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Moisture and Temperature Effects on the Dielectric Spectrum of Transformer Pressboard

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Abstract: The dielectrometry spectrum of pressboard is a function of its temperature and moisture content. In transformer pressboard, it has been shown that the dielectric spectrum does not vary in shape with temperature and moisture content, but that there is a shift in amplitude and frequency. Thus it is possible to create a master curve, with appropriate temperature correction factors, containing information about the moisture contents from transformer pressboard dielectrometry measurements. Extensive measurements of dielectric properties of oil-free transformer pressboard as a function of nine moisture levels (0-5.7 %) and five temperature levels (30-70°C) were conducted in order to quantify effects that will allow the prediction of moisture content of insulation by measuring its dielectric spectrum, thus allowing an on-line non-destructive moisture measurement method in pressboard. A dielectric model for biological tissue is adopted for the cellulose-structured pressboard. The master curve is found by fitting the data to the model. The paper presents measured curves that show similar trends as reported in the literature. In addition, new quantitative analysis is presented for oil-free pressboard.

Introduction

The complex dielectric permittivity of pressboard, $\varepsilon^* = \varepsilon' - j\varepsilon''$, is a function of its temperature, moisture content, and frequency. The real part of the complex permittivity gives the permittivity, while the imaginary part characterizes the power dissipation in the material. In general, both permittivity and conductivity increase with temperature. The conductivity of the solid insulation can change up to three orders of magnitude between 0°C and 80°C [1].

In transformer pressboard of medium and low humidity, it has been shown that the dielectric spectrum does not vary in shape with temperature and moisture content, but there is a logarithmic shift in amplitude and frequency. Research conducted by Y. Sheiretov at MIT [2], Jonscher et al at Chelsea Dielectrics Group in the UK [3], and Nettelblad et al at ABB [4] suggest the existence of such a master curve. This paper presents a master curve with appropriate temperature correction factors, containing information about the moisture contents from transformer pressboard dielectrometry measurements.

Extensive measurements of dielectric properties of transformer pressboard as a function of moisture and temperature were conducted in the interest of quantifying effects that will allow the prediction of moisture content of insulation by measuring its dielectric spectrum, thus allowing an on-line non-destructive method. From oil-free pressboard measurements, it can be observed that a master curve does exist. Similar tests have been done by Nettelblad [4] for oil-free cellulose, but no quantitative relationship is given. Nettelblad's results exhibit a very similar shape to our measured results discussed in this paper.

Measurements for Oil-Free Pressboard

Measurement Technique

The pressboard is placed in a parallel-plate capacitor structure whose complex impedance is measured. The values of the complex permittivity of the material, averaged across the thickness, were obtained from the complex admittance Y according to

$$\varepsilon^* = Yd / j\omega A = (G + j\omega C) \cdot d / j\omega A = \varepsilon' - j\varepsilon'' \quad (1)$$

where d is the electrode gap, A is the electrode area, G is the AC conductance between electrodes, and C is the capacitance between electrodes. Once a quantitative mapping is established for dielectric properties as a function of moisture and temperature, dielectric measurements can be used to continuously monitor the moisture distribution in the transformer insulation.

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Hi-Val transformer pressboard manufactured by EHV-Weidmann Inc. is used for all experiments. The 1.7 mm thick pressboard was placed between a parallel-plate sensor. The test cell was then placed in the test vessel whose temperature and moisture levels were monitored and controlled.

Temperature and relative humidity were monitored in the vessel. The relative humidity inside the vessel was varied in order to achieve different moisture contents of the pressboard. The moisture content in the pressboard is estimated using Jeffries' curves [5] by measuring the relative humidity in the test vessel. Oil-free measurements were taken at the moisture and temperature levels shown in Table 1.

Table 1 Moisture and temperature levels for measurements performed for oil-free pressboard.

Moisture Level (%)	0, 0.6, 1.1, 1.9, 2.0, 2.3, 2.6, 3.2, 5.7
Temperature (°C)	30 (35), 40, 50, 60, 70

Measurement Results

Dielectrometry data was collected for the five temperatures at the nine moisture levels in Table 1 for forty-five data sets in all. Data of different moisture levels at the same temperature were also compared. Both ε' and ε " increase as moisture and temperature are increased. All results are plotted in 3-D in Figure 1 and Figure 2. It is observed that a general shape is common to all temperatures and moisture levels.

Discrete logarithmic frequency shifting with an increment of 0.1 in $\log_{10}(f)$ of all forty-five measured oil-free pressboard data sets to minimize least square differences confirm the existence of a master curve.

Master Curve Model

In order to find an analytical form for the master curve to analytically relate moisture level to its dielectric spectrum at a given temperature, various analytical models were explored. A polynomial fit is easiest and can fit the data fairly well at the measured frequency. However it blows up at high frequency, and has no physical meaning. A time invariant RC circuit model does not fit the dispersive nature of the pressboard. Even simple dielectric models such as the low frequency dispersion model in [6] would not account for the double inflection points in the measurements.

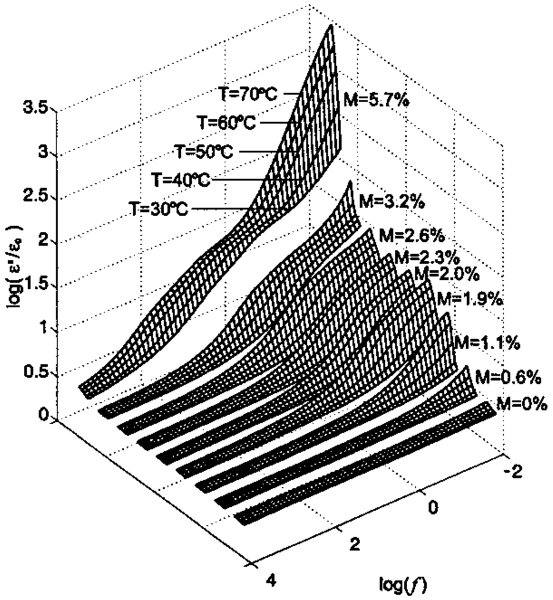

Figure 1: A full spectrum of ε' obtained for nine moisture levels and five temperatures.

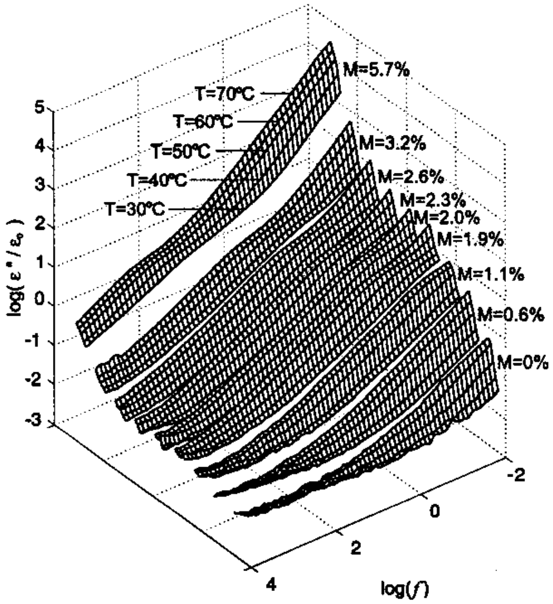

Figure 2: A full spectrum of ε" obtained for nine moisture levels and five temperatures.

The complex dielectric permittivity has the following relationship with the complex susceptibility

$$\varepsilon(\omega) = \varepsilon_0(1+\chi^*(\omega)) = \varepsilon_0(1+\chi'(\omega) - j\chi''(\omega)) \\ \equiv \varepsilon'(\omega) - j\varepsilon''(\omega) \quad (2)$$

Helgeson [7] considered different polarization processes with dielectric response functions described by such models as: Curie-von Schweidler, General Response, Stretched Exponential, Stretched Exponential+General Reponse, Debye. Most of these functions have analytical Fourier transforms and their shapes are shown in Figure 3.

None of the above individual models in Figure 3 will give the shape of our experimental curves.

It was observed that the complex permittivity data for Jade leaves by Hill et al.[8] have similar double inflection features to the data presented in this paper. Furthermore, three elements in Hill's model may well likely be good representations of the cellulose/porous pressboard filled with moisture molecules, similar to biological cell tissue. Therefore, the model developed by Hill et al. was used to model the test data here.

Hill et al.'s model consists of three elements in series:

1. Low frequency diffusion described by relative permittivities ε_{diff} and ε_b (capacitors in parallel).
2. Low frequency dispersion for the single series capacitor described by relative permittivities ε_{qdc}.
3. A lossy bulk dielectric described by the RC parallel structure with constant conductivity σ_p and relative permittivity ε_p. The model parameters are further described by the following relationships:

$$\varepsilon_{diff} = \varepsilon_d (j\omega/\omega_d)^{n_d - 1} \quad (3)$$

$$\varepsilon_{qdc} = \varepsilon_q \left((j\omega/\omega_q)^{n_q - 1} + (j\omega/\omega_q)^{-p} \right) \quad (4)$$

where n_d, n_q, and p have values between zero and one. Other model parameters ε_b, ε_p, and σ_p are frequency independent.

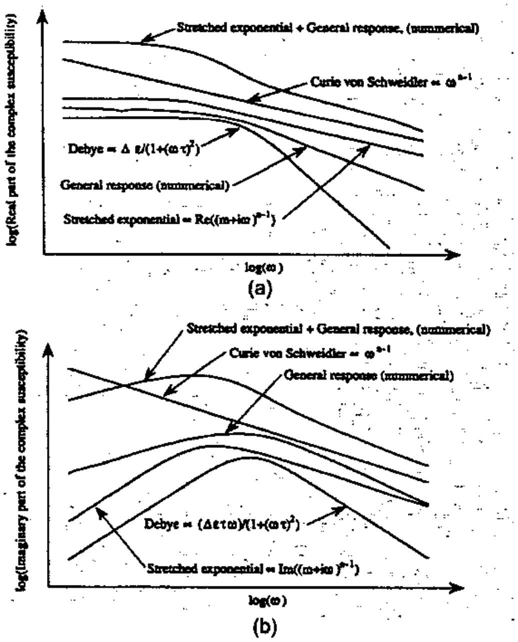

Figure 3: The real and imaginary parts of the complex susceptibility for different models of a dielectric material in the frequency domain [7].

Parameter Estimation

The goal is to define the master curve and to establish a unique relationship among temperature T, moisture M, and complex permittivity of the pressboard at given frequency f and the equivalent complex permittivity value on the master curve at a shifted frequency f_{shift}. This relationship is connected by the shifted frequency f_{shift}, defined to be a function of T, M and f as:

$$f_{shift} = f \cdot 10^k \quad (5)$$

where

$$k = E_a \cdot (1/T - 1/T_0)/\kappa + k_1(M - M_0) \\ + k_2(M - M_0)^2 + k_3(M - M_0)^3 \quad (6)$$

and E_a is the thermal activation energy, κ is Boltzmann's constant, T is the temperature in °Kelvin, T_0 is the reference temperature and chosen to be 323°K (50°C), M is the moisture concentration in percent, and M_0 is the reference moisture concentration and in this case is 2.0%.

Using a constrained minimization routine of Matlab, *constr*, the parameters of the model are listed in Table 2 and the shifting parameters are listed in

Table 3 by fitting the experimental data. The master curve found and the shifted data to reference temperature and moisture are shown in Figure 4.

Table 2: The parameters of the master curve model by a least squares fit of the experimental data.

ε_d	ω_d (rad/s)	n_d	ε_b	ε_q
1.27	0.455	0.045	30.7	2.96
ω_q (rad/s)	n_q	p	σ_p (pS/m)	ε_p
4.17	0.996	0.656	3.48×10^4	1.16×10^4

Table 3: The parameters of the logarithmic shifting for the experimental data to fit to the master curve in Figure 4.

E_a/κ(°K)	k_1	k_2	k_3
3.79×10^3	-1.23	0.218	-0.0348

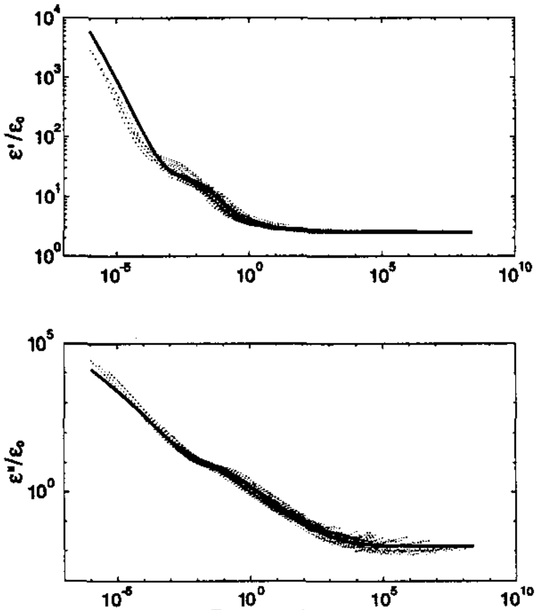

Figure 4: Master curve for oil-free pressboard. The solid line is the curve calculated from the model. The dotted lines are the data points of Figure 1 and Figure 2 shifted in frequency according to the parameters in Table 3 with (6).

Conclusion

To relate measurable dielectric properties to absorbed moisture, the moisture and temperature effects on the dielectric spectrum of oil-free pressboard were measured using a parallel-plate geometry sensor for nine moisture levels and five temperature levels. The results agree with other literature previously reported. A dielectric model for biological tissue is adopted here for cellulose structured pressboard. A master curve was found relating dielectric properties to moisture concentration and temperature by fitting the data to the model.

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