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PS2: Materials

Water Saturation Limits and Moisture Equilibrium Curves of Alternative Insulation Systems

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SUMMARY

A method developed for establishing moisture equilibrium curves for any combination of liquid and solid insulation is presented in this paper. Moisture saturation curves for natural and synthetic esters have been presented in the temperature range up to 140°C together with curve for mineral oil as a reference. Sorption isotherms have been established for cellulose based and aramid fiber based materials. Eventually, the moisture equilibrium diagrams have been created for given combinations of solids and liquids.

Moisture equilibrium curves have been created for combinations of mineral oil and ester fluids with aramid fiber based papers and boards, as they are commonly used in alternative insulation systems. The new curves give information on moisture distribution within the alternative insulation systems and may be critical for setting the material choices, design rules and maintenance guidelines for equipment using these combinations. Only then the materials could be used optimally and their specific characteristics could bring full range of benefits to the equipment. Also the condition monitoring and diagnostics for the purpose of asset management will be more reliable when these new characteristics are used.

It has been observed that insulation components made of aramid insulation may have lower water content comparing to cellulose based conventional materials at the same water content measured in dielectric liquid. As a result, the performance of aramid insulation components may be less sensitive to moisture in oil (aging processes, dielectric strength, partial discharge performance) comparing to conventional systems based on cellulose.

KEYWORDS

moisture equilibrium, water content in liquid/solid, alternative insulation system, ester fluid, aramid insulation

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1. DEFINITIONS, EXPERIMENTAL AND MEASUREMENT SETUP

Two concepts are used to describe the water content of a material. The first is water content by weight, which is often called absolute moisture. As mineral oils cannot dissolve much water, a convenient unit is ppm, which translates to µg water in one gram of oil. Paper can absorb much more water and therefore percent by weight is used that is based on the mass of a dry sample. The other concept of describing moisture content is based on water saturation, the vapour pressure compared to the partial pressure at saturation. This is often called relative moisture content (RH). It should be noted that the values are temperature dependent. Absolute moisture content is measured by coulometric Karl-Fischer titration. Oil samples are injected directly into the measurement cell with a syringe. Samples of solid insulation are heated in vials in an oven at 170°C and the water vapour is transferred by dry air with a tubing system into the reaction cell. Relative moisture content is measured with capacitive sensors and the unit is percent. They consist of a capacitor with a very hygroscopic dielectric where water ingress is reflected in a change of permittivity and thus capacity. They work in gases as well as liquids.

2. WATER SATURATION LIMITS OF INSULATING LIQUIDS

To obtain the lowest possible spread of the data values, it is important that the oils are as wet as possible. Because the water absorption and thus the saturation curves of the insulating liquids are dependent on the temperature, several samples were analyzed at different temperatures. The investigations are made for temperatures up to 140°C. They are necessary because esters are also suitable for use at a higher temperature range. The samples up to 100°C were heated and moistened in a climate chamber, which could heat up to 100°C. The relative moisture can be controlled up to 100% RH, although at high temperature the maximum was 45% RH. For temperatures above 100°C they were heated in a sealed container on a hot plate and moistened by adding a calculated amount of water. The relative humidity of the oil was determined with the capacitive sensor.

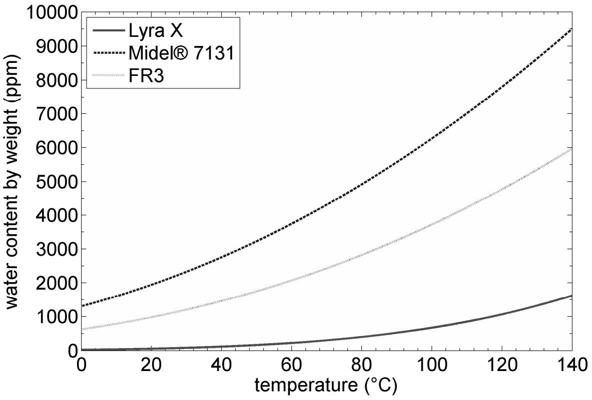


Figure 1. *Water saturation curves for different insulating liquids*

For the mathematical description of the saturation curves a function can be used as seen in equation (1) [1]. . The average deviation is calculated by averaging the relative deviation of each data point from the fitted curve. Figure 1 shows the curve and measurement points for mineral oil, natural ester Envirotemp® FR3™ and synthetic ester Midel® 7131.

$$W_S(T) = a \cdot e^{(-b/T)} \tag{1}$$

In formula (1) W_S is the water saturation limit in ppm for a given absolute temperature in Kelvin. The parameters *a* and *b* are material parameters.

Table 1. *Water saturation parameters for different liquids*

Oil	Parameter a	Parameter b	Avg. deviation
Lyra X	6.013·10^6	3396	11%
Envirotemp® FR3™	4,900·10^5	1821	8.6%
Midel® 7131	4,586·10^5	1602	10.3%

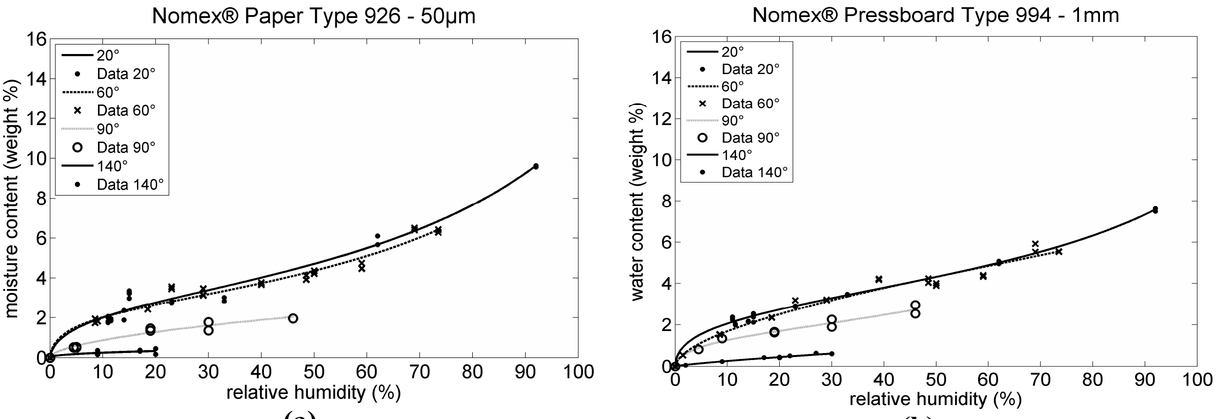
3. SORPTION ISOTHERMS OF SOLID INSULATING MATERIALS

Dried samples of 1mm thick high density (HD) pressboard from Krempel and Nomex® pressboard Type 994 (1 mm) as well as Nomex® paper Type 926 (50µm) were conditioned in the climatic chamber for 24 hours. The relative moisture content of the atmosphere was then slightly elevated each day up to the possible maximum. From each sample the water content was determined by Karl-Fischer Titration in relation to its dry mass. Different materials can have a different shape for their sorption isotherms. Porous materials, like paper and pressboard typically have an S-shaped curve [2]. In order to get a mathematical model a curve has to be found, which makes most sense to fit. In literature the Antoine function (2) has been introduced for these kinds of isotherms [4, 5]

$$f(RH/100) = \frac{C \cdot (RH/100)^{\left(\frac{A}{B}\right)}}{1 + (C-1) \cdot (RH/100)^{A \cdot B \cdot (RH/100)}} \cdot D \tag{2}$$

where *A*, *B*, *C*, *D* are material parameters and *RH* is the value of relative humidity in percent. This function can take three different slopes. In following tables an overview of the determined parameters will be given. Generally Nomex® absorbed circa half the amount of water than cellulosic high density pressboard for sheets of 1mm thickness (Figure 2 b and c). The difference between Nomex® paper Type 926 and Nomex® pressboard Type 994 is rather small, but like the cellulosic counterparts the high density pressboard has somewhat lower moisture content than the paper.

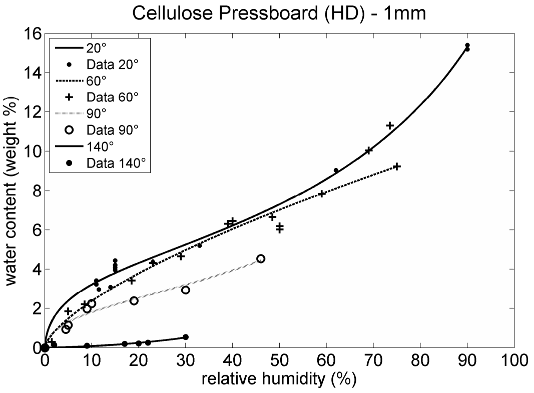
Sorption curves for very high temperatures over the boiling point at 140°C were very difficult to measure. Only small relative humidities could be achieved with the experimental setup. This can be seen in the high average deviation of the 140°C curves in table 2. The average deviation is a mean value of the relative standard deviation of each data point from the fitted curve. It resembles a value that describes the quality of a fit.



(a) **(b)**

Table 2. Parameters for fitting the sorption isotherms

	A	*B*	*C*	*D*	*deviation*
HD Pressboard - 1mm					
20°C	0.09861	0.1619	0.007038	19.80	6.3%
60°C	0.08298	0.1227	0.018890	12.94	10.1%
90°C	0.06369	0.0847	0.001205	20.69	11.1%
140°C	0.37580	0.1832	0.001599	98.95	32.8%
Nomex® Pressboard Type 994 - 1mm					
20°C	0.7110	1.3590	0.42	8.684	4.1%
60°C	1.1830	1.9750	0.87	7.069	5.5%
90°C	0.1533	0.2436	0.01	8.494	6.1%
140°C	0.1941	0.2429	1.00	1.609	11.2%
Nomex® Paper Type 926 - 50µm					
20°C	0.0427	0.0705	0.0017	11.50	14.7%
60°C	1.8610	3.2130	0.1751	33.38	6.3 %
90°C	0.4956	0.8869	1.0000	3.152	9.7%
140°C	0.1398	0.3230	0.9116	0.667	27,7%



(c)

Figure 2. *Sorption curves for solid insulation*

4. CONSTRUCTION OF MOISTURE EQULIBRIUM DIAGRAMS

In order to create the moisture equilibrium diagrams, it is assumed that the relative humidity of the oil and relative humidity of the preparation atmosphere lead to the same absolute moisture content in the solid insulation. Thus it is possible to combine the moisture isotherms of oil and the solid material sorption curves into moisture equilibrium diagrams.

The sorption diagrams were measured at temperature of 20°C, 60°C, 90°C and 140°C. The missing curves for temperature between the measured values at 40°C, 80°C, 100°C and 120°C were determined by a shape-preserving interpolation in Matlab. With these measured and calculated values the complete diagrams could be calculated.

Fig. 3 presents the classical diagrams for conventional insulation systems built of cellulose and mineral oil. In all these kinds of diagrams the dominant parameter is the temperature. Perfect thermodynamic and hydrokinetic equilibrium is assumed. As the investigated esters have completely different moisture solubility and the aramid material has somewhat different sorption curve, the new diagrams are different. At first they seem similar, but one should note the completely changed x-axis scale (Fig. 4).

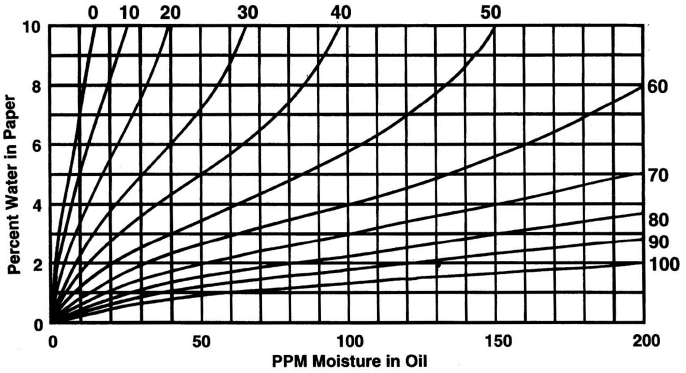
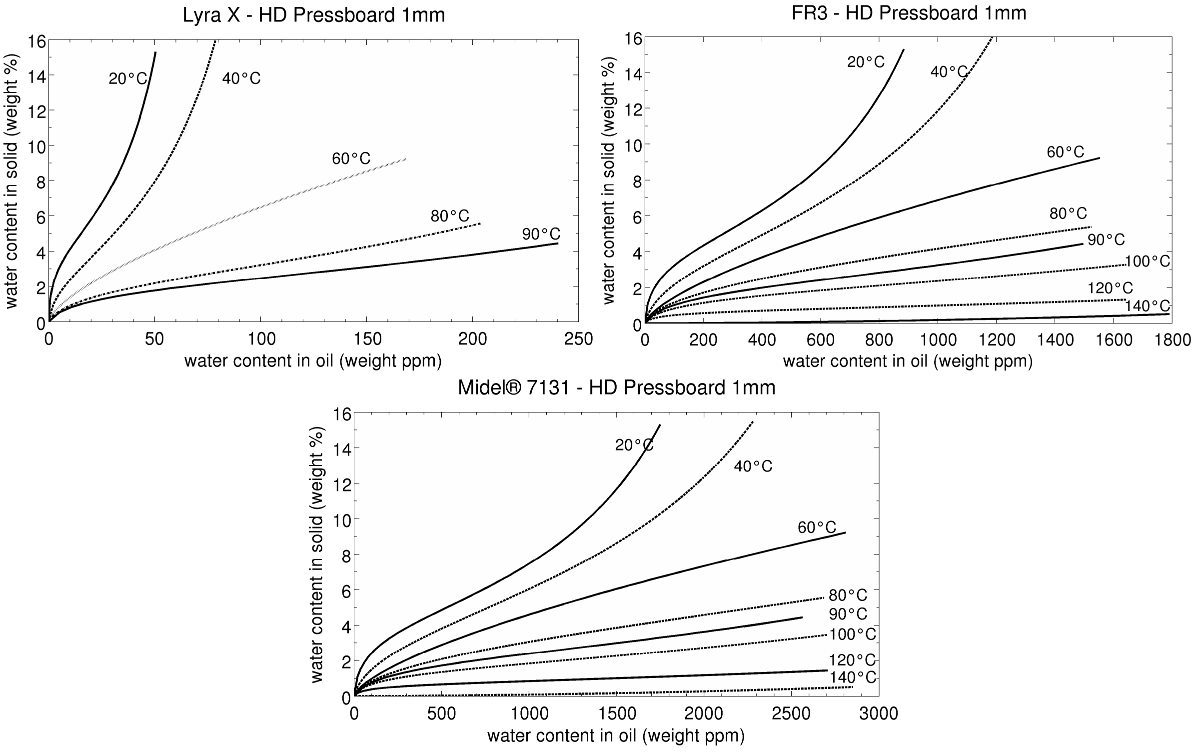


Figure 3. *Moisture equilibrium diagram based on Oommen for mineral oil and cellulose paper [3]*


Lyra X - HD Pressboard 1mm

FR3 - HD Pressboard 1mm

Midel® 7131 - HD Pressboard 1mm

Figure 4. *Moisture equilibrium diagrams for various liquids in combination with high density pressboard*

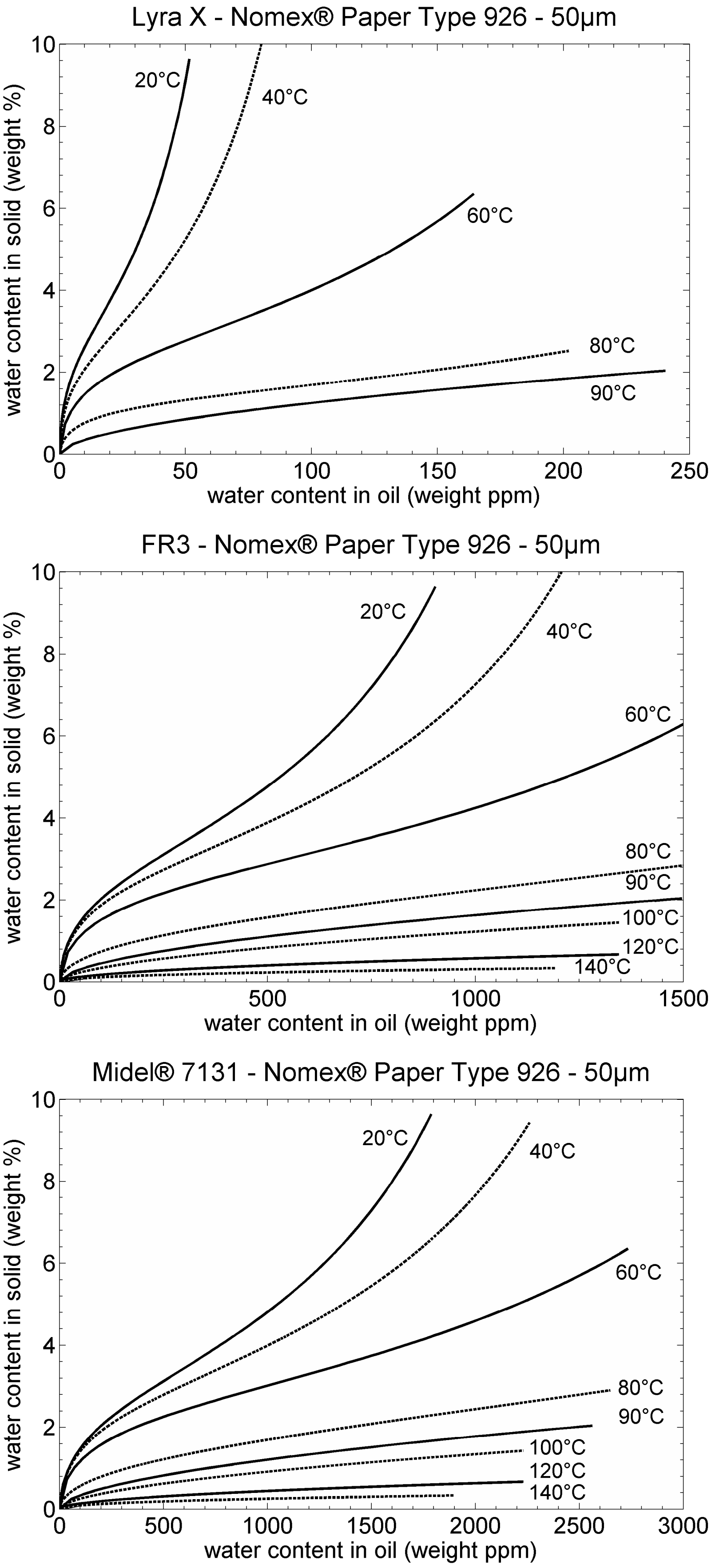
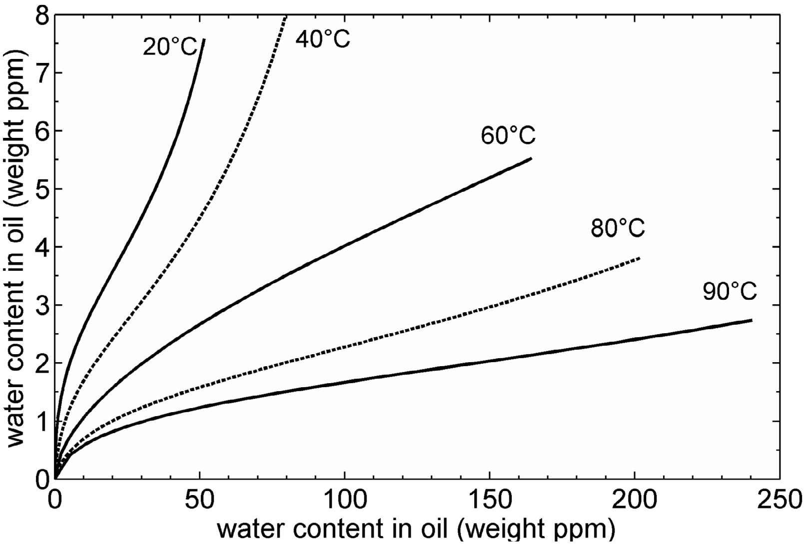
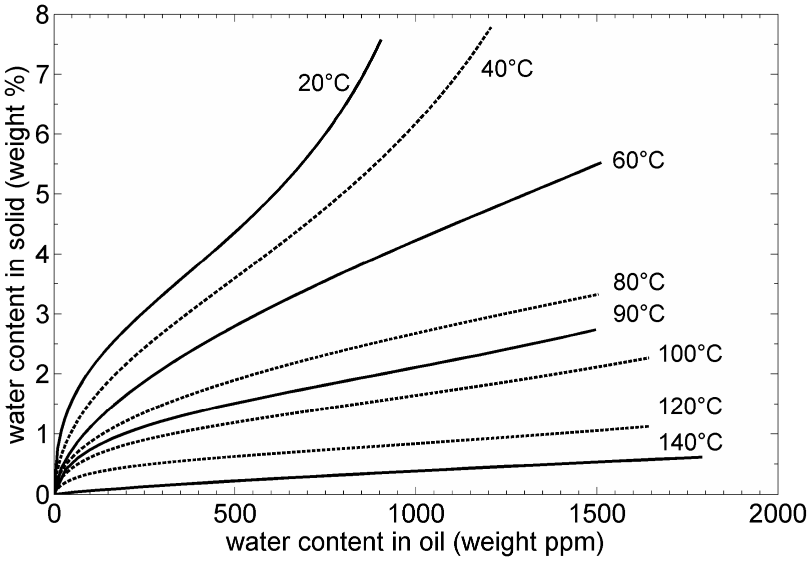


Figure 5. *Moisture equilibrium diagrams for Nomex® paper in combination with different liquids*


Lyra X - Nomex® Pressboard Type 994 - 1mm


FR3 - Nomex® Pressboard Type 994 - 1mm

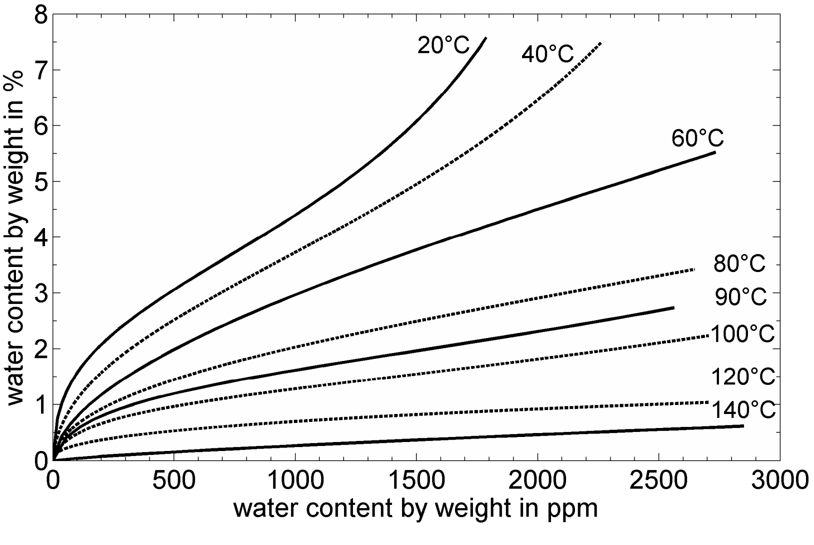

Midel® 7131 - Nomex® Pressboard Type 994 - 1mm

Figure 6. *Moisture equilibrium diagrams for Nomex® pressboard in combination with different liquids*

5. DISCUSSION ON NEWLY CREATED EQUILIBRIUM CURVES

Moisture in transformer insulation can affect transformer performance in several ways:

- negative influence on development of partial discharge,
- reduced dielectric strength,
- cause bubbling effect,
- age the insulation prematurely.

The first three effects can lead to premature failure of otherwise good transformer; the last one could shorten transformer life expectancy.

There are no direct methods of measurement moisture levels in transformer solid insulation; hence, the right method for estimation of water content in solid based on water in liquid is very important. The diagrams derived above enable estimation of current condition of liquid-immersed insulation system based on one measurement of water content in oil. The accuracy of new derived curves may need to be further verified. Also, using equilibrium curves requires making a number of assumptions related to water and temperature distribution within the transformer volume and related to steady state condition. Still, they may become an important tool for analysis of average moisture levels in various insulation systems.

As seen in Fig. 4-6, the distribution of moisture between liquid and solid is very much different for different fluids. Due to their higher water solubility, esters accept much more water comparing to mineral oil. With the same moisture content in solid insulation, the moisture content observed in esters is much higher that in mineral oil. For example, at 60°C and moisture in high density cellulose board being at the level of 4%, the water content in liquids would be:
~50 ppm in mineral oil,
~430 ppm in FR3,
~800 ppm in Midel 7131.

The difference is also observed between different solid insulations. The study shows that aramid fibre based materials may absorb different moisture content comparing to cellulose based materials. Table 3 shows example of expected moisture levels in insulation components at 40 ppm water in mineral oil. There is no significant difference observed in moisture contents in papers, but there is some trend visible in high density board comparison. Independent on temperature the moisture in aramid board is always lower than in cellulose. This could mean that operation of a transformer built with aramid board would be less sensitive to moisture in oil. This would have positive impact on the dielectric performance of the material. The material dielectric strength would be less affected, the probability of partial discharge related to existing moisture would be lower, and the aging of material would not be supported as much as in case of cellulose board that not only absorbs more moisture, but also its aging process is accelerated by water.

Table 3. *Comparison of moisture content in different solid insulation materials (at 40 ppm moisture content in mineral oil)*

Temperature	Cellulose paper	Aramid paper	Cellulose board	Aramid board
20°C	10.0%	6.6%	10.2%	5.6%
40°C	4.3%	4.3%	6.2%	3.8%
60°C	2.3%	2.5%	3.6%	2.4%
80°C	1.4%	1.2%	2.0%	1.4%
90°C	1.1%	0.8%	1.7%	1.1%

Further evaluation of presented results is required in terms of their usability not only as a tool for diagnostics of transformer and condition assessment but also in optimisation of transformer design. For example, well aged wet transformers may face the situation when relatively high water content accumulates in lower cold areas of the tank. Dielectric strength of oil is getting significantly reduced in those areas together with solid insulation components (e.g. barriers). As seen in Table 3, the difference between moisture content between cellulose board and aramid board at 20°C and 40 ppm of water in oil is 10.2% vs. 5.6%. This significant difference could have an impact on the dielectric strength of the barrier in critical location as described. Hence, to ensure long time reliable operation of transformer it might be useful to consider moisture migration phenomena for given insulation systems or at least for selected components of the insulation system.

6. CONCLUSIONS

This paper described the methodology on how to determine saturation curves for dielectric liquids and sorption isotherms for solid insulating materials, so that they could be later combined into the moisture equilibrium curves for given combinations of insulating materials. The curves derived for combination of cellulose board and aramid materials with alternative fluids may contribute to improved diagnostics solutions for transformers using alternative insulation systems (e.g. hybrid insulation with cellulose and aramid combined). With increasing number of transformers using these kind of insulation systems the curves developed may become important component for their proper condition monitoring and management.

Information from the created diagrams may be also used for evaluating different design concepts in terms of material selection. Further work could be recommended on how the results obtained could be applicable in optimization of transformer designs with regards to phenomena of moisture migration between solid and liquid insulation materials.

BIBLIOGRAPHY

[1] Cigre Brochure 349, "Moisture equilibrium and moisture migration within Transformer insulation systems", Working Group A2.30, June 2008

[2] S. Brunauer, P.H. Emmett, E. Teller "On the theory of the adsorption of van der Waals gases", Journal of the American Chemistry Society

[3] T. V. Oommen, "Moisture Equilibrium Charts for Transformer Insulation Drying Practice", IEEE Transaction on Power Apparatus and Systems, Vol, PAS-103, No. 10, October 1984

[4] V. G. Arakelian and I. Fofana, "Water in Oil-Filled High-Voltage Equipment Part I: States, Solubility, and Equilibrium in Insulating Materials", IEEE Electrical Insulation Magazine, July/August 2007 - Vol.23, No. 4

[5] V. G. Arakelian and I. Fofana, "Water in Oil-Filled High-Voltage Equipment Part II: Water Content as Physicochemical Tools for Insulation Condition Diagnostic", IEEE Electrical Insulation Magazine, September/October 2007 - Vol.23, No. 5

[6] M. Koch, S. Tenbohlen, T. Stirl, “Diagnostic Application of Moisture Equilibrium for Power Transformers”, IEEE Transactions on Power Delivery, Vol. 25, No. 4, October 2010, page 2574-2581

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