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A Review of Moisture Diffusion Coefficients in Transformer Solid Insulation—Part 2: Experimental Validation of the Coefficients

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Introduction

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Part two of this two-part article provides experimental validation of the moisture diffusion coefficients for Kraft paper and pressboard insulations in transformer oil that have been proposed by various researchers.

Moisture dynamics in cellulosic insulation can be estimated using a mathematical model of diffusion based on Fick's second law [1], [2]. The main parameter of this mathematical model is the moisture diffusion coefficient, and the precision of the model is dependent on using an accurate value of this coefficient.

Various researchers have obtained expressions for the moisture diffusion coefficient for cellulosic insulation, such as Kraft paper or pressboard, applying different methodologies [3]–[10]. Several values of the diffusion coefficient can be found in the literature represented by mathematical expressions, tables, or experimental curves, relating the dependence of the coefficient with the local moisture concentration and temperature. Some of these coefficients have been determined for nonimpregnated insulation (mainly Kraft paper and pressboard) and others for oil-impregnated paper. Most of these coefficients were determined more than 25 years ago [11], and until now, no coefficients have been proposed for oil-impregnated pressboard.

The objective of this article is to experimentally verify the diffusion coefficients proposed by the various researchers. To validate these coefficients, drying experiments were carried out on impregnated and nonimpregnated paper and on pressboard samples. Taking into account the characteristics of the tested samples, two different experiments were performed:

- For nonimpregnated insulation, thermo-gravimetric experiments were performed determining the weight of a sample while being dried.
- For impregnated paper, drying experiments were carried out in hot oil in which samples were periodically extracted and analyzed by the Karl Fischer method.

The drying experiments were simulated using a diffusion model [2], solved by finite element analysis. The simulations

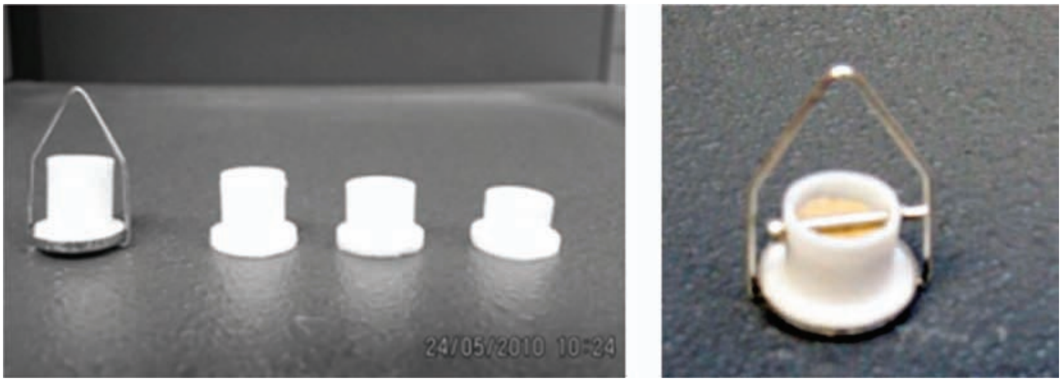


Figure 1. Teflon pans filled with Kraft paper or pressboard to the required thickness for thermo-gravimetric analyzer experiments.

were carried out using the diffusion coefficients proposed by the various researchers. Finally, the experimental results were compared with the simulated ones, and the accuracy and the range of application of the various coefficients were determined.

Experimental

The verification of the diffusion coefficients was performed by using the data obtained from two sets of drying experiments. Drying processes were carried out on nonimpregnated and on oil-impregnated insulation, and the tests were done on Kraft paper and pressboard, at various temperatures, and for several insulation thicknesses.

Experiments on Nonimpregnated Insulation

To validate the moisture diffusion coefficients for nonimpregnated Kraft paper and pressboard proposed by the various researchers, drying tests were carried out using a thermo-gravimetric analyzer (TGA).

A TGA continuously monitors the weight of a sample subjected to a temperature profile selected by the user. In the case of nonimpregnated insulation samples, the weight loss is related to the loss of water, and thus with the rate of drying of the sample. Thermo-gravimetric analysis has been used by several researchers [12], [13] in analyzing the drying processes in various materials, for example, food and construction materials.

In this work, thermo-gravimetric experiments were carried out using a thermo-gravimetric analyzer TA model Q500 on several thicknesses of Kraft paper subjected to various drying temperatures. Additionally, these tests were repeated on pressboard samples.

Table 1. Kraft Paper and Pressboard Samples for Thermo-Gravimetric Analyzer Tests.

	Kraft paper	Pressboard
Thickness (mm)	1, 2, 3, 4	1, 2, 3
Temperature (°C)	40, 50, 60, 70, 80	40, 50, 60, 70, 80, 90, 100, 120

Sample Preparation

Before beginning the TGA experiments, the samples were prepared with high initial moisture content. To achieve uniform moisture content, Kraft paper and pressboard samples were kept in a climatic chamber under controlled humidity and temperature. According to the Jeffries' curves [14], the paper samples were moistened at 30°C and at 67.5% relative air humidity for a minimum of 48 hours. In the case of pressboard, which is characterized by a higher density, the humectation conditions were 35°C and 70% relative air humidity for at least four weeks.

Before beginning the TGA tests, the initial moisture content of the samples was determined using the Karl Fischer titration method, obtaining values of water content around 7.5 wt %.

Multiple layers of Kraft paper, 6 mm in diameter and 0.1 mm thick, were compressed into a Teflon pan with a single opening at the top until the required thickness was attained (Figure 1). As an example, to obtain a 5-mm-thick sample, 68 layers of Kraft paper were used. The pressboard samples were also put into these pans to ensure unidirectional diffusion during the TGA drying experiments. The conditions applied to Kraft paper and pressboard samples during the drying experiments are summarized in Table 1.

TGA Experiments

The pans, filled with the insulations, were introduced into the TGA oven (Figure 2), where they were dried under controlled temperature until full moisture desorption. The loss of mass of the samples was continuously monitored during the drying experiments.

During the tests, dry nitrogen was circulated through the oven to prevent oxidation of the materials and to ensure a moisture-free atmosphere. Moreover, by fixing the gas flow, rapid release of moisture from the sample surface is achieved, making diffusion the dominant mechanism in the drying process.

The TGA experiments give plots of weight loss due to the release of water as a function of time, from which the average moisture as a function of time can be calculated (Figure 3).

Experiments on Oil-Impregnated Insulation

To carry out drying experiments on oil-impregnated samples, an apparatus was constructed to achieve moisture desorption by

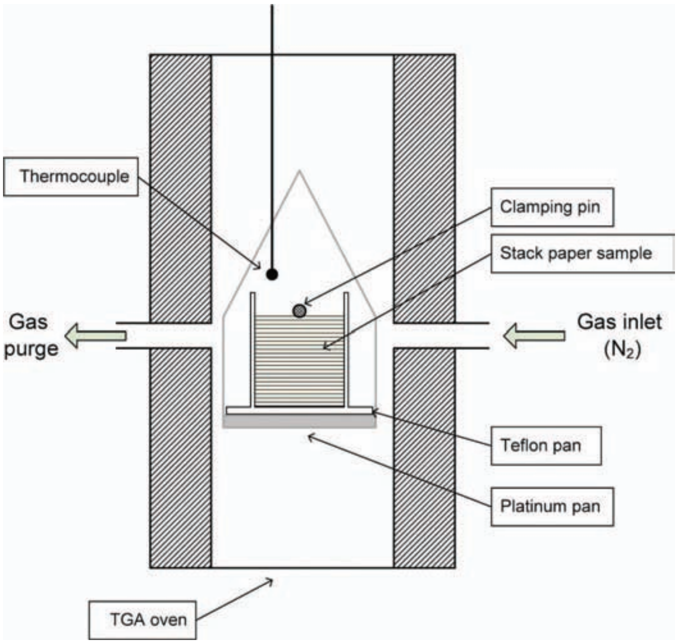


Figure 2. Illustration of pan filled with insulation in thermogravimetric analyzer (TGA) oven.

circulating hot and dry oil. Figure 4 shows the oil circulation drying apparatus.

Sample Preparation

Experiments were performed on insulation specimens of 1-, 3-, and 5-mm thicknesses obtained by paper sheets of Kraft paper of 0.1-mm thickness wound on an aluminum core (Figure 5). The core is fitted with stoppers at the top and bottom limiting moisture desorption in longitudinal direction.

Before impregnating the samples with oil, the specimens were kept in a climatically controlled chamber at 35°C and 70% relative air humidity for a minimum of two weeks. The conditions applied during this period were established, taking into account the Jeffries' curves [14], to obtain an equilibrium concentration close to 8%. The specimens were then submerged in oil at room temperature and at atmospheric pressure for a minimum of one week. Finally, the oil-impregnated test specimens were reintroduced into the climatic chamber to rewet the insulation prior to the drying experiments.

Drying Experiments

As mentioned above, the drying experiments consisted of subjecting the specimens (Figure 6), previously wetted and impregnated with oil, to a constant flow of hot dry oil. Before beginning the experiments, samples were extracted from test specimens and analyzed by Karl Fischer titration to determine the initial moisture content, which is the average moisture throughout the thickness of the samples.

Throughout the drying process, samples were carefully extracted (Figure 7) from the specimens to determine the moisture evolution. To validate the diffusion coefficients for oil-impregnated paper, specimens of three thicknesses (1, 3, and 5 mm) were dried by oil circulation at four temperatures (60, 70, 80, and 85°C).

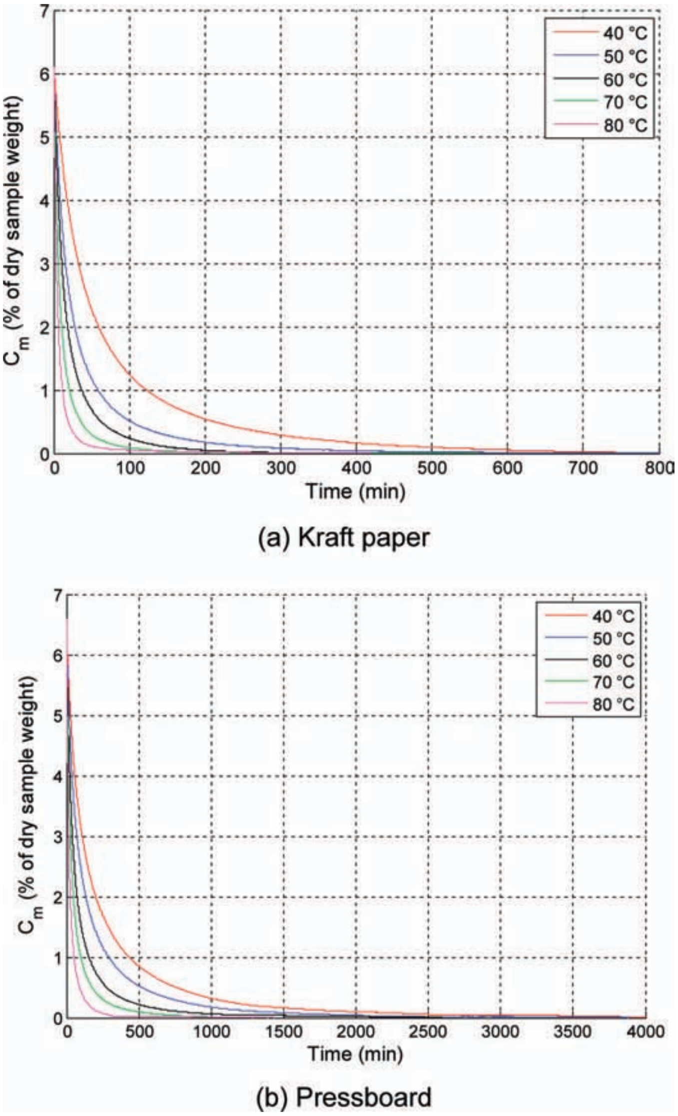


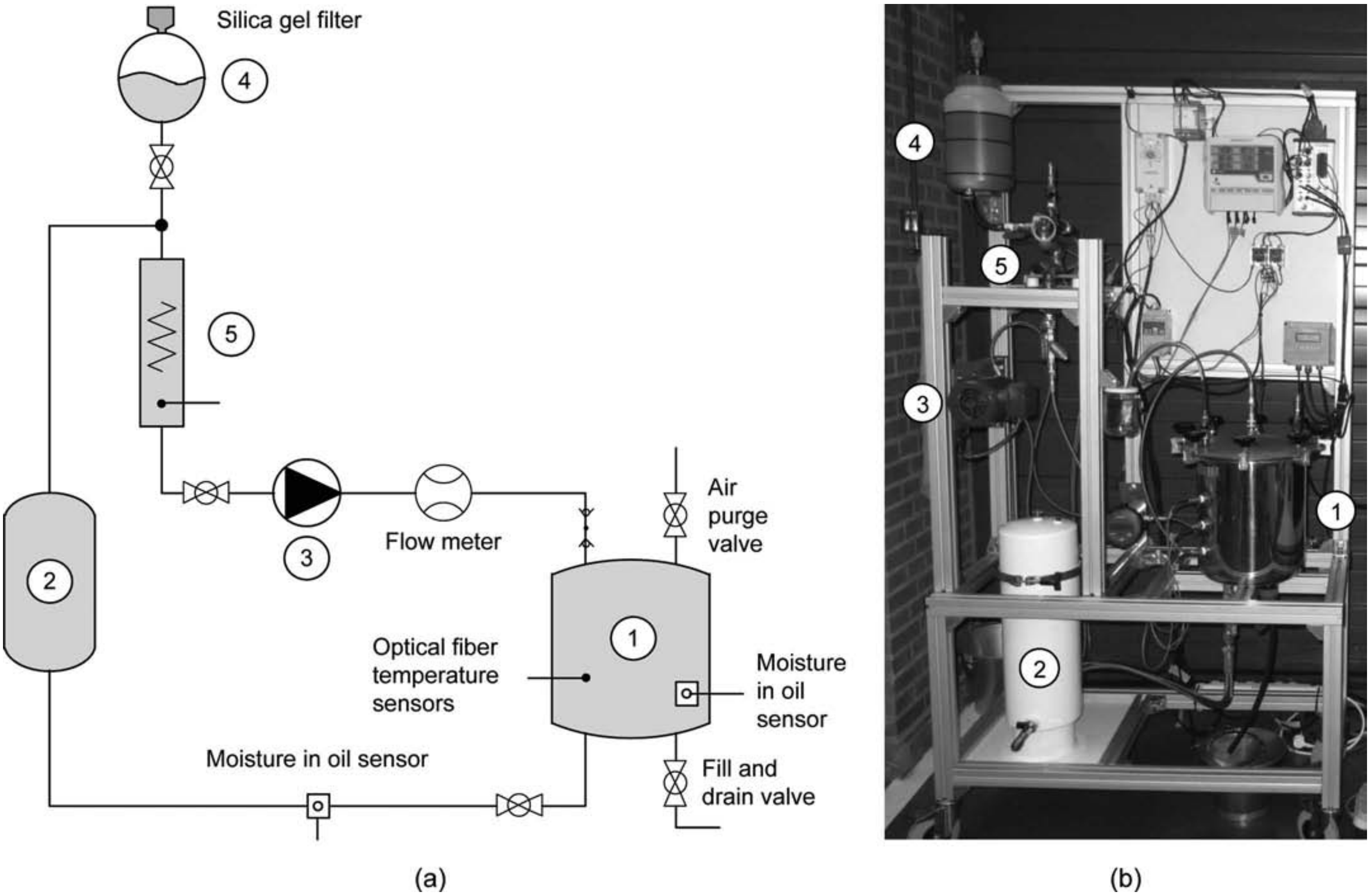
Figure 3. Evolution of average moisture content from Kraft paper in (a) and pressboard in (b) at various temperatures and for insulation thickness of 2 mm.

Simulation of Drying Experiments

Diffusion Model

To validate the coefficients proposed by the various researchers, the drying experiments were simulated by a diffusion model based on Fick's second law (1) using the various coefficients. As described in part one of this article [11], the diffusion coefficient of cellulosic insulation depends on moisture concentration, giving a nonlinear second-order differential equation. To solve this equation, the finite element method was applied by using Comsol Multiphysics®.

$$\frac{\partial c}{\partial t} = \frac{\partial}{\partial x}\left(D \cdot \frac{\partial c}{\partial x}\right) \tag{1}$$



(a) (b)

Figure 4. Oil circulation drying apparatus; general scheme in (a) and photograph in (b) showing sample container (1), oil filter (2), circulating pump (3), expansion cup (4), and heater (5).

Boundary Conditions

To define the boundary conditions in the simulations of the experiments on nonimpregnated and on oil-impregnated samples, several assumptions were made. In both cases, impermeability, with regard to moisture diffusion, was considered in the inner part of the insulation, as in both experiments the insulation was either in contact with a Teflon pan or an aluminum core. Regarding the boundary condition on the contact surface between the insulation and the surrounding medium, equilibrium was considered. In the TGA experiments, a moisture-free atmosphere was created by nitrogen, and thus the moisture concentration on the surface was considered to be zero. However, in the drying experiments using the oil circulation apparatus, the equilibrium condition was calculated from Fessler's approach (2)

$$C_{\text{equil}} = 2.173 \cdot 10^{-5} \cdot p_v^{0.6685} \cdot \exp\left(\frac{4725.6}{T}\right), \qquad (2)$$

where C_{equil} is the equilibrium moisture in paper, expressed as a percentage, and p_v is the moisture partial pressure, in atmospheres, that can be calculated from oil relative humidity *HR* as

$$p_v = HR \cdot p_{v,\text{sat}} = \frac{\text{ppm}}{\text{ppm}_{\text{sat}}} \cdot p_{v,\text{sat}}, \qquad (3)$$

where ppm is moisture concentration in oil expressed in parts per million and ppm_{sat} and $p_{v,\text{sat}}$ are moisture concentration and partial pressure (atm) at saturation [5]. The partial pressure of the saturated water was obtained by the correlation proposed by Foss in [8], and the moisture concentration for saturation can be obtained from the following expression:

$$\log(\text{ppm}_{\text{sat}}) = A - B/T, \qquad (4)$$

where A and B are constants adjusted to the experimental data [5], and the values $A = 7.42$ and $B = 1{,}670$ have been used in this work.

Fitting Quality Quantification

The difference between the simulated and the experimental curves was quantified by the root-mean-square deviation (RMSD) (5) applied to the complete drying time:

$$\text{RMSD} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left[C_{\exp}(t_i) - C_{\text{est}}(t_i)\right]^2}, \qquad (5)$$

where n is the number of experimental measurements, $C_{\exp}$ is the measured average moisture concentration, C_{est} is the estimated average moisture concentration, and t_i is the instant of the drying experiment when the ith measurement was performed.

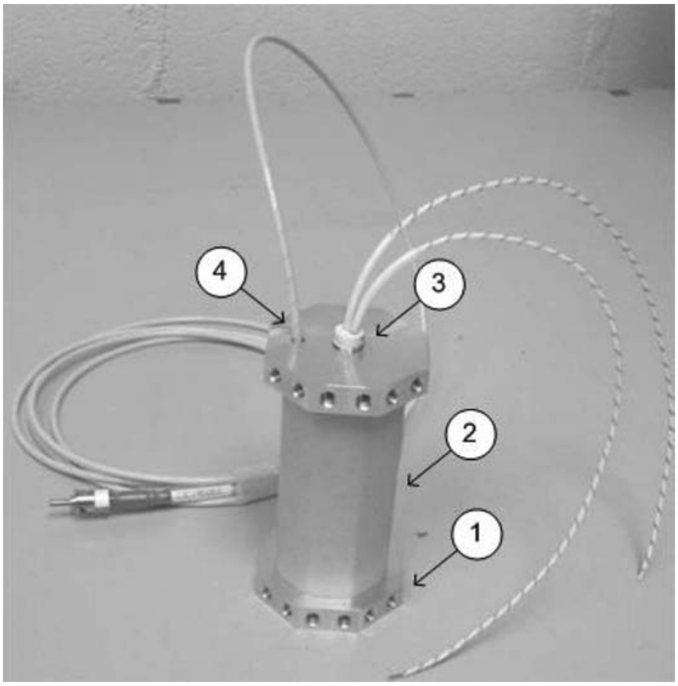


Figure 5. Insulation test sample details: aluminum core (1), paper insulation (2), heating element lead (3), and internal insulation temperature sensor (4).

Results

It was shown in part one of this article [11] that several researchers obtained coefficients for paper or pressboard, while others proposed curves or equations that can be used to simulate moisture dynamics in transformer insulation, and a summary is shown in Table 2. Most of the available coefficients are based on the empirical equation (6) proposed by Guidi [5]. The experimental drying curves were compared with those obtained by simulation using the model described, and the coefficients that have been proposed by the various researchers were validated. The agreement between the curves was quantified by means of (5).

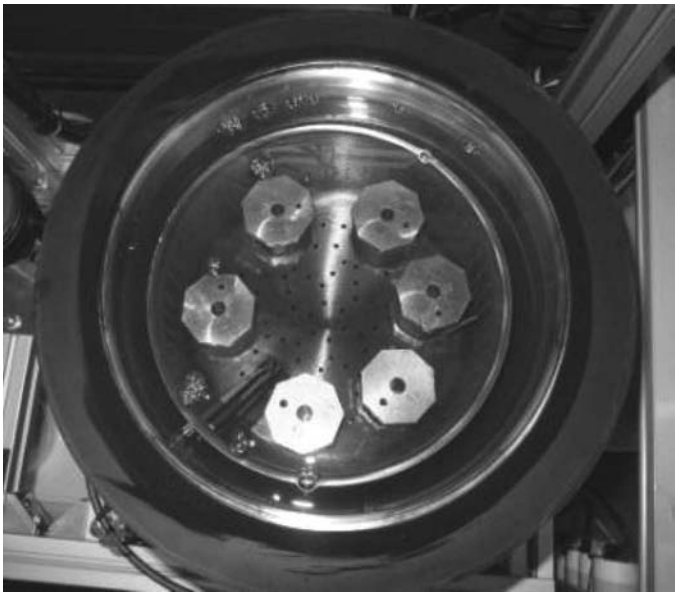
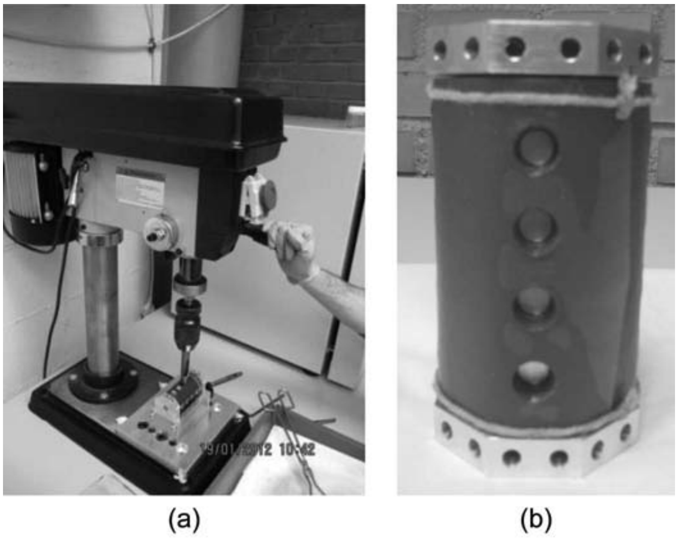


Figure 6. Insulation specimens inside the sample container.



(a) (b)

Figure 7. Punch extraction (a) of insulation samples (b) to determine moisture content during drying.

$$D = D_G \cdot e^{\left[kc + E_a\left(\frac{1}{T_0} - \frac{1}{T_k}\right)\right]} \qquad (6)$$

It must be pointed out that Howe and Asem [3], [7], [9] used a very particular experimental method, subjecting and analyzing pressboard samples under mechanical compression during the drying experiments. Moreover, these researchers obtained the coefficients at a single temperature. For these reasons these coefficients will not be validated experimentally in this article.

Nonimpregnated Pressboard

As reflected in Table 2, Du proposed to use Guidi's equation (6) to calculate the moisture diffusion coefficient for pressboard [6] and determined the values of its parameters for nonimpregnated pressboard. To this aim, she performed experiments on nonimpregnated pressboard using an interdigital dielectrometry sensor, and the following values were obtained: D_G = 2.25 × 10^{-11} $m^2 \cdot s^{-1}$, k = 0.1955, and E_a = 8,834 K.

As described above, drying experiments were performed using TGA to validate Du's coefficient. Pressboard samples of several thicknesses were subjected to various temperatures until total moisture desorption was achieved. These experiments were simulated by finite element analysis applying Du's coefficient to (1), and the difference between the measured and simulated drying curves was calculated using (5).

The RMSDs obtained for all of the simulated cases are shown in Figure 8 and Table 3. It can be seen that the RMSDs are very different, and as large as two orders of magnitude, depending on temperature and sample thickness. It is observed that lower RMSDs between measured and simulated drying curves are obtained with the experiments performed on 1-mm-thick samples. For thicker samples, the results of Du's coefficient are worse.

Table 2. Moisture Diffusion Coefficients for Transformer Insulation Proposed by Various Researchers.

Researcher	Paper (nonimpregnated)	Paper (impregnated)	Pressboard (nonimpregnated)	Coefficient expression
Ast	x			Equation D(C,T)[1]
Guidi		x		Equation D(C,T)
Howe	x[2]		x	Tables and curves
Asem	x	x	x	Tables and curves
Foss	x	x		Equation D(C,T)
Du			x	Equation D(C,T)

[1] Equation obtained by Du from Ast's experimental data.
[2] Determination on Manila paper.

To grasp the significance of the RMSD, the results of two simulations are shown in Figure 9. Figure 9(a) corresponds to a measurement performed on a 1-mm-thick sample dried at 60°C. In this case the obtained RMSD is 1.30×10^{-01}, and the simulated values show good agreement with the experimental ones. On the other hand, Figure 9(b) shows the same comparison on a 2-mm-thick sample dried at 70°C. In this case the obtained RMSD is 9.20×10^{-01}, and the simulated values show poor agreement with the experimental ones, with drying times estimated by Du's coefficient being one-third of the actual times, i.e., 500 verses 1,500 minutes.

From the analysis it can be concluded that Du's coefficient works well when it is applied to thin samples while the estimation of the moisture diffusion for thick samples is poor. To

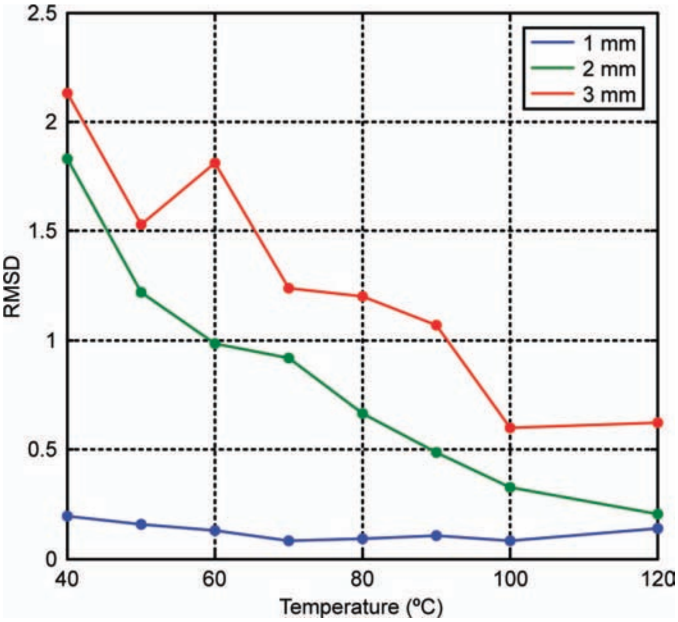


Figure 8. Root-mean-square deviation (RMSD; difference between the simulated and experimental values) of Du's coefficient for nonimpregnated pressboard.

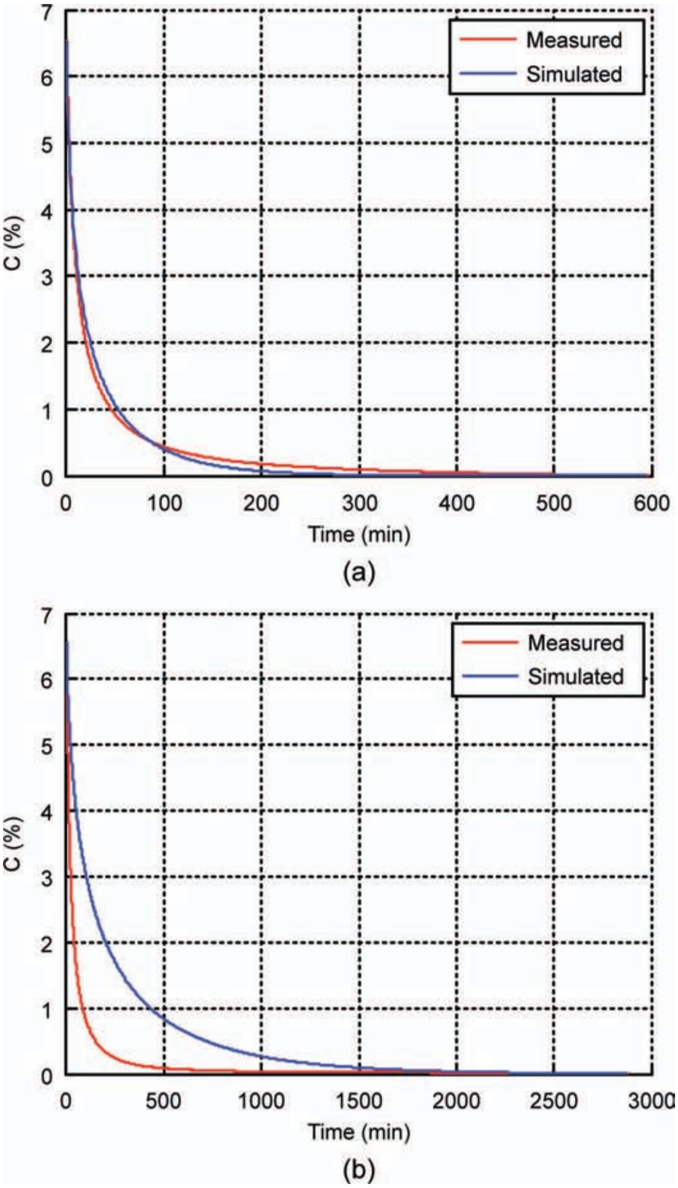


Figure 9. Simulated and measured moisture diffusion coefficients in pressboard: (a) 1-mm thickness at 60°C and (b) 2-mm thickness at 70°C.

Table 3. Root-Mean-Square Deviation (RMSD) Obtained by Du's Coefficient for Nonimpregnated Pressboard.

Temperature (°C)	Thickness (mm)	RMSD D_{Du}
40	1	1.94×10^{-01}
	2	$1.83 \times 10^{+00}$
	3	$2.13 \times 10^{+00}$
50	1	1.57×10^{-01}
	2	$1.22 \times 10^{+00}$
	3	$1.53 \times 10^{+00}$
60	1	1.30×10^{-01}
	2	9.84×10^{-01}
	3	$1.81 \times 10^{+00}$
70	1	8.25×10^{-02}
	2	9.20×10^{-01}
	3	$1.24 \times 10^{+00}$
80	1	9.10×10^{-02}
	2	6.64×10^{-01}
	3	$1.20 \times 10^{+00}$
90	1	1.08×10^{-01}
	2	4.85×10^{-01}
	3	$1.07 \times 10^{+00}$
100	1	8.32×10^{-02}
	2	3.26×10^{-01}
	3	6.01×10^{-01}
120	1	1.40×10^{-01}
	2	2.04×10^{-01}
	3	6.22×10^{-01}

understand this result, it must be remarked that all the diffusion experiments performed by Du for the determination of her coefficeint were carried out on samples of 1.5-mm thickness, and the obtained results seem to indicate that the coefficient is valid in the thickness range studied, whereas the obtained results are poorer when applied to thicker insulation.

The dependence of the moisture diffusion coefficient on sample thickness has not been considered by any of the researchers who worked on transformer insulation. However, that dependence has been described by other researchers in the determination of moisture diffusion coefficients of various hygroscopic materials [15]–[19].

Table 4. Root-Mean-Square Deviations (RMSD) Obtained by Foss's and Ast's Coefficient for Nonimpregnated Paper.

Temperature (°C)	Thickness (mm)	RMSD	
		D_{Foss}	D_{Ast}
40	2	4.54×10^{-01}	1.56×10^{-01}
	3	1.29×10^{-01}	5.01×10^{-01}
	4	2.52×10^{-01}	9.36×10^{-01}
	5	4.99×10^{-01}	1.37
50	2	3.67×10^{-01}	1.71×10^{-01}
	3	1.22×10^{-01}	2.60×10^{-01}
	4	1.26×10^{-01}	4.05×10^{-01}
	5	1.39×10^{-01}	6.18×10^{-01}
60	2	4.26×10^{-01}	2.68×10^{-01}
	3	1.85×10^{-01}	9.02×10^{-02}
	4	2.38×10^{-01}	1.84×10^{-01}
	5	1.73×10^{-01}	4.46×10^{-01}
70	2	3.47×10^{-01}	2.50×10^{-01}
	3	2.14×10^{-01}	1.15×10^{-01}
	4	2.14×10^{-01}	9.23×10^{-02}
	5	1.80×10^{-01}	1.72×10^{-01}
80	2	2.87×10^{-01}	2.29×10^{-01}
	3	1.80×10^{-01}	1.26×10^{-01}
	4	1.79×10^{-01}	8.22×10^{-02}
	5	2.49×10^{-01}	1.02×10^{-01}

Nonimpregnated Kraft Paper

In the case of nonimpregnated Kraft paper, two different coefficients have been proposed by Foss and Ast (Table 2), and both are based on Guidi's equation. The values proposed for the parameters in each case being $D_{G\ \mathrm{Foss}} = 2.62 \times 10^{-11}$ m^2·s^{-1}, $k_{\mathrm{Foss}} = 0.5$, $E_{a\ \mathrm{Foss}} = 8{,}140$ K and $D_{G\ \mathrm{Ast}} = 2.25 \times 10^{-11}$ m^2·s^{-1}, $k_{\mathrm{Ast}} = 0.1955$, $E_{a\ \mathrm{Ast}} = 8{,}834$ K.

These coefficients are used to simulate the TGA drying experiments of Kraft paper samples dried at various temperatures (Table 1). The RMSDs between the simulated and measured values when Foss's or Ast's coefficients are used are shown in Table 4 and also in Figure 10. The experimental and simulated curves for two different cases are plotted in Figure 11. It can be seen in Figure 10 that Foss's coefficient is more accurate in most cases, especially at low temperatures.

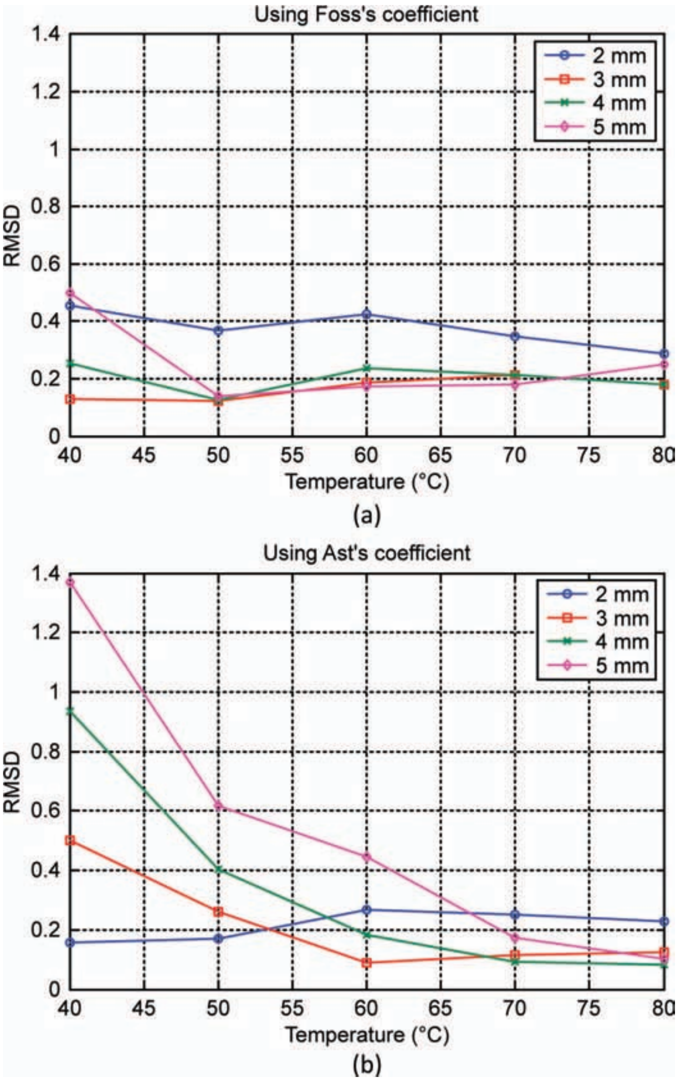


Figure 10. Root-mean-square deviation (RMSD) of Foss's (a) and Ast's (b) for the moisture diffusion coefficient in nonimpregnated paper.

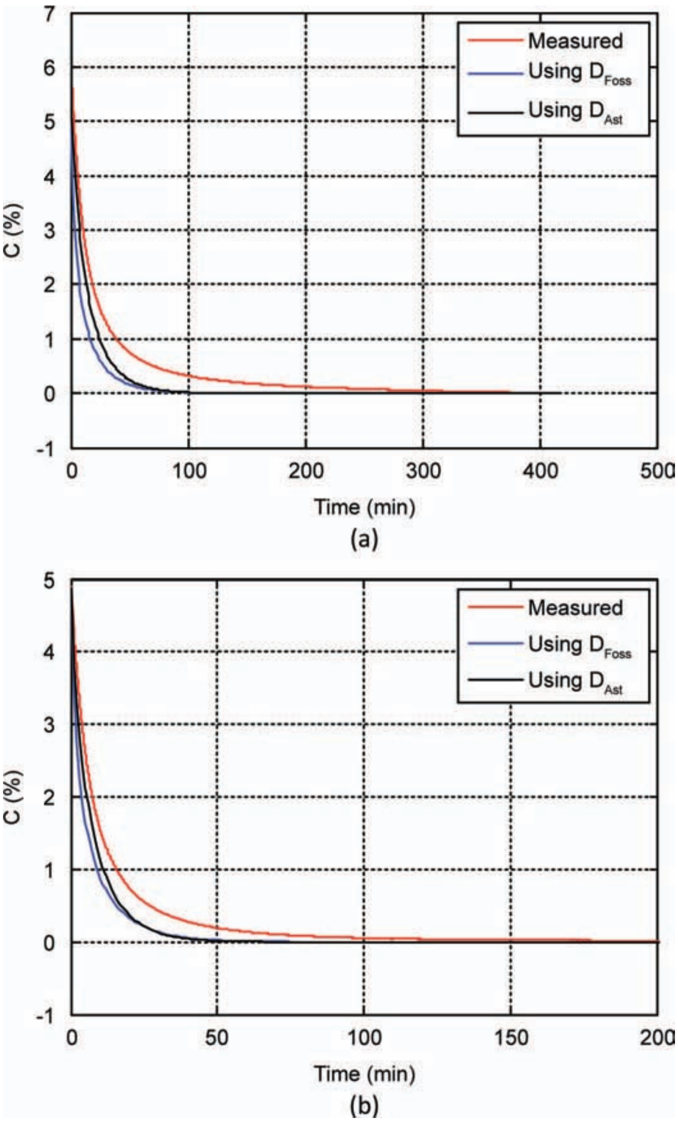


Figure 11. Simulated and measured moisture diffusion coefficients for nonimpregnated paper: (a) 2-mm thickness at 60°C and (b) 3-mm thickness at 80°C.

Oil-Impregnated Kraft Paper

The moisture diffusion coefficients proposed by Foss and Guidi were validated on samples of oil-impregnated Kraft paper of various thicknesses and oil temperatures. The moisture content in the oil, required for the simulation of the drying process, was measured by a moisture sensor in the drying apparatus. The RMSDs for the diffusion coefficients (Table 5) are significantly higher than those simulated for nonimpregnated insulation. Possible reasons for the increased RMSD include the uncertainty in the Karl Fischer measurements and the discrete rather than continuous moisture measurements during the drying experiments. On the other hand, the determination of the moisture diffusion coefficient in oil-impregnated materials is complex, and the obtained expressions are less precise compared with those on nonimpregnated samples. It may also be observed that Guidi's coefficient provides better estimates than does Foss's coefficient.

The comparison between the measured and estimated values for two simulations is shown in Figure 12. The simulations correspond to a 5-mm-thick sample dried in oil at 60°C and a 3-mm-thick sample dried at 70°C. By analyzing these two experimental cases, the precision of Foss's and Guidi's coefficients can be estimated.

From the plots shown in Figure 12, the moisture level after the drying process was about 3%, in both cases, and the time to attain this level was nearly 25 days for the 5-mm sample at 60°C (Figure 12a) and about 20 days for the 3-mm-thick sample dried at 70°C (Figure 12b). In Figure 12a, it is observed that Guidi predicts a realistic evolution of moisture, while Foss estimates that 3% moisture is reached in 10 days, which is too optimistic. In Figure 12b, the estimates using the coefficients from both researchers are unrealistic in that Guidi's coefficient predicts that a moisture level of 3% is attained in just over four days while Foss's coefficient is even more optimistic, predicting the same level in less than two days. Similar patterns are found in the other simulations. Guidi's, and specially Foss's, coefficients pre-

Table 5. Comparison of Root-Mean-Square Deviation (RMSD) Obtained by Foss's and Guidi's Coefficient of Moisture Diffusion for Impregnated Paper.

Temperature (°C)	Thickness (mm)	RMSD	
		D_{Foss}	D_{Guidi}
60	5	1.628	0.737
70	1	2.260	2.046
	3	3.080	2.293
	5	2.462	1.465
80	1	3.529	3.430
	3	2.612	2.083
	5	1.677	0.569
85	1	2.178	2.094
	3	2.097	1.385
	5	1.708	0.585

dict a moisture desorption much too fast in most cases, although Guidi's coefficient works better on 5-mm-thick samples.

Conclusions

The coefficient of moisture diffusion is an important parameter in the modeling of moisture dynamics in transformer solid insulation, and various researchers have proposed coefficients valid for Kraft paper and pressboard insulating materials. In this work, the proposed coefficients have been tested by means of drying experiments performed at various temperatures.

The behavior of Du's moisture diffusion coefficient in nonimpregnated pressboard has been tested. The coefficient works well for 1-mm-thick samples but not for thicker samples. The dependence of the diffusion coefficient on thickness has also been observed in other materials, but none of the proposed coefficients for transformer insulation include that dependence.

The coefficients proposed by Foss and Ast for nonimpregnated Kraft paper were validated using the results of thermogravimetric experiments. Foss's coefficient is more accurate in most cases, although the behavior of both coefficients changes for different experimental conditions. This is especially true at low temperatures.

The coefficients proposed by Foss and Guidi for oil-impregnated paper were verified by experiments in a hot oil drying apparatus, and using these coefficients in simulations, large differences between the experimental and estimated results are obtained, in that the estimated diffusion times are very short in comparison with the measured ones. In addition, Guidi's coefficient provides more precise estimates of the diffusion times than does Foss's.

As a general conclusion, it appears that the available coefficients for modeling moisture dynamics in transformer insulation are not as precise as would be desirable. Additional work needs to be done to obtain the moisture diffusion coefficient expressions as a function of thickness, temperature, and moisture concentration. Moreover, no coefficient is available to calculate the moisture diffusion in oil-impregnated pressboard, and the need for this great, as this part of transformer insulation retains the larger percentage of moisture.

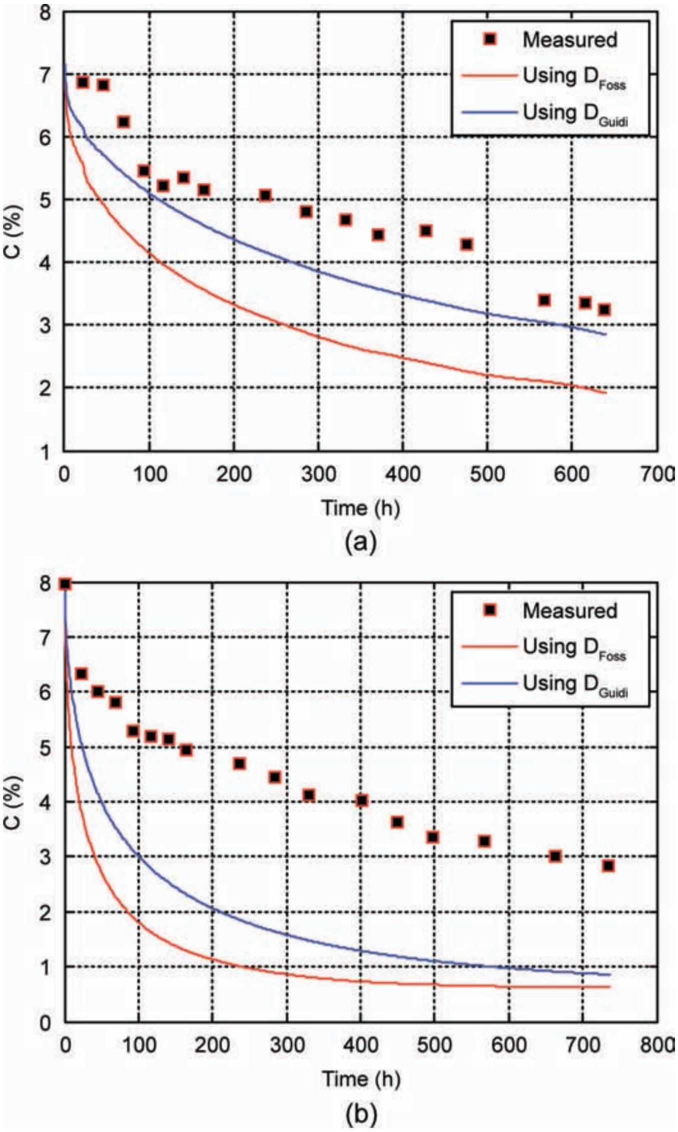


Figure 12. Simulated and measured coefficients of moisture diffusion in impregnated paper: (a) thickness of 5 mm at 60°C and (b) thickness of 3 mm at 70°C.

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