



**DIELECTRIC STRENGTH AND VISCOSITY OF PALM OIL
BASED NANOFUIDS FOR LIQUID INSULATION IN POWER
TRANSFORMER**

MOHD SAFWAN BIN MOHAMAD

MASTER OF SCIENCE IN ELECTRICAL ENGINEERING

2018

**DIELECTRIC STRENGTH AND VISCOSITY OF PALM OIL BASED
NANOFLUIDS FOR LIQUID INSULATION IN POWER TRANSFORMER**

MOHD SAFWAN BIN MOHAMAD

**A thesis submitted
in fulfilment of the requirement for the degree of Master of Science
in Electrical Engineering**

Faculty of Electrical Engineering

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

2018

DECLARATION

I declare that this thesis entitled “Dielectric Strength and Viscosity of Palm Oil Based Nanofluids for Liquid Insulation in Power Transformer” is the result of my own research except as cited in the references. The thesis has not been accepted for any degree and is not concurrently submitted in candidature of any other degree.

Signature :

Name : Mohd Safwan Bin Mohamad

Date :

APPROVAL

I hereby declare that I have read this thesis and in my opinion this thesis is sufficient in terms of scope and quality for the award of Master of Science in Electrical Engineering .

Signature :.....

Supervisor Name : Assoc. Prof. Dr. Hidayat Bin Zainuddin

Date :.....

DEDICATION

To my beloved parent, wife and kid

ABSTRACT

The liquid insulation system of high voltage oil-immersed transformers is involved in this thesis. Until now, mineral insulation (MI) oils are typically used in high voltage oil-immersed transformers because of their excellence in dielectric strength and cooling performance. However, MI oils are non-renewable and non-sustainable sources. This has led scientists and researchers to formulate alternative insulation liquids such as natural ester insulation (NEI) oils to replace MI oils. Palm fatty acid ester (PFAE) is one of the ester types of insulation oil and the alternative oil to replace MI oils. This PFAE oil was developed in 2006 by Lion Corporation as insulation oil for transformer applications which have several advantages compared to MI oils i.e. good biodegradability, excellent performance in insulation and cooling medium. Nowadays, nanotechnology is one of the most important research fields especially in electrical insulation system due to the increasing demand for the electrical power in the world. Therefore, adding the nanoparticles is one of the approaches used by researchers to improve the performance of liquid insulation also known as nanofluids. The use of nanofluids in insulation system give more benefit in terms of insulation performance, design and power capacity of transformer. Based on this premise, the objectives of this research is to formulate PFAE oil-based nanofluids by dispersing three types of nanoparticles (i.e. conductive, semi-conductive and insulating nanoparticles) into PFAE oil. The potential of these nanofluids as insulation liquids is validated based on its Alternating Current (AC) breakdown voltage and viscosity. In sample preparation of PFAE oil-based nanofluids, four specific procedures must be followed i.e. weighing, homogenizer treatment, vacuum oven and moisture removal treatment process. The AC breakdown voltage was measured which complies with the specifications of the ASTM D1816 and the viscosity of the oil samples was measured according to ASTM D445 and ASTM D2983. The findings from the AC breakdown voltage suggested that the PFAE oil-based conductive nanofluid has the highest dielectric strength enhancement at weibull probability of 63.2 % with a value of 50.57 % relative to that for virgin PFAE oil. Besides that, the histogram for this nanofluids is skewed to the left, whereby most of the data fall within a range of 45 – 49 kV. In terms of heat transfer, the PFAE oil-based insulating nanofluid has the lowest viscosity compared to the other oil samples, particularly at 60 °C, based on viscosity values. Both of these parameters (AC breakdown voltage and viscosity) are crucial to designers of high voltage equipment and systems. In conclusion, the effects on breakdown voltage is more significant compared to the viscosity when nanoparticles are added into the PFAE oil.

ABSTRAK

Sistem penebat cecair bagi pengubah minyak-tenggelam voltan tinggi didedahkan dalam tesis ini. Sehingga kini, penebat minyak mineral (MI) kebiasaannya digunakan dalam pengubah minyak-tenggelam voltan tinggi kerana ianya sangat baik dalam kekuatan dielektrik dan keupayaan penyejukan. Walau bagaimanapun, minyak MI adalah sumber yang tidak boleh diperbaharui dan tidak lestari. Hal ini menyebabkan ramai saintis dan penyelidik mengkaji penebat cecair alternatif seperti penebat minyak semulajadi ester (NEI) untuk menggantikan minyak MI. Asid lemak kelapa sawit ester (PFAE) merupakan salah satu penebat minyak jenis ester dan minyak alternatif untuk menggantikan minyak MI. Minyak PFAE ini telah dibangunkan pada tahun 2006 oleh Lion Cororation sebagai minyak untuk aplikasi pengubah yang mempunyai beberapa kelebihan berbanding minyak MI iaitu tahap pereputan yang bagus, sangat baik dalam penebatan dan media penyejukan. Pada masa kini, teknologi nano merupakan salah satu bidang penyelidikan yang terpenting terutamanya dalam sistem penebatan elektrik yang disebabkan permintaan elektrik yang semakin meningkat untuk kuasa elektrik dunia. Oleh itu, menambah nanopartikel adalah salah satu kaedah yang digunakan oleh ramai penyelidik untuk meningkatkan prestasi penebat cecair yang dikenali sebagai cecair nano. Penggunaan cecair nano dalam sistem penebat memberi banyak manfaat dari segi prestasi, reka bentuk dan kapasiti kuasa bagi pengubah. Berdasarkan pernyataan ini, objektif kajian ialah untuk merumuskan PFAE berasaskan cecair nano dengan menyebarkan tiga jenis nanopartikel (iaitu konduktif, separuh konduktif dan penebat nanopartikel) ke dalam minyak PFAE. Potensi cecair nano sebagai penebat cecair disahkan berdasarkan voltan pecah tebat arus ulang alik (AU) dan kelikatan. Dalam penyediaan sampel cecair nano, empat langkah khusus mesti diikuti iaitu penimbangan, rawatan homogenisasi, ketuhar vakum dan rawatan penyingkiran kelembapan. Voltan pecah tebat (AU) diukur dengan mematuhi spesifikasi ASTM D1816 dan kelikatan diukur berdasarkan ASTM D445 dan ASTM D2983. Penemuan yang dicadangkan daripada voltan pecah tebat (AU) ialah minyak PFAE berasaskan cecair nano konduktif mempunyai peningkatan kekuatan dielektrik yang paling tinggi iaitu pada kebarangkalian Weibull 63.2 % dengan nilai 50.57 % berbanding minyak PFAE dara. Selain itu, histogram bagi cecair nano adalah condong ke kiri, yang mana kebanyakan data berada pada julat 45 – 49 kV. Dari segi pemindahan haba, minyak PFAE berasaskan cecair nano penebat mempunyai kelikatan yang rendah berbanding sampel minyak lain, terutamanya pada 60 °C, berdasarkan nilai kelikatan. Kedua – dua parameter ini (voltan pecah tebat (AU) dan kelikatan) adalah penting kepada pereka peralatan voltan tinggi dan sistem. Kesimpulannya, kesan terhadap voltan pecah tebat adalah lebih ketara berbanding dengan kelikatan apabila nanopartikel ditambah ke dalam minyak PFAE.

ACKNOWLEDGEMENTS

Alhamdulillah thanks to ALLAH, for giving me the strength to complete this thesis through the help of various parties either directly or indirectly. I would like to take this opportunity to express my sincere acknowledgement to my supervisor, Assoc. Prof. Dr. Hidayat Bin Zainuddin and co-supervisor, Ir. Imran Bin Sutan Chairul from the Faculty of Electrical Engineering, Universiti Teknikal Malaysia Melaka (UTeM) for their essential supervision, support and encouragement towards the completion of this thesis.

I would also like to thank to Ir. Sharin Bin Ab Ghani from Faculty of Electrical Engineering for his advice and suggestions that significantly helped in my work. Special thanks to Research Acculturation Grant Scheme (RAGS) Kementerian Pendidikan Malaysia (RAGS/1/2014/TK03/FKE/B00055), MyBrain15 program and Universiti Teknikal Malaysia Melaka for the opportunity to pursue my master study as well as the financial sponsorship.

I would also like to thank to Mr. Mohd Wahyudi Bin Mohd Hussain and Mr. Norhisham Bin Abu Seman (Assistant Engineers from the UTeM High Voltage Engineering Research Laboratory (HVERL)), Mrs. Rusni Binti Abdullah and Mr. Azrul Syafiq Bin Mazlan, (Assistant Engineers from the Chemical and Tribology Laboratory, Faculty of Mechanical Engineering), for their assistance and efforts in all the lab works. A big thank you to the entire college members for meaningful helps, discussions, and opinions while performing the work in this research project.

Special thanks to my mother, Mrs. Zainab Binti Abdullah and beloved father, Mr. Mohamad Bin Teh for moral supports in completing this research. To my beloved wife, Mrs Siti Norzulaiha Binti Asrin and my little children, Muhammad Umar Zahran, thank you for your supports and motivations until the end of this research project.

TABLE OF CONTENTS

	PAGE
DECLARATION	
APPROVAL	
DEDICATION	
ABSTRACT	i
ABSTRAK	ii
ACKNOWLEDGEMENTS	iii
TABLE OF CONTENTS	iv
LIST OF TABLES	vii
LIST OF FIGURES	ix
LIST OF APPENDICES	xiii
LIST OF SYMBOLS	xiv
LIST OF ABBREVIATIONS	xvii
LIST OF PUBLICATIONS	xix
CHAPTER	
1. INTRODUCTION	1
1.1 Overview	1
1.2 Background of the research	1
1.3 Motivation of this research	2
1.4 Objectives of this research	5
1.5 Scope of this research	6
1.6 Organization of the thesis	6
2. LITERATURE REVIEW	8
2.1 Overview	8
2.2 Oil filled transformer	8
2.2.1 Traditional and alternative liquid insulation	9
2.2.1.1 Mineral oil	10
2.2.1.2 Synthetic oil	10
2.2.1.3 Natural esters	13
2.3 Palm Fatty Acid Ester (PFAE)	14
2.4 Synthesis of nanofluids	17
2.4.1 History	17
2.4.2 Material used	19
2.4.2.1 Filler material	19
2.4.2.2 Surface modification material	20
2.4.3 Procedure of preparing nanofluids	21
2.4.4 Water removal treatment	25
2.5 Characteristics of liquid dielectric	26
2.5.1 Electrical properties	27
2.5.2 Heat transfer characteristics	28
2.5.3 Viscosity in liquid	29
2.5.3.1 Effect of the material, size and shape of nanoparticles	30
2.5.3.2 Effect of nanoparticle concentration	32
2.5.3.3 Effect of base fluid	33
2.5.3.4 Effect of additives	33

2.5.3.5	Effect of fluid temperature	34
2.6	Data analysis tools	34
2.7	Summary	40
3.	METHODOLOGY	42
3.1	Overview	42
3.2	Synthesis of PFAE oil-based nanofluids	42
3.2.1	Brief overview	43
3.2.2	Preparation procedure	46
3.2.2.1	Selection of materials	46
3.2.2.2	Weighing of materials	46
3.2.2.3	Homogenization treatment	48
3.2.2.4	Vacuum process	51
3.2.2.5	Moisture removal treatment	52
3.2.2.6	Moisture Measurement	54
3.3	AC Breakdown voltage test	55
3.3.1	Experimental set-up	55
3.3.2	Experimental procedure	55
3.3.2.1	Procedure A – Sample preparation	55
3.3.2.2	Procedure B – Sample testing	56
3.3.2.3	Procedure C – Data analysis tools	58
3.4	Viscosity test	59
3.4.1	Experimental set-up	59
3.4.2	Experimental procedure	60
3.4.2.1	Procedure A – Sample preparation	60
3.4.2.2	Procedure B – Sample testing	60
3.4.2.3	Procedure C – Data analysis tools	61
3.5	Summary	61
4.	RESULT AND DISCUSSIONS	63
4.1	Overview	63
4.2	Physical appearance of the samples	63
4.3	Moisture content of the samples	64
4.4	AC Breakdown Voltage	66
4.4.1	AC breakdown voltage measurements	66
4.4.2	Scatter diagram analysis of the AC breakdown voltage	69
4.4.3	Weibull statistical analysis of the AC breakdown voltage	73
4.4.4	Histogram analysis of the AC breakdown voltage	78
4.4.5	Mechanism behind the dielectric strength enhancement of PFAE oil-based nanofluids	81
4.5	Viscosity	83
4.5.1	Viscosity measurements	83
4.5.2	Bar chart analysis of the viscosity measurements	86
4.5.3	Mechanism behind the heat transfer enhancement of PFAE oil-based nanofluids	88
4.6	Summary	88

5.	CONCLUSION AND RECOMMENDATIONS	91
5.1	Conclusion	91
5.2	Recommendations for future work	92
	REFERENCES	93
	APPENDICES	101

LIST OF TABLES

TABLE	TITLE	PAGE
1.1	Failure component survey by Tamil Nadu Transmission Corporation Limited from 2009 to 2013 in India	3
2.1	Types of mineral oil	11
2.2	Inhibitors and uninhibited mineral oil	12
2.3	Material used for synthesis nanofluids	19
2.4	The group and examples of nanoparticles as filler materials	20
2.5	Transformer oil based nanofluids system	22
2.6	Water content removal treatment	26
2.7	Effect of nanofluid parameters on the viscosity of nanofluids	30
2.8	Correlation patterns in a scatter diagram	35
2.9	Possible shapes of a histogram	39
2.10	Comparison between the properties of PFAE oil and MI oil	40
3.1	Physical and chemical properties of the nanoparticles	46
3.2	Details of the ASTM D1816 standard test method	56

4.1	Moisture content of the virgin PFAE oil and PFAE oil-based nanofluids after homogenization treatment, vacuum process and moisture removal treatment	65
4.2	AC breakdown voltage data of the virgin PFAE oil and PFAE oil-based nanofluids	68
4.3	Overview of the AC breakdown voltage results for the virgin PFAE oil and PFAE oil-based nanofluids measured in accordance with the ASTM D1816 standard test method	69
4.4	Shape parameter, scale parameter and correlation coefficient obtained from the two-parameter Weibull probability plots for the virgin PFAE oil and PFAE oil-based nanofluids	77
4.5	AC breakdown voltage of the virgin PFAE oil and PFAE oil-based nanofluids at various Weibull probabilities obtained from the two-parameter Weibull probability plots	77
4.6	Viscosity data of the virgin PFAE oil and PFAE oil-based nanofluids measured using Brookfield viscometer at a water bath temperature of 40 °C	84
4.7	Viscosity data of the virgin PFAE oil and PFAE oil-based nanofluids measured using Brookfield viscometer at a water bath temperature of 60 °C	85
4.8	Factors that affect the viscosity of nanofluids	90

LIST OF FIGURES

FIGURE	TITLE	PAGE
1.1	Sources of energy used globally	4
2.1	Power distribution network	9
2.2	Liquid insulation for oil filled transformer application	11
2.3	Timeline in the development and application of synthetic esters dielectric fluids	12
2.4	Timeline in the development and application of natural esters dielectric fluids	13
2.5	Three layer for the palm nut; Endocarp, Kernel and Mesocarp	14
2.6	Characteristics of liquid dielectric	27
2.7	Illustration of the streamer process in the insulation oil with and without conductive nanoparticles	29
2.8	Relationship between heat transfer performance and various nanofluid parameters	31
2.9	Variation of viscosity as a function of the volume fraction of Al ₂ O ₃ nanoparticles	32
2.10	Variation of viscosity as a function of the volume fraction of TiO ₂ nanoparticles	33

3.1	Flow chart which shows a brief overview of the procedure used to prepare the PFAE oil-based nanofluids	44
3.2	Detailed flow chart of the procedure used to prepare the PFAE oil-based nanofluids	45
3.3	Personal protective equipment used while handling the nanoparticle powders	48
3.4	Labsonic P laboratory homogenizer used to disperse the nanoparticles into the virgin PFAE oil	50
3.5	Schematic diagram of the set-up used for homogenization treatment	51
3.6	Vacuum oven used to remove gases and moisture remaining in the oil sample after homogenization treatment	52
3.7	Flow chart of the moisture removal treatment	53
3.8	Schematic diagram of the laboratory set-up used for moisture removal treatment	54
3.9	Photograph of an oil sample in the Megger OTS60PB portable oil tester	58
4.1	Photograph of the prepared samples (from left to right): virgin PFAE oil, PFAE oil-based Fe_3O_4 nanofluid, PFAE oil-based TiO_2 nanofluid and PFAE oil-based Al_2O_3 nanofluid	64
4.2	Nitrogen gas structure	66
4.3	Scatter diagram of the AC breakdown voltage for the virgin PFAE oil	71

4.4	Scatter diagram of the AC breakdown voltage for the PFAE oil-based Fe ₃ O ₄ nanofluid	71
4.5	Scatter diagram of the AC breakdown voltage for the PFAE oil-based TiO ₂ nanofluid	72
4.6	Scatter diagram of the AC breakdown voltage for the PFAE oil-based Al ₂ O ₃ nanofluid	72
4.7	Two-parameter Weibull probability plot of the AC breakdown voltage for the virgin PFAE oil	75
4.8	Two-parameter Weibull probability plot of the AC breakdown voltage for the PFAE oil-based Fe ₃ O ₄ nanofluid	75
4.9	Two-parameter Weibull probability plot of the AC breakdown voltage for the PFAE oil-based TiO ₂ nanofluid	76
4.10	Two-parameter Weibull probability plot of the AC breakdown voltage for the PFAE oil-based Al ₂ O ₃ nanofluid	76
4.11	Histogram of the AC breakdown voltage for the virgin PFAE oil	79
4.12	Histogram of the AC breakdown voltage for the PFAE oil-based Fe ₃ O ₄ nanofluid	79
4.13	Histogram of the AC breakdown voltage for the PFAE oil-based TiO ₂ nanofluid	80
4.14	Histogram of the AC breakdown voltage for the PFAE oil-based Al ₂ O ₃ nanofluid	80
4.15	Effect of three type nanoparticles on the AC breakdown voltage of PFAE oil-based nanofluids at a Weibull probability of 63.2%	82
4.16	Viscosity of the virgin PFAE oil and PFAE oil-based nanofluids at a water bath temperature of 40°C	87

4.17	Viscosity of the virgin PFAE oil and PFAE oil-based nanofluids at a water bath temperature of 60°C	87
------	--	----

LIST OF APPENDICES

APPENDIX	TITLE	PAGE
A	Viscometer (Small Sample Adapter) Set-Up	101

LIST OF SYMBOLS

Al_2O_3	-	Aluminum oxide
CO_2	-	Carbon dioxide
CuO	-	Copper (II) oxide
Cu_2O	-	Copper (I) oxide
exp	-	Exponential
Fe_2O_3	-	Iron (III) oxide
Fe_3O_4	-	Iron (II,III) oxide
g/cm^3	-	gram per cubic meter
g/L	-	gram per litre
kPa	-	kilopascal
kV	-	kilovolts
kV/s	-	Kilovolts per second
mg/kg	-	milligram per kilogram
mg	-	Milligrams of potassium hydroxide per gram KOH/g
min	-	minute
mL	-	millilitre
mm	-	millimetre
mm^2/s	-	millimetre square per second
mPa.s	-	millipascal seconds

nm	-	nanometer
Pa	-	Pascal
PPM	-	Part per million
Psi	-	Pound per square inch
$PVF_{(nm)}$	-	The particles volume fraction of the nano material
SiC	-	Silicon carbide
SiO ₂	-	Silicon oxide / silica
TiO ₂	-	Titanium oxide / Titania
$V_{(oil)}$	-	The volume of oil
$W_{(nm)}$	-	The quantity of nano material
ZnO	-	Zinc oxide
b	-	Intercept
g	-	Gram
j	-	The sequence of data
m	-	Slope
η	-	Scale parameter
ρ	-	Correlation coefficient
$\rho_{(nm)}$	-	The density of nano material
wt	-	Total mass of the solution
β	-	Shape parameter
$F(x)$	-	The probability of the AC breakdown voltage
M_a	-	Mass of nanoparticles
M_b	-	Mass of insulating oil
MF_a	-	The mass fraction of nanoparticles

N	-	The number of data
%	-	Percent

LIST OF ABBREVIATIONS

AC	-	Alternating Current
ASTM	-	American Society for Testing and Materials
BDV	-	Breakdown Voltage
BN	-	Boron Nitride
CN	-	Conductive Nanoparticles
CPO	-	Crude Palm oil
IEC	-	International Electrotechnical Commission
IEEE	-	Institute of Electrical and Electronics Engineers
HV	-	High Voltage
IN	-	Insulating Nanoparticles
KFC	-	Karl Fischer Coulometer
LPG	-	Liquefied Petroleum Gas
MI	-	Mineral Insulation
MO	-	Mineral Oil
MR	-	Median Rank
NEI	-	Natural Ester Insulation
OECD	-	Organisation for Economic Co-operation and Development
OLTC	-	On-Load Tap Changers
PFAE	-	Palm Fatty Acid Ester

PKO	-	Palm Kernel Oil
RBPO	-	Refine Bleached Palm Oil
RBPDO	-	Refine Bleached Deodorized Palm Oil
SN	-	Semi-conductive Nanoparticles
VO	-	Vegetable Oil

LIST OF PUBLICATIONS

Journal Papers

Mohd Safwan Mohamad., Hidayat Zainuddin, Sharin Ab Ghani and Imran Sutan Chairul,. 2017. AC Breakdown Voltage and Viscosity of Palm Fatty Acid Ester (PFAE) Oil-based Nanofluids. *Journal of Electrical and Engineering Technology (JEET)*, pp. 1921-1929, 2017.

Mohamad, M.S., Zainuddin, H., Ghani, S.A. and Chairul, I.S., 2016. Comparative Study on the AC Breakdown Voltage of Palm Fatty Acid Ester Insulation Oils Mixed with Iron Oxide Nanoparticles. *International Journal of Electrical and Computer Engineering (IJECE)*, 6(4), pp. 1482-1488, 2016.

Conference Papers

Mohamad, M.S., Zainuddin, H., Ghani, S.A. and Chairul, I.S., 2016. Breakdown and Partial Discharge Performance of Palm Fatty Acid Ester (PFAE) Oil – based Fe₃O₄ Nanofluids. *IEEE 6th International Conference on Power and Energy (PECON2016)*, 2016.

Mohamad, M.S., Zainuddin, H., Ghani, S.A. and Chairul, I.S., 2016. Study of Breakdown Voltage of Palm Oil Based Nanofluids. *MyHVnet Newsletter – Special focus on 2016 MyHVnet Colloquium*, pp.49, 2016.

Mohamad, M.S., Zainuddin, H., Ghani, S.A. and Chairul, I.S., 2015. AC Breakdown Voltage of Natural Ester Mixed with iron Oxide for Oil-Immersed Power Transformer Application. *13th IEEE Student Conference on Research & Development 2015 (SCORED 2015)*, pp. 16-20, 2015.