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Dynamic moisture diffusion in transformer winding insulation

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Abstract. Wind power production is intermittent due to varying wind conditions. This leads to frequent temperature changes in the wind farm transformers, which in turn affects the lifetime of the transformer winding insulation. To extend the lifetime through prediction of effects from dynamic loading, new models for degradation of insulation systems are needed. This article is laying the foundations of a model for dynamic moisture migration in the winding insulation of wind farm transformers. Relevant equations and approximations are presented and an experimental setup for laboratory testing of transformer insulation ageing related moisture migration under dynamic loading is described. The demonstration experiment clearly shows moisture migration through paper layers in a simple physical winding insulation model. As the ageing of cellulose is very moisture-dependent, the migration should clearly be included in models of ageing under dynamic load.

Symbols and abbreviations

Listed in the order of first appearance.

DP	Degree of Polymerisation
A	A pre-exponential factor in ageing equations.
E	Activation energy in ageing equations
R	The molar gas constant
T	Temperature (may be in K in some equations and °C in others).
t	Time
ρ	Moisture density (weight moisture per weight cellulose or oil)
$\boldsymbol{J}$	Moisture migration flow vector
D	Diffusion coefficient or diffusivity
P	Equivalent vapour pressure above moist oil or paper
W	Weight of moisture per weight of paper
λ	A material constant in a diffusivity formula
P_s	P at saturation
Φ_q	Heat flux
k	Heat conductivity
ρ_p	Density of moist, oil-impregnated paper
c_p	Heat capacity of moist, oil-impregnated paper at constant pressure
W_{oil}	Weight of moisture in oil per weight of oil
$W_{oil\ rel}$	Relative moisture saturation in oil (W_{oil} divided by W_{oil} at saturation)
RS	$W_{oil\ rel}$, but in %. Equivalent to relative humidity (RH) in air.

1. Introduction

Wind farms have frequent changes in production due to varying wind conditions. Thus, wind farm transformers experience frequent temperature changes. Electrical insulation in transformers is usually made from cellulose, including the paper functioning as winding insulation. Ageing rate of this cellulose increases with increasing temperature and increasing moisture content. Furthermore, the cleavage of the polysaccharide chains of which cellulose consists during ageing produces water and carboxylic acids, which also accelerates ageing. Temperature and moisture content varies from place to place in the transformer insulation, even radially locally through the paper insulation on a winding. At equilibrium, moisture in the paper insulation of the transformers will be distributed according to the temperature, with the insulation being drier at higher temperatures. The varying wind conditions ensure that the moisture distribution never reaches an equilibrium, and the moisture is shuffled around in the transformer due to the varying temperature distribution. The rate of ageing of paper insulation increases with increasing temperature and increasing moisture content, so the shuffling of moisture may affect the lifetime of the insulation.

There exists a lot of information about equilibrium distributions [1-11]. [1] is the "classic" set of curves for moisture equilibrium between mineral transformer oil, paper in oil, and air. [2] gives moisture equilibrium curves between wood pulp and air. [3] develops curves for the paper – oil system by using [2] and doing own experiments with the air – oil system. This is tempting because experiments with moisture absorption in oil impregnated cellulose takes very long time at low temperatures [3, 4, 5]. [5] reviews a large number of equilibrium curves and their development methods, in addition to constructing a new set of curves, again by using [2]. It also shows that there are significant differences between the different curves in the literature. [6] measures curves for both new and aged oils and promotes measuring relative moisture saturation instead of absolute moisture in oil for transformer maintenance purposes. [7] is mainly about the rate of water absorption in both non-impregnated and oil-impregnated cellulose. The importance here is that it also shows that moistening cellulose gives the same moisture end result for both non-impregnated and oil-impregnated cellulose, while the time to reach the end result is very different. This justifies making paper – oil curves from separate paper – air and oil – air moisture equilibrium curves. [8] is about ageing of cellulose in transformers and treats moisture equilibrium because moisture is an important ageing accelerator. [9] shows an oil-paper moisture equilibrium curve set in an easy-to-use format. [10] is a comprehensive description of moisture equilibrium in transformers, even including some information about the radial distribution in winding insulation. "Oil" is either exclusively or mainly mineral transformer oil in [1-10]. [11] is one of few works which treats the moisture equilibrium also for natural ester oils.

Less is known about the dynamic distribution under varying load, and this makes it difficult to make models for predicting insulation lifetime, even when the load history is well known. [10] develops some equations for calculating moisture dynamics. Some of them are included here in Chapter 2. Experimental work seems totally absent except for a work which is about moisture dynamics for the purpose of drying transformer insulation which has become wet by e. g. ageing [12].

This article is laying the foundations for a model for the ageing of transformers under dynamic load. It presents essential equations which may be used in such a model, as well as an experimental setup for laboratory testing of transformer insulation ageing under dynamic loading. Experimental results demonstrating radial dynamic moisture distribution in winding insulation are also included.

2. Equations for later modelling work and for analysis of the experiment

The usual measure of ageing of paper is the change in degree of polymerisation (DP). DP is the number of monomers which a polymer (in this case cellulose) on average consists of. An equation describing this ageing is [13]:

$$\frac{1}{DP_{aged}} - \frac{1}{DP_{original}} = Ae^{\left(-\frac{E}{R(T+273)}\right)} \cdot t \tag{1}$$

Here E is known as "activation energy", R is the molar gas constant, T is the temperature in degrees Celsius and t is the time. The factor A contains the effect of moisture and acids. No closed formula depending on moisture and acidity exists. Values of both E and A for a small number of experimental conditions can be found in [14].

Current in a winding generates heat. This is conducted through the insulation to the circulating oil, which acts as a coolant. The heat conductivity is temperature dependent and slightly moisture dependent [15].

At equilibrium conditions, moisture is in principle distributed in such a way that there is constant relative saturation throughout the insulation. However, relative saturation is poorly defined in paper, and it is better to consider it as having a constant equivalent vapour pressure throughout the insulation. There exist experimental curves describing this relationship [1-9, 11], which is non-linear both in temperature and absolute moisture content dependence. Out of equilibrium, the moisture will try to migrate in such a way as to obtain constant equivalent vapour pressure according to the momentary temperature distribution. Diffusion is normally thought of as being driven by a concentration gradient, but the above means that it is also driven by a temperature gradient.

If it is assumed that the temperature changes and moisture migration take place on a time scale which is short compared to the time scale of ageing, the continuity equation for moisture migration may be written without a source term:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot \boldsymbol{J} = 0 \tag{2}$$

Here ρ is the moisture density (weight of moisture per weight of paper), t is the temperature and $\boldsymbol{J}$ is the moisture migration flow vector (vectors are written in bold). Fick's law connects $\boldsymbol{J}$ and the moisture gradient:

$$\boldsymbol{J} = -D\nabla\rho \tag{3}$$

where D is the diffusion coefficient. This is the standard mathematical expression for diffusion, but here diffusion is also driven by temperature differences. This can be handled by a modified "diffusivity", which can be written as [10]:

$$D = \frac{\lambda}{\rho\sqrt{T}} \frac{\partial P}{\partial W} \tag{4}$$

where T is the temperature, P is the equivalent vapour pressure above the moist paper and W is the weight of moisture per weight of paper. While $\partial P / \partial W$ can be deduced from some experimental equilibrium curves, λ, which is a material constant, is generally unknown. Approximations exist, e.g. [10,15]:

$$D = 10.64 \cdot 10^{-12} \cdot P_s \cdot \mathrm{e}^{0.52W} \tag{5}$$

where P_s is the (temperature-dependent) saturation vapour pressure in torr, giving D in m^2/h.

There is also a heat flux:

$$\phi_{\mathrm{q}} = -k\nabla T \tag{6}$$

where k is the heat conductivity, which is a function of both T and W. The internal energy can be written as $u = \rho_p c_p T$ with ρ_p being the density of the moist, oil-impregnated paper and c_p being the heat capacity of the moist, oil-impregnated paper at constant pressure. To a first approximation, both these parameters can be considered to be the same as for dry, oil-impregnated paper since the degree of moisture usually is less than 5% by weight. Using this in a continuity equation for energy, the temperature equation becomes

$$\rho_p c_p \frac{\partial T}{\partial t} - \nabla \cdot (k \nabla T) = 0 \tag{7}$$

Here it has been assumed that there is no heat source within the paper insulation. The heat comes from the copper windings, and the inner paper surface can be assumed to have the same temperature as the winding, to a first approximation. The equivalent for the outer surface towards the flowing oil is not likely to be true: The outer paper surface probably has a higher temperature than the oil. An equation describing the energy transfer between paper and oil has not been found in the literature. Also missing in this equation set is an equation for moisture transfer between the outer paper surface and the oil. A further complication is that the moisture level in the oil depends on the moisture level everywhere in the transformer insulation.

For the analysis of the demonstration experiment it will be necessary to convert from measured relative moisture saturation in an oil pocket to absolute moisture in oil, and further to absolute moisture in paper in contact with that oil. From curves of moisture saturation in oil vs. temperature [10] it has been found that for clean, new naphthenic mineral transformer oil,

$$W_{\mathrm{oil}} = W_{\mathrm{oil\ rel}} \cdot 50.0224 \mathrm{e}^{0.0294724 \cdot T} \tag{8}$$

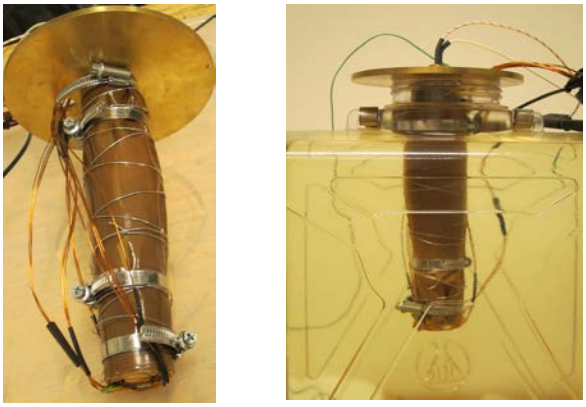
is a good approximation, where rel refers to moisture relative to saturation moisture, equivalent to relative humidity in air. In this equation T is in °C and W_{oil} in ppm weight. Further, from an easy-to-use curve set which is a good approximation in the relevant humidity range (figure 6.3.3.2 in [9], based on figure 23 in [8]), the absolute equilibrium moisture in paper can be approximated as

$$W = \mathrm{e}^{(0.6046 - 0.02767T + 0{,}6152 \cdot \ln W_{\mathrm{oil}})} \tag{9}$$

with W being in percent by weight.

3. Experimental setup

For laboratory testing of the potentially ageing-influencing moisture migration in transformer insulation under dynamic loading, 97 layers of 100 µm thick paper was wound on a 200 mm long brass tube



(a) (b)

Figure 1. The insulated tube with sensors.

(a) The tube, with paper insulation and wires from the sensors.
(b) The tube in place in the oil-containing vessel.

containing an electric heater. One end of the tube was closed. The large number of layers was chosen to ensure that migration would be slow and easy to observe. Four sensors (Sensirion SHT 75) registering relative humidity and temperature were used, with one on the tube (layer 0) and one outside each of these layers: 35, 70 and 95. To avoid mutual influence on the migration, the sensors were placed 90 degrees to each other around the tube, but all sensors were placed at mid-position along the tube. The sensors digitized the measurements. The paper initially had 4% by weight moisture. The tube was placed vertically in a vessel containing mineral transformer oil (NYNAS Nytro 10XN). Wires from the sensors came out from the paper at the bottom end of the tube. Heating current was supplied by a DC source and both current and voltage were monitored with digital instruments. The temperature and relative humidity development was registered on a computer with software from the sensor manufacturer. The tube is shown in Figure 1.

One weakness of this setup is that the sensors necessarily do not register moisture in the paper, but moisture in an oil pocket between two paper layers. The moisture in the adjacent paper layers must then be calculated by using equations (7) and (8). This may introduce some errors since (8) is valid for equilibrium and there is no equilibrium in this case. Further, moisture will be driven from the paper into the oil pockets when heating and from the oil pockets into the paper when cooling. This problem should be minimised by using sensors requiring as small oil pockets as possible. A slightly bulky shield was removed from the sensors to reduce the required space, but they are still 2 mm thick. Hose clamps were used to force the paper layers together outside the area where the bulkiness of the sensors forced the layers apart, as can be seen in Figure 1.

4. Experimental results

One initial experiment was performed with too little heating, raising the temperature on the tube from 22 to 30°C. This was too little, and since the moisture would need months to revert to before-state after an experiment with higher temperature, significantly higher heating power was used in the second attempt. This became too much. The humidity part of the sensor on the tube failed permanently after 1600s, and the temperature reported from it got stuck on 120°C which was the maximum digital value it could give out. Results for the heating period can be found in Figure 2 – Figure 6, while results from the following cooling period are shown in Figure 7 – Figure 9.

Figure 2 shows the relative saturation in the oil pockets in the early part of the heating. It can be seen that the relative saturation (RS) initially drops as the oil pocket is heated, but eventually the RS increases as moisture is forced out of the paper and into the oil pocket. This happens later the further the sensor is from the tube. Figure 3 shows the calculated absolute moisture in the pocket, showing an enormous increase close to the tube. Figure 4 shows the calculated moisture in the paper adjacent to the sensors. There is a dip which may be explained as moisture being forced from the paper and into the oil pockets, but there is no time delay between the dip in the oil relative saturation and this dip, so it may just as well be an artefact of using equilibrium conversion data for a non-equilibrium situation. The moisture in the paper soon rises again. This may be because moisture migrates towards the oil pockets from the layers further from them. There also appears to be a fairly rapid increase to a moisture level slightly higher than the original one. This should not be possible and may also be caused by the use of equilibrium conversion data in a non-equilibrium situation.

Figures 5 and 6 show the relative saturation in oil and the resulting calculated development of the absolute moisture in the paper, respectively, but during a much longer time scale than in figures 2 and 4. The temperature at layers 35 and 70 stabilize after about 4000 s, while there is a slow increase at layer 95 throughout the rest of the experiment. In the same time interval, the bulk oil temperature in the vicinity of the outer paper layer increased slowly from 21 to 24°C. It can be seen that at layer 35, moisture initially increases, showing that moisture migrates from the hotter layers closer to the tube, but then decreases slowly as the inner layers become drier and the moisture migrates further outwards. At layer 70, the moisture increases slowly throughout the experiment, and the comparatively cold layer 95 shows no increase on the time scale of the experiment. This means that the experiment should have been run for a much longer time than it was. Nonetheless, as a demonstration experiment it clearly shows moisture migration. On this longer time scale, the use of equilibrium conversion data should cause less trouble and the results are more likely to be correct.

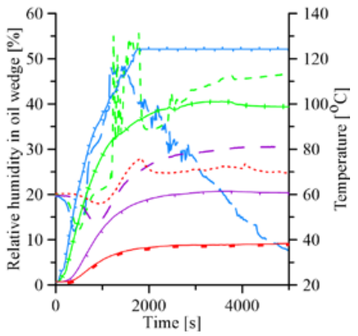


Figure 2. Initial development of the relative moisture saturation in oil wedges around the sensors, and temperature.

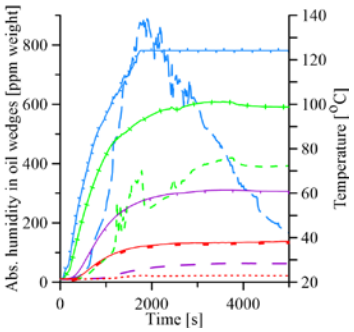


Figure 3. Initial development of absolute moisture in the oil wedge around the sensors, and temperature.

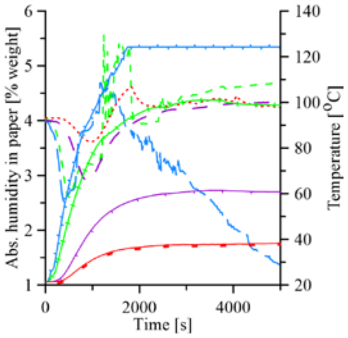


Figure 4. Initial development of absolute moisture in the paper, and temperature.

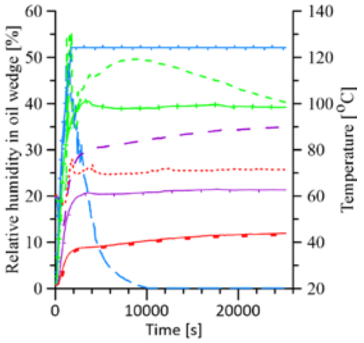
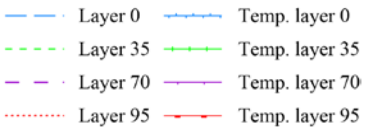


Figure 5. As figure 2, but for the entire heating period.



Legend for figures 2-9.

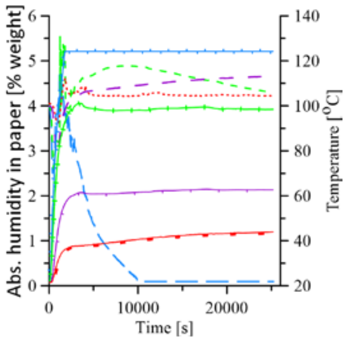


Figure 6. As figure 4, but for the entire heating period.

After the heating, the setup was allowed to cool down naturally to room temperature over 94 hours. Some of the results are shown in figures 7-9.

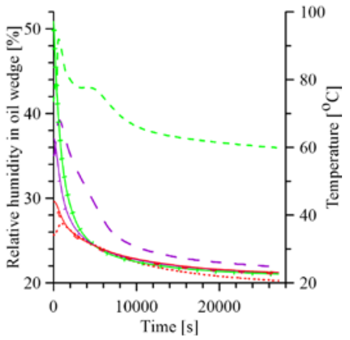


Figure 7. Relative moisture saturation in oil wedge during early cooling. Legend as for figures 2-6.

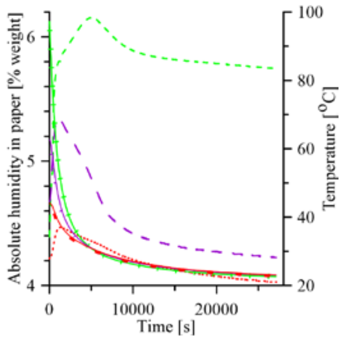


Figure 8. Absolute moisture in paper during early cooling. Legend as for figures 2-6.

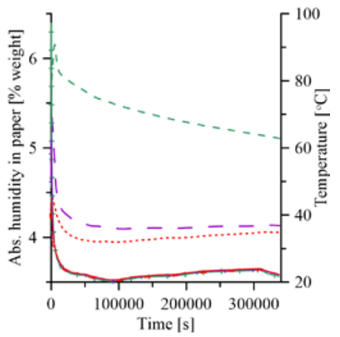


Figure 9. Absolute moisture in paper during long duration cooling. Legend as for figures 2-6.

Results from the defective sensor at the tube (layer 0) are not shown. The temperature, even at layer 35, falls to less than about 25 °C within an hour, leading to an increase in relative moisture saturation, since the saturation limit is lower at lower temperatures [10]. With a delay of 3-4 minutes at layer 95, increasing to almost 1.5 hours at layer 35, this leads to an increase in calculated absolute moisture in the paper next to the oil wedges. This is an expected result, but there is again a possibility that some of the apparent effect is an artefact of using equilibrium conversion data. The effect is more believable here, however, because the subsequent decay in moisture level as moisture migrates away from the paper layers close to the oil wedges is slow, as should be expected with the entire insulation at room temperature. In figure 9, layers 70 and 95 have reverted to the moisture level before heating, while further in, at layer 35, the higher peak value contributes to the moisture having decreased only halfway to the level before heating.

The demonstration experiment clearly shows moisture migration under load changes. Thus, moisture at a given site is far from constant. As the ageing of cellulose is very moisture-dependent, this is clearly something that should be included in a model of ageing under dynamic load.

5. Conclusion

Equations for moisture migration in paper under the influence of position-dependent, changing temperature have been presented. These are relevant for modelling of moisture migration in transformer winding insulation in wind farms, where the changing wind conditions may cause almost continuous load variation. What is still missing are equations for the transfer of heat and moisture between the windings and the surrounding oil.

A demonstration experiment has clearly shown moisture migration in a winding model, especially during heating where moisture in one location passed through a maximum as the location changed from being a net receiver of moisture from the hotter inner layers to becoming a net transmitter to the colder layers further out. Because the ageing of cellulose is strongly dependent on temperature and moisture, the load-dependent dynamic temperature distribution and migration of moisture should clearly be included when modelling ageing under dynamic load.

In the further work, a model for dynamic moisture migration in the winding insulation of wind farm transformers will be developed.

6. Recommendations for further work

In addition to modelling of the moisture migration, there clearly should be done systematic migration experiments. The present single experiment could only demonstrate the migration phenomenon.

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