Simulation of Heat Transfer Characteristics on Palm Oil as Electrical Insulating Material Using Finite Difference Method

Yanuar Z. Arief
Dept. of Electrical and Electronic Eng.
Faculty of Engineering
Universiti Malaysia Sarawak (UNIMAS)
Kota Samarahan,, Sarawak, Malaysia
ayzulardiansyah@unimas.my

Mohd. Shuffy Suhaidi
Dept. of Electrical and Electronic Eng.
Faculty of Engineering
Universiti Malaysia Sarawak (UNIMAS)
Kota Samarahan, Sarawak, Malaysia

Naemah Mubarakah
Dept. of Electrical Engineering,
Faculty of Engineering
Universitas Sumatera Utara (USU)
Medan, Indonesia
naemah@usu.ac.id

May Raksmey
Dept. of Civil Engineering
Faculty of Engineering
Universiti Malaysia Sarawak (UNIMAS)
Kota Samarahan, Sarawak, Malaysia

Irza Sukmana
Department of Mechanical Engineering
Faculty of Engineering,
Universitas Lampung (UNILA),
Bandar Lampung, Lampung, Indonesia

Rosyid Ridlo Al Hakim
Dept. of Electrical Engineering
Faculty of Eng. and Information System,
Jakarta Global University, Depok,
Indonesia

***Abstract*—The purpose of this research work is to study the heat transfer characteristics of palm oil as insulating material using finite difference method (FDM). Analysis and investigations of several heat transfer characteristics of palm oil were performed to determine the heat transfer performance of this oil. The characteristics obtained is then compared to other insulating oils to determine the performance of the insulating material. The simulation was done using Computational Fluid Dynamics (CFD) software that uses finite difference method concept that could perform 2D simulation to visualize the heat transfer characteristics inside the design of 2D transformer model geometry. The winding temperature is set into initial condition under full load temperature. The fluids properties of insulating material such as density, viscosity, thermal conductivity and specific heat capacity are set as constant, respectively. The simulation is set to constant running time of 30 minutes with interval of 5 minutes. The heat transfer characteristics such as fluid temperature, winding temperature, velocity profile, density and viscosity, heat flux from the winding and heat transfer characteristics are defined as variables, respectively. The results shows significant decrease of fluid and winding temperature of a transformer with palm oil as insulating material and has better heat transfer performance than other vegetative oils.**

Keywords—heat transfer characteristics, vegetative-based oil, electrical insulating material, finite difference method, computational fluid dynamic.

I. Introduction

Transformer is a very important and essential electrical component in power distribution and transmission. Power transformer is an electrical machine that transfers electrical energy from one circuit to another either by stepping up the voltage or stepping down the voltage according to the needs. Basically, it is a device that changes voltage levels. There are many classes of transformer used in the distribution and transmission of power. Hermetic type of transformer is one of the many transformers that widely used in this world. Hermetic type transformer is a fully filled with oil where the oil expansion is compensated by deformable radiator fins [1-7].

For decades, mineral oil has been used in electrical power system for transformer oil. However, mineral oil possesses disadvantages where its application in electrical power system can cause environmental problems when accidents occur like oil spillage or transformer explosion due to the non-biodegradable and high flammability properties of mineral oils. To resolve this issue, the alternative insulating oils with biodegradable properties with good electric and chemical properties has been researched for potential insulating material that can replace the commercial oil.

Mineral oil is a petroleum-based oil. As oil petroleum sources becomes relatively low, vegetable or natural ester oil specifically palm-based oil becomes another option to replace the transformer oil. Looking into economics aspects, Malaysia is the one of main producer of palm oil which given the advantage to the economy growth of the country. Palm oil is categorized also as vegetable oil which they are popular because they perform better than products made from the commercial oil and have definite environmental and safety benefits [4]. A good type of insulating liquid must have good electrical properties which ensure the performance of the insulating material itself. The electrical properties for palm-oil such as the partial discharge magnitudes test, shows palm fatty acid ester (PFAE) are slightly lower than those of commercial mineral oil during aging period [5].

Heat produce in transformer generally occurs at the windings and core of the transformer due to power loss. The windings temperature may exceed 110°C under full load or 80°C rise above surrounding temperature in industrial standards [6]. In industry, analyzing the hot-spot temperature is a crucial to keep the life span of transformer. Hot spot temperature can

2021 5th International Conference on Electrical, Telecommunication and Computer Engineering (ELTICOM) | 978-1-6654-1200-1/21/$31.00 ©2021 IEEE | DOI: 10.1109/ELTICOM53303.2021.9590126

be measured at the hottest part of the windings. Under normal load condition, transformer that have rating of 112.5 and 10,000 kVA would have windings temperature from 80 to 90℃ [8]. As for the transformer oil temperature, the temperature must always maintain from 20 to 90℃ to reduce the chance of transformer failure [9].

Heat transfer can be simulated in computational fluid dynamics (CFD) software such as ANSYS, COMSOL Multiphysics, MATLAB, FLOW 3D, etc. These CFD software uses numerical method and specific algorithms to analyze and solve free surface fluids flow problems such as convection flow, temperature fluids profile, etc. FLOW 3D is widely used in CFD industry in various engineering fields. It more user friendly, easy to use yet have advance features in the software. In this work, for heat transfer characteristics of palm-based ester oil, FLOW 3D can be employed to simulate the problems.

Main objective of this research work is to simulate and analyze heat transfer characteristics of palm-based ester using finite difference method in term of fluid temperature velocity, windings temperature, density, viscosity, heat flux and heat transfer coefficient, respectively. Furthermore, comparison of heat transfer performance characteristics of several transformer oil with other vegetative oils were also carried out.

II. Methodology

A. Simulation Procedure

The simulation of heat transfer characteristics of palm-based ester oil can be simulated by using FLOW 3D. FLOW 3D is a computational fluid dynamics (CFD) software that can be used for various areas of engineering fields. CFD is used in wide engineering areas for conceptual designing, complete product development, optimization, testing and troubleshooting and redesigning. According to FLOW 3D webpage, FLOW 3D is a precise and versatile software that can be used by engineers to analyze behavior of liquids and gas in a various range in industrial applications. FLOW 3D solvers are based on finite differences method (FDM).

Conduction, convection and radiation can be classed as ways of heat transfer in transformer. Conduction is driven by the Law of Fourier, in which the one-dimensional form is represented in the equation (1) [9].

$$q = -k\nabla T \qquad (1)$$

Where,

q = heat flow rate (W/m^2)

∇T = rate of change of temperature with the path in the direction of heat transfer (K/m).

Usually, natural convection occurs inside the transformer where density plays a big role in for the fluid motion. From the surface of the core to the windings of the transformer, the heat is transferred by the movement of oil inside transformer tank. Convection equation is based on Newton's Law of Cooling as expressed in equation (2) [9].

$$q = h(T\_s - T\_\infty) \qquad (2)$$

Where,

q = heat flow rate (W/m^2)

h = heat transfer coefficient of convection (W/m^2.℃)

T_s = temperature of surface

T_∞ = fluid temperature between the surface

By rearranging the equation (2), heat transfer coefficient is the heat flux per difference between the fluid temperature and the winding temperature which shows in equation (3).

$$h = \frac{q}{T_s - T_\infty} \qquad (3)$$

Where,

h = heat transfer coefficient of convection (W/m^2.℃)

q = Heat flux of winding transformer

T_s = temperature of surface

T_∞ = fluid temperature between the surface

The heat transport processes in a transformer are primarily conduction and convection, radiation is less concerned [10].

The simulation of heat transfer characteristics of palm-based ester oil is done by using FLOW 3D software. The first step is to collect data and information from previous journals and papers studies that are related to this project. After done doing so, in the simulation, using the data collected, the pre-analysis and parameters that needed in the simulation are defined which the problems and variables are identified and setting up the constant value. Next, the design modelling of transformer will be performed. The type of the model will be analyzed, and dimension will be identified. Then, the model will be sketched at the software geometry interface. After model design process, the physics and fluids involved in the simulation will be defined. Physics setup can be defined according to specific conditions of the simulation. Physics setup basically consists of gravity and non-inertial reference frame, heat transfer, density evaluation and viscosity and turbulence, respectively. The fluids setup is being defined the types of fluids involved in the simulation as palm-based ester is being defined. Then, meshing and boundary conditions will also be defined. The area and sizing of the meshing will be specified. After defining the mesh, then the material properties and initial conditions will also be defined in the simulation. The material for windings and core of the transformer will be defined specifically to yield most possible accurate results and the initial conditions of the fluids, core and windings of transformer must also be setup. After done so, the variables and conditions will be manipulated such as the variables that will be displayed on results interface. In this work, temperature and velocity will be selected as variables. Then, the simulation will be run to process the results. If the results meet the project objectives and scopes, then the results obtained will be analyzed and discussed to be included in the report.

B. Design Modelling

In this simulation, a complete 2D slice model of transformer is being created at the geometry interface of the simulation software. The model created will be the core and the windings of the transformer. Both geometry will be created using Primitives of FLOW 3D which Primitives are the basic shapes that can be used to create subcomponents [11]. The primitives used are the cylinder and rectangular box which need to design and define on all planes (XY plane, YZ plane and ZX plane). Fig. 1 shows the develop 2D slice model of transformer.

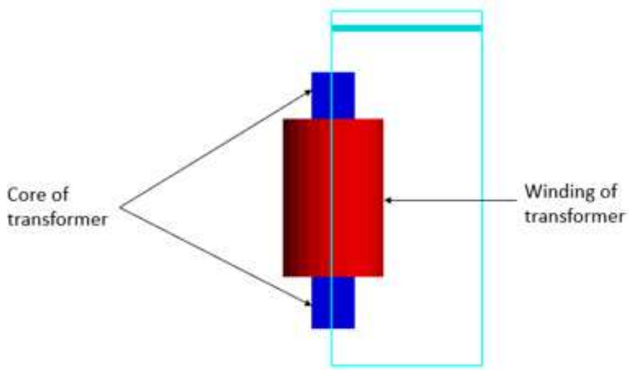


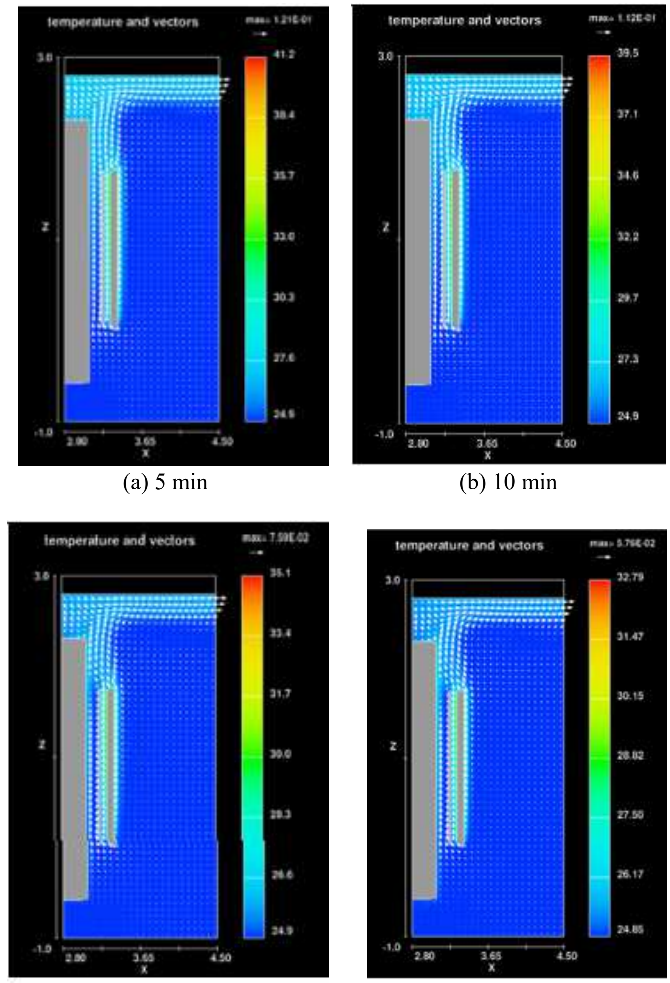
Fig.1. 2D slice model of transformer winding

III. Result and Discussion

A. Temperature Profile

Fig.2 shows the fluid temperature profile of palm-based oil as insulating material in 30 min time at interval of 5, 10, 20, and 30 min, respectively. The different value of time gives different fluid temperature of palm oil. As can be seen from the figure, the blue contour represents the fluid of insulating material inside the transformer which is palm-based ester oil. Furthermore, the change of temperature mainly occurs at the top of the windings. the fluid is hot near the 2D model which represent lighter blue color contour. As the fluid moves down to the bottom of the model, the temperature decreases which represents darker blue color.

Table 1 and Fig. 3 show the data extracted from the Fig. 2. which shows the fluid temperature profile of palm-based ester oil for 30 min time. Based on Table 1 and Fig. 3, the initial temperature of fluids is 24.85℃. After heat is introduced, it shows that as the time increases, the fluid temperature of palm-based ester oil decreases which shows a downtrend of temperature from 5 min, namely is 41.2℃ to the lowest temperature of palm-based ester oil achieve after 30 min is 32.79°C. The heat produced is dissipated from the windings of transformer to the palm-based ester oil by convection which confirms the heat transfer occurs. As the heat dissipates along the time, the fluid temperature of palm oil getting lower.



(a) 5 min (b) 10 min

(c) 20 min (d) 30 min

Fig. 2. The fluid temperature profile of palm-based ester against time (min).

TABLE I. Fluid Temperature of Palm-Based Oil in Different Time

No.	Time (min)	Fluid Temperature (ºC)
1.	0	24.85
2.	5	41.2
3.	10	39.5
4.	15	37.1
5.	20	35.1
6.	25	34.3
7.	30	32.79

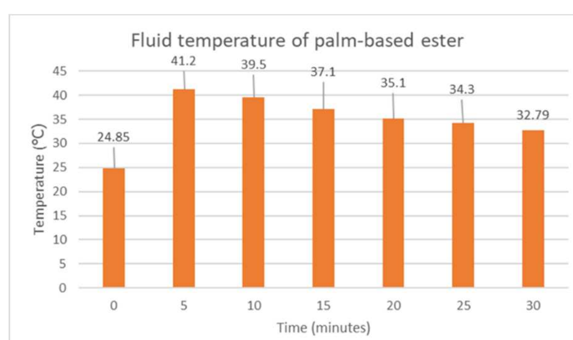


Fig. 3. The fluid temperature of palm-based ester against time (min).

Table 2 and Fig. 4 below show the data extracted from the simulation result in winding temperature of transformer for observation time of 30 min. As can be seen clearly from the data and graph, it shows that as the time increases, the winding temperature of transformer decreases which shows a downtrend of temperature from 120℃ to 39.4 ℃ after 30 min time. In this case, the winding of transformer has higher temperature than the fluid temperature because the winding is made from solid and as sources of heat. The temperature of winding is getting lower because the heat transfer mechanism is also by convection where the hot surface of winding dissipates heat to the insulating material of palm oil where the winding was immersed in it. This causes the winding temperature to decrease overtime.

TABLE II. WINDING TEMPERATURE OF PALM OIL IN DIFFERENT TIME

No.	Time (min)	Fluid Temperature (°C)
1.	0	120
2.	5	84.2
3.	10	72.7
4.	15	57.3
5.	20	47.8
6.	25	44.4
7.	30	39.4

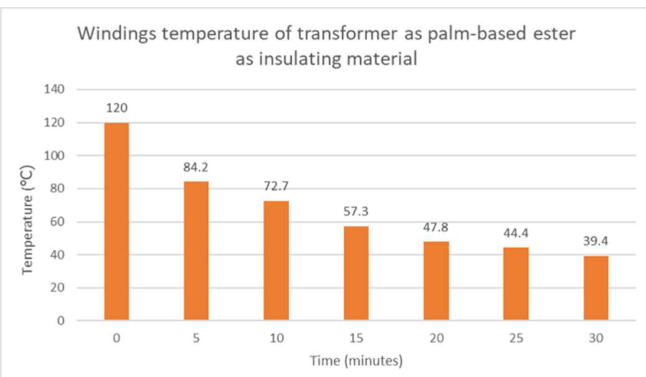


Fig.4. Winding temperature of palm oil against time (min).

B. Velocity Profile

Table 3 and Fig. 5 show the velocity profile simulation results of palm oil as insulating material in time observation of 30 min with interval of 5, 10, 15, 20, 25, and 30 min, respectively. The different value of time gives different velocity profile of palm-based ester. Based on Table 3, the fluid moves up at the top of the model. The blue contour represents the lower velocity of fluids of insulating material. The velocity at the bottom is close to 0 m/s which shows the velocity of fluid mainly occurs at the middle and top of the windings. The movement of fluids is at the top of the model which causes high velocity due to heat energy concentrated at the hot area. The red contour shows the highest velocity in the model. The fluid moves mainly vertically rather than horizontally. The presence of velocity of the fluids can be observed as natural convection.

TABLE III. VELOCITY PROFILE OF PALM-BASED OIL

No.	Time (min)	Fluid Velocity (m/s)
1.	0	0.121
2.	5	0.112
3.	10	0.094
4.	15	0.076
5.	20	0.069
6.	25	0.0576
7.	30	39.4

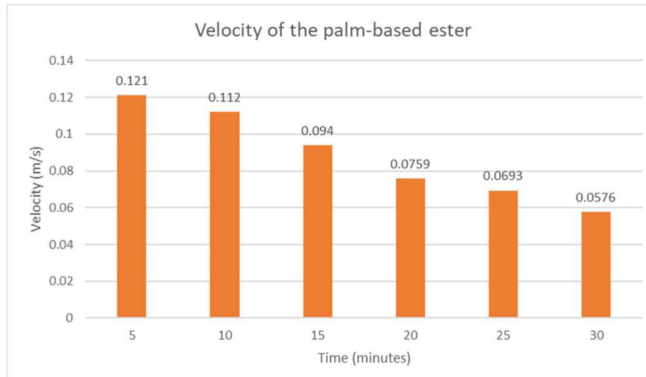


Fig.5. Velocity profile of palm oil against time (min).

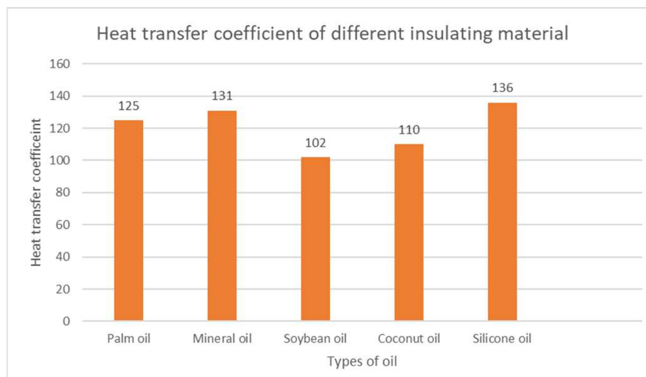


Fig.6. Heat transfer coefficient for different types of oil.

The heat transfer coefficients of all insulating materials, namely palm oil, mineral oil, soybean oil, coconut oil, and silicone oil were calculated using heat transfer coefficient equation in equation (3). Fig. 6 shows the simulation results of heat transfer coefficient of all oil types after 30 min of observation time. The results are then compared with the simulation results as shown in Table 4 and the percentage error is calculated by using equation (4). As can be seen from the results, the heat transfer coefficient of palm oil is close to mineral oil's so that the velocity, fluid temperature, and winding temperature have similar performance with mineral oil.

$$\%\ error = \frac{Simulation\ value - Calculated\ vale}{Calculated\ value} \times 100 \quad (4)$$

TABLE IV. HEAT TRANSFER COEFFICIENT FOR DIFFERENT TYPE OF OILS

Oil Type	Simulation Result	Calculated Result	% Error
Palm Oil	125	117.9	6.02
Mineral Oil	131	125.5	4.3
Soybean Oil	102	98.3	3.8
Coconut Oil	110	106.9	2.9
Silicone Oil	136	130.6	4.13

IV. CONCLUSION

The heat transfer characteristics of palm-based ester as insulating material can be simulated using finite difference method (FDM) software. There are many reports and journals being referred to complete this project. The simulation was conducted using finite difference method software and the area of study are based on the heat transfer characteristics of palm oil. The palm oil has the high potential to replace commercial insulating transformer oil as the most suitable liquid insulation for transformer oil based on characteristics that the oil provides for the insulation material. Nowadays, natural esters are being adapted to replace insulating liquid in transformer because of its biodegradable and environmentally friendly properties as the world now adapts trend on implementing green technology in electrical power system. Hence, adapting natural esters particularly palm-based ester needs to be assure its reliability and performances to replace commercial transformer oil.

The results shows significant decrease of fluid and winding temperature of a transformer with palm oil as insulating material and has better heat transfer performance than other vegetative oils. The heat transfer of palm oil is close to mineral oil so that the characteristics oil palm oil exhibits the similar performance with the transformer oil.

ACKNOWLEDGEMENTS

The authors would like to thank *Universiti Malaysia Sarawak* (UNIMAS) for facilitating of this works by awarding the research grants of Small Grant Scheme (SGS) under vot number: F02/SGS/1784/2018 and International Matching Grant Scheme under vot number: GL/F02/UNILAK/2020.

REFERENCES

[1] A. Mahersa, “Transformer: Knowledge Sharing,” *Encycl. Knowl. Manag.*, vol. 1, pp. 914–923, 2010, doi: 10.4018/978-1-59904-931-1.ch087.

[2] R. Sanghi, “Chemistry behind the life of a transformer,” *Resonance*, vol. 8, no. 6, pp. 17–23, 2003, doi: 10.1007/bf02837865.

[3] N. D. Ahmad *et al.*, “A Study of Palm Oil as an Insulating Medium,” vol. 7, pp. 17–20, 2018.

[4] M. Rafiq *et al.*, “Use of vegetable oils as transformer oils-A review,” *Renewable and Sustainable Energy Reviews*. 2015, doi: 10.1016/j.rser.2015.07.032.

[5] D. K. Mahanta and S. Laskar, “Electrical insulating liquid: A review,” *J. Adv. Dielectr.*, vol. 7, no. 4, pp. 1–9, 2017, doi: 10.1142/S2010135X17300018.

[6] G. Swift and T. Molinski, “Power Transformer Life-Cycle Cost Reduction,” Power, pp. 1–11.

[7] T. O. Rouse, “Mineral insulating oil in transformers,” IEEE Electr. Insul. Mag., vol. 14, no. 3, pp. 6–16, 1998.

[8] Functional specification for three-phase substation distribution transformers, vol. 1993, no. October, pp. 1–13, 2015.

[9] L. L. Rui, “Heat Transfer Performance of Oil-Based Nanofluids in Electric Transformers,” Universiti Teknologi Petronas, 2015.

[10] R. Karadağ, “Temperature Distribution in Power Transformers,” Middle East Technical University, 2012.

[11] FLOW 3D, “FLOW 3D.” 2016, [Online]. Available: file:///C:/flow3d/v11.2/help/index.html#.