UDC 620.3

DEVELOPMENT OF A NEW HIGHLY EFFECTIVE INSULATION FOR ELECTRICAL TRANSFORMERS BASED ON NANOFIBRILLATED CELLULOSE

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Cellulose insulating paper, together with oil is being widely used in oil-immersed power transformers due to their accessibility and good insulating performance. The purpose of insulating paper impregnated with insulating oil is to resist the flow of electric current between the conductors (Lundgaard et al. 2004; Prevost and Oommen 2006). Also cellulose insulating paper has relatively good properties, insulating breakdown is still the major factor that causes the electrical failures of oil-immersed power transformers. Especially, the development of ultra-high voltage power transmission,(+-1100kV) transmission system under the construction in China, the reliability of oil-impregnated insulating paper has become a challenge that requires better insulation and mechanical properties of insulating paper(Ziomek 2012).

With the development of nanotechnology, new approaches may be considered for the modifications of insulating paper.

Moreover, the recent studies show that observing the improvement of both breakdown behavior and mechanical properties by the introduction of nanofibrillated cellulose(NFC) to ordinary cellulose fibers. Although the enhancement is no more than 30%, this study inspires our interest in the electrically insulating performance of paper made from 100% nanofibers, namely nanopaper.

Because nanofiber has a width less than the wavelength of visible light, the pores inside nanopaper formed by nanofibers can be small enough to avoid light scattering. The major difference between nanopaper and regular paper is that the former is optical transparency. In addition to that, nanopaper also shows good mechanical thermal properties. The tensile strength of nanopaper can reach 200-400 Mpa, which is obviously higher than that of regular paper. Coefficient thermal expansion of nanopaper is lower than 8.5ppm/K, whereas that of plastic is about 50ppm/K. Even at 150C degree, nanopaper can maintain its high optical transparency and smooth surface. Due to its high mechanical properties, a lot of studies have been published the potential application of nanopaper. However, the possibility of being used as n electrically insulating, one of the most important aplications of regular paper, has been rarely reported.

In this study, the suitability of using nanopaper as an electrically insulating material was discussed. Breakdown strength, thermal durability, tensile strength of nanopaper was evaluated and compared to that of conventional insulating paper.

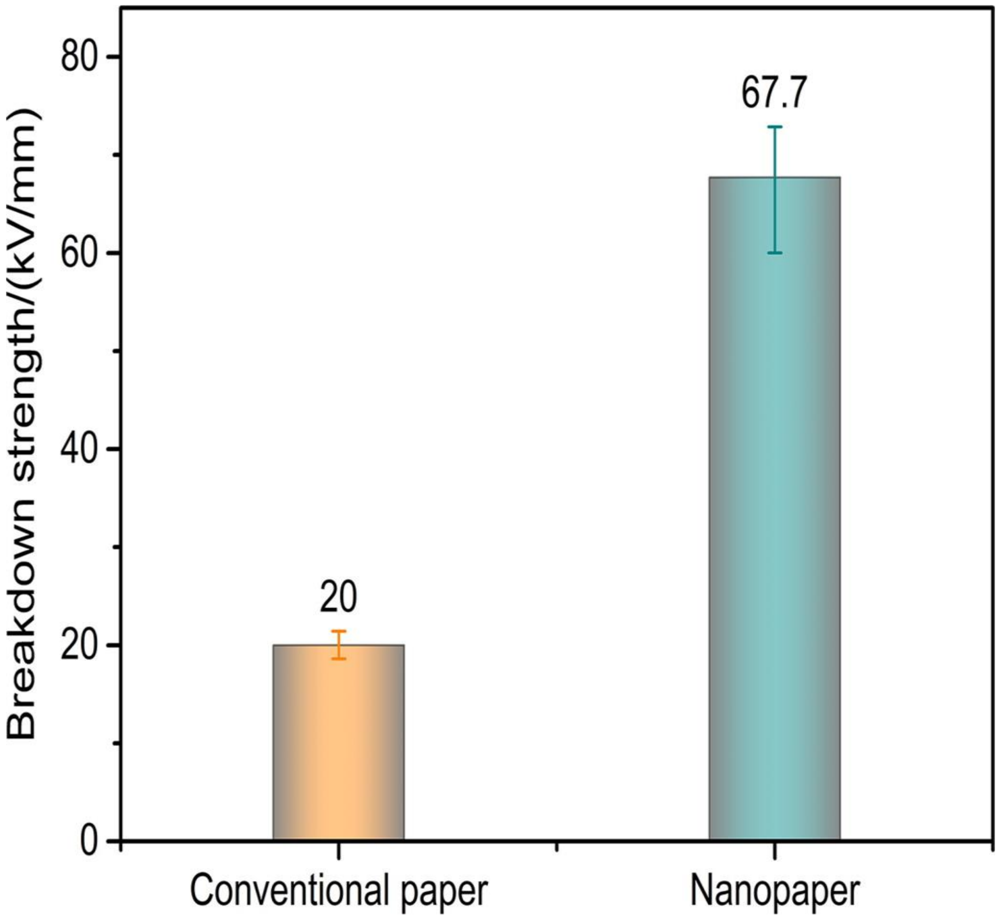

Figure 1- DC breakdown strengths of conventional insulating paper and nanopaper.

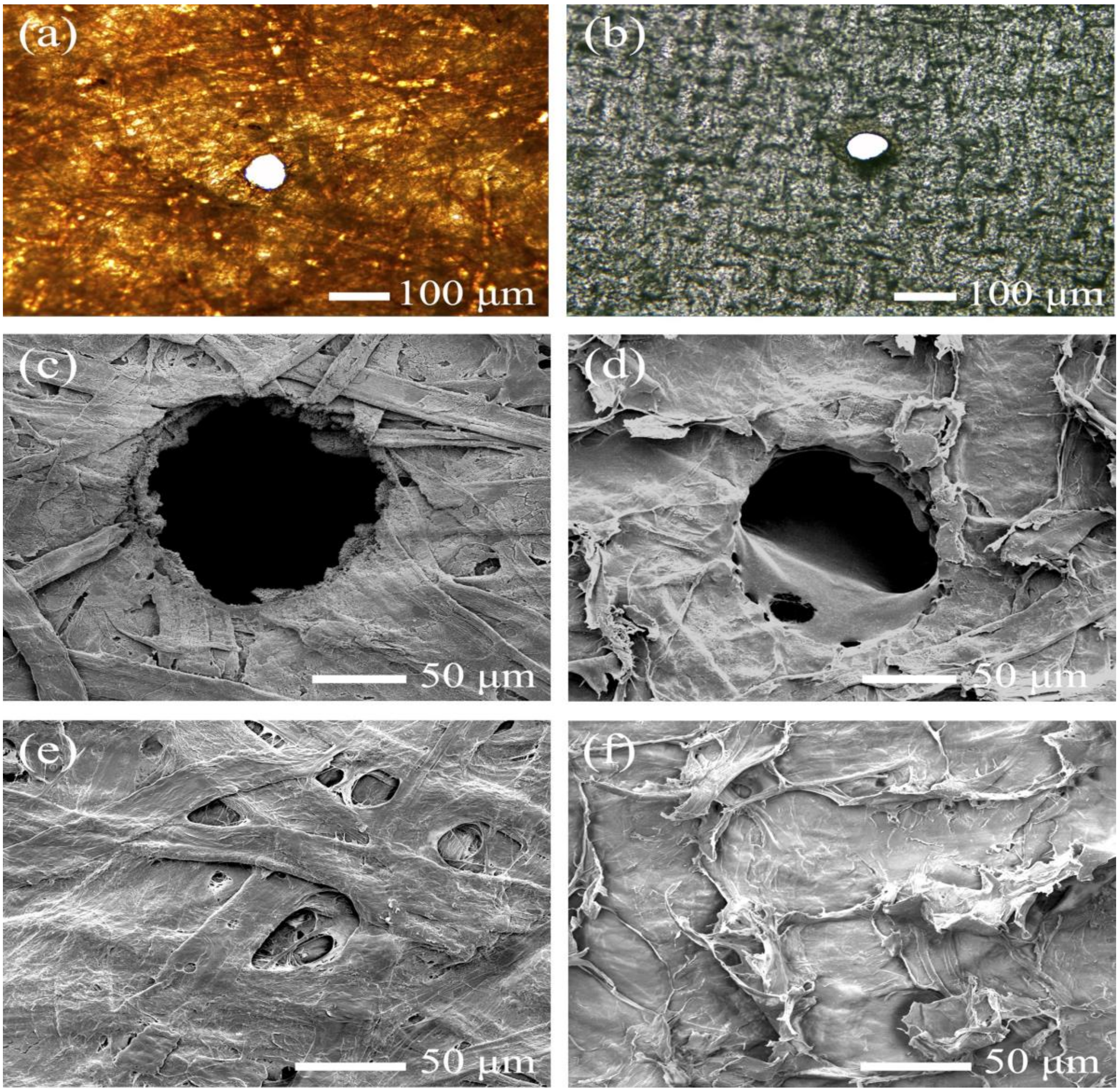

Figure 2 - (a) Optical microscope images of breakdown site in conventional paper. (b) Optical microscope images of reakdown site in nanopaper. (c) SEM images of breakdown site in conventional paper. (d) SEM images of breakdown site in nanopaper. (e) SEM images of conventional paper. (f) SEM images of nanopaper.

Since paper can be regarded as a composite material composed of cellulose fibers and air voids. Properties of wood fibers and the porous structure probably have a great effect on the breakdown behaviors. Therefore, the following discussion will focus on these two aspects. Because nanofibers are prepared from regular wood fibers, chemical structures and properties of nanofibers and wood fibers are almost the same.[7] Consequently, difference in fiber properties is less likely to be the reason for the increased breakdown strength. Porous structure is normally described by porosity and pore size distribution. Porosity of conventional paper or nanopaper can be calculated by

$$P = 1 - \frac{p(samle)}{p(cellulose)}$$

Where p is porosity; ρ_{sample} and $\rho_{cellulose}$ represent the densities of test sample and cellulose fiber, respectively. Density of cellulose fiber is usually assumed to be 1.53 g/cm^3.

Conclusion

In summary, breakdown strength of nanopaper was evaluated and compared to that of conven- tional insulating paper. Results show that breakdown strength of nanopaper is dramatically enhanced to 67.7 kV/mm, which is more than two times higher than that of conventional paper. Diameters ofair voids in conventional paper and nanopaper are 1.7 µm and 2.8 nm, respectively. The good agree- ment between the experimental data and the calculated values indicates that the increased breakdown strength of nanopaper is mainly due to the decreased pore size. Because of its outstanding breakdown strength, thermal and mechanical properties, nanopaper is considered to be a promising material forelectrical insulation in ultra-high voltage electrical apparatus.

In addition, in the second reviewed article compared two types of nanofibrilated cellulose nanopaers: Two types of CNC, prepared by TEMPO-oxidized (T-CNC) and sulfuric acid hydrolysis (S-CNC) respectively, were used as nano-additive in the insulating paper. The functional groups and crystallinities of the insulating paper were characterized by Fourier transform infrared spectroscopy (FTIR), X-ray diffraction (XRD), and scanning electron microscopy (SEM). To achieve a comprehensive understanding of the effect of CNCs, the performance including tensile strength, breakdown behavior, and oil absorptionrate of insulating paper were measured and analyzed. Also, the effect of pulp properties onthe properties of insulating paper containing CNC were investigated.

The preparation process of the nanopaper: The dry unbleached kraft softwood pulp was soaked in deionized water for 12 h. The soaked pulp was refined by a PFI beater (KRK, Tokyo, Japan) to approximately 30 Schopper-Riegler freeness (°SR). The 0.5 wt% pulp suspension was transferred to a Rapid-Köthern sheet former (Xi'an papermaking machine Co., Ltd, Xi'an, China) to make a handsheet with a basis weight of 80 g/m^2 according to the ISO 5269-2 (2004). Finally, theinsulating paper were obtained after drying at 105 °C for 15 min.

Analyzing if this two types of nanopapers The XRD patterns investigations of insulating paper containing different CNCs were measured on a D/MAX2200X X-ray diffractometer (Tokyo, Japan) with a Cukαradiation source energized at 45 kV. Measurements were collected in the 2θ range from 10° to 50° at a rate of 1°/min. The measurement resolution was 0.02°. The peak height method was used to calculate the crystallinity index (*CI*) (Martins *et al.* 2011). The equation is:

$$CI = \frac{I002 \text{ x } IAM}{I002} \text{ x100\%}$$

In this equation, *CI* expresses the relative degree of crystallinity, I 002 was the intensity of the 002 crystalline peak, and IAM was the intensity of the amorphous halo. All the measurements were carried out at least in duplicates. The software of MDI Jade and Origin were used to process the XRD curve.

AC breakdown voltage of insulating paper was measured using an HT-5/20A breakdown voltage tester produced by Guilin Electric Research Institute Co. Ltd. (Guilin, China) according to the IEC 60243-3 (2001). The electrode consists of two metal cylinders,where one edge is inverted into a circular arc with a radius of 3 mm ± 0.2 mm. One of theelectrodes had a diameter of 25 mm ± 1 mm and a height of 25 mm, and the other one was75 ± 1 mm in diameter and 15 mm in height. The AC breakdown voltage in air wasmeasured at room temperature in the air, and the AC breakdown voltage in oil wasmeasured using the insulating oil as the dielectric surrounding the equipment. The size ofthe paper samples was 75 mm × 75 mm, which was large enough to prevent surface flashover. For each kind of insulation paper, eight measurements were taken.

The TEM of two kinds of CNC are shown in Fig. 1. It can be observed that the T-CNC was thin and short. The length (*L*) and diameter (*D*) of T-CNC was 150±50 nm, and 30±10 nm, respectively, and the aspect ratio (*L*/*D*) was 5 to 10. The S-CNC had the characteristics of coarse and long, with an *L* value of 250±50 nm, a *D* value of 50±20 nm, and an *L*/*D* ratio of 4 to 10. Both kinds of CNC had a certain agglomeration, which was caused by poor stability of CNC suspension in solution.

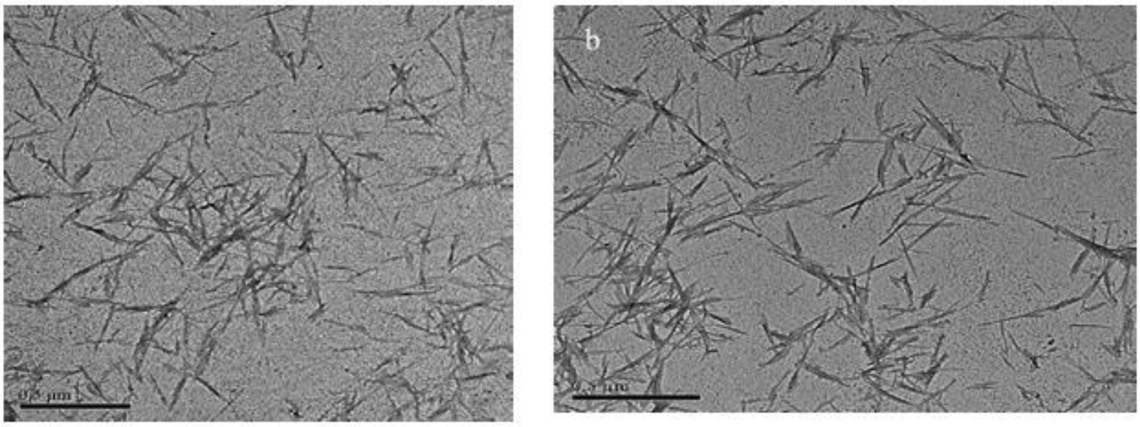

Figure 3- TEM of T-CNC (a) and S-CNC (b)

Spectral Analysis

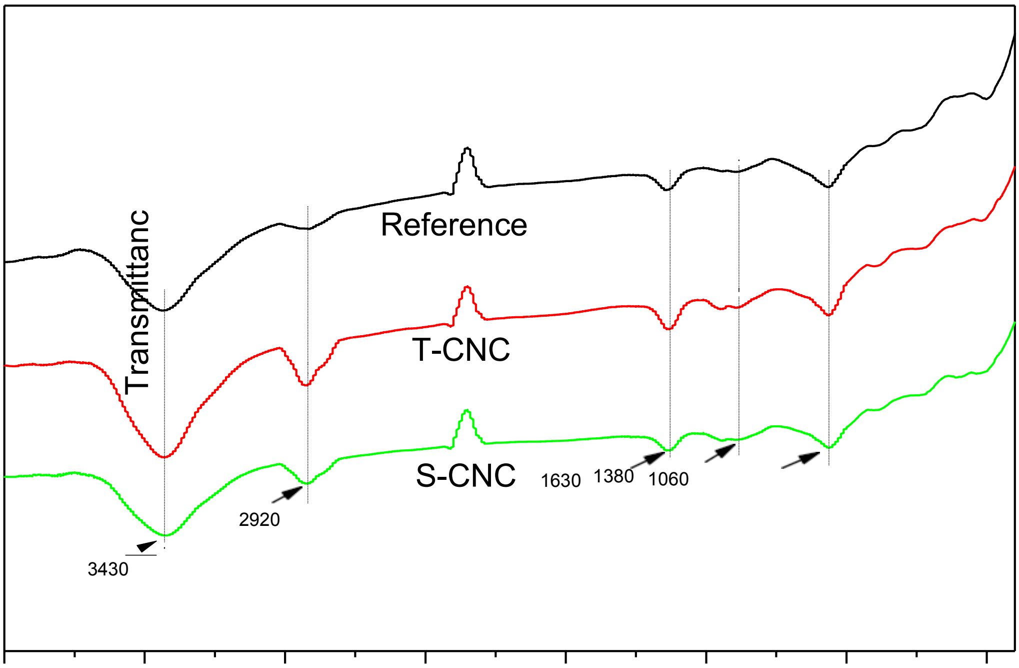

Figure 4- FTIR spectra of reference insulating paper and insulating paper containing T-CNC and S-CNC

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