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Simulation Investigation on Heat Transfer Characteristics of Palm-Based Oil as Biodegradable Dielectric for Power Transformer Oil Application Using Quickfield Software

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ABSTRACT

Mineral oil was utilized as an insulating medium in transformers, which play a significant part in power transmission systems. Mineral oil has been used in the electrical power system for decades. However, due to the nonbiodegradable and high flammability features of mineral oils, their usage in electrical power systems can cause environmental difficulties when incidents such as oil spills or transformer explosions occur. To address this issue, alternative insulating oils with biodegradable qualities and good electric and chemical properties have been investigated as viable materials that can replace commercial oil. This research work examines the heat transfer properties of palm-based ester oil as an insulating material using QuickField software, which employs the finite difference approach. The transformer's 2D simulation model geometry was performed to show its heat transfer characteristics. Numerous heat transfer properties of palm-based ester were investigated to evaluate the heat transfer performance of palm oil-based ester and compared with mineral oils and other vegetative oils. It was found that palm-based oil shows the lowest temperature and heat flux among the other insulation oils.

1. Introduction

A power transformer is an electrical equipment that transmits electrical energy from one circuit to another using electromagnetic induction. It is also a device that distributes electrical energy from an alternating-current circuit to one or more circuits by varying (increasing or decreasing) the voltage. One of the various transformers extensively employed in our globe is the hermetic type of transformer. A hermetic transformer is filled with oil and compensates for oil expansion using deformable radiator fins [1-3].

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Mineral Oil has been a liquid insulation material in power system equipment such as transformers, switchgear, and cables since the early 1900s [14-16]. In large or medium ranges of high-voltage equipment, liquid insulation is critical. It is essential to ensure the dependability of equipment to ensure the long-term sustainability of power delivery. For more than 100 years, oil-filled transformer technology has been used [4-6]. In reality, failures caused by insulation in power system equipment can result in lengthy interruptions and lost income owing to replacement or maintenance work. It has been statistically proven that a substantial fraction of shutdown time is due to insulation system failure [7-10].

Mineral oil is generally effective and performs well as an insulator in transformers, although it has some disadvantages. Mineral oil is non-biodegradable since it is generated from petroleum and refined expressly for use [11]. The mineral oil will harm the environment, such as a transformer leak if an accident happens [17]. To address the issue of degradation and reduce maintenance costs, biodegradable oils from vegetative-based like palm oil with greater thermal conductivity are being developed. Real-world testing of the proposed biodegradable oils for efficacy within transformer heat transfer fluids, on the other hand, has yet to be widely published and clearly explained.

The main objective of this research work is to conduct a simulation investigation of heat transfer characteristics of palm-based oil using *Quickfield* software.

2. Method

2.1 Quickfield Software

The simulation of heat characteristics of liquid insulating material is done by using *QuickField 6.6* software. *QuickField* is based on the concept of finite element analysis (FEA) as a tool for electromagnetic, thermal, and stress design simulation, as well as connected multi-field analysis. It combines analytic modules that use cutting-edge solver technology with a simple model editor (preprocessor) and a powerful postprocessor. This software was developed by the Danish company Tera Analysis Ltd. in cooperation with Russian firm Tor Ltd.

Figure 1 shows the block diagram of the simulation procedure in this software. The first step is to create a new or empty problem. Next, specify the problem parameters. The problem pertains to a specific physical problem that *QuickField* solves. It covers general issue parameters such as analysis kind (electrostatics, magnetostatics, heat transport, and so on) and model type (planar or axisymmetric). After identifying the problem, we may begin defining the model's geometry, part names, and mesh. A geometric model is a detailed description of a model's geometry, part names, and mesh.

Fig. 1. Block diagram of the simulation procedure using Quickfield software in this work

A further step is to provide data for materials, loads, and boundary conditions afterward. Property descriptions are tailored to various sorts of analysis (Electrostatics data, Stress Analysis data, etc.). It will keep track of the material qualities, loadings, and boundary conditions for each part label. To tackle a wide range of issues, data documents can be employed as material libraries. In the fifth step, the solution is obtained. To solve a problem, numerous factors must be satisfied, including the problem type, plane, necessary precision, and other components in the problem description. The model document must include the whole model, including mesh and labels. Finally, go over the findings and get the postprocessing settings. The simulation will be conducted in order to process the results. If the results are consistent with the project objectives and scopes, they will be reviewed and evaluated for inclusion in the report. In this work, the properties of palm-based ester oil and other oil samples like specific heat transfer, thermal conductivity, etc were obtained from related references [12,13].

2.2 Design of Modeling

This simulation creates a complete 2D winding transformer including the core of the power transformer using the QuickField software. The model made will be the air, core, high voltage, low voltage, and liquid insulation. Figure 2 shows the development of the model winding transformer as well as its core and Table 1 shows the dimension values of the 2D geometry model for this simulation.

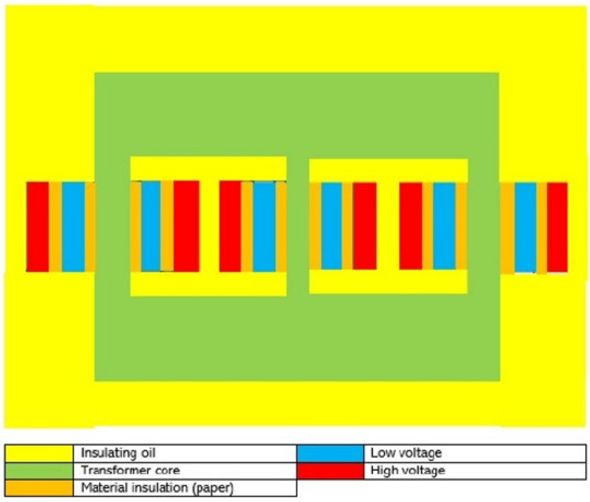

Fig. 2. Side view of 2D power transformer in this simulation work

Table 1
Dimension values of 2D geometry model [12,13]

Parameters	Dimension (mm)
Length of core	2740
Height of core	2010
Length of high voltage and low voltage winding	100
Height of high voltage and low voltage winding	1130
Length of cellulose (paper) between high voltage and low voltage winding	70
Height of cellulose (paper) between high voltage and low voltage winding	1130

In the simulation, the solid geometry that has been created must be defined as its properties. The properties ensured that later results would achieve the project objectives and scopes. The transformer core and the windings (high voltage, low voltage) as solid thermal conductivity properties and initial temperature need to be defined. The properties are shown in Table 2.

Table 2
Solid properties of transformer windings [12,13]

Type of solid	Thermal conductivity (W/m.K)
Transformer core (steel)	43
Transformer winding (copper)	398
Palm-based oil	0.04158
Coconut oil	0.154
Mineral oil	0.1056
Cellulose (paper)	0.040
Soybean oil	0.169

Heat flux is a significant variable to find in heat transfer characteristics as the heat flux value will be calculated in finding the heat transfer coefficient [18]. It measures the quantity of heat energy transported per unit of time via a surface. Heat flux is commonly given in watts per square meter (W/m2). The change of heat flux mainly occurs at the transformer winding.

3. Results and Discussion

Figure 3 shows the mesh analysis of the transformer model in Figure 2 as stated in step 5 of the simulation procedure. Figure 4 shows a 2D transformer modelling in the color mapping of temperature for palm-based oil. The simulation runs for 10 hours with different temperatures set in both transformer windings (low voltage (LV), and high voltage (HV)). It is found that the transformer core reaches 89.73 °C as the highest temperature among 5 different readings when both transformer windings are set in maximum temperature (LV = 80°C, HV = 130 °C).

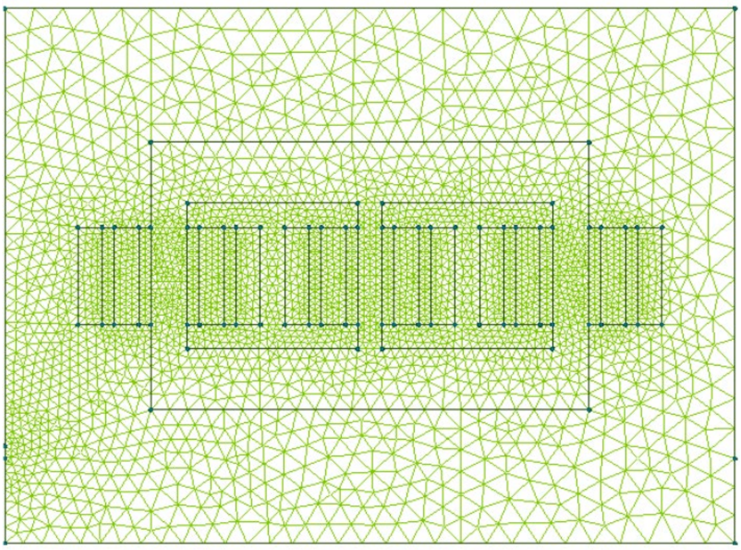

Fig. 3. Mesh analysis for transformer model in Figure 2

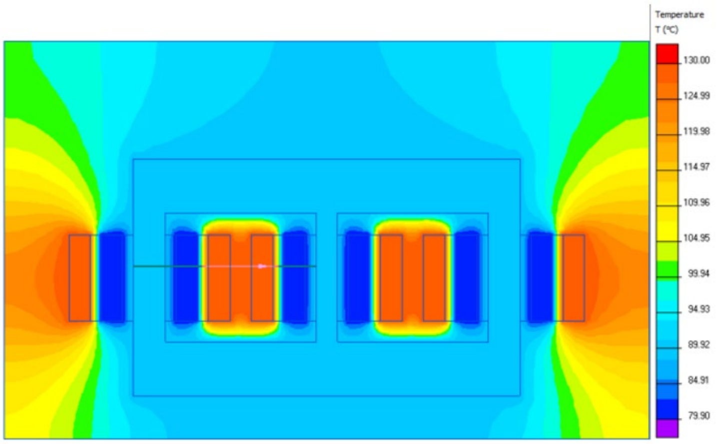

Fig. 4. Simulation results of transformer core temperature for palm-based oil

When a transformer's winding temperature is set to its maximum, it might cause a rise in the temperature of the transformer core due to the heat transfer mechanism. A transformer's winding is responsible for carrying electric current, and as a result, it creates heat owing to resistance. Conduction and convection transmit this heat to the surrounding components, including the transformer core. When the winding temperature rises, so does the heat transfer to the core, causing it to rise in temperature as shown in Figure 5. Furthermore, transformer cores are commonly constructed of laminated steel sheets. The magnetic characteristics of these sheets are critical for effective energy transmission. At higher temperatures, however, the core material suffers from increasing hysteresis and eddy current losses. These losses create extra heat within the core, leading to a rise in temperature.

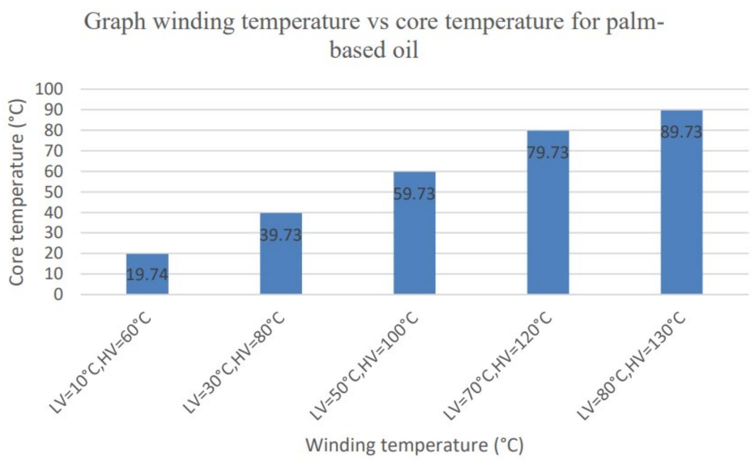

Fig. 5. Graph of core temperature due to the temperature of transformer windings

It is essential to remember that maintaining optimal operating temperatures is critical for transformer reliability and efficiency. Long-term operation of a transformer at exceptionally high temperatures can result in accelerated aging, insulation damage, and possible failure. To guarantee safe and optimal functioning, transformers should be operated within their intended temperature limitations.

Figure 6 shows a color mapping of the heat flux values for palm-based oil simulation that will be simulated at different times with intervals of 60 minutes, 300 minutes, 600 minutes, 3000 minutes, and 6000 minutes. Heat flux can be defined as the rate of heat energy transfer from the surface or winding [1].

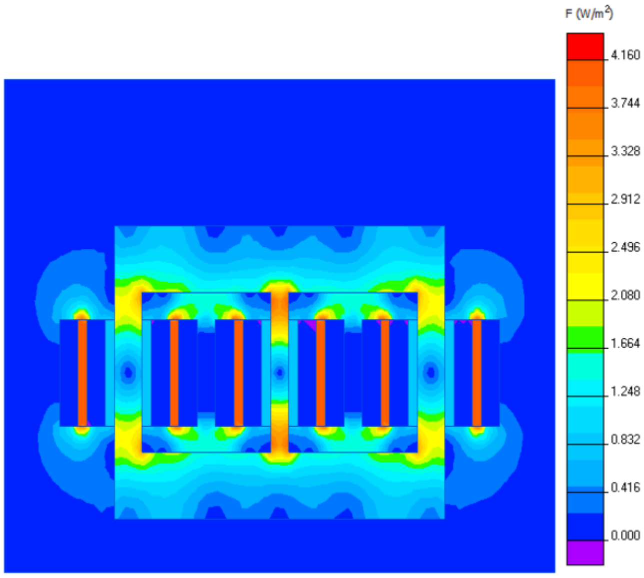

Fig. 6. Simulation results of heat flux values for palm-based oil samples

Mathematically, heat flux (Q/A) is calculated using the following equation:

$$\frac{Q}{A} = \frac{\triangle Q}{\triangle t} \quad (1)$$

where,

Q/A: the heat flux (W/m2)
ΔQ: the amount of heat transferred (in watts)
Δt: time interval over which the heat transfer occurs (in seconds)
A: surface area through which the heat is transferred (in square meters)

Figure 7 shows the data extracted from the simulation of heat flux from the core to the winding of the transformer for different time operations. As can be seen from the simulation results, as the time increases, the heat flux decreases which shows a downtrend from 1.037 W/m2 to the lowest heat flux at 6000 minutes is 0.373 W/m2. The heat produced in the winding is conducted and convectively connected to the surrounding components, which include the transformer core and the cooling system.

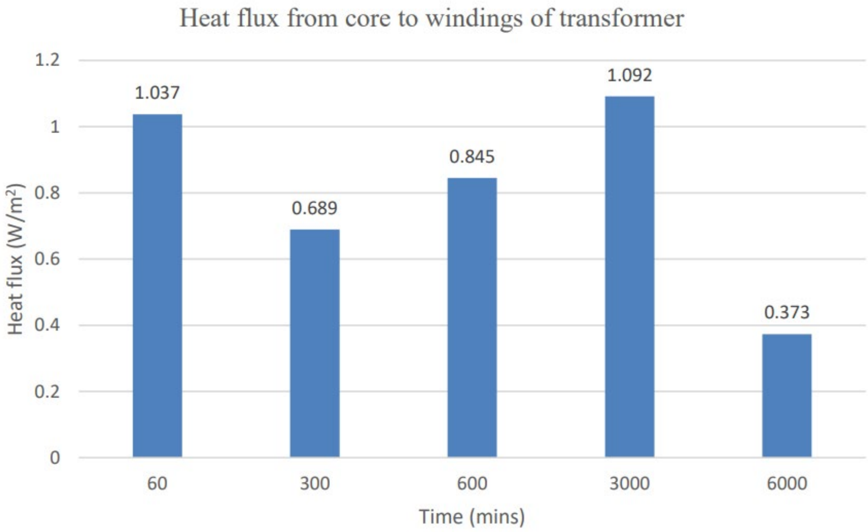

Fig. 7. Graph of heat flux values from core to windings of the transformer

The heat flux of the transformer winding is influenced by various factors namely load current. The heat produced in the winding is proportional to the load current running through it. Higher load currents cause more heat generation and, as a result, a higher heat flux. Besides, the heat flow in the winding is affected by the effectiveness of the cooling system. A more efficient cooling system may remove heat from the winding more effectively, hence lowering heat flux [19]. As the running time increases, the temperature in transformer winding gets cooler.

The temperature of the steel core within a power transformer is often referred to as the transformer core temperature. To regulate the core temperature, the transformer is immersed in insulating oil that helps dissipate the heat generated during the operation [17,20].

Figure 8 shows the data obtained when the winding temperatures were set at LV=80°C and HV=130°C for different types of insulating oil. From the results, we can see that soybean oil has the highest core temperature which is 96.49°C and the smallest core temperature is 89.73°C which is obtained by palm-based oil.

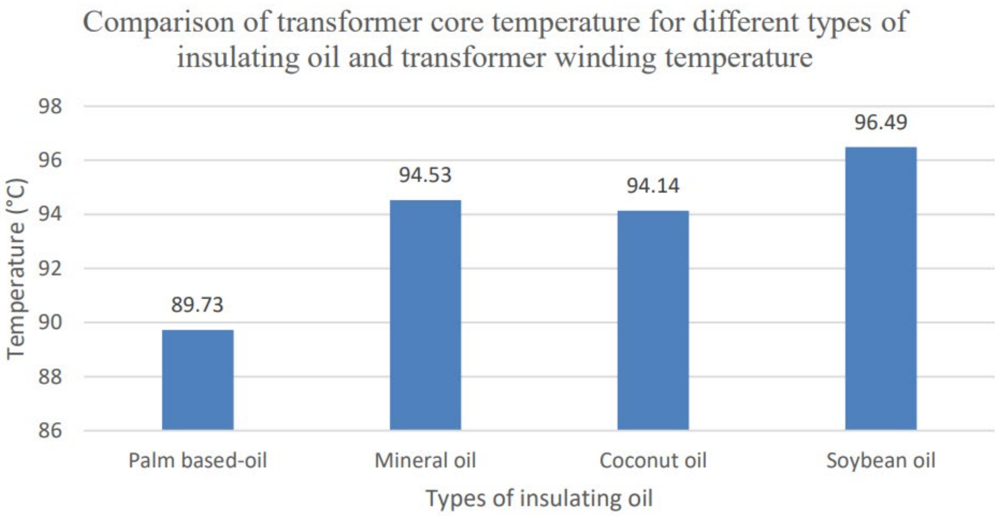

Fig. 8. Graph of transformer core temperature for different types of insulating oils (LV=80°C, HV=130°C)

From the results, we can conclude that palm-based oil gives the smallest value of core transformer in different temperature sets on transformer winding. Insulation materials can maintain their intended performance and resistivity when the core temperature is working at low temperatures, ensuring dependable insulation between conductive parts, and reducing insulation breakdown or failures. In addition, transformers perform best within temperature ranges. Lower core temperatures minimize resistive losses in transformer windings, resulting in higher overall energy efficiency. Lower resistive losses imply that less energy is lost as heat, resulting in lower operating costs and an influence on the environment. Lower core temperatures contribute to the transformer's greater dependability and stability. Heat-related strains are reduced on components such as the core, windings, and insulation, lowering the likelihood of mechanical failure or thermal expansion problems. This results in a more robust and dependable transformer that is less susceptible to performance decline or unexpected failures.

Soybean oil gives the highest value of core transformer in different temperatures set on transformer winding. When the core temperature of a transformer becomes overly high, it can cause a variety of problems that influence the transformer's performance, efficiency, and dependability. Higher core temperatures can cause greater resistive losses within the transformer, lowering the transformer's overall efficiency. This inefficiency generates more heat and exacerbates the temperature rise, producing a vicious cycle. Besides, to disperse heat, transformers use cooling devices such as radiators, fans, or oil pumps. If the core temperature rises too high, it may surpass the capacity of the cooling system, resulting in insufficient cooling. This can lead to a rise in temperature and perhaps system failure.

Figure 9 shows the simulation results of the heat flux from the core of the transformer to the windings of the transformer for different types of insulating oils with the time of operation of 60, 300, 600, 3000, and 6000 min, respectively. As can be seen from the graph, when the time increases, the heat flux does not constantly decrease or increase as a result. When we compare the result from the first 60 minutes until 6000 minutes, soybean oil shows the largest increase in heat flux while palm-based oil shows a decreasing trend. This may be due to palm-based oil reaching stability faster for 6000 minutes than the other three insulating oils

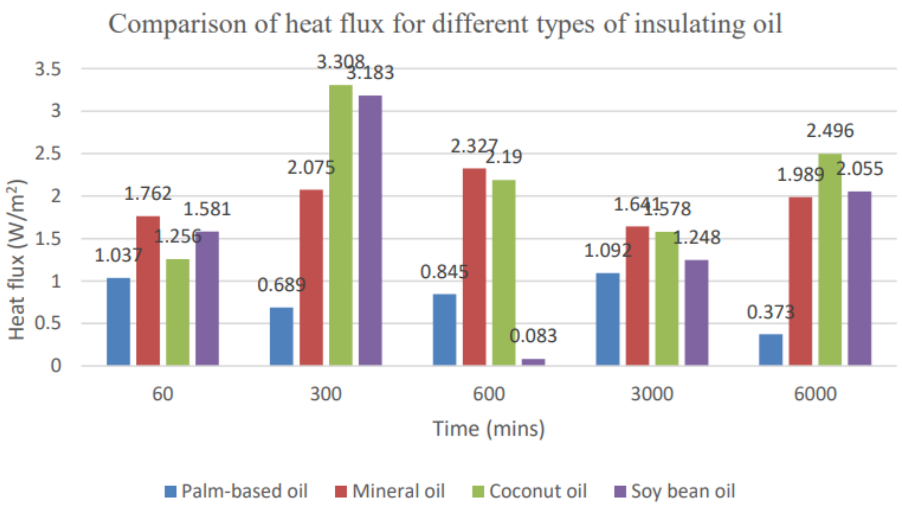

Fig. 9. Graph of the heat flux value for different types of insulating oils

4. Conclusions

The heat transfer properties of palm-based oil as an insulating material have been successfully investigated using Quickfield software, a finite element analysis-based software.

Based on the properties that the oil offers for the insulation material, palm-based oil has a high potential to replace commercial insulating transformer oil as the most suited liquid insulation for transformer oil. Because of their biodegradable and ecologically benign features, natural esters are now being used to replace the insulating liquid in transformers as the globe adjusts to the trend of applying green technology in electrical power systems. There were three goals for this project.

It is found that palm-based oil shows the lowest temperature and heat flux among the three other insulation oils. The thermal transfer capabilities of palm-based oil revealed that the temperature of the core of palm-based oil is the lowest among the three different insulation oils in this study.

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