulose bridges generate gaseous paths to discharges in oil due to its high conductivity.**

Index Terms - **HVDC transmission, oil-pressboard insulation, partial discharges, cellulose impurities.**

## 1 INTRODUCTION

**DUE** to many advantages such as good insulating performance, reliable mechanical strength and long service life, oil-pressboard insulation is widely adopted in modern electric power transmissions [1-3]. However, in operation conditions, oil-pressboard insulation still faces multiple challenges such as local overheating, mechanical impact and partial discharges etc., which imperil the reliability of dielectrics [4-6]. Out of so many threats, self-generating cellulose impurity is always ignored. Studies in spinning science indicate that fiber molecular chains will rupture under high electric fields [7]. This conclusion also applies to cellulose molecular chains in pressboards. For AC apparatus where electric field alternates, the rupture process does not appear frequently and causes no big threats. However, the rapid growth of HVDC transmission network and thus an increasing number of DC transmission equipment (especially in China) makes this problem significant again. Under operating conditions, DC equipment, like converter transformer, has to endure a HVDC component [8-10], and therefore a constant high electric field, which promotes the abovementioned rupture process and makes cellulose detach from the pressboard. Previous studies in our laboratory indicate that these detached molecular chains will form impurity bridges and influence discharges [11], but no direct evidence was provided to prove this announcement.

In this letter, supplementary experiments to previous studies were conducted. The authors firstly determined the generation time of cellulose bridges under different voltage level. Afterwards, by using shadow photographic method, a bridge-triggered discharge in oil was observed. The results explain the sequential relationship between the generation of cellulose impurities and PDs, and confirm the influence of cellulose impurities on PD process visually.

## 2 EXPERIMENTALS

Figure 1 shows the experimental setup, which mainly consists of two parts: I. Discharge measurement platform (in rectangle with dashed line) and II. Optical detection platform (in rectangle with dotted line). In discharge measurement platform, we used a voltage doubling circuit (Maximum output 141 kV, 15 pC noise at 100 kV) to generate positive DC voltage, and a high frequency current transformer (HFCT, -6 dB bandwidth 1-80 MHz) to measure PDs. In optical detection platform, the shadow images of the sample were generated by a cold light source and then enlarged via a set of optical lens. To acquire the image, a PC controlled high speed camera (HSC, Redlake HS-4, 150,000 frames/second) was adopted.

For the convenience of observation, a needle-plane oil-pressboard insulation model was used. The curvature radius of the

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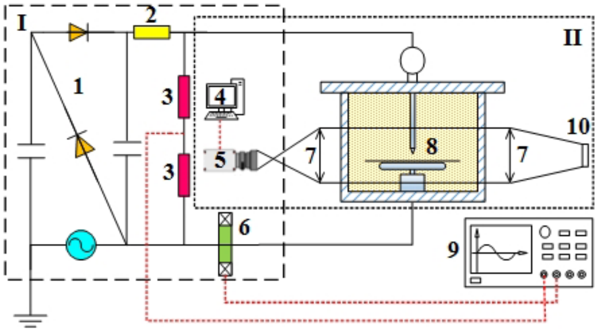
needle electrode was 1 mm; the diameter and thickness of the plane electrode were 80 mm and 10 mm separately. Electrodes were all made of stainless steel. IEC type B 3.1 pressboards (permittivity 4.3 after impregnation, volume resistivity ≈ $10^{14}$ Ω·m, density 1.15 g/cm$^3$) were cut into 100 mm ×100 mm×0.5 mm squares and fixed at plane electrode's surface by epoxy resin tie rods. About insulation liquid, we chose Kunlun KI25X transformer oil (conforms to IEC 60296-2012 and ASTM D3487-2009 standards) in the experiment. The distance of the oil gap was 1 mm. Oil and pressboard samples were pre-treated according to IEC 60422 and IEC 60641-2 before further discharging experiments.



1-Voltage doubling circuit; 2-Protective resistor; 3-Resistor divider; 4-PC; 5-High speed camera; 6-High Frequency Current Transformer(HFCT); 7-Optical lens; 8-Experimental chamber; 9-Oscilloscope; 10-Cold light source

**Figure 1.** Schematic diagram of the experimental setup

According to IEC 60270-2000, $U_{\mathrm{pdiv}}$ is defined as the voltage under which repetitive partial discharges can be observed. Based on this criteria, we adopted step boosting method to determine $U_{\mathrm{pdiv}}$. Voltage between each step was 1 kV, and was boosted within 10 s. At each voltage, the duration time was 30 min. If PDs were more than 30 times in this 30 min, the voltage at this step was $U_{\mathrm{pdiv}}$. For the above-mentioned model, the $U_{\mathrm{pdiv}}$=24 kV. To determine the generation time of cellulose bridge, the voltage was boosted at a speed of 1 kV/s to a certain level, and then kept until the emergence of impurities. On the other hand, the bridge-triggered discharge phenomenon was observed in a continuous voltage boosting experiment. The voltage was boosted at 1 kV/s until discharge in oil occurred. To acquire shadow images of bridge-triggered discharge, the HSC was set to the continuous shooting mode. The number of frames was 10,000 fps.

## 3 RESULTS AND DISCUSSION

Figure 2 shows the formation process of a cellulose bridge in the needle-plane experimental model. For the convenience of observation, the oil gap was widened to 15 mm. Based on figure 2, the formation process is divided into three stages:

*Stage I.* After the voltage was applied, very small impurities can be observed on pressboard's surface. Due to the influence of the electric field, these impurities all pointed to the same direction along the field;

*Stage II.* Impurities generated in *stage I* moved along the direction of the electric field. Meanwhile, these impurities entangled with each other and formed a cellulose bundle;

*Stage III.* The cellulose bundle continued to grow in length along the field and in width vertical to the field. Finally, the bundle connected the oil gap, and became a cellulose bridge.

However, for samples with narrow oil gap like 1 mm, stage II can be ignored, because once impurities generate, their length and quantity are enough to form a bridge immediately. Therefore, for narrow oil gap samples, the generation process of cellulose bridges can be divided into two stages.

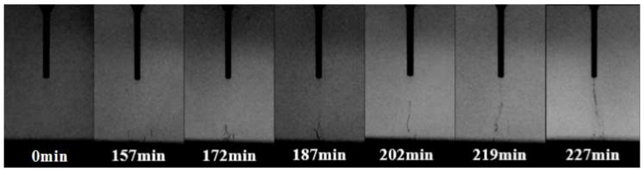


**Figure 2.** The formation process of a cellulose bridge (50 kV, 15 mm oil gap).

One significant link of the above generation process was the detachment of cellulose molecular chains from the pressboard, which in our experiment, was mainly caused by DC electric field. Figure 3 is the schematic diagram of cellulose's monomer structure. Under DC electric field, the polarized carbon atoms (with positive charges) and oxygen atoms (with negative charges) of cellulose molecule will move to the opposite direction, which stretches the glycoside bond between cellulose monomers, and eventually cause the detachment of cellulose.

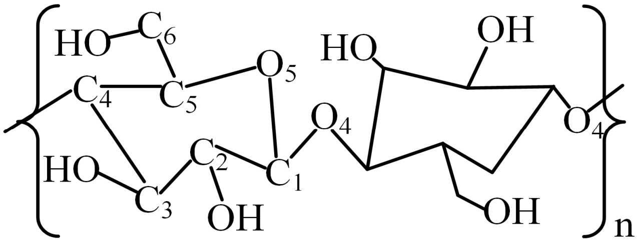


**Figure 3.** The schematic diagram of cellulose's monomer structure.

On the other hand, in article [12], researchers got the conclusion that the bending of polyethylene chains will introduce space charge traps. Similar conclusion on cellulose chains can be deduced. The influence of space charges will accelerate the degradation of cellulose chains.

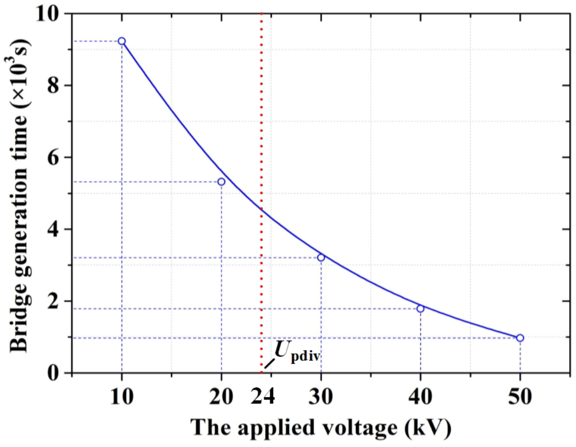
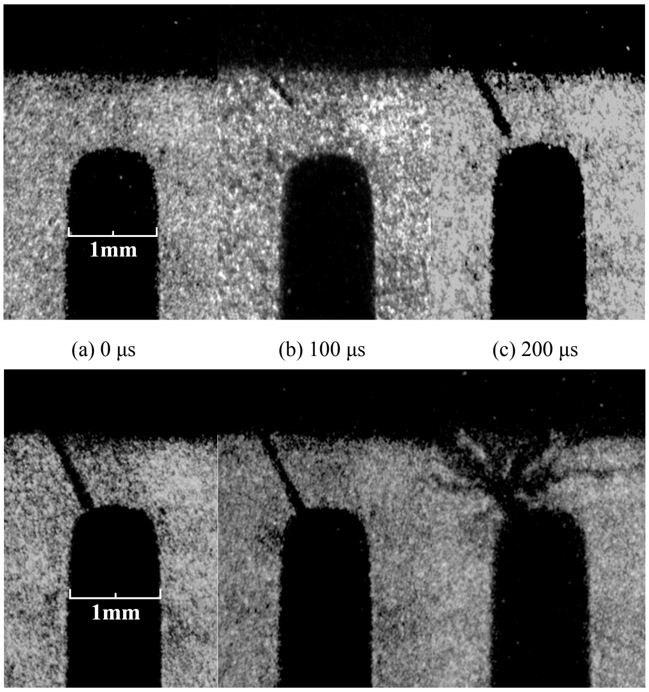


**Figure 4.** Relationship between bridge generating time and the applied voltage (1 mm oil gap).

Further studies of a 1 mm oil gap model in figure 4 indicate that cellulose bridges might be quite ubiquitous among DC equipment with oil-pressboard insulations. Even the applied voltage was much lower than $U_{\mathrm{pdiv}}$, bridges could still emerge after several hours. Notice that here the bridge generation time is the total timespan of the experiment, including stage I and stage III (stage II ignored). Typically the stage I accounts for a long time, because the breaking of molecular chains needs suitable conditions and only when certain amount of molecular chains break can a cellulose chain detach. However, once the chain is detached, a bridge can be generated in a very short time. Compared with the operating life of DC equipment, several hours are really too short. This conclusion makes the cellulose bridge problem to be even severe. Different from moisture or conducting particles, cellulose from pressboards is internal impurity, which means it can always regenerate after filtering. Once the equipment is put into operation, cellulose impurities will constantly emerge. For some oil-flowing equipment, cellulose impurities might not easily accumulate, but their concentration in oil will always increase.

One outcome of cellulose bridges' generation is the partial discharges they initiate. Figure 5 shows a bridge-triggered discharging process, which also describe the stage III in 1 mm oil gap sample. During this process a cellulose impurity was stretched from the pressboard. Then under the influence of electric field, the impurity became a bridge immediately. The oil gap was 1 mm, which made the bridge generation process complete in 400 μs. Finally, in Figure 5f, the breakdown of oil gap occurred along the bridge.



(a) 0 μs (b) 100 μs (c) 200 μs

(d) 300 μs (e) 400 μs (f) 500 μs

**Figure 5.** Shadow images of a bridge-triggered discharging process (30 kV, 1 mm oil gap).

Images in Figure 5 show clearly that cellulose bridges can initiate partial discharges in oil-pressboard insulation. The most basic way to influence discharges is to distort the electric field distribution. When cellulose chains detach from pressboard, their morphology becomes amorphous, which means a large amount of free hydroxyl exist. Since hydroxyl is a polar group, it is easy to adsorb water molecules. Therefore, moisture in oil will accumulate around the cellulose bridge and increase the conductivity of the whole system, which consequently lead to a large leakage current and therefore the local overheating. The increased temperature will initiate the vaporization of moisture impurity and the decomposition of oil, both of which generate gas bubbles. Under the influence of the electric field, these bubbles will get together and form a "bubble bridge". Final breakdown happens along this bubble bridge.

The results of the experiment give warnings to the manufacture and operation of oil-pressboard insulation equipment, especially to those under DC voltage. Because cellulose impurities can always generate from the surface of the pressboard, any purification will be invalid. Developing non-paper fiber insulating materials can be an expensive but beneficial attempt to avoid threats from cellulose impurities.

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