

Analysis of the Impregnation Process of Cellulosic Materials by Ester-Based Insulating Fluids

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Abstract -- Ester insulating fluids have higher viscosities than mineral oils. This complicates the impregnation of cellulosic insulation and has slowed down the adoption of these dielectrics in high voltage power transformers. This paper studies the dependence of the impregnation characteristics of a mineral oil, a natural ester and a synthetic ester on temperature. For this purpose, impregnation experiments were carried out and the results were compared with an analytical model. The main factors governing the impregnation mechanism related to dielectric liquids are surface tension and viscosity. Results show that increasing the temperature effectively reduces the viscosities of esters, allowing the performance of the synthetic esters to approach that of mineral oil. In addition, an exponential model is proposed to predict the impregnation rates associated to a given temperature.

Index Terms - Capillary action, cellulose, ester oil, impregnation, power transformer insulation, surface tension, temperature, viscosity.

I. INTRODUCTION

THE cellulosic insulation used in high voltage power transformers requires full impregnation in the dielectric fluid. This ensures that the air cavities present in the insulation solid are filled by the oil, preventing partial discharges that would deteriorate the insulation. In oil-immersed power transformers mineral oil has been the most commonly used dielectric liquid, although it has been slowly transitioning towards alternative fluids such as ester oils.

Ester fluids present certain advantages when compared to mineral oils, such as higher fire point and improved biodegradability over traditional transformer oils, which are poorly biodegradable and are potential contaminants in case of leakages [1]. Additionally, the cellulosic insulation has been proven to degrade significantly slower in ester fluids than in conventional oils. In [2], the ageing rate was reduced by an order of magnitude in the cellulosic insulation impregnated with natural ester, due to the ester elevated affinity for water, which removes water from the paper and slows its degradation.

However, esters have considerably higher viscosity than mineral oils, suggesting it would take longer to complete the impregnation process, prolonging the manufacturing time. This arises the need to develop different impregnation procedures. As the factors implied in the impregnation process are mainly surface tension and viscosity [3], which are temperature dependent, higher temperatures can effectively reduce the viscosities of esters and achieve the same degree of impregnation as mineral oils in the same time.

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II. FACTORS GOVERNING OIL IMPREGNATION

A. Viscous Flow of Liquid in the Capillary

An analytical equation for the volume of insulation fluid per unit time flowing into the capillaries within the cellulosic material has been proposed in [3]. It assumes that the implicated cellulosic insulation is composed of parallel capillaries and that the oil impregnation follows Hagen-Poiseuille's law;

$$\frac{dV}{dt} = \frac{\pi r^4}{8\eta L} (P_o - P_l), \quad (1)$$

where:

V = Volume of oil inside the capillary

r = Equivalent average capillary radius

P_o = P_E + P_S, P_E is the external pressure and P_S is the pressure created by the capillary action of oil

L = Impregnated depth or length (Increases with time t)

η = Insulating oil viscosity

P_l = Internal pressure (Increases with time due to oil impregnation)

Therefore, the viscous flow of fluid within the cellulose mainly depends on the capillary size, the internal and external pressures, and the viscosity of the dielectric fluid.

Equation (2) can be obtained by integrating (1), with the volume in the capillary being V=πr²L, [4]:

$$L = \frac{1}{2} \cdot r \cdot \sqrt{\frac{P_E + P_S - P_l}{\eta}} \cdot \sqrt{t} \quad (2)$$

According to (2), the depth of impregnation obeys a nonlinear relationship with time and is inversely proportional to the fluid's viscosity.

B. Viscosity of Oil

The viscosity of a fluid is an intrinsic property that measures its resistance to deformation. For a given force, the more viscous a fluid is, the greater its resistance to movement becomes, and hence the lower the flow rate. To facilitate the impregnation process, dielectric liquids with lower viscosities are preferred.

In order to characterize and quantify the differences between the studied dielectrics, some relevant properties (dynamic viscosity and surface tension) are measured. The dynamic viscosities were measured using a viscometer. Their approximate values at 20°C, 40°C and 60°C are shown in Table I.

Table I. Viscosities at 20°C, 40°C and 60°C.

Type of oil		Mineral oil	Natural ester	Synthetic ester
Dynamic viscosity (mPa·s)	20°C	17.60	82.85	51.60
	40°C	9.85	39.23	27.40
	60°C	8.03	21.05	15.95

Table I unveils two marked patterns. First of all, there is a significant reduction of viscosity with temperature. Increasing the temperature from 20°C to 60°C, viscosities are more than halved for all three fluids. On the other hand, esters show much higher viscosities than mineral oils, which confirms previous evidence [4]. In particular, at 20°C the natural ester is roughly five times more viscous than mineral oil, whereas the viscosity of synthetic ester triples that of mineral oil.

Plotting the measured data shows that the viscosity of insulation fluids decreases exponentially with temperature, Fig. 1.

The impregnation rate is therefore highly dependent on the viscosity, as stated by (2), implying that a lower viscosity is preferred to shorten the total impregnation time.

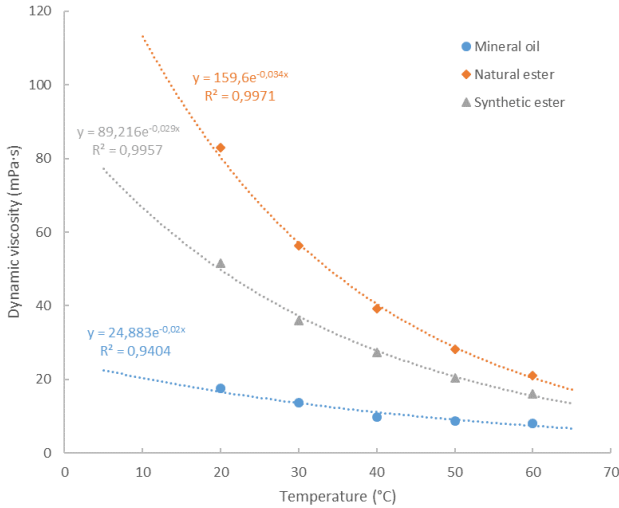


Fig. 1. Dynamic viscosities vs temperature

C. Capillary Action

Capillarity is a property of fluids related to surface tension that allows them to flow in narrow spaces without requiring external forces. The capillary action occurs when the cohesive intermolecular forces of the liquid are smaller than the interfacial tension between the liquid and surrounding solid surfaces. This curves the surface of the liquid and the surface tension creates a pressure that propels the liquid into the capillary. This pressure can be calculated as:

$$P_s = \frac{2 \cdot T \cdot \cos\theta}{r}, \quad (3)$$

where:

T = Surface tension of the oil

r = Equivalent average capillary radius

θ = Contact angle between the oil and cellulose

The pressure originated from the surface tension is inversely proportional to the capillary radius. When the internal and external pressure are the same, the impregnation process is dominated by the capillary action, created by the surface tension and by the viscosity of the liquid (2). Under these conditions, combining (2) and (3) yields:

$$L = \sqrt{\frac{rT \cos\theta}{2\eta}} \sqrt{t}. \quad (4)$$

The impregnation length has a linear relationship with the square root of time. The impregnation slope λ is then defined as:

$$\lambda = \sqrt{\frac{rT \cos\theta}{2\eta}}. \quad (5)$$

Surface tensions were determined using the Du Noüy ring method in a KRÜSS Force Tensiometer K20. Measurements were made at different temperatures with the three fluids, in order to study the dependency of surface tension on temperature, indicating a nearly linear relationship, as shown in Fig. 2.

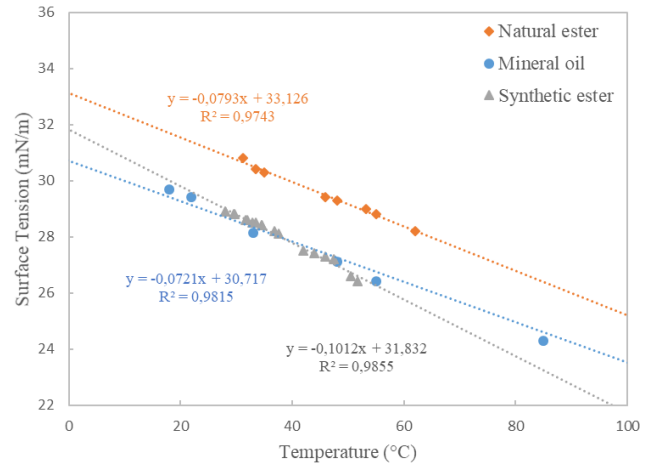


Fig. 2. Surface tensions vs temperature.

These results are in accordance with the Eötvös rule, which states that the surface tension is a linear function of temperature for most known liquids.

Some surface tension values at significant temperatures are shown in Table II, estimated from the linear regression model above. At a given temperature, surface tensions vary at most 10% across fluids, although natural ester exhibits the highest surface tension, which according to (3) is associated to a stronger capillary action.

Table II. Surface tensions at 20°C, 40°C and 60°C.

Oil type		Mineral oil	Natural ester	Synthetic ester
Surface Tension (mN/m)	20°C	29.5	31.5	29.8
	40°C	28.0	30.0	27.8
	60°C	26.4	28.4	25.8

D. Inner Pressure

According to (2), the impregnation process can be accelerated by reducing the internal pressure and maintaining the external pressure. To reduce the internal pressure, vacuum is applied to the transformer before the impregnation, but a small pressure still exists within the solid insulation [5]. Once the transformer is immersed in oil, this internal pressure will rise as the impregnation depth increases, as it is in an enclosed space. Therefore, the internal pressure can be expressed as:

$$P_i = P_0 \cdot \frac{L_0}{L_0 - L} \quad (6)$$

Where P_0 is the initial internal pressure and L_0 the initial capillary length. Therefore, it becomes crucial to keep the

initial internal pressure as low as possible and avoid long impregnation length.

III. METHODOLOGY AND RESULTS

A. Experimental Setup

Four different cellulose-based insulation materials were used in the experiments: Crepe, Diamond Dotted Paper (DDP), Kraft and pressboard (PSP 3055).

These papers have a moisture content of around 7-8% at room condition. After an initial drying at 105°C for 24 hours, the papers are placed in a vacuum oven at 5 mbar and 50°C for 64h, reducing the moisture to less than 2%.

For the impregnation study, the mineral oil, natural ester and synthetic ester were also dried in the vacuum oven, resulting in a moisture content of 10 ppm, 30 ppm, and 45 ppm, respectively. The esters showed higher water content both before and after the drying process, as a result of the previously acknowledged greater affinity for water. The moisture content was controlled using Karl-Fischer Titration (IEC 60814) in a Metrohm 899 Coulometer.

The impregnation was carried out in the vacuum oven at 5 mbar and different temperatures to determine its effect, given that both viscosity and surface tension are temperature dependent. For these tests, the papers were cut into 1.5 cm wide strips and held vertically, with the bottoms immersed in the oil samples.

To simplify the data collection process, a camera was used to take pictures of the stripes at regular intervals. Once each experiment was completed, the impregnation lengths were extracted from the captured images by simply observing the color change in the stripes, which darkens in the impregnated areas (Fig. 3, Fig. 4).

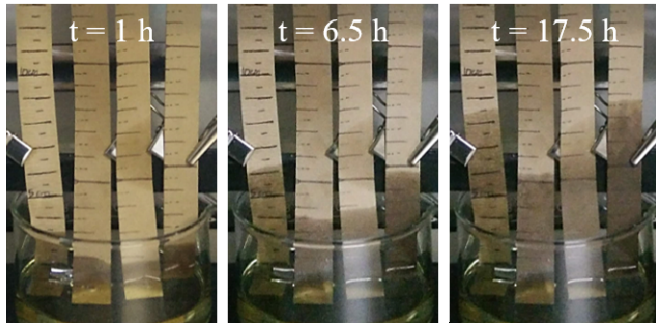


Fig. 3. Samples of the captured images showing the progress of the impregnation process (Natural ester, Crepe paper).

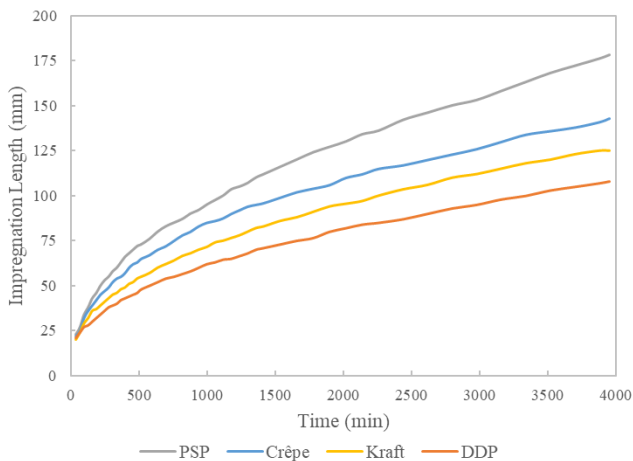


Fig. 4. Variation of impregnation length with time (Different papers with natural ester at 60°C).

B. Impregnation Results

Plotting the impregnation length against the square root of time shows the linear relationship described in (4). An example of this behavior is shown in Fig. 5 for all three studied fluids.

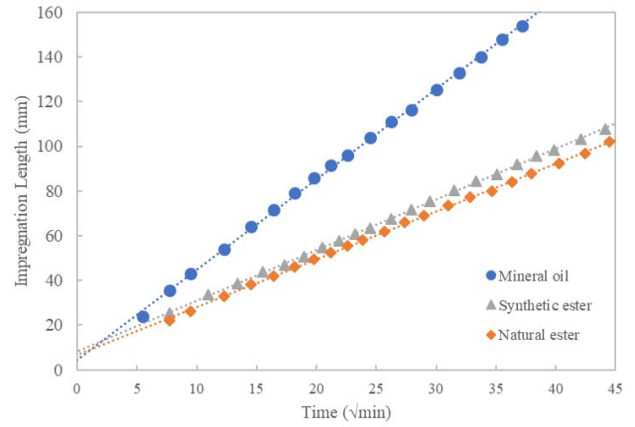


Fig. 5. Impregnation length against square root of time at 40°C (Crepe paper)

Multiple experiments were performed to obtain the average impregnation slopes at different temperatures. The results are summarized in Table III.

Table III. Summary of impregnation slopes

Type of oil		Mineral oil			
Type of paper		Crepe	DDP	Kraft	PSP
Slope (mm/ $\sqrt{\text{min}}$)	24°C	3.26	1.94	2.37	3.59
	40°C	3.91	2.36	2.90	4.17
	60°C	4.60	2.88	3.40	5.02

Type of oil		Natural ester			
Type of paper		Crepe	DDP	Kraft	PSP
Slope (mm/ $\sqrt{\text{min}}$)	24°C	1.79	0.98	1.19	1.79
	40°C	1.97	1.20	1.41	2.03
	60°C	2.45	1.53	1.86	2.62

Type of oil		Synthetic ester			
Type of paper		Crepe	DDP	Kraft	PSP
Slope (mm/ $\sqrt{\text{min}}$)	24°C	1.85	1.11	1.32	1.92
	40°C	2.27	1.32	1.57	2.53
	60°C	2.97	1.84	2.13	3.12

The impregnation slopes can be plotted against the temperature for each of the dielectric liquids, revealing the influence of temperature on the impregnation rates. This effect is illustrated in Fig. 6, where an almost linear dependence of the impregnation slopes of synthetic ester with temperature can be discerned. Similar results have been found for the rest of insulation fluids.

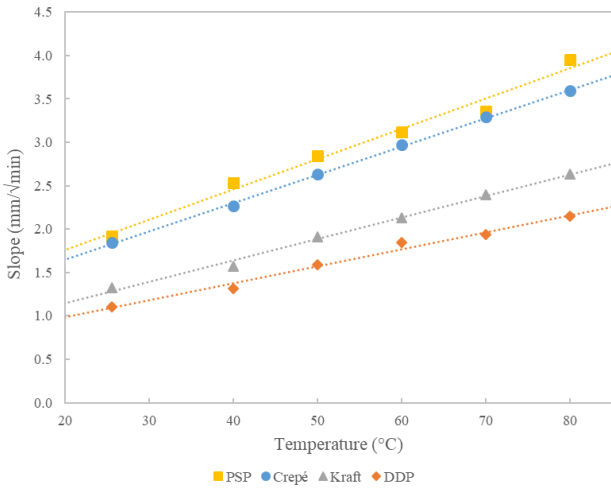


Fig. 6. Variation of the impregnation slope of synthetic ester with temperature.

C. Analysis of Results

With these experiments, the factors affecting the impregnation process can be traced to their origins: the properties of the insulation oils and the properties of the insulation solids.

For the same oil, each paper exhibits different impregnation slopes due to their physical properties, mainly the average radius of the capillaries, as appreciated in Fig. 4. In general, a lower density would imply bigger capillaries, and therefore a steeper slope (5), even though the pressure created by capillary action decreases (3). For example, DDP impregnation slopes are about 1.8 times greater than those of PSP for the same dielectric fluid.

Fig. 5 shows a direct comparison between the three dielectric fluids, where the differences on slopes are directly related to their properties. As expected, the mineral oil has the steepest slope for a given temperature, and the synthetic ester shows slight improvement over the natural ester.

These results (Fig. 6) show that a linear regression model is a good enough approximation to the variation of the impregnation slopes with temperature. However, the influence of temperature in surface tension and viscosity indicates a more complicated relationship, hence a nonlinear model can potentially lead to better results. Back to (5), and given that the capillary radius and contact angle depend uniquely on insulation solids, the only variables left explain the variation with temperature are surface tension and viscosity.

First, surface tension showed a linear relationship with temperature (Fig. 2), but with small variations in the temperature range of interest. As the slope is proportional to the square root of surface tension, we can expect its influence to be almost negligible. For example, natural ester's surface tension decreases 10% when heated from 20°C to 60°C, but the slope would only decrease 5.2%, if considering only the effect of surface tension.

Secondly, the viscosity was found to decrease exponentially with the temperature, and therefore would increase exponentially the slope, according to (5). This effect will be the main contributor to the slope variation with temperature. For example, natural ester's viscosity is quartered when heated from 20°C to 60°C, which translates to almost doubling the slope, if considering only the effect of viscosity.

Therefore, an exponential regression model would be the best to predict the slope variation with temperature, as illustrated by Fig. 7.

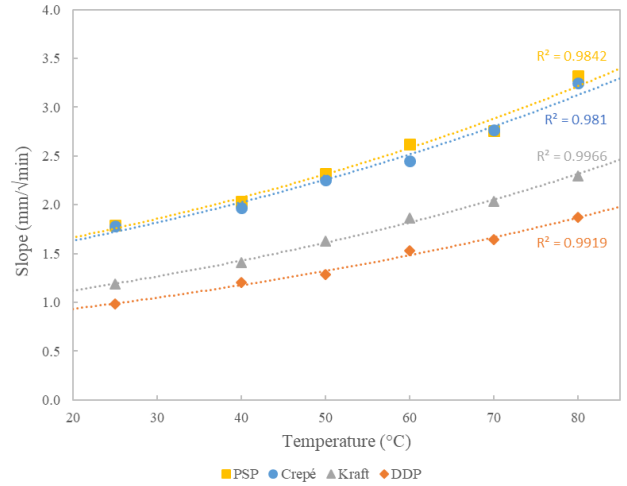


Fig. 7. Exponential regression of impregnation slope on temperature, for natural ester.

Table IV. Exponential regression model to predict the impregnation slope at a given temperature.

Exponential regression model: $\lambda(T)=\alpha \cdot \exp(\beta \cdot T)$					
Type of oil		Type of paper			
		Crepe	DDP	Kraft	PSP
Mineral oil	α	2.752	1.554	1.951	2.874
	β	8.43E-03	1.02E-02	9.42E-03	9.30E-03
Natural ester	α	1.328	0.749	0.890	1.350
	β	1.07E-02	1.14E-02	1.19E-02	1.08E-02
Synthetic ester	α	1.408	0.837	0.977	1.496
	β	1.21E-02	1.22E-02	1.27E-02	1.21E-02

These models allow to predict the impregnation slope associated to any of these materials for a given temperature.

One useful application would be to approximate the temperature at which the esters offer similar impregnation performance as the mineral oil at room temperature. These temperatures are about 84°C and 70°C, for the natural ester and synthetic ester, respectively, with slight variations depending on the cellulosic material.

Another application would be to estimate the optimal temperature to perform the impregnation process at which total impregnation time and energy required minimize the manufacturing costs.

IV. CONCLUSIONS

This paper has sought to expand the knowledge of the impregnation process of cellulosic insulation, studying the main factors that affect the impregnation mechanism, both from a theoretical and experimental point of view.

The impregnation is a nonlinear process, where the speed of impregnation decreases as the impregnated depth increases. The factors that affect this process are viscosity and surface tension of the dielectric liquid, as well as the average capillary radius of the cellulosic insulation.

After analyzing the dependency of the properties of insulation fluids on temperature, it has been shown that increasing the temperature is an effective method to reduce

the high viscosities of esters, and thus improve the impregnation rate. This increase on temperature also reduces the surface tension, although the reduced resistance to the viscous flow compensates for the diminished capillary action. This happens due to the significant dependence of viscosity on temperature, which decreases exponentially as it raises, whereas surface tension is less sensitive to temperature and decreases linearly.

Temperatures around 84°C and 70°C, for natural ester and synthetic ester, respectively, are needed to achieve similar performance to mineral oil at room temperature (24°C). Conversely, elevated temperatures during the impregnation process may lead to premature ageing of cellulose or the oxidation of insulation oil [5]. The regression models developed may help to determine the optimal impregnation temperature as a trade-off between time and energy consumption.

V. REFERENCES

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