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FINAL YEAR PROJECT REPORT II

STUDY OF MOISTURE EFFECT ON BREAKDOWN VOLTAGE AND STRUCTURE OF MINERAL AND PALM OIL BASED INSULATION OILS

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STUDY OF MOISTURE EFFECT ON BREAKDOWN VOLTAGE AND STRUCTURE OF MINERAL AND PALM OIL BASED INSULATION OILS

NORHASHIDAH BINTI MOHD NAJRI

A report submitted in partial fulfillment of the requirements for the degree of Bachelor of Electrical Engineering (Industrial Power)

Faculty of Electrical Engineering

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

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I declare that this report entitle "*Study of Moisture Effect on Breakdown Voltage and Structure of Mineral and Palm Oil Based Insulation Oils*" is the result of my own research except as cited in the references. The report has not been accepted for any degree and is not concurrently submitted in candidature of any other degree

Signature :…………………………………….

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Date :…………………………………….

To my beloved mother and father

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ABSTRACT

Theoretically, insulation oil of transformer purposely used to cool down the power transformer when heat dissipation condition occurs during operation. Most of power transformer failure is caused by physicochemical reaction such as heat, moisture content and oxygen in transformer oil. Therefore, the aim of this project is to measure Breakdown Voltage (BdV) and to obtain the spectral characteristic for mineral and vegetables-based transformer insulating oil under moisture influence. Besides that, relationship between BdV and Fourier Transform Infrared Spectrometry (FTIR) test are studied. In order to achieve objectives of this project, two type of testing are used namely BdV and FTIR. The standard of IEC 60156:1995 and ASTM D2144 are used as a guidelines in testing procedure and confirmation of the finding. The result shows that influence of moisture gave effect of the breakdown voltage and spectral characteristic in mineral and vegetables-based transformer insulating oil. It also showed that BdV and FTIR test have similarities in determining the condition or performances of transformer insulating oil.

ABSTRAK

Secara teorinya, tujuan sebenar minyak penebat alat pengubah digunakan untuk menyejukkan pengubah kuasa apabila keadaan pelesapan haba berlaku semasa operasi. Kebanyakan kegagalan kuasa pengubah adalah disebabkan oleh reaksi fizikokimia seperti haba, kelembapan dan oksigen dalam minyak pengubah. Oleh itu, tujuan kajian ini adalah untuk mengukur Voltan Pecahan (BdV) dan untuk mendapatkan ciri-ciri spektrum minyak penebat alat pengubah yang berasaskan mineral dan sayur-sayuran di bawah pengaruh kelembapan. Selain itu, hubungan antara BdV dan *Fourier Transform Infrared Spektrometri* (FTIR) ujian dikaji. Dalam usaha untuk mencapai objektif projek ini, dua jenis ujian digunakan iaitu BDV dan FTIR. Piawaian IEC 60156: 1995 dan ASTM D2144 digunakan sebagai garis panduan dalam prosedur ujian dan pengesahan dapatan. Hasil kajian menunjukkan bahawa pengaruh kelembapan memberi kesan kepada nilai voltan pecahan dan sifat spektrum dalam minyak penebat alat pengubah yang berasaskan mineral dan sayur-sayuran. Ia juga menunjukkan bahawa BDV dan FTIR mempunyai persamaan dalam menentukan keadaan minyak penebat alat pengubah.

TABLE OF CONTENTS

LIST OF ABBREVIATIONS

BdV	-	Breakdown Voltage
FTIR	-	Fourier Transform Infared Spectrometry
PFAE	-	Palm Oil Fatty Acid Ester
DGA	-	Dissolved Gas Analysis
UV	-	Ultra Violet
kV	-	kilovott
ATR	-	Attenuated total reflectance
IR	-	InfraRed

LIST OF TABLES

LIST OF FIGURES

LIST OF APPENDIX

CHAPTER 1

INTRODUCTION

1.1 Research Background

Power Transformer is one of the valuable assets in delivering power throughout nation. There are many types of transformer in industry such as dry type and liquid oil type. Generally in Malaysia, liquid oil type transformer is used in distribution phases. Breakdown event of transformer may cause highly loss and cost to power provider companies. Each parts of it need to be monitored and diagnosed for reducing the breakdown event. One major parts of transformer is the insulation oil; used for heat dissipation medium, arc quenching media and insulator. There are two types of insulation oil currently used in transformer such as mineral-based oil and vegetables-based oil. Mineral oil is used in Malaysian transformer for many years.

The primary factor of failure of the power transformer which consist of oil is due to physicochemical reaction in presence of heat, oxygen and moisture during the operation. There are many diagnostic technique that been used to measure the quality and performance of the insulation oil of the transformer in laboratory. The traditional diagnostic technique of insulation oil are interfacial tension (IFT), dissipation factor (Tan Delta), water content, and acidity are widely used in oil laboratory. There is an alternative diagnostic technique of insulation oil that can be used such as Fourier Transform Infrared Spectrometry (FTIR). FTIR is one of the monitoring tool to evaluate the condition of the insulation oil. This alternative technique can identify the changing or difference of the structure in insulation oil with the original finger print of the waveform of the insulation oil. This experimental project were done by using mineral and vegetables based insulating oil. In this project, the result were analyzed to determine the effect of moisture on both insulation oil by using BdV test and FTIR.

1.2 Project Motivation

The motivation to conduct and contribute into this project is to measure dielectric strength and analyses structure of different type of oil used in transformer. The common insulation oil used in transformer is mineral oil. But a few years back, vegetable oil was introduced as an insulation of transformer such Palm Oil Fatty Acid Ester (PFAE), MIDEL and Envirotemp FR3. This project is proposed to investigate the physicochemical reaction changes in presence of moisture that affecting the transformer oil. The physicochemical reaction in presence of heat, oxygen and moisture will affect the operation of power transformer and can cause failure to a transformer. FTIR is one of the chemical testing that can be used to measure the properties of the oil. FTIR and BdV will be used in this project to measure the properties for both transformer oil based.

1.3 Problem Statement

The diagnostic for transformer oil is divided into chemical properties and electrical properties. The example of electrical properties tests are BdV and dielectric dissipation factor. This is used for measure the dielectric strength of the transformer oil. In chemical properties part, Dissolve Gas Analysis (DGA) and moisture content are widely used in laboratory. In fact, there is an alternative technique for chemical properties test that can be introduced. The technique is FTIR. This technique is infrequently used for transformer oil and mostly this technique commonly used in lubricants oil condition monitoring. Thus, this project applied FTIR to analyze the functional group of the transformer oil under moisture effect.

1.4 Project Objectives

The objectives of this project are stated below:

1. To measure Breakdown Voltage (BdV) for both mineral and vegetable based transformer insulating oil under moisture influence.

2. To obtain the spectral characteristics for both mineral and vegetable based transformer insulating oil under moisture influence by using Fourier Transform Infrared Spectrometry (FTIR).

3. To study the relationship between Breakdown Voltage (BdV) and Fourier Transform Infrared Spectrometry (FTIR) tests.

1.5 Project Scopes

The scope of this project necessitated as followed:

1) Magnetic Hot Stirrer is used to well stir the water droplets in the insulating oil sample.

2) The moisture effect in insulating oil sample is conducted using water addition in milliliter unit (ml).

3) The *International Electrotechnical Commission* (IEC) 60156:1995 standard is used as a guide for the result of Breakdown Voltage (BdV) while *American Society for Testing and Materials* (ASTM) D2144 used for procedure of FTIR.

4) The insulation mineral oil based is Hyrax Hypertran, meanwhile insulation vegetables oil based is Lion PFAE.

1.6 Report Outlines

The thesis of the project covered the five chapter. Chapter 1 explained about the project background, problem statement, objective and scope of project. Chapter 2 describes the theory or general concept that related to the project and review from previous research works. It will be more focusing on the performances of the insulation oil that been affected by the moisture. Then, Chapter 3 illustrated methodology applied in order to get the required output. The flow of project development will be explained by a flow chart. Chapter 4 interpreted and explained the result by represents tables, graph and diagrams. Analysis and discussion on the problem issued were discussed. Lastly, Chapter 5 gives a summarized work and conclusion for overall of this project. Suggestion for further research of this study were also stated.

CHAPTER 2

LITERATURE REVIEW

2.1 Theory and Basic Principles

This topic will discuss about theory of transformer, properties of insulation material, type of transformer oil in power transformer, diagnostic technique that widely used for monitoring the condition of insulation and the software that will be used.

2.2 Transformer

Transformer is an important device that used in electrical power system. Transformer is a mechanism that transmit energy by electromagnetic induction from one circuit to another circuit. Function of the transformer is to step up and step down voltage [1]. The main component of the transformer is core, winding and insulation material. Insulation material that used in transformer are kraft paper and insulation oil. The insulation material should provide high insulating to protect the other component from collapse.

2.3 Insulating Material Properties

The basic properties of insulating material are resistivity, breakdown voltage, permittivity, and dielectric loss. However, the insulating material properties should be high dielectric strength, resistivity, tensile strength for solid insulation, degree of thermal stability and good thermal conductivity to become perfect. Besides that, the insulating material must have well mechanical properties for example capable to withstand moisture, vibration, bending and it also should have competence to withstand chemical strike and condition of service in other adversative. [2]

2.4 Transformer Oil

Power transformer is one of the important device in electrical power system. Transformer can be categorized depend on the purpose and different ways. There are five categorized in power transformer which is pole mounted transformer, house hold transformer, dry type distribution transformer, current transformer (CT), and oil immersed power transformer. [3]

Power transformer is filled with the liquid insulation oil. The purpose of the liquid insulation oil is to dissipate heat inside the transformer. In addition, the insulating oil also prevent direct contact of oxygen with cellulose paper insulation of winding and preserve the core and winding.

There are many type of the liquid insulation oil in industry. But the mineral oil is widely used as a liquid insulation for insulation of transformer. In few year back, many researcher is investigated more about the vegetable oil for using as an insulation oil for transformer because of the characteristic is similarly to the mineral oil.

Mineral oil is known as a petroleum based oil. The function of the mineral oil is a coolant or thermal fluid in electric component but not as a conduct electricity and this oil widely used in industry and also for mechanical part. This mineral oil is made up from mixtures of different organic compound that composed mainly of carbon and hydrogen in molecules. Mineral oil is divided into three categories crudes oil which are paraffinic, napthenic and mixed crude. Mixed crudes is the combination of paraffinic and napthenic crude. The advantages of the mineral oil are good resistance to oxidation, good viscosity index, relatively low fire point but mineral oil are low moisture tolerance and possible to sulphur corrosion.[4]

Vegetable oil is one of the new liquid insulation oil of the transformer to replacing the mineral oil and known as a natural ester. Ester is the reaction of an acid with oil in elimination of water. The esterification of glycerin and fatty acid produce the fat and oil. The collective term for mono- carboxylic acids, which consist of a carboxyl group (-COOH) and of a variable long, but nearly exclusively unbranched hydrocarbon chains is called a "fattyacid". [5] Figure 2.1 shows the process of the esterification and the inverse reaction called hydrolysis. The chemical constitution of rapeseed oil and all natural ester molecules are similar in composition as shown in Figure 2.2. The advantages of the vegetables oil are low dielectric losses at frequency higher than 1 kHz, readily biodegradable but is low oxidation stability. [4]

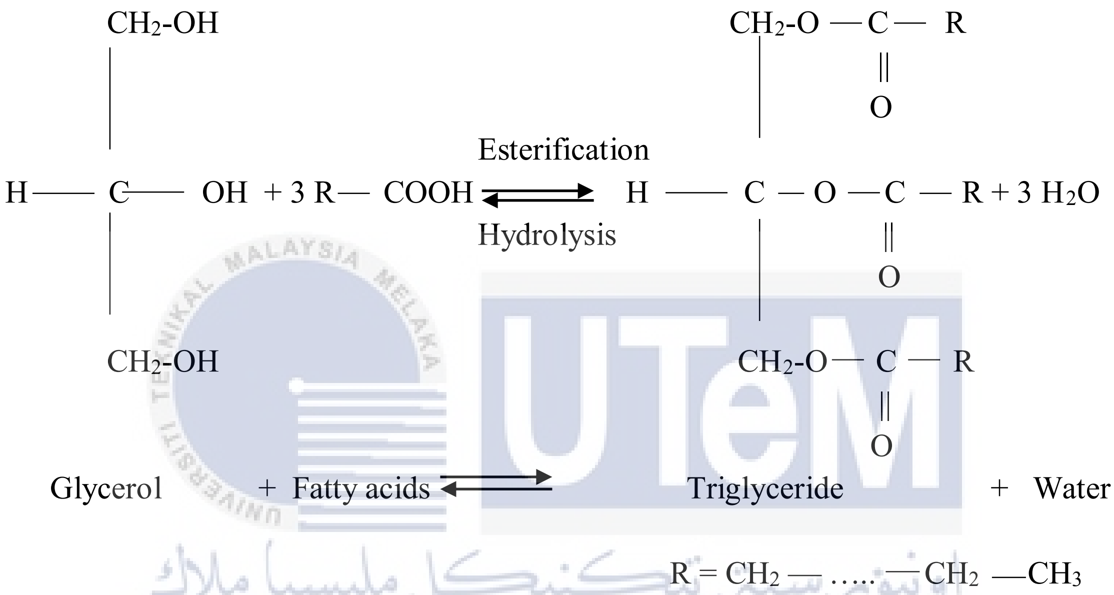


Figure 2.1: Synthesis of triglyceride by esterification. [5]

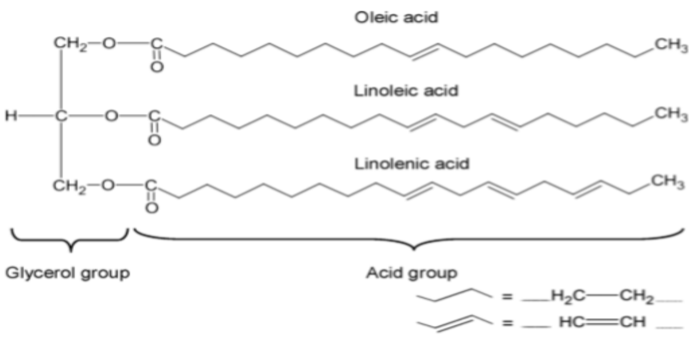


Figure 2.2: Chemical constitution of natural ester. [5]

There are many type of the vegetables oil such as palm fatty acid ester (PFAE), Envirotemp FR3 Fluid (Cooper Power Systems), Midel eN (M&I Materials Ltd.), and Midel 7131 (M&I Materials Ltd.). This research only focusing on Palm Oil Fatty Acid Ester

(PFAE). PFAE is the new vegetables based insulation oil for transformer. PFAE is contains a wide composition of fatty acids that include carbons 8 to 18 as shown in Table 2.1.[6] PFAE has a few advantages such as good biodegradability, excellent insulating performance, high cooling ability and good oxidation stability and a potential substitute of mineral oil. The properties of PFAE are listed in Table 2.2 is compared with different oil. It show that the value of the relative permittivity and breakdown voltage is higher. This shows PFAE is able to replace the mineral oil as insulation oil for transformer.

Table 2.1: Composition of fatty acid in oils [6]

Fatty Acid	Soy-bean oil	Rape-seed oil	Sun-flower oil	Palm		Coconut oil	Beef feat
				Palm oil	Palm kernel oil		
C8:caprylic acid	-	-	-	-	3.3	7.8	-
C10:capric acid	-	-	-	-	3.1	7.6	-
C12:lauricacid	-	-	-	-	45.7	44.8	-
C14:myristic acid	-	-	0.2	1.1	16.4	18.1	2.0
C16:palmitic acid	6.7	5.4	7.1	44.4	8.9	9.5	32.5
C18:stearic acid	3.3	2.0	2.8	4.3	2.3	2.4	14.5
C18:oleic acid	41.7	68.0	30.0	39.9	17.1	8.2	48.3
C18:linoleic acid	41.3	21.0	59.5	9.4	2.7	1.5	2.7
C18:linolenic acid	5.9	-	-	-	-	-	-
others	1.1	3.6	0.4	0.9	0.5	0.1	-

Table 2.2: The properties of PFAE, mineral oil and vegetable oil [7]

Items	Condition unit	PFAE	Mineral oil	Vegetable oil
Density	(15ºC)g/cm^3	0.86	0.88	0.93
Kinetic Viscosity 40ºC	Mm^2/s	5.1	8.1	32.9
Flash point COC	ºC	186	152	330
Pour point	ºC	-32.5	-45	-20
Total acid value	mgKOH/g	0.005	<0.01	0.035
Moisture	Mg/kg	15	<10	43
Relative Permittivity	(80ºC)	2.95	2.2	2.91
tan δ	(80ºC)%	0.31	0.001	0.67
Volume resistivity	(80ºC)Ω.cm	1.9 x 10^{13}	7.6 x 10^{15}	3.7 x 10^{12}
Breakdown voltage	(2.5mm)kV	81	70.75	77

2.5 Failure of Transformer

The failure of power transformer will cause huge economic impact and affect our daily life and industry production. [8] There are many factor can caused the failure of transformer. Referring to the report by William H.Bartley, The Hartford Steam Boiler Inspection and Insurance Company explained the cause of failure of transformers. [9] The Table 2.3 showed the factor that cause of transformer failure.

Table 2.3: Cause of transformers failure. [9]

Cause of Failure	Number	Total cost to pay
Insulation failure	24	$149 967 277
Design/material/Workmanship	22	$64 696 051
Unknown	15	$29 776 245
Oil Contaminant	4	$11 836 367
Overloading	5	$8 568 768
Fire/Explosion	3	$8 045 771
Line Surge	4	$4 959 691
Improper Maint/Operation	5	$3 518 783
Flood	2	$2 240 198
Loose Connection	6	$2 186 725
Lightning	3	$657 935
Moisture	1	$175 000
Total	94	$286 628 811

Based on that Table 2.3, insulation failure is the high cause of failure about 24 events and cost to pay about $149 967 277. This insulation failure consist of four major factor that accountable for insulation weakening which are heat or pyrolosis, oxidation, acidity and moisture. The moisture existed when it cause by leaky pipes, leaking roofs, water inside the tanks, bushing or fitting leaking and moisture presence in insulation oil. [9] So, moisture in insulation oil is being study to overcome the problem of insulation failure and to minimize the cost.

2.6 Diagnostic Technique

The diagnostic be conducted to determine whether transformer is in normal condition or not. The failure of the transformer can be happen due to physicochemical reaction in transformer oil. The factor of the failure is presence of heat, oxygen and moisture inside the transformer oil. Thus, the transformer must be avoided from the failure because of the cost required to manufacture of transformer is very expensive. The diagnosis for transformer oil must be conducted to maintain the performance and increase the age of transformer.

A Breakdown Voltage (BdV) is one of the testing. The purpose of this testing is to measure the ability of oil to withstand electrical stress without failure. The particles of the water content in the oil will give affected the result of BdV. The equipment for BdV according to the standard MS IEC 60156:2012 have two electrode which fixed with a gap of 2.5 mm between them and the oil. [10] BdV measuring kit and inside the kit is shown in Figure 2.3. The operation of the equipment is as follow:

1. An AC voltage is applied at controlled rate to two electrodes immersed in the dielectric liquid
2. The gap between the two electrodes is set at a specified distance
3. When the current across the gap, the voltage is recorded at that instants which also the dielectric breakdown of the liquid

The result of BdV of the sample from the mean or average of the six times test according to the standard. The value of the BdV is lower if the moisture content is increased. [10]

Figure 2.3: Example of BdV tester equipment

FTIR was widely used in doing the research or testing for oil and it known as chemical testing. Mostly, FTIR is used to analyze the physical and chemical bonding in the lubricant or engine oil. Now, there are research work about the performance and condition of the transformer oil was used FTIR. FTIR technique is used the method of infrared spectroscopy that InfraRed (IR) radiation was passed through the sample. The molecular fingerprint of the sample is created by the resulting of the spectrum that represent the molecular absorption and transmission. The information FTIR provide will identify unknown material, determine the quality or consistency of a sample and determine the amount of component in a mixture. [11] Figure 2.4 shows the basic method of the infrared spectroscopy.

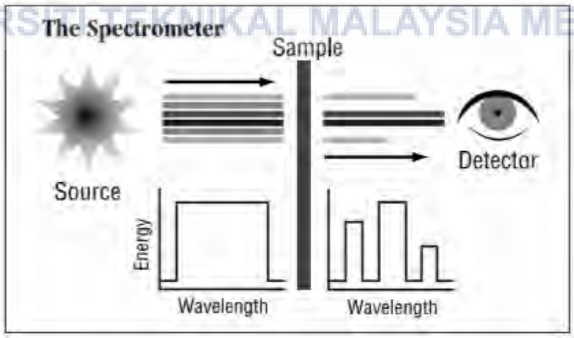


Figure 2.4: The spectrometer method [11]

In order to overcome the limitations encountered with dispersive instrument, the FTIR is developed [11]. The solution for made the measurement all of the infrared frequencies in simultaneously, the interferometer is developed that which employed a very simple optical device. An interferometers take on a beamsplitter which takes the entering infrared beam and optical beams was divides into two. First, one beam reflects off of a flat mirror which is fixed in place and another one beam reflects off of a flat mirror which is on a mechanism which allows this mirror to move a very short distance that typically a few millimeters away from the beamsplitter.

After that, the two beam recombined when they meet back at the beamsplitter. The resulting signal was known as interferogram when the signal exits the interferometer that two beam “interfering” with each other. This signal is unique property because of the every data point that makes up the signal has information about every infrared frequency which comes from the source. After that, the interferogram was encoded by using the mathematical method that called as Fourier transformation. This Fourier transformation was performed by the computer for easier to analysis the signal. Figure 2.5 shows the flow of the process using FTIR. [11]

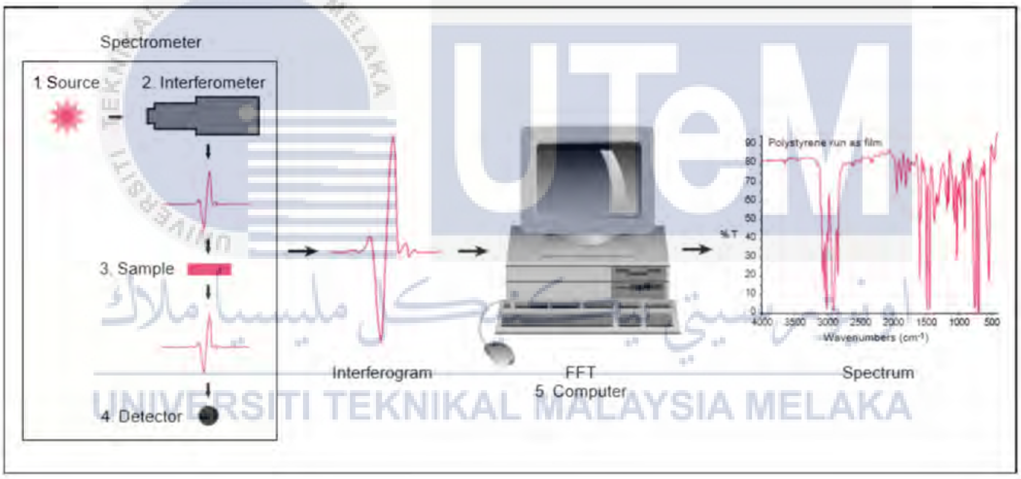


Figure 2.5: The process of FTIR test. [11]

2.7 Review of Previous Related Works

A journal written by Abubakar A. Suleiman [10] discussed about an effect of moisture on Breakdown Voltage (BdV) and structure of palm based insulation oils using two method which are BdV and FTIR [11]. The oil sample used are Red Palm oil, RBDPO oil (refined, bleached and deodorized palm oil), Palm oil Fatty Acid Ester (PFAE) and mineral oil. This paper explain about the change of the functional group because of the moisture and also shown the categorization of molecular bond motion by using FTIR method. The result obtained from the BdV method are shows in Table 2.4:

Table 2.4: The result of breakdown voltage of three different oil

Type of Oil	Moisture increase (%)	BdV (kV)
Red Palm Oil	0	21.47
	0.07	11.55
	0.2	12.72
	0.3	14.49
RBDPO	0	44.79
	0.07	14.82
	0.2	9.1
	0.3	11.55
PFAE	0	52.69
	0.07	9.18
	0.2	13.89
	0.3	12.33

From the Table 2.4, this result is represented using graph. The graph show the fluctuations for three type of the oil. Because of not linear decreasing moisture and oil breakdown, this paper came out the function for three type of oil based on the graph. After that, the result from the experimental was comparing with calculated and show a little percentage different. The result FTIR show that there are different functional group changes on three type of oil because of the moisture. The functional group changes almost same pattern with the breakdown voltage result.

A conference paper from Y. Hadjadj, I. Fofana and J. Jalbert discussed about insulating oil decaying assessment by FTIR and Ultra Violet (UV) spectrophotometry measurement. In this research, oil quality assessment and classification of the assessment is explained which include in ASTM standard. This research conducted the experiment using ageing of mineral oil and analysis by using traditional and alternative testing method which are IFT and acidity for traditional and Dissolved Decay Product (DDP) and Fourier FTIR for alternative testing method. The aim of this research is to investigate the relationship or correlation between traditional and alternative testing method. The result shows that a correlation was found between IFT and analysis of DDP by using spectrophotometry UV-Visible. Other than that, FTIR and Total Acid Number (TAN) had a good correlation. In

FTIR analysis, this research found transmittance at 1710 cm^{-1} show the process of ageing of oil was occurred. Thus, traditional and alternative testing method having a good correlation although there are different procedure in testing method [12].

A conference paper written by Nur Syamimi Murad [13] studied about oil moisture absorption level and voltage breakdown on palm oil-based. This research was study about level of moisture was absorbed in four different type of insulation oil which are RBDPO oil (refined, bleached and deodorized palm oil), Red Palm oil, Palm oil Fatty Acid Ester (PFAE) and mineral oil. The biodegradable oil was used in this research because the researcher seen that this type of oil have potential to replace the mineral oil and also can protect the environment. The method that was used in this research are Karl Fisher titration method and breakdown voltage method. The process of addition water in insulation oil is done by using addition deionization water and heated at 40ºC. The result from the Karl Fisher titration method indicated that Red Palm oil have water content on it and percentage of the water content increase when the water content in ppm is increased. From the breakdown voltage method, the result shows the PFAE is high maximum of breakdown voltage when moisture content increased in oil. So, the best insulation oil that can be replace for mineral oil is PFAE because PFAE have a greater electrical resistance.

A research conduct by P. Prosr, M. Brandt, V. Mentlik and J. Michalk [14] discussed about condition assessment of oil transformer insulating system. Three method is used in this research to analyse the condition of the transformer insulating oil which are Infrared spectroscopy (FT-IR-ATR) and Gas Chromatography. Parameter being observed is relative humidity, total of dissolved gas and increasing of temperature. For monitoring system, the experimental is done in laboratory and used two distribution transformer. The result of the monitoring system shows that dissolved gas change when load in transformer changes, changes of the temperature make faster response from water and amount dissolved gas increased if the mechanical configuration was changed. Secondly, FT-IR-ATR testing is done by using four different samples. The result indicate that at certain region, there have changes of the spectrum. It show new chemical appear in oil samples. DGA given a total of the dissolved gas in insulation oil. Thus, this three method is very useful to indicate the condition of the transformer insulation oil.

A thesis paper written by S. Hembrom [2] analysed an aged insulating oil for early detection on incipient fault inside the high voltage equipment. The main objectives of this research is to study the degradation oil and presence of contamination in insulation oil. This research used two method which are FTIR and Ultra Violet (UV) Spectrophotometer and three sample have been analyzed which are pure transformer oil, transformer oil with copper and transformer oil with kraft paper. There are two type case was studied. Firstly, analysis from the transformer oil degrade of time during operation of transformer and secondly, analysis from the degradation of transformer oil in laboratory. The sample of transformer oil with kraft paper show the presence of the carbon dioxide (CO_2), methane (CH_4) and ethylene (C_2H_4) and large in degradation using FTIR and by using UV Spectrophotometer, the two sample of transformer oil which are with copper and kraft paper shows the contamination was happen that detection by the value of absorption and shifted of the spectrum for the first cases. For the second case, the sample was heated with different temperature which are 60°C, 120°C and 150°C within 3 hours. The result show the sample of transformer oil with kraft paper is presence contamination when temperature increase at 150°C by using FTIR. Based on UV Spectrophotometer, transformer oil with copper and kraft paper show the increasing of the absorption level under thermal effect. So, the degradation of the transformer oil is depend on the ageing time and used of the insulation oil transformer.

2.8 Summary

In this research, BdV and FTIR are the test that will be used. Thus, the related previous research work with using this two test is reviewed to get more information and idea to complete the research. Thus, BdV and FTIR test has been applied to monitor the condition or performances of transformer insulation oil and the result from BdV and FTIR shows condition of transformer insulation oil is strongly influence by the factor of temperature, moisture and changes of load with decreasing of the average value of the breakdown voltage and also changing of the chemical structure of transformer insulation oil.

CHAPTER 3

METHODOLOGY

3.1 Process of the project

The flow chart is representing the step from the starting until completed the project. Method that was used will be discussed in this chapter based on the standard. Figure 3.1 shows a flow chart representing the description of work.

3.2 Experimental Review

Experimental review or literature review is the first step in this project. Literature review discussed about the information or theory that related to this project. This part also explained previous research done by other researchers. All information are gain from journals, magazines, websites, papers and standards as guidelines and reference. This part also discussed the causes or factor of transformer failure, BdV test and FTIR test.

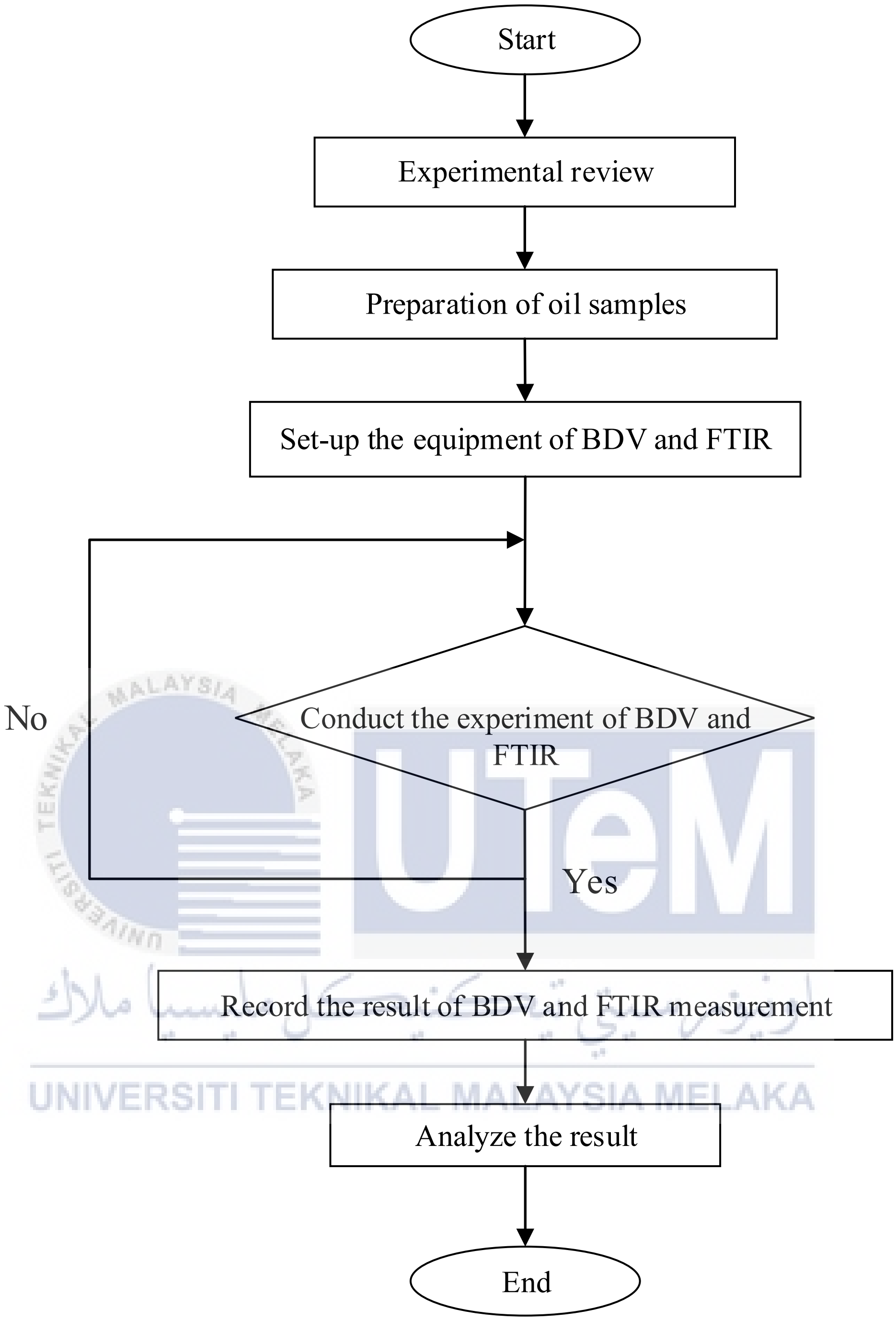


Figure 3.1: Flow chart of the project

3.3 Sampling

The second step of this project are preparing the oil samples. Two different type of transformer oil is used namely PFAE as a vegetables-based oil manufactured by Lion Corp. and mineral oil from Hyrax Hypertran. The most critical part is oil preparation because contamination will be happen during the process. Thus, the process must be done with proper procedure starting from selecting a container and technique of sampling.

Size of the sample must be three times the volume of the test cell. The container that preferred for sample is an amber glass bottle as shows in Figure 3.2. This type of container is not necessary covered or shielded from direct light until ready to be tested. This container must be sealed by using screw caps with polyoletine or polytetraflucroethlene. A container and screw caps should be cleaned by using suitable solvent to remove remaining part of early sample. Then, these containers is rinsed with acetone and blowed with warm air. Lastly, immediately capped the container and seal it until used. Containers shall be filled with oil sample but leaving about 3% of the container volume when sampling is conducted [15].

Figure 3.2: Sampling container

3.4 Oil Samples

In this experiment, moisture adding process is done by adding or inject the distilled water in oil samples either vegetables or mineral oil by using syringe. The value of the distilled water that been added in oil are 1ml, 2ml, 3ml, 4ml and 5ml. After distilled water is added in oil, magnetic hot stirrer is used to heat up and stir the samples at $50^{o}C$ and 250 rmp respectively as shows in Figure 3.3. Time taken are about 30 minutes per samples. All samples are placed into the bottle and stored at room temperature after stirring process completed.

Figure 3.3: Magnetic hot stirrer

3.5 BdV Test

The equipment of BdV measurement is set up according to the IEC 60156:1995 standard. The minimum and maximum volume of the cell should be 350ml to 600ml. The characteristic of the test cell is must be transparent, electrically insulating and chemically inert. In the experiment, the example of suitable test cell design from the standard is used as in figure 3.4. [15]

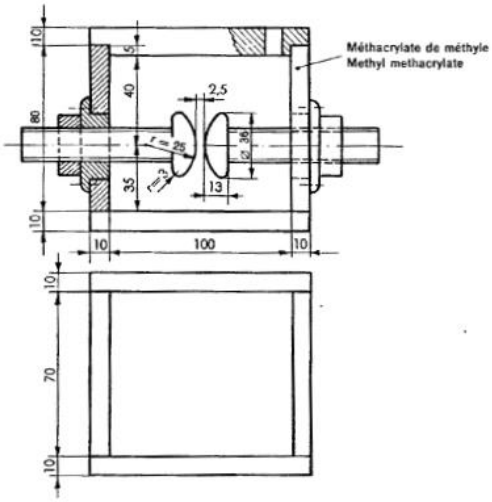


Figure 3.4: The example of the test cell. [15]

The electrodes used is made up from the brass and must be polished after used several application. The gap between the electrodes should be 2.5mm ± 0.05mm. [15]

3.6 FTIR Test

Based on ASTM 2144 standard, the equipment of FTIR is set up. Figure 3.5 shows the FTIR-6100 JASCO device used in this testing. The cell before and after been used by rinsing it with a suitable chemical grade or functionally equivalent organic solvent like 2-propanol. After that, rinsing it again with a suitable chemical grade or functionally equivalent hydrocarbon solvent such as petroleum naptha and keep the cell until it is to be used. The cell is clean again using the same process when after been used. [16]

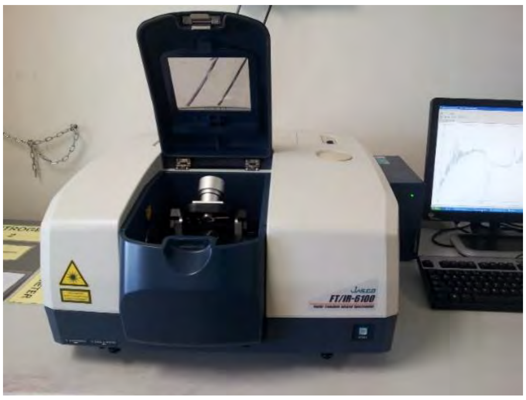


Figure 3.5: FTIR test set

3.7 Procedure of BdV Test

The step of BdV as below:

1. The Megger tester is turned on.
2. The samples from the bottle is filled in test cell about 350ml as in Figure 3.6.

Figure 3.6: The sample filled in test cell

3. The test cell is placed in the Megger testing area. Make sure that the electrodes sink in the oil and the cover is closed as in Figure 3.7 and Figure 3.8.

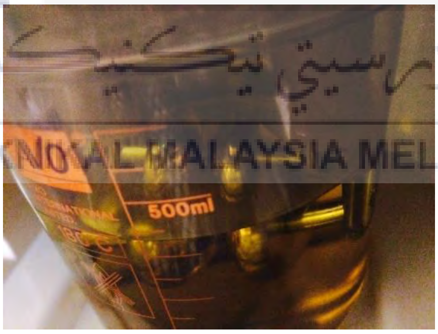


Figure 3.7: The electrodes sink in the oil

Figure 3.8: The equipment of the Megger tester.

4. After that, the standard of IEC 60156:1995 is selected and run the Megger tester
5. This testing will be conducted six time and at the end of the testing, the value of the average is appeared.
6. The value of the six time testing and the average is recorded.

3.8 Procedure of FTIR Test

In FTIR measurement, there have two step must be followed to get the result. Firstly, the sample is measured and secondly, the result from the measurement is analysed based on the library that store in the software.

a) Measure the sample

1. FTIR software is opened
2. "Spectra Measurement" is clicked on the software
3. New window is appeared and "Background" is clicked on it.
4. The compartment lid is opened
5. The Attenuated total reflectance (ATR) knob is turned in counter clockwise and fill a few oil samples in ATR compartment as in Figure 3.9 below.

Figure 3.9: The ATR compartment

6. The ATR knob is turned back in clockwise and the compartment lid is closed
7. “Sample Measurement” is clicked at the same window.
8. The measurement is completed at few second.
9. “Analyse send” is clicked on the file menu
10. New window of analyse send is appeared.
11. “Correction” is clicked on processing at tool bar
12. “Smoothing” is selected and click “ok”
13. “ AutoBaseline” is clicked on tool bar and click “ok”
14. Export on the file menu is clicked and Spectrum in three different file is saved which CSV, Old-format Standard and Jcamp.dx

b) Analyze the result

1. “ Run Know It” is clicked on the “analyse send” window
2. New window is appeared and “open spectrum” is clicked on file menu
3. Name file is selected to open the spectrum
4. “ Analyze IR” is clicked at tool bar
5. The peak on the spectrum is selected which according to the standard

3.9 Recording the Result of BdV and FTIR

This part is done when completed the testing. Table 3.1 shows the template that the result of the BdV test. The template is created to give the work more easily and effective. For the FTIR test, the result of this measurement is in the form of spectrum will recorded and saved. The range of the spectrum is within 4000 to 400 cm^{-1}. This spectrum is opened again by using “Speakwin”.

Table 3.1: Template of the BdV result

Moisture (ml)	Moisture (%)	Breakdown Voltage (kV)						
		1	2	3	4	5	6	Average
0	0							
1	0.286							
2	0.571							
3	0.857							
4	1.143							
5	1.429							

3.10 Analyzing the Result

Lastly, both result from the BdV test and FTIR test is analysed based on the correlation of the transformer oil effect with the moisture and changed or type functional group appear in the oil that effect with the moisture.

CHAPTER 4

RESULT AND DISCUSSION

4.1 BdV Test Results

Breakdown voltage of insulation liquids is one of the experimental testing to designate of the contaminant like a water and solid suspended matter. Water or moisture content is the factor will be affect the electrical strength of the insulating oil. Naidu et al [17] stated that presence of 0.01 % water will reduces the electrical strength about 20%. BdV test in this research is conducted in two different type of transformer oil sample which are mineral oil and PFAE. All the result of breakdown voltage is recorded from the test 1 until test 6 based on the standard IEC 60156:1995. The average value of breakdown voltage is calculated from the result of the six test. The main goal of the research is to study the effect of the moisture content in transformer oil. So, the changing parameter in this research is addition of the distilled water from 1ml until 5ml and represented in percentage. The result of BdV test for mineral oil and PFAE with changing moisture content are show in Table 4.1 and Table 4.2 respectively.

Table 4.1: The result of BdV test for mineral oil under moisture effect

Moisture (ml)	Moisture (%)	Breakdown Voltage (kV)						
		1	2	3	4	5	6	Average
0	0	60	60	60	60	60	60	60
1	0.286	20	10	16	13	12	34	18
2	0.571	11	11	15	14	11	19	14
3	0.857	10	10	10	9	10	11	10
4	1.143	9	10	10	12	9	9	10
5	1.429	9	7	8	9	10	7	8

Table 4.2: The result of BdV test for PFAE under moisture effect

Moisture (ml)	Moisture (%)	Breakdown Voltage (kV)						
		1	2	3	4	5	6	Average
0	0	60	60	60	60	60	60	60
1	0.286	12	12	12	15	16	14	14
2	0.571	10	10	13	11	12	13	12
3	0.857	13	11	13	11	10	9	11
4	1.143	8	13	13	14	14	9	12
5	1.429	11	13	13	11	10	19	13

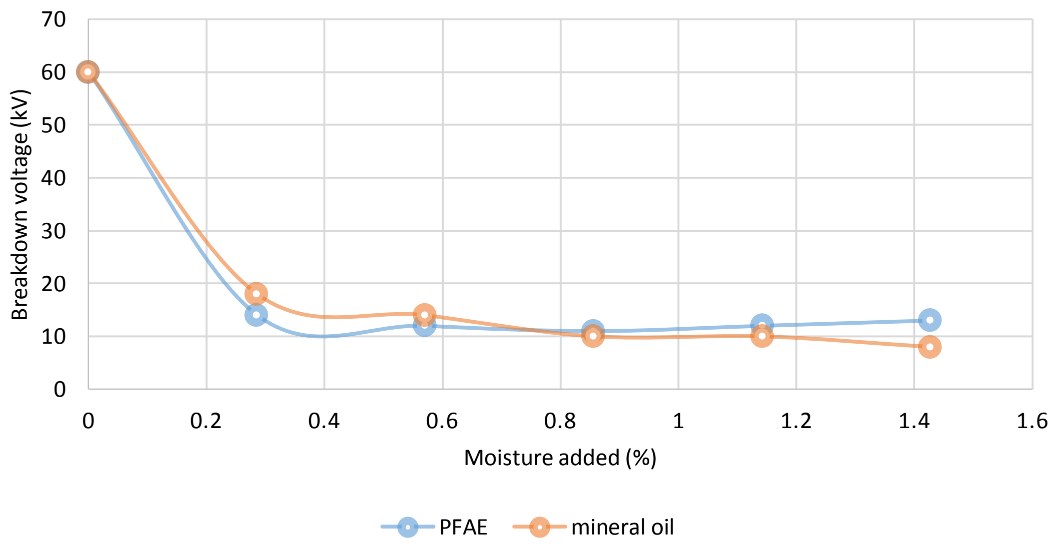


Figure 4.1: The line graph of BdV test for PFAE and mineral oil under moisture effect

Result in Table 4.1, the average value of breakdown voltage for new mineral oil is 60kV that indicate the high breakdown voltage and passes the requirement as a good transformer oil. After oil samples content 0.286% of water, the average reading showed drastically decrease to 18kV and remain declining to 14kV of the average value when 0.571% of water addition in oil sample. The result of the average value indicate that the breakdown voltage for oil sample with 0.857% and 1.143% of water addition into oil samples is same which is 10kV and maintain decrease to 8kV with 1.429% of water in oil samples.

The method of the measurement for mineral oil is the same on a changing of moisture content parameter and also the standard that is used with the measurement of the mineral oil. Based on the Table 4.2 indicate the average of the breakdown voltage for PFAE without moisture content at constant temperature and constant humidity of 71% is 60 kV. When 0.286% of water in oil sample, the average value of the breakdown voltage is rapidly decrease to 14 kV which is not achieved the requirement of the breakdown voltage should passes as a good transformer insulating oil. The average value of breakdown voltage is remain decrease to 12kV at 0.571% of water in oil samples and also reading of the average value at 0.857% of water in samples of oil decreasing to 11kV. However, the reading of the average value of breakdown voltage indicated slightly increased to 12kV for 1.143% of water addition and exactly same with the average value at 0.286% of water in oil samples. When 1.429% of water in oil samples, the value of the average is maintain increased to 13kV.

The line graph as in Figure 4.1 is plotted by referring to the result of Breakdown Voltage (BdV) test from the table above. This Figure 4.1 shows the breakdown voltage of the vegetables oil versus mineral oil under moisture effect. The X-axis represent as a percentage of water addition in oil samples and for Y-axis represent as the average of breakdown voltage in kilovolt (kV). The value of the standard deviation between two lines of PFAE and Mineral oil in the graph is 2.887 and it show the difference between two line is not large.

As a result, the average of breakdown voltage for PFAE is show the fluctuating pattern while for the mineral oil, display the decline pattern. This verified that the moisture is given the effect in dielectric strength of the mineral oil except PFAE because PFAE show the increasing of the average breakdown voltage for oil samples with 1.143% and 1.429% of water. This describe that PFAE has advantage to absorb the moisture in the oil which also agreed with [10].

4.2 FTIR Test Result

In this part, FT/IR-6100 JASCO device is used in order to get FTIR test result. This device was recorded the sample at 20 scan per second with a resolution of 0.5cm^{-1} and the wavelength range within 400 cm^{-1} to 4000 cm^{-1}. The purpose of this measurement is to find the physical changing of the chemical structure. The oil samples that used in this measurement are same parameter with breakdown voltage measurement. The result of this testing is in term of spectrum. In this result, X- axis is wavelength number in unit of cm^{-1} and Y-axis is percentage of Transmittance number.

The Figure 4.1 shows the spectrum of FTIR test for mineral oil samples under moisture effect while Figure 4.2 shows the spectrum of FTIR test for PFAE samples under the moisture effect. The new PFAE and new mineral oil is spectrum in black color. The red color represents addition of 0.286% water in oil samples, green color present addition of 0.571% water in oil samples, blue color present addition of 0.857% water in oil samples, light blue present addition of 1.143% water in oil samples and purple color represent addition of 1.429% water in oil samples.

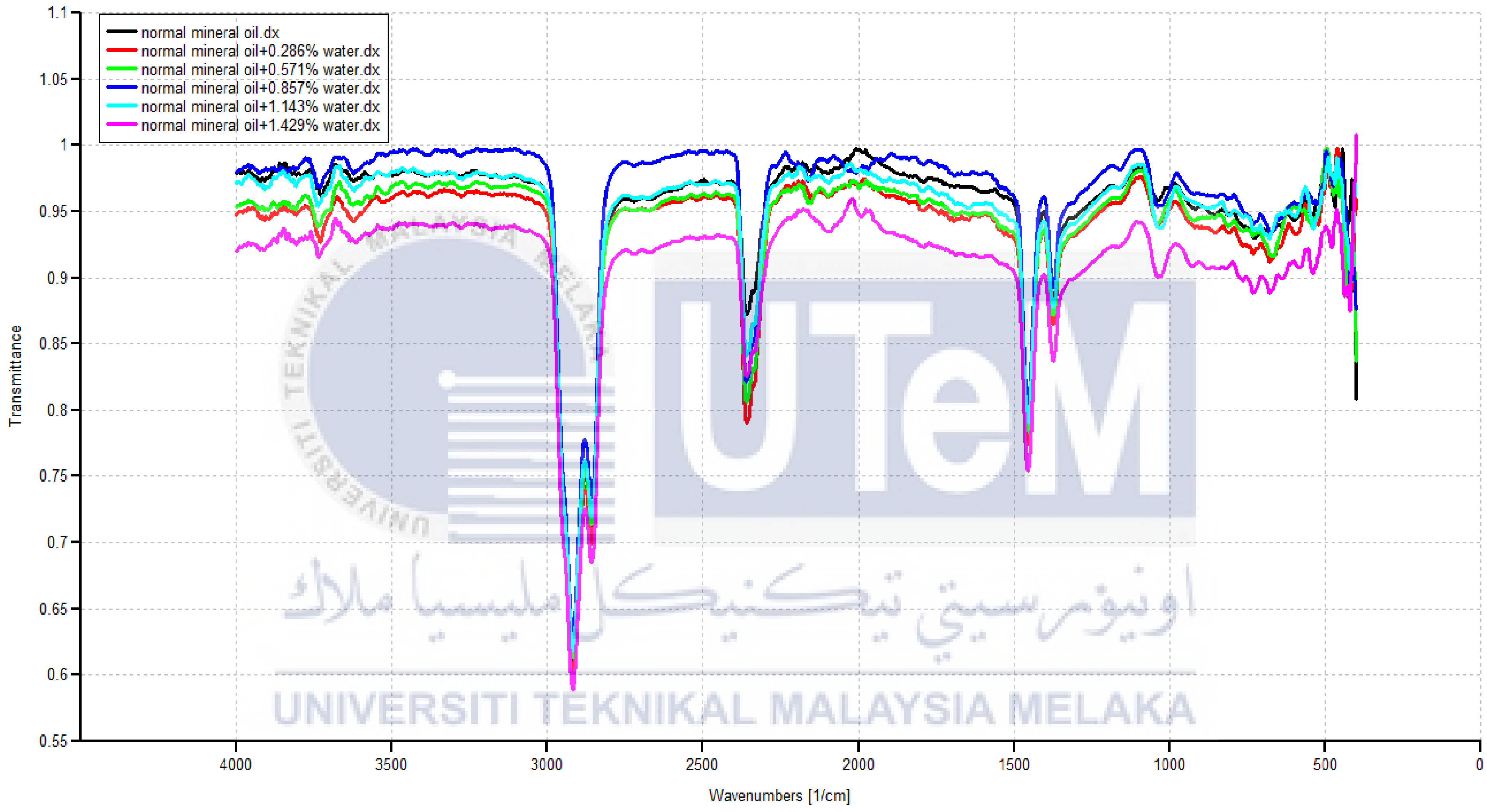


Figure 4.3: FTIR spectra for mineral oil samples

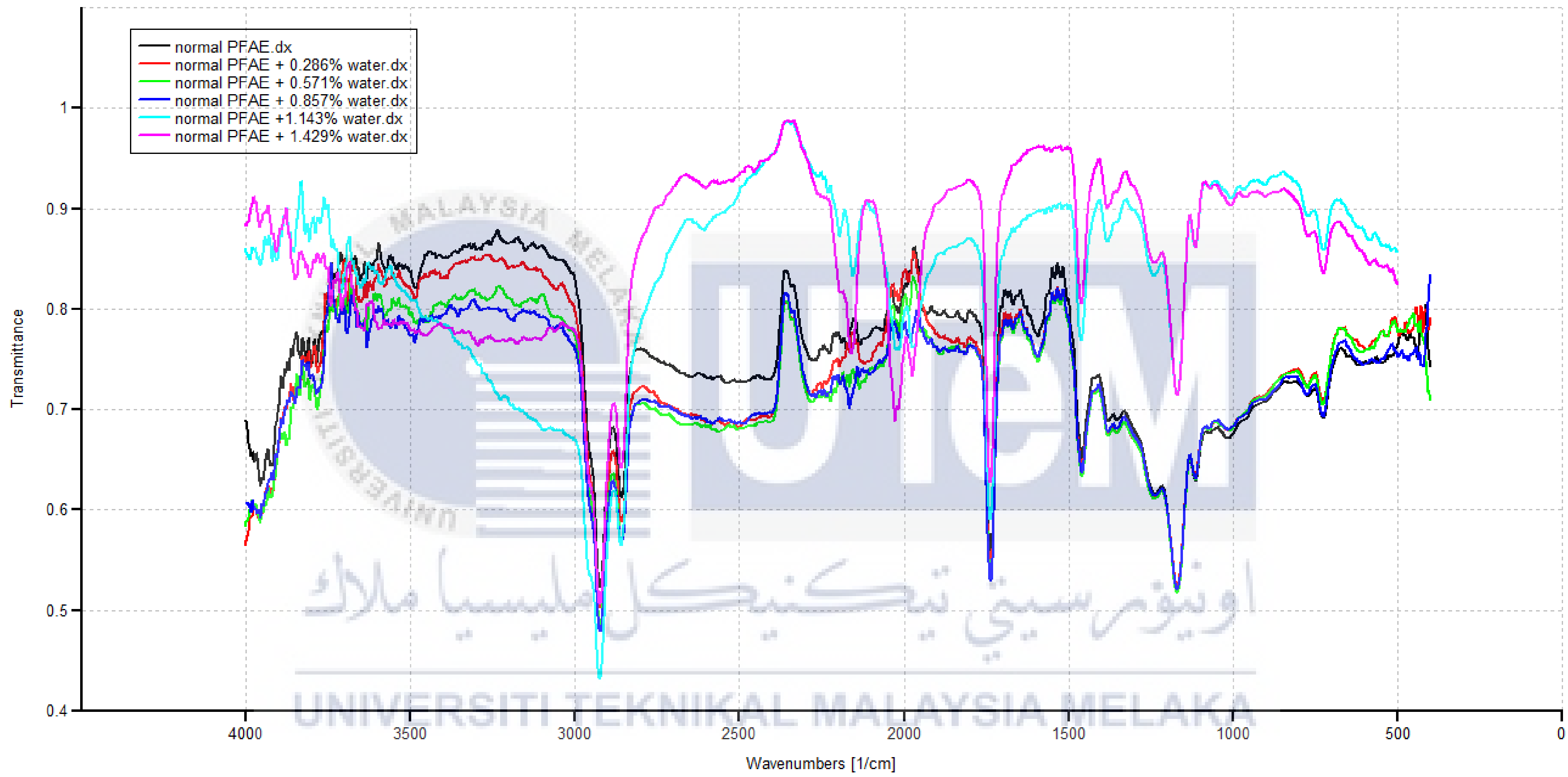


Figure 4.2: FTIR spectra for PFAE samples

4.3 Description of the FTIR Results

According to the ASTM D2144, the range of the wavelength between 3700 to 3570 cm^{-1} show the carboxylic acid O-H and amide N-H stretching vibration. The Figure 4.4 indicates the region of O-H and N-H stretching vibration with zoom range (2000cm^{-1} - 4000 cm^{-1}). Based on the region of 3570 to 3700 cm^{-1}, the value of the peak that selected is at 3621 cm^{-1} because this peak indicate the changing at spectrum. At 3621 cm^{-1}, the normal mineral oil spectrum in black color indicate 0.97% of Transmittance, the red color show 0.94% of Transmittance which below than normal mineral oil, green color indicate 0.95% of Transmittance closed to normal mineral oil, the blue color show the value slightly increase than normal mineral oil which is 0.978% of and light blue color indicate very closed to mineral oil that is 0.966% of Transmittance. However, purple color of the spectrum that present increasing of the moisture show the drastically changes at 3621 cm^{-1} which shifted to downwards at 0.92% of Transmittance. Hence, the spectrum is shifted to downwards when moisture in mineral oil increased.

The Figure 4.5 shows the substances or chemical structure appear in mineral oil with 1.143% of water that is analyzed by IR analyzer. The other result that analyzed by IR analyzing are inserted in Appendix A. The spectrum of the oil sample is compared with selected region from the library included in the IR analyzer as shows in Figure 4.5 (a). The Figure 4.3 (b) display the selected fragment structure appear from the result of comparison with the library and Figure 4.3 (c) present the list of the structure which exist in the spectrum.

As a result, Figure 4.5 proved the chemical structure of water H_2O exist at 3615cm^{-1} wavelength in mineral oil with 1.143% of water and this result of the analyzing same with Appendix A: Figure A.5. For new mineral oil as in Appendix A: Figure A.1, the analyzing of the spectrum verified no other chemical structure is appeared at the region of 3570 to 3700 cm^{-1}. The result of analyzing the spectrum in mineral oil with 0.286% and 0.571% water that can been seen in Appendix A: Figure A.2 and Figure A.3 display silicon-IR with bond of O-H is exist while there is different at result of analyzing the spectrum in mineral oil with 0.857% of water that can be seen in Appendix A: Figure A.2 which show carboxylic acid – IR with bond of O-H is appeared. The result shows moisture in mineral oil will effect the main structure of the mineral oil. If the chemical structure of water is increased in the mineral oil, the properties of the insulation become low or weak and not long after that transformer will be collapse.

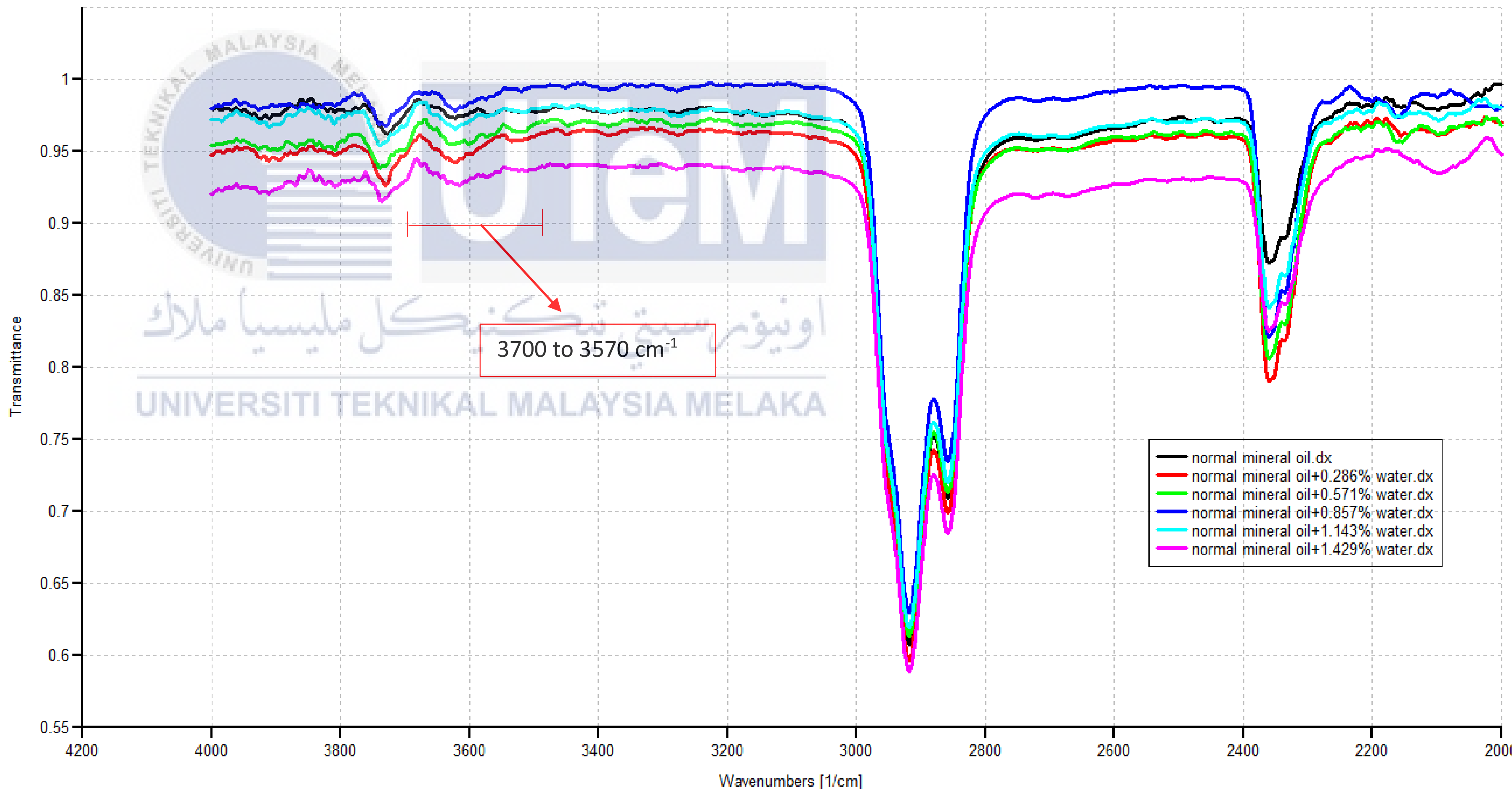


Figure 4.4: The O-H and N-H stretching vibration in mineral oil with zoom range (2000 cm^{-1} - 4000 cm^{-1})

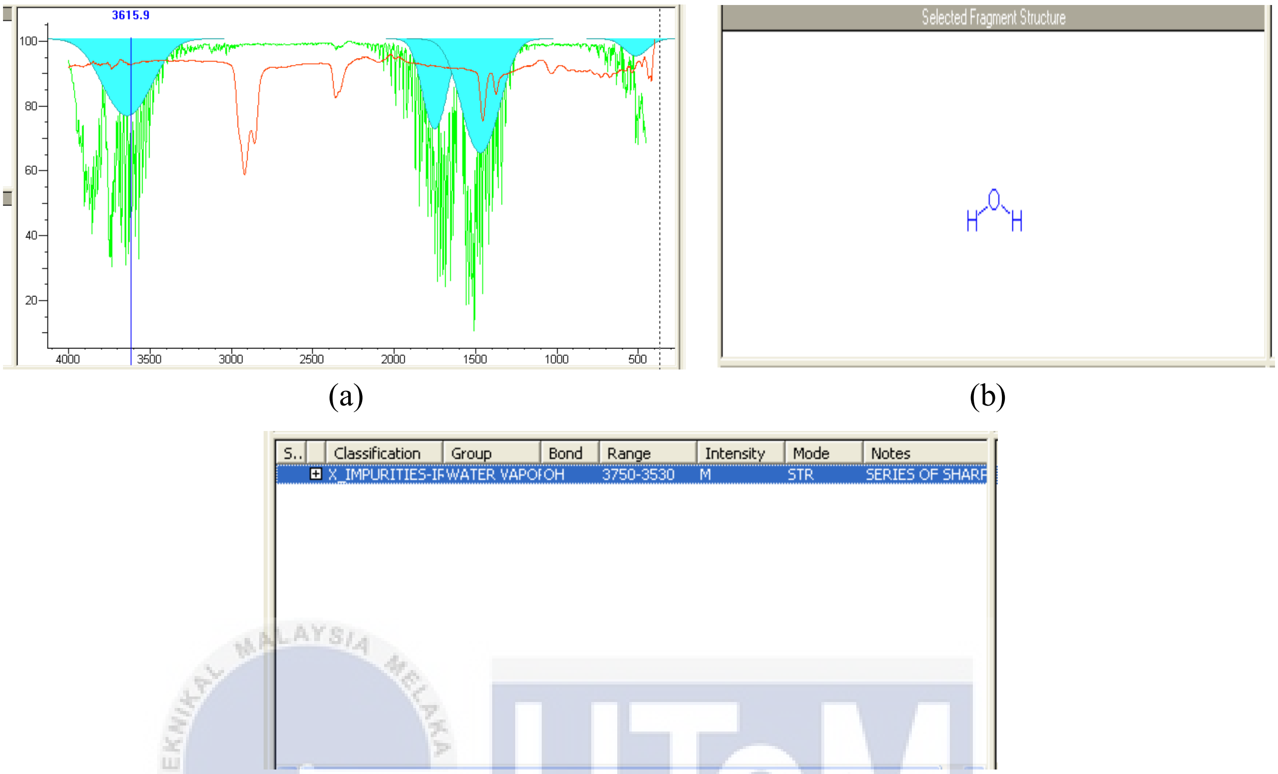


Figure 4.5: Substances appear in mineral oil with 1.143% of water, (a) spectral analysis (b)selected fragment structure and (c) library of chemical bond

The testing of FTIR for PFAE, there is no more standard to verify which region that show the problem in the insulation oil. Therefore, a research work from Abubakar A. Suleiman [11] is used as a guide to validate the result of PFAE for this research. The chemical structure of PFAE is totally different with the mineral oil. PFAE is the biodegradable oil that cannot destructive the environment.

Based on a research work from Abubakar A. Suleiman [11], the range of the wavelength between 1000 to 1250 cm^{-1} indicate C-OH stretching vibration in PFAE as in Figure 4.6. The value of the peak that really observable is selected at 1170 cm^{-1}. The percentage of Transmittance for new PFAE as in black color is 0.52% at the selected wavelength which is at 1170 cm^{-1}. The red, green and blue color of the spectrum appearances at 1170 cm^{-1} very closed to the percentage of Transmittance for new PFAE which are 0.526% and 0.518% and the different of red and green color is about 0.006% and 0.002%. Nevertheless, the light blue and purple color of the spectrum show exactly different with other four spectrum which are 0.716% and 0.714% of Transmittance at 1170 cm^{-1}. Based on the result in Figure 4.2, the spectrum of light blue and purple shows the different with other spectrum that is shifted to upwards.

The result of the spectrum illustrated water content in PFAE will effect the spectrum if the water content exceed 1.143%. Therefore, the changing chemical structure of the carboxylic acids and alcohol is occurred at the region of 1000 to 1250 cm^{-1}. All sample of PFAE spectrum is analyzed same with mineral oil samples which is using IR analyzer. The aim of used IR analyzer is to identify the structure appear in spectrum of the sample. The substance appear in PFAE with 0.286% of water show as in Figure 4.7. The Figure 4.7 (a) display selected fragment of the structure and Figure 4.7 (c) show the list of the structure that exist in the spectrum after analyze with library in IR-analyzer. The other result of the other oil samples is in the Appendix B.

Refer to the Figure 4.7, the chemical structure that appear in the 1169.6 cm^{-1} is alcohol-IR for the PFAE with 0.286% of water and the result also same for other PFAE sample that can be seen in Appendix B: Figure B.1 until Figure B.2. This proved if water content in PFAE sample, the chemical structured is not affected because the result from the analyzing is same with new PFAE sample. Thus, PFAE able to replace the existing insulation oil which is mineral oil because other insulation oil cannot absorb more moisture than PFAE capable to absorb and the kraft paper always in dry condition. [10, 18]

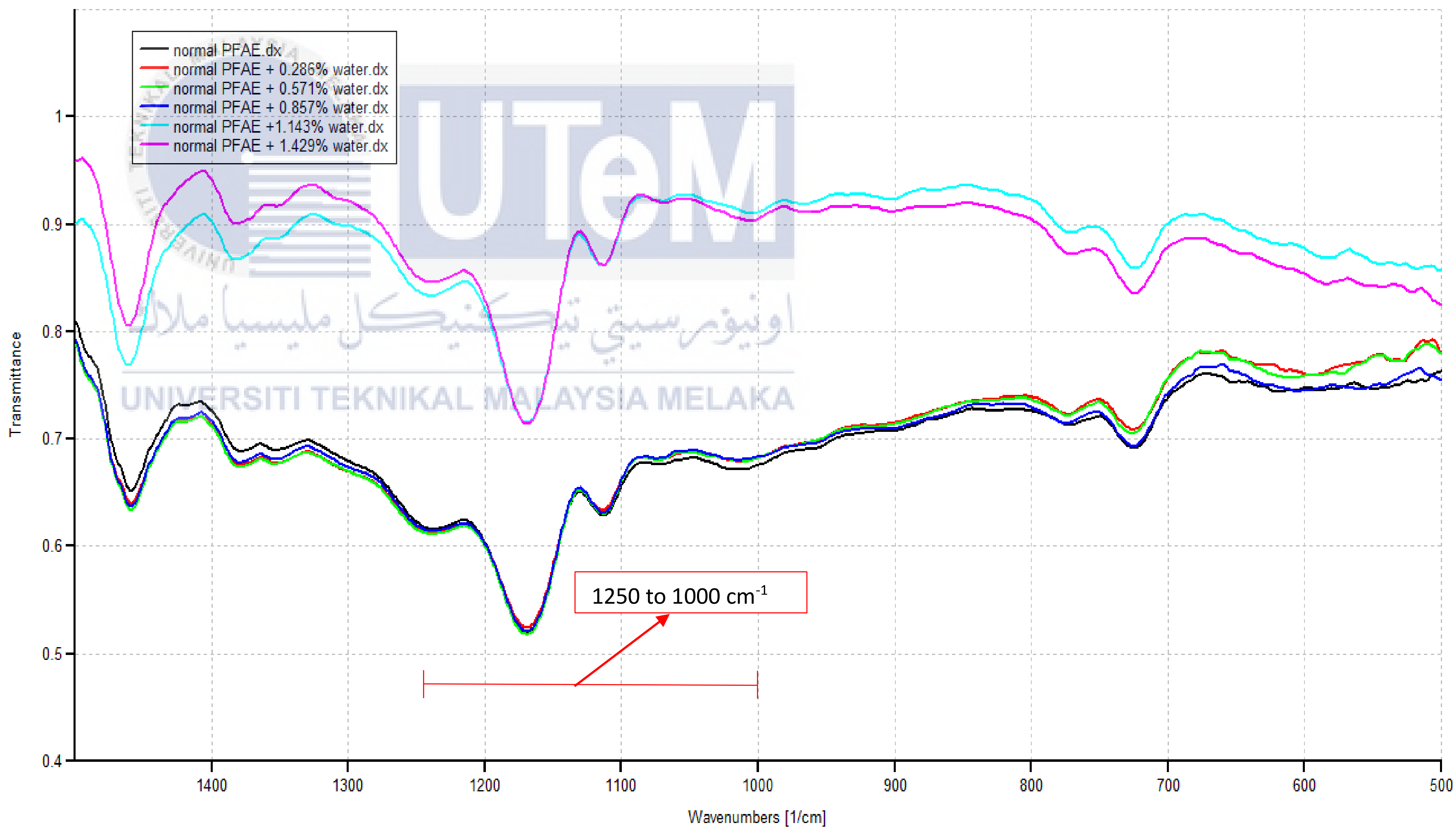
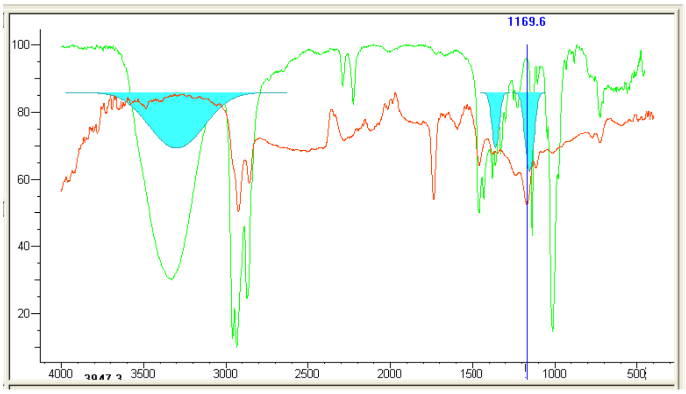
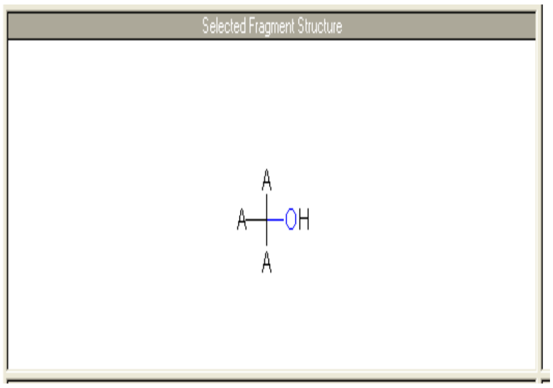


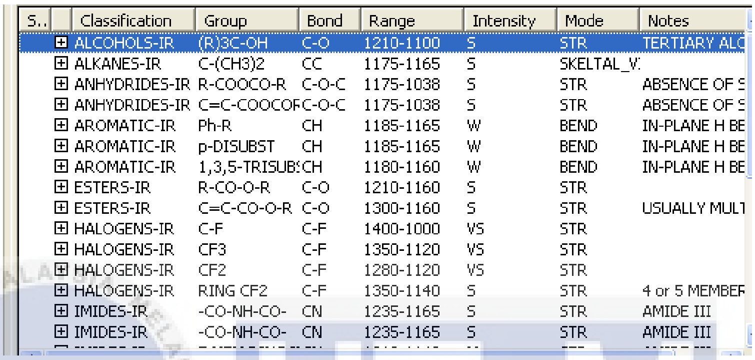
Figure 4.6: The C-OH stretching vibration in PFAE with zoom range (500 cm^{-1} - 1500 cm^{-1})



(a)



(b)



S..		Classification	Group	Bond	Range	Intensity	Mode	Notes
	⊞	ALCOHOLS-IR	(R)3C-OH	C-O	1210-1100	S	STR	TERTIARY ALC
	⊞	ALKANES-IR	C-(CH3)2	CC	1175-1165	S	SKELTAL_V:	
	⊞	ANHYDRIDES-IR	R-COOCO-R	C-O-C	1175-1038	S	STR	ABSENCE OF S
	⊞	ANHYDRIDES-IR	C=C-COOCOF	C-O-C	1175-1038	S	STR	ABSENCE OF S
	⊞	AROMATIC-IR	Ph-R	CH	1185-1165	W	BEND	IN-PLANE H BE
	⊞	AROMATIC-IR	p-DISUBST	CH	1185-1165	W	BEND	IN-PLANE H BE
	⊞	AROMATIC-IR	1,3,5-TRISUB:	CH	1180-1160	W	BEND	IN-PLANE H BE
	⊞	ESTERS-IR	R-CO-O-R	C-O	1210-1160	S	STR	
	⊞	ESTERS-IR	C=C-CO-O-R	C-O	1300-1160	S	STR	USUALLY MULT
	⊞	HALOGENS-IR	C-F	C-F	1400-1000	VS	STR	
	⊞	HALOGENS-IR	CF3	C-F	1350-1120	VS	STR	
	⊞	HALOGENS-IR	CF2	C-F	1280-1120	VS	STR	
	⊞	HALOGENS-IR	RING CF2	C-F	1350-1140	S	STR	4 or 5 MEMBER
	⊞	IMIDES-IR	-CO-NH-CO-	CN	1235-1165	S	STR	AMIDE III
	⊞	IMIDES-IR	-CO-NH-CO-	CN	1235-1165	S	STR	AMIDE III

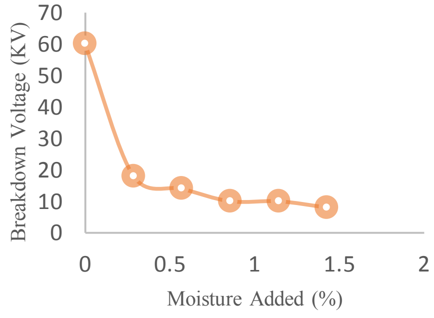
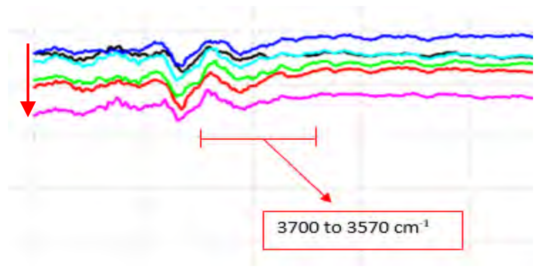
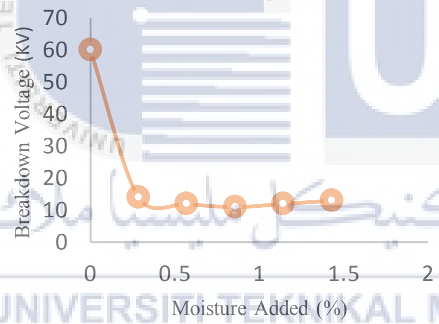
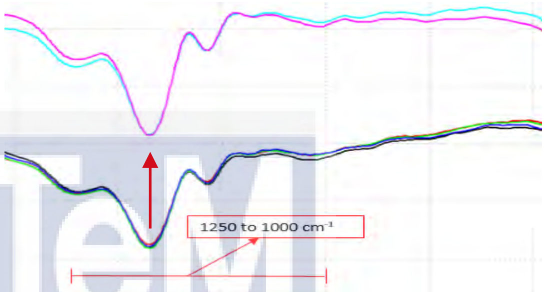
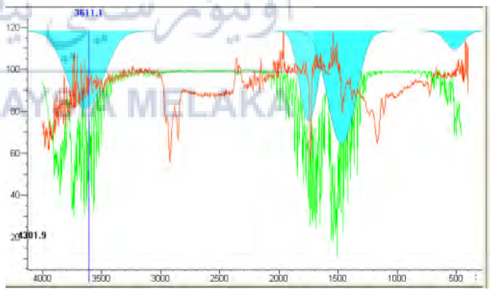
(c)

Figure 4.7: Substances appear in PFAE with 0.286% of water,(a) spectral analysis, (b) selected fragment structure and (c) library of chemical bond

4.4 Summary

Table 4.3 shows the summary of the result of Bdv and FTIR. When moisture increase in mineral oil, the average of breakdown voltage is decreased. The chemical structure is also changed respectively and spectrum shifted to downwards at region 3570 to 3700 cm^{-1} proved by using FTIR test. For PFAE, the average of breakdown voltage shows the fluctuation pattern in the result of BdV test when moisture increase. Analyzing of the spectrum at region 1000 to 1250 cm^{-1} indicate same chemical structure for all sample but when moisture increase, spectrum shifted to upwards at certain spectrum in PFAE. At region 3570 to 3700 cm^{-1}, proved that the chemical structure of new PFAE contain of water based structure. So, the region is not suitable to determine moisture content in PFAE.

Table 4.3: Summary of the result

	BdV	FTIR
Minera l Oil		**Region 3570 to 3700 cm^{-1}** 
PFAE		**Region 1250 to 1000 cm^{-1}** 
		Region 3700 to 3570 cm^{-1} 

S..	Classification	Group	Bond	Range	Intensity	Mode	Notes
	SILICONS-IR	Si-OH	O-H	3700-3200	M	STR	BROAD PEAK
	X_IMPURITIES-IFWATER VAPOFOH			3750-3530	M	STR	SERIES OF SHARP PE

CHAPTER 5

CONCLUSION AND RECOMMENDATION

5.1 Conclusions

This project has been conducted in order to study a changing of the properties and the physical structure in insulation which effect from the moisture content in insulating oil of transformer. Two type of the insulation oil which are PFAE and mineral oil has been used as oil samples in this project because this two type of insulation oil have different chemical structure. The result from this project can be concluded as below:

1. The average value of the breakdown voltage show drastically decrease after added the water in insulation oil sample from the result of the breakdown voltage for new insulation oil and continuously decrease for mineral oil sample but for Palm oil Fatty Acid Ester (PFAE) sample, the result of the breakdown voltage show increasing at certain water addition in oil.

2. However, the pattern for both oil samples of the breakdown voltage is totally different. The PFAE show fluctuating pattern but the mineral oil indicate decreasing pattern. So, this experiment prove that mineral oil easily affected with moisture compare to PFAE.

3. In FTIR test, the result shows that spectrum in mineral oil change when oil is added with water and by using IR-analyze, it proved that mineral content has new chemical structure which is H_2O. Moreover, PFAE spectrum, shows differences which is

upwards but when analyzed in IR-analyzer, there no have changes in chemical structure.

Finally, the objective has been achieved successfully and it shows that BdV and FTIR tests can be used to determine the performance or condition of transformer insulating oil.

5.2 Recommendations

The properties of the insulation oil decreasing because of the physicochemical reaction such as heat, moisture, oxidation and other in insulation during operating time of the transformer. One of the physicochemical reaction in insulation which is moisture has been studied in this project. As a suggestion, this project will be continuous to study the other of physicochemical reaction such as temperature by using the same tests which are BdV and FTIR. The reason is temperature in the transformer are different based on their operation and these will be effect the performance or condition of the insulation oil. The suggestion of changing parameter in temperature are 30ºC, 40ºC, 50ºC, 60ºC, 70ºC, 80ºC, 90ºC and 100ºC.

Besides that, other recommendation is to analysed the electric field for High Voltage (HV) testing unit by using Ansoft Maxwell software. This software can design and analyze the electromagnetic and electromechanical devices such motor, transformer and others. The Figure 5.1 show the example of 2D design of test cell.

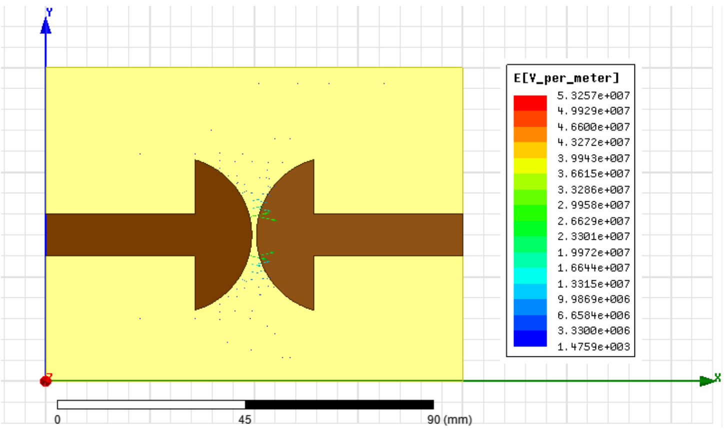


Figure 5.1: Example of 2D design of test cell

REFERENCES

[1] Energy Division. Transformers. Published by Tyco Electronic Corporation Crompton Instrument, Kennesaw, Georgia, United Stated.

[2] S. Hembrom, "Analysis of aged insulating oil for early detection of incipient fault inside the high voltage equipment". Unpublished Master of Technology in Power control and Drives, Department of Electrical Engineering, National Institute of Technology, Rourkela, India.

[3] N. Zawani, "Introduction to Power Engineering" BEKP2443 Lecture 5: Power Transformers, Universiti Teknikal Malaysia Melaka (UTeM), 2011.

[4] I. Fofana "50 years in the Development of Insulating Liquids", DEIS feature article, September 2013, vol.29, no.5.

[5] S. Tenbohlen and M. Koch "Aging Performance and Moisture Solubility of Vegetable Oils for Power Transformer", IEEE Transactions on power delivery, vol. 25, no.2, April 2010.

[6] T. Kanoh, H. Iwabuchi, Y. Hoshida, J. Yamada, T. Hikosaka, A. Yamazaki; Y. Hatta and H. Koide, "Analyses of electro-chemical characteristics of Palm Fatty Acid Esters as insulating oil", IEEE International Conference Dielectric Liquids, 2008. ICDL 2008.

[7] Lion Corporation "Environmentally Friendly Insulating Oil Palm Fatty Acid Ester (PFAE)", in slide presentation.

[8] C. Tang, R. Liao, L. Yang and F. Huang, "Research on the dielectric properties and breakdown voltage of transformer oil-paper insulation after accelerating thermal ageing", IEEE, 2010.

[9] W. H. Barliey (2013). *An analysis of International Transformer Failures, Part 1*. The Engineering Department of the Hartford Steam Boiler Inspection and Insurance Company.

[10] A. A. Suleiman, N. A. Muhamad, N. Bashir, N. S. Murad and Y. Z. Arief. “Effect of Moisture on Breakdown Voltage and Structure of Palm Based insulation Oils”, IEEE Transaction on Dielectric and Electrical Insulation, vol.21, no.5, October 2014.

[11] Thermo Nicolet Team (2001). Introduction to Fourier Transform Infrared Spectrometry. Published by Thermo Nicolet Corporation, United Stated.

[12] Y. Hadjadj, I. Fofana and J. Jalbert, “Insulating Oil Decaying Assessment by FTIR and UV-Vis Spectrophotometry Measurements”, IEEE Annual Report Conference on Electrical Insulation and Dielectric Phenomena, 2013.

[13] N. S. Murad and N. A. Muhamad, "Palm Oil as Liquid Insulator: Moisture Absorption Level and Voltage Breakdown", IEEE Conference on Electrical Insulation and Dielectric Phenomena, China, 14 June 2013, 2013.

[14] P. Prosr, M. Brandt, V. Mentlik and J. Michalk, “Condition Assessment of Oil Transformer Insulating System”, International Conference on Renewable Energies and Power Quality (ICREPQ’10), Granada (Spain), March, 2010.

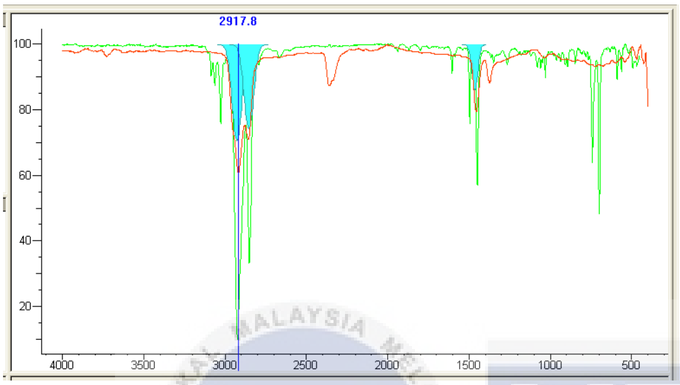
[15] IEC 60156 (1995). “Insulating Liquids-Determination of the Breakdown Voltage at Power Frequency-Test Method”.

[16] ASTM D2144 (2013). “Standard Practices of Electrical Insulating Oils by Infrared Absorption”

[17] M. S. Naidu and V. Kamaraju (2004). *High Voltage Engineering*. New Delhi. Published by Tata McGraw-Hill Company Limited.

[18] M. A. G. Martins, "Vegetables Oils, an Alternative to Mineral Oil for Power Transformer – Experimental Study of Paper Aging in Vegetables Oil versus Mineral Oil" in IEEE Electric Insulation Mag, Vol.26, No.6, pp. 7-13, 2010.

APPENDIX A



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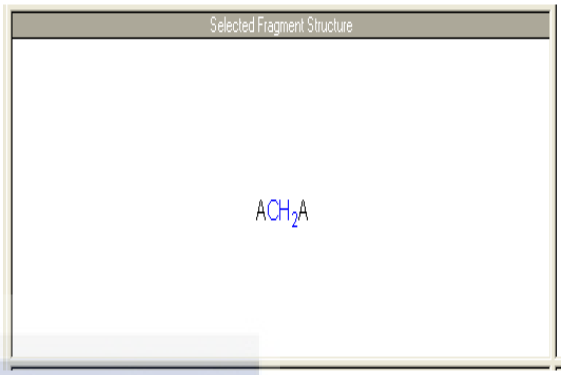

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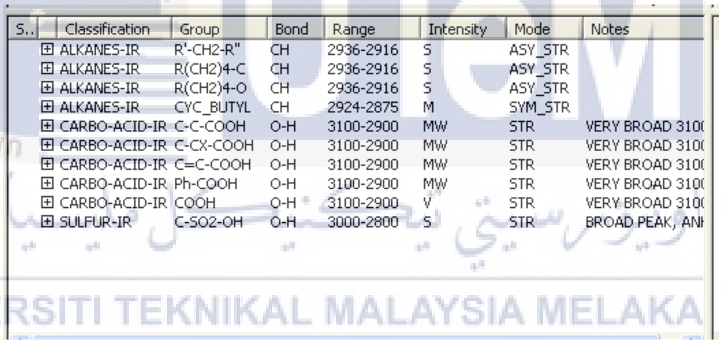
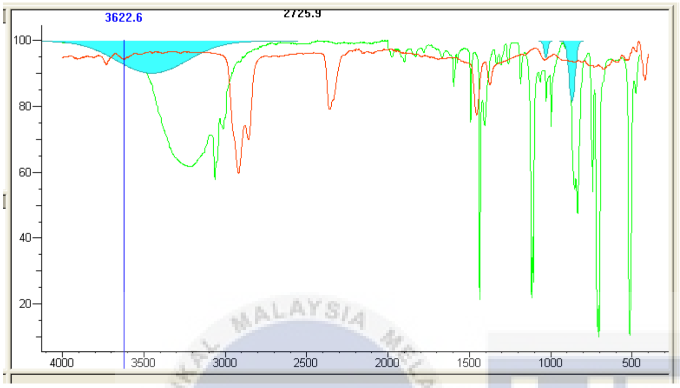


S..	Classification	Group	Bond	Range	Intensity	Mode	Notes
⊞	ALKANES-IR	R'-CH2-R"	CH	2936-2916	S	ASY_STR	
⊞	ALKANES-IR	R(CH2)4-C	CH	2936-2916	S	ASY_STR	
⊞	ALKANES-IR	R(CH2)4-O	CH	2936-2916	S	ASY_STR	
⊞	ALKANES-IR	CYC_BUTYL	CH	2924-2875	M	SYM_STR	
⊞	CARBO-ACID-IR	C-C-COOH	O-H	3100-2900	MW	STR	VERY BROAD 310(
⊞	CARBO-ACID-IR	C-CX-COOH	O-H	3100-2900	MW	STR	VERY BROAD 310(
⊞	CARBO-ACID-IR	C=C-COOH	O-H	3100-2900	MW	STR	VERY BROAD 310(
⊞	CARBO-ACID-IR	Ph-COOH	O-H	3100-2900	MW	STR	VERY BROAD 310(
⊞	CARBO-ACID-IR	COOH	O-H	3100-2900	V	STR	VERY BROAD 310(
⊞	SULFUR-IR	C-SO2-OH	O-H	3000-2800	S	STR	BROAD PEAK, ANI

(c)

Figure A.1: Substances appear in mineral oil without water content, (a) spectral analysis (b)selected fragment structure and (c) library of chemical bond



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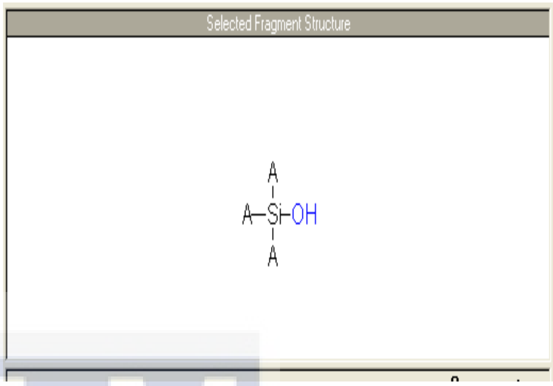
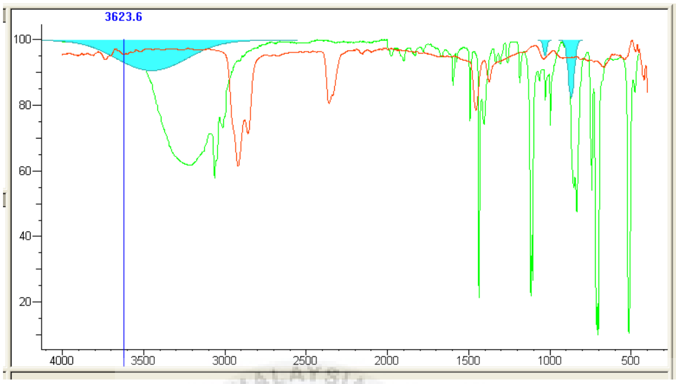


(b)

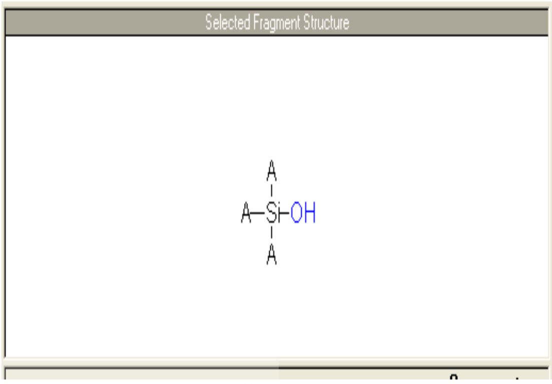
S..	Classification	Group	Bond	Range	Intensity	Mode	Notes
⊞	SILICONS-IR	Si-OH	O-H	3700-3200	M	STR	BROAD PEAK
⊞	X_IMPURITIES-IF	WATER VAPOF	OH	3750-3530	M	STR	SERIES OF SHARF

(c)

Figure A.2: Substances appear in mineral oil with 0.286% of water, (a) spectral analysis (b) selected fragment structure and (c) library of chemical bond



(a)

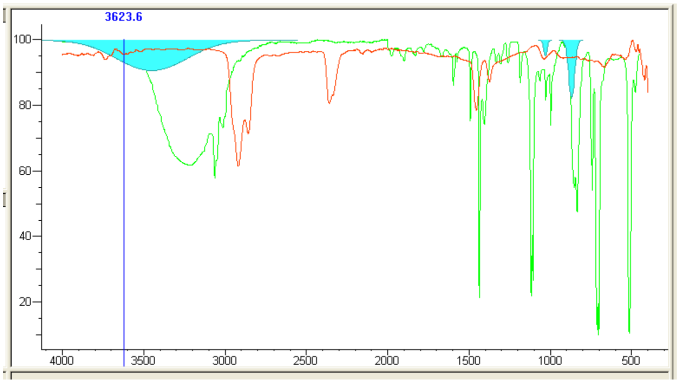


(b)

S..	Classification	Group	Bond	Range	Intensity	Mode	Notes
	⊞ SILICONS-IR	Si-OH	O-H	3700-3200	M	STR	BROAD PEAK
	⊞ X_IMPURITIES-IF	WATER VAPOF	OH	3750-3530	M	STR	SERIES OF SHARF

(c)

Figure A.3: Substances appear in mineral oil with 0.571% water content, (a) spectral analysis (b)selected fragment structure and (c) library of chemical bond



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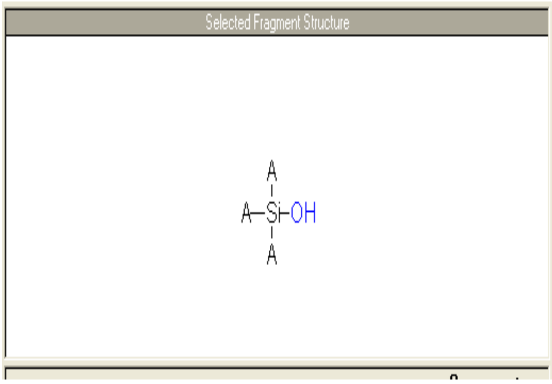
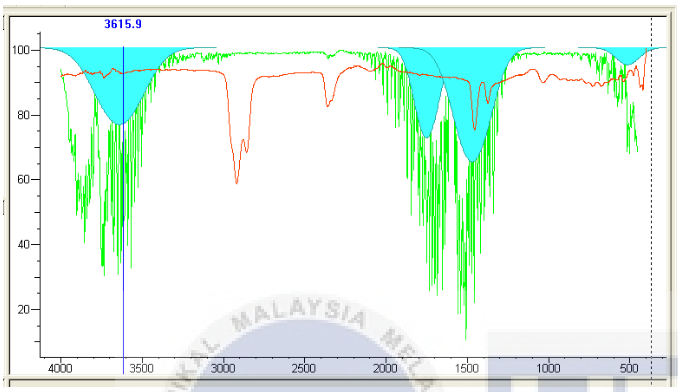


(b)

S..	Classification	Group	Bond	Range	Intensity	Mode	Notes
	⊞ SILICONS-IR	Si-OH	O-H	3700-3200	M	STR	BROAD PEAK
	⊞ X_IMPURITIES-IF	WATER VAPOI	OH	3750-3530	M	STR	SERIES OF SHARF

(c)

Figure A.4: Substances appear in mineral oil with 0.857% water content, (a) spectral analysis (b)selected fragment structure and (c) library of chemical bond



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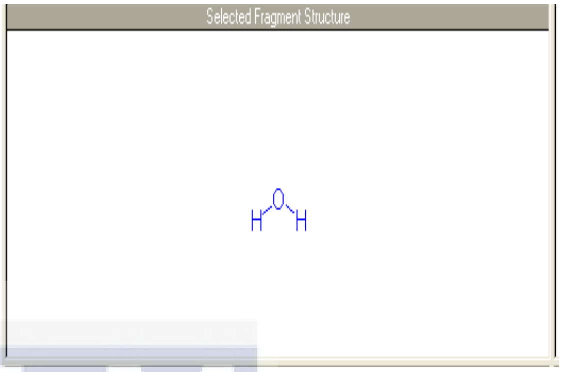
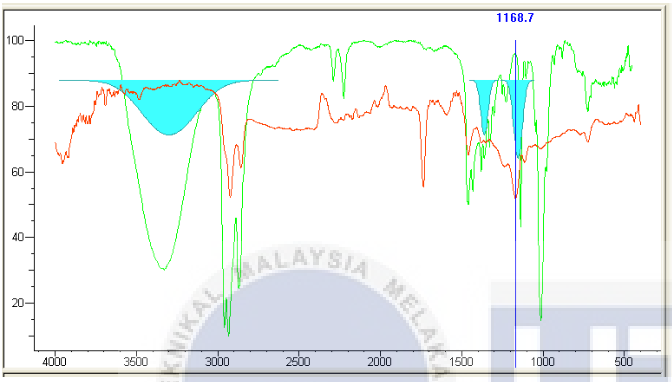


(b)

(c)

Figure A.5: Substances appear in mineral oil with 1.429% of water, (a) spectral analysis (b)selected fragment structure and (c) library of chemical bond

APPENDIX B



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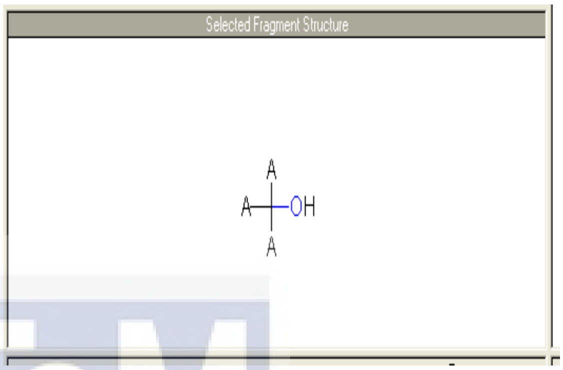

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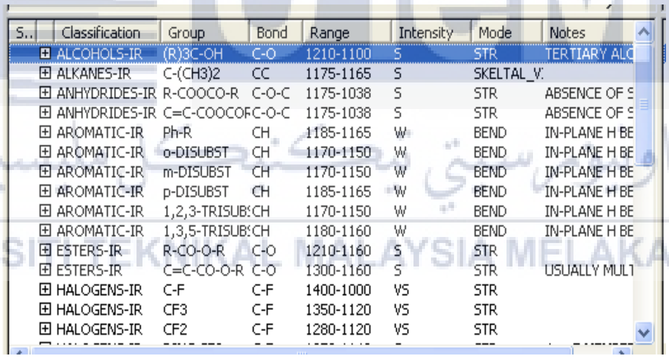
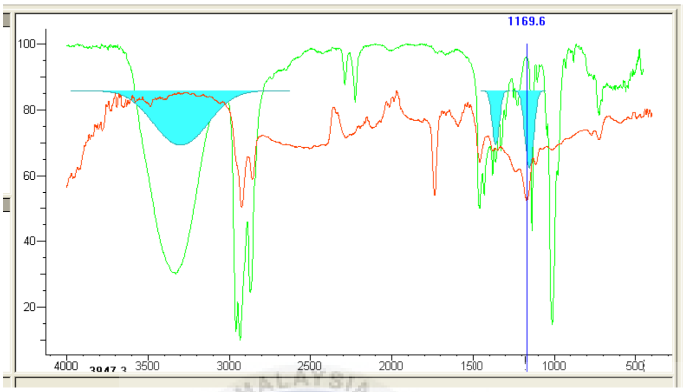


S..	Classification	Group	Bond	Range	Intensity	Mode	Notes
	ALCOHOLS-IR	(R)3C-OH	C-O	1210-1100	S	STR	TERTIARY ALC
	ALKANES-IR	C-(CH3)2	CC	1175-1165	S	SKELTAL_V.	
	ANHYDRIDES-IR	R-COOCO-R	C-O-C	1175-1038	S	STR	ABSENCE OF S
	ANHYDRIDES-IR	C=C-COOCOF	C-O-C	1175-1038	S	STR	ABSENCE OF S
	AROMATIC-IR	Ph-R	CH	1185-1165	W	BEND	IN-PLANE H BE
	AROMATIC-IR	o-DISUBST	CH	1170-1150	W	BEND	IN-PLANE H BE
	AROMATIC-IR	m-DISUBST	CH	1170-1150	W	BEND	IN-PLANE H BE
	AROMATIC-IR	p-DISUBST	CH	1185-1165	W	BEND	IN-PLANE H BE
	AROMATIC-IR	1,2,3-TRISUB:	CH	1170-1150	W	BEND	IN-PLANE H BE
	AROMATIC-IR	1,3,5-TRISUB:	CH	1180-1160	W	BEND	IN-PLANE H BE
	ESTERS-IR	R-CO-O-R	C-O	1210-1160	S	STR	
	ESTERS-IR	C=C-CO-O-R	C-O	1300-1160	S	STR	USUALLY MULT
	HALOGENS-IR	C-F	C-F	1400-1000	VS	STR	
	HALOGENS-IR	CF3	C-F	1350-1120	VS	STR	
	HALOGENS-IR	CF2	C-F	1280-1120	VS	STR	

(c)

Figure B.1: Substances appear in PFAE without water, (a) spectral analysis, (b) selected fragment structure and (c) library of chemical bond



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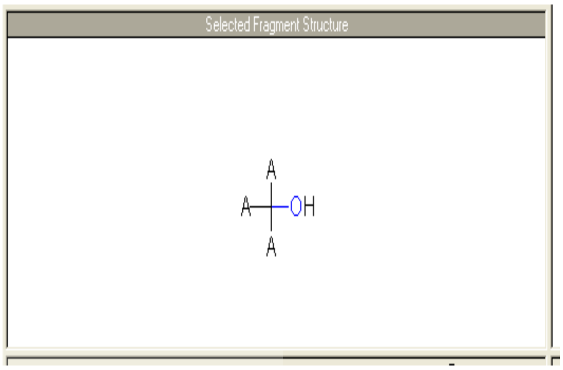
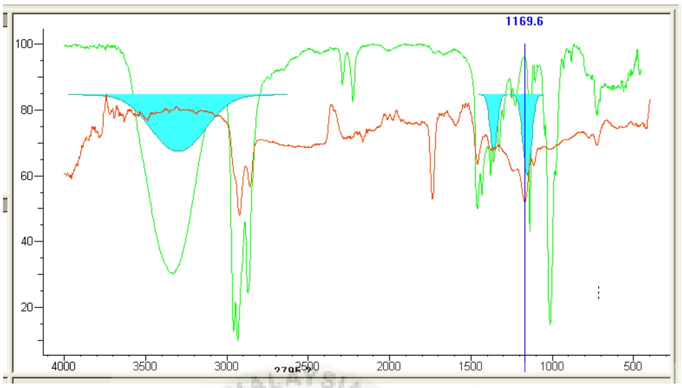


(b)

S..	Classification	Group	Bond	Range	Intensity	Mode	Notes
	ALCOHOLS-IR	(R)3C-OH	C-O	1210-1100	S	STR	TERTIARY ALC
	ALKANES-IR	C-(CH3)2	CC	1175-1165	S	SKELTAL_V.	
	ANHYDRIDES-IR	R-COOCO-R	C-O-C	1175-1038	S	STR	ABSENCE OF S
	ANHYDRIDES-IR	C=C-COOCOF	C-O-C	1175-1038	S	STR	ABSENCE OF S
	AROMATIC-IR	Ph-R	CH	1185-1165	W	BEND	IN-PLANE H BE
	AROMATIC-IR	o-DISUBST	CH	1170-1150	W	BEND	IN-PLANE H BE
	AROMATIC-IR	m-DISUBST	CH	1170-1150	W	BEND	IN-PLANE H BE
	AROMATIC-IR	p-DISUBST	CH	1185-1165	W	BEND	IN-PLANE H BE
	AROMATIC-IR	1,2,3-TRISUB:	CH	1170-1150	W	BEND	IN-PLANE H BE
	AROMATIC-IR	1,3,5-TRISUB:	CH	1180-1160	W	BEND	IN-PLANE H BE
	ESTERS-IR	R-CO-O-R	C-O	1210-1160	S	STR	
	ESTERS-IR	C=C-CO-O-R	C-O	1300-1160	S	STR	USUALLY MULT
	HALOGENS-IR	C-F	C-F	1400-1000	VS	STR	
	HALOGENS-IR	CF3	C-F	1350-1120	VS	STR	
	HALOGENS-IR	CF2	C-F	1280-1120	VS	STR	

(c)

Figure B.2: Substances appear in PFAE with 0.571% of water,(a) spectral analysis, (b) selected fragment structure and (c) library of chemical bond



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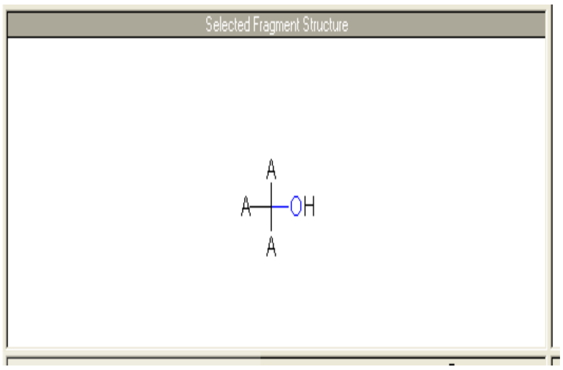

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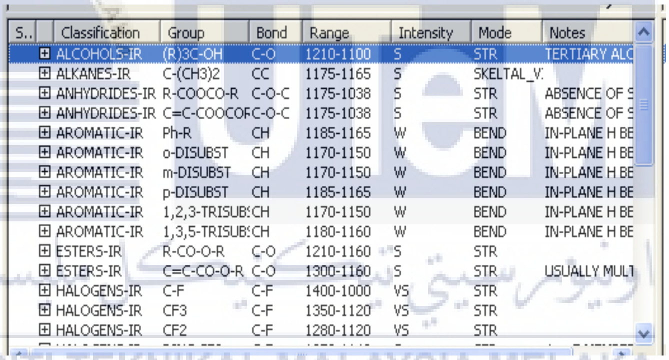
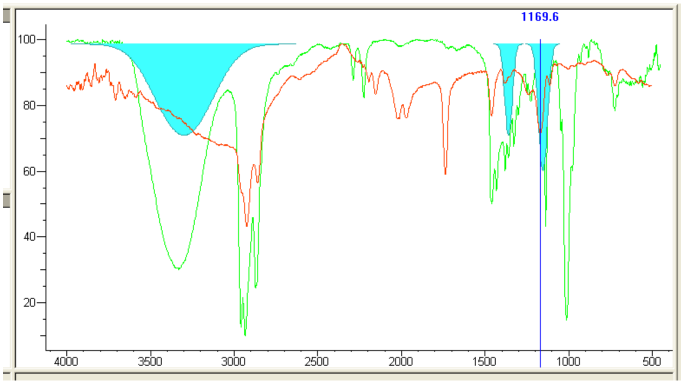


S..		Classification	Group	Bond	Range	Intensity	Mode	Notes
	⊞	ALCOHOLS-IR	(R)3C-OH	C-O	1210-1100	S	STR	TERTIARY ALC
	⊞	ALKANES-IR	C-(CH3)2	CC	1175-1165	S	SKELTAL_V:	
	⊞	ANHYDRIDES-IR	R-COOCO-R	C-O-C	1175-1038	S	STR	ABSENCE OF S
	⊞	ANHYDRIDES-IR	C=C-COOCOF	C-O-C	1175-1038	S	STR	ABSENCE OF S
	⊞	AROMATIC-IR	Ph-R	CH	1185-1165	W	BEND	IN-PLANE H BE
	⊞	AROMATIC-IR	o-DISUBST	CH	1170-1150	W	BEND	IN-PLANE H BE
	⊞	AROMATIC-IR	m-DISUBST	CH	1170-1150	W	BEND	IN-PLANE H BE
	⊞	AROMATIC-IR	p-DISUBST	CH	1185-1165	W	BEND	IN-PLANE H BE
	⊞	AROMATIC-IR	1,2,3-TRISUB:	CH	1170-1150	W	BEND	IN-PLANE H BE
	⊞	AROMATIC-IR	1,3,5-TRISUB:	CH	1180-1160	W	BEND	IN-PLANE H BE
	⊞	ESTERS-IR	R-CO-O-R	C-O	1210-1160	S	STR	
	⊞	ESTERS-IR	C=C-CO-O-R	C-O	1300-1160	S	STR	USUALLY MULT
	⊞	HALOGENS-IR	C-F	C-F	1400-1000	VS	STR	
	⊞	HALOGENS-IR	CF3	C-F	1350-1120	VS	STR	
	⊞	HALOGENS-IR	CF2	C-F	1280-1120	VS	STR	

(c)

Figure B.3: Substances appear in PFAE with 0.857% of water,(a) spectral analysis, (b) selected fragment structure and (c) library of chemical bond



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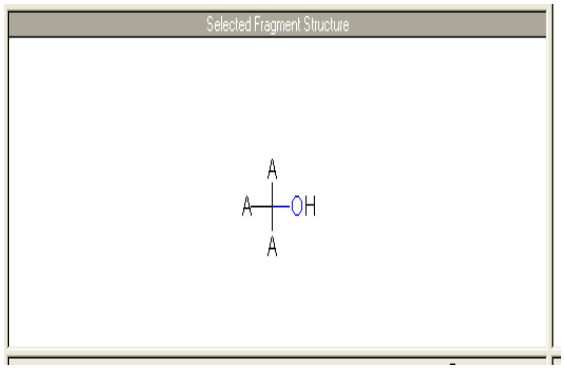

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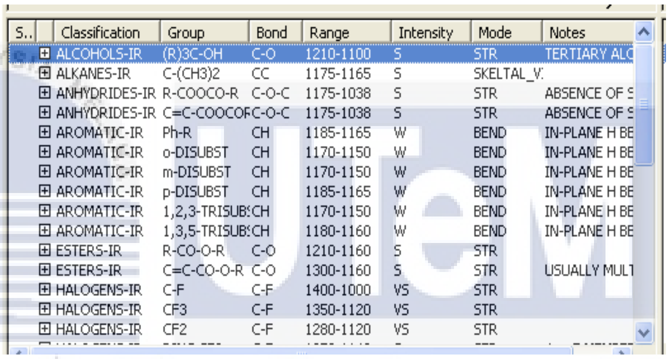
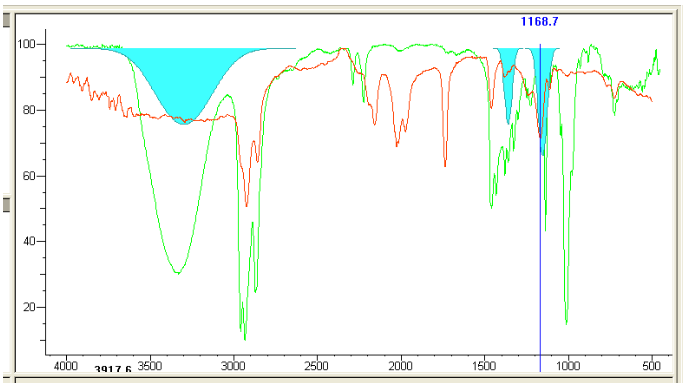


S..		Classification	Group	Bond	Range	Intensity	Mode	Notes
	⊞	ALCOHOLS-IR	(R)3C-OH	C-O	1210-1100	S	STR	TERTIARY ALC
	⊞	ALKANES-IR	C-(CH3)2	CC	1175-1165	S	SKELTAL_V.	
	⊞	ANHYDRIDES-IR	R-COOCO-R	C-O-C	1175-1038	S	STR	ABSENCE OF S
	⊞	ANHYDRIDES-IR	C=C-COOCOF	C-O-C	1175-1038	S	STR	ABSENCE OF S
	⊞	AROMATIC-IR	Ph-R	CH	1185-1165	W	BEND	IN-PLANE H BE
	⊞	AROMATIC-IR	o-DISUBST	CH	1170-1150	W	BEND	IN-PLANE H BE
	⊞	AROMATIC-IR	m-DISUBST	CH	1170-1150	W	BEND	IN-PLANE H BE
	⊞	AROMATIC-IR	p-DISUBST	CH	1185-1165	W	BEND	IN-PLANE H BE
	⊞	AROMATIC-IR	1,2,3-TRISUB:	CH	1170-1150	W	BEND	IN-PLANE H BE
	⊞	AROMATIC-IR	1,3,5-TRISUB:	CH	1180-1160	W	BEND	IN-PLANE H BE
	⊞	ESTERS-IR	R-CO-O-R	C-O	1210-1160	S	STR	
	⊞	ESTERS-IR	C=C-CO-O-R	C-O	1300-1160	S	STR	USUALLY MULT
	⊞	HALOGENS-IR	C-F	C-F	1400-1000	VS	STR	
	⊞	HALOGENS-IR	CF3	C-F	1350-1120	VS	STR	
	⊞	HALOGENS-IR	CF2	C-F	1280-1120	VS	STR	

(c)

Figure B.4: Substances appear in PFAE with 1.143% of water, (a) spectral analysis, (b) selected fragment structure and (c) library of chemical bond



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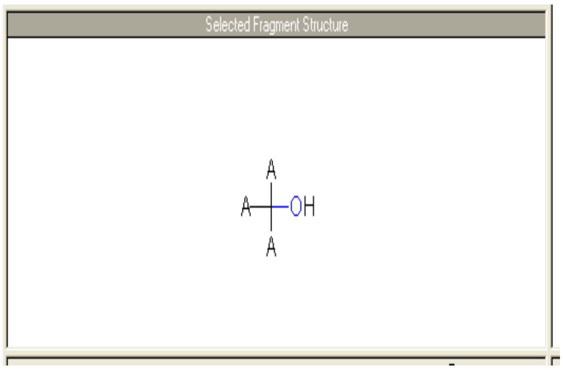

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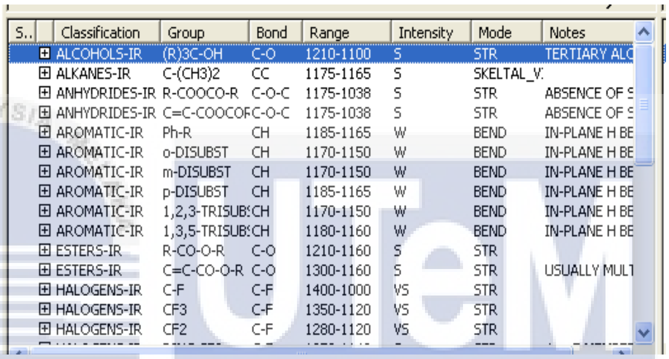

S..	Classification	Group	Bond	Range	Intensity	Mode	Notes
⊞	ALCOHOLS-IR	(R)3C-OH	C-O	1210-1100	S	STR	TERTIARY ALC
⊞	ALKANES-IR	C-(CH3)2	CC	1175-1165	S	SKELTAL_V.	
⊞	ANHYDRIDES-IR	R-COOCO-R	C-O-C	1175-1038	S	STR	ABSENCE OF S
⊞	ANHYDRIDES-IR	C=C-COOCOF	C-O-C	1175-1038	S	STR	ABSENCE OF S
⊞	AROMATIC-IR	Ph-R	CH	1185-1165	W	BEND	IN-PLANE H BE
⊞	AROMATIC-IR	o-DISUBST	CH	1170-1150	W	BEND	IN-PLANE H BE
⊞	AROMATIC-IR	m-DISUBST	CH	1170-1150	W	BEND	IN-PLANE H BE
⊞	AROMATIC-IR	p-DISUBST	CH	1185-1165	W	BEND	IN-PLANE H BE
⊞	AROMATIC-IR	1,2,3-TRISUB	CH	1170-1150	W	BEND	IN-PLANE H BE
⊞	AROMATIC-IR	1,3,5-TRISUB	CH	1180-1160	W	BEND	IN-PLANE H BE
⊞	ESTERS-IR	R-CO-O-R	C-O	1210-1160	S	STR	
⊞	ESTERS-IR	C=C-CO-O-R	C-O	1300-1160	S	STR	USUALLY MULT
⊞	HALOGENS-IR	C-F	C-F	1400-1000	VS	STR	
⊞	HALOGENS-IR	CF3	C-F	1350-1120	VS	STR	
⊞	HALOGENS-IR	CF2	C-F	1280-1120	VS	STR	

(c)

Figure B.5: Substances appear in PFAE with 1.429% of water, (a) spectral analysis, (b) selected fragment structure and (c) library of chemical bond