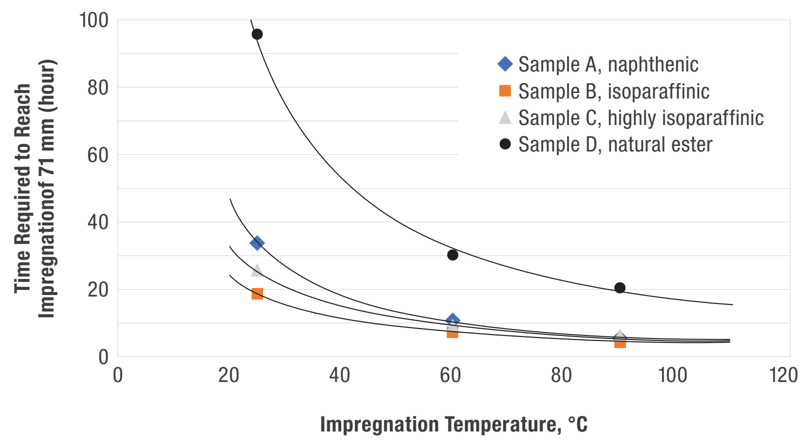

Figure 5.
Impregnation Temperature vs Time to Achieve 71 mm

The data in Table 1 and Figure 5 demonstrate the differences in the impregnation rate with viscosity and temperature. The mineral oils of similar viscosities have similar impregnation rates.

Conclusion

This study shows that the currently available low-viscosity mineral insulating liquids, naphthenics, isoparaffinics, and highly isoparaffinics are all comparable regarding impregnation times, especially at the normally used temperatures. The natural ester, with its higher viscosity, even at elevated temperatures, requires approximately 3.6 times longer across the tested temperatures. It was found that even at 90°C, the natural ester impregnates slower than the mineral oils at 60°C and is somewhat similar to the mineral oils at 25°C. These differences need to be taken into account prior to energizing. The data presented here should not be used to determine the absolute impregnation time for a given power transformer, since they are unique in design and the solid insulation material will be different from that tested

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How Insulating Liquids Affect The Impregnation Rate Into Laminated Pressboard

Abstract

The ability for the insulating system of an oil-filled transformer to perform properly relies on the relationship between the solid and liquid insulation. Neither the solid nor the liquid insulation can be used independently of one another, and they should be designed and observed as a single insulating system.

Four insulating liquids of varying chemistry and viscosity were tested to determine the rate of penetration/impregnation into a laminated pressboard at three temperatures (25, 60, and 90°C). Three of the liquids were mineral oils (naphthenic, isoparaffinic, and highly isoparaffinic), and the fourth was a natural ester (soybean based).

Introduction

The ability for impregnation to take place is largely dependent on two factors: how permeable the solid insulation is (based on the density of the solid insulation) and the dynamic viscosity of the liquid insulation (largely affected by temperature), Figure 1.

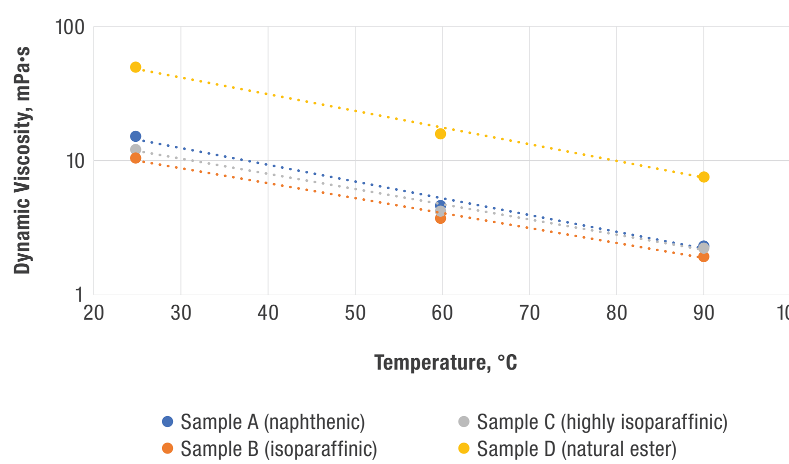

Figure 1.
Viscosity Dependence with Temperature

Procedure

Twenty-five mm thick pieces of laminated pressboard (Weidmann TX2) 100 x 200 mm were painted with a polyurethane sealant on all surfaces except the 25 x 100 mm ends of the material. This resulted in only a 25 mm by 100 mm area on either end for impregnation to take place; see Figure 2. Prior to impregnation, pressboard samples were dried less than 0.5 wt% moisture.

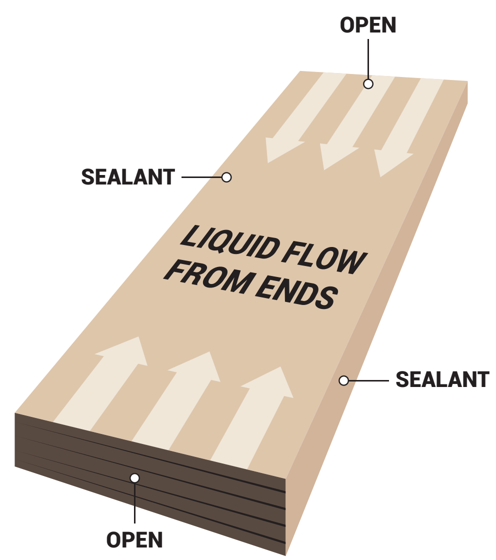

Figure 2.
Lamination of TX2 Block

Results

The impregnation distance from each end (A and B) was measured after 2, 4, 6, 8, 12, 24, 48, 72, 96, 120, 144, 168, and 192 hours or until complete impregnation was achieved. The estimated time for complete impregnation was then calculated as the time required for a maximum impregnation length of 71 mm.

The power function (Equation 1) closely approximates the data for each liquid/temperature combination,

$y = b * x^a$ *Equation 1*

where:
- y is the length of impregnation in mm
- b is the y-intercept
- x is the impregnation time in hours
- a is the slope

The Lucas-Washburn equation is used to describe the movement of liquids into capillaries. The penetration depth is proportional to the square root of time and the inverse of the square root of the dynamic viscosity,

$$L = \sqrt{\frac{\gamma r t \cos(0)}{2\eta}}$$ *Equation 2*

where:
- L = length
- γ = surface tension
- r = radius of the capillary
- t = time
- Ø = contact angle
- η = dynamic viscosity

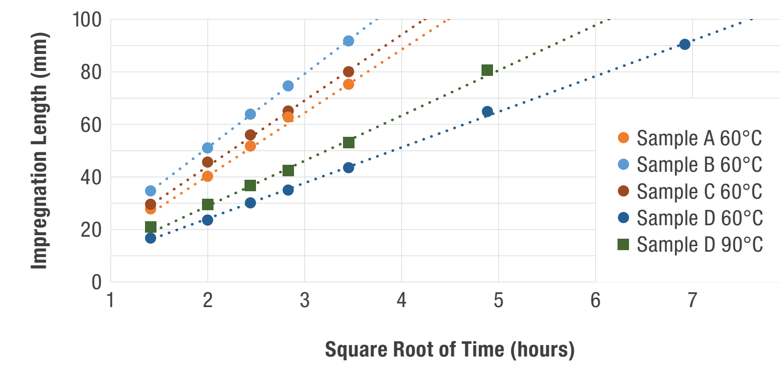

Figure 3.
Impregnation Depth vs Square Root of Time for Mineral Oils vs Natural Ester

The Lucas-Washburn equation also describes the relationship between the length of penetration and the viscosity. The length is inversely proportional to the square root of the dynamic viscosity. One example is given to illustrate this point, Figure 5. The data for the four samples were plotted for 60°C and times from 2 to 12 hours. The rate of penetration varies with the viscosity of the liquid such that reducing the viscosity by half increases the rate of penetration by about 40%.

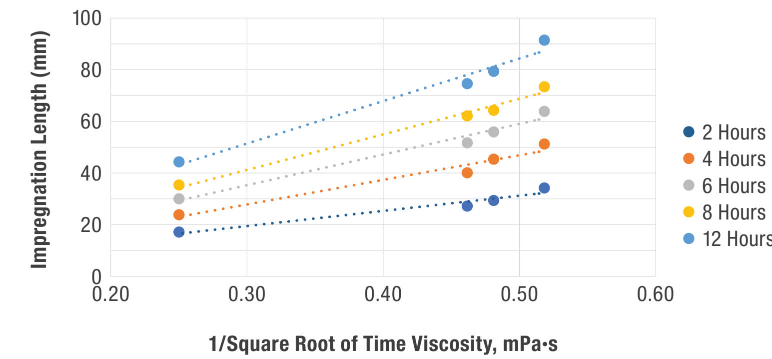

Figure 4.
Impregnation Depth at 60°C vs Viscosity

Equation 3 was then used to calculate the time for complete impregnation as defined as 71 mm, Table 1 and Figure 5,

$x = e^{\ln(y/b)/a}$ *Equation 3*

where:
- x is the impregnation time in hours
- y is the length of impregnation (71 mm)
- b is the y-intercept
- a is the slope

	25°C	60°C	90°C
Sample A, naphthenic	33.67	10.63	5.45
Sample B, isoparaffinic	18.46	7.48	4.24
Sample C, highly isoparaffinic	25.46	9.46	6.03
Sample D, natural ester	95.67	30.03	20.28

Table 1.
Estimated Time to Reach Complete Impregnation, 71 mm (Hours)