Reclamation of Old Transformer Oil Using kaolin clay

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ABSTRACT:

Kaolin clay used in this investigation was collected from kalabsha quarry in Aswan City South Egypt. The analysis of kaolin revealed that it is enriched withaluminium and silicon oxides as a major constituents and other trace element such as Fe and Ti. The using of kaolin clay as sorbent material for the removal of acidity, water content and some impurities from aged transformer oil by adsorption methodology was investigated using lab-scale refining unit. Kaolin was found to improve the electrical and physical properties of aged transformer oils. The changes in acidity, breakdown voltage, viscosity, specific gravity, water content were discussed briefly. Nevertheless some of undesirable gases in aged oil (more than ten years in service) were removed by using the lab-scale refining unit containing kaolin clay.
Keywords: - Transformer oils, kaolin, Refining unit.

1. INTRODUCTION:

Kaolin is a natural material has both rock and clay mineral term include quartz, smectites, feldspars and micas. Kaolin is widely utilized in the paper, paint, rubber, ceramic and plastic industries. Other applications in wine and vegetable clarifiers, oil absorbers, iron smelting [1-3].

Transformer mineral oil is one of the expensive extracts of the crude oil, produced by its refinement. Refining is the collective term for the processes involved in changing the crude oil into fragments with the required properties for particular applications. Because of the importance of the power transformers in electrical network, permanent taking care of the oil quality is indispensable. Insulating oil in service is subjected to heat, oxygen and electrical discharge, which may lead to its degradation .The main step in the regeneration of transformer oil is carried out using the adsorption process, which consists of removal of theacidcomponents, water and oxidation products with an adsorbent material.

Currently, activated bauxite and bentonite are used as low cost adsorbents for the recovery of aged oil in order to, maintain its properties to be to some extent like the new oil [4,5]. One of the problems of the regeneration process with bauxite is the great volume of waste that is discarded in landfill sites [6]. It is thusnecessary to examine the effectiveness of other raw materials, especially from renewable sources, that possess adsorbent properties for removing impurities in the treatment of insulating oil without any impacts on the environment. Oils, which are essentially electrical insulators,are used in electrical power transformers, mainly totransfer the heat and to increase the dielectricstrength of the insulating paper [7,8]. However,ageing, dust and metal particles, as well as humidity,deteriorate the isolating and cooling properties of thetransformer oil, which increase the risk on equipmentand operators. Degradation of transformer insulation,which in part defines the life span of a transformer, ismonitored by sampling the transformer oil [9,10].

Therefore, oil test should be scheduled regularly inorder to determine its breakdown voltage. This testhelps to increase the lifetime of the transformers andtherefore, new investment to replace thesetransformers could be delayed. The transformer oiltest is mandatory in some countries. Thermal,electrical, physical and chemical characteristics ofthe transformer oil are typically tested.

In order to increase the equipment lifetime, oilsare usually replaced with fresh ones at regular basis,which is not a cost effective solution. Bothenvironmental and conomical reasons preventdiscarding the spent oils, after use. The used oilscontain a large proportion of valuable base oil thatmay be reused, if undesirable pollutants are removed.

This is to say that transformer oil can be regeneratedand its original specifications can be restored.The regeneration of the transformer oil is a greentechnology and could be done in continuousoperation and is decomposed into different steps:

- Heat and filtration
- Adsorption process
- Fine filtration
- Degasification and dehydration

If oil is regenerated properly, its main propertiescan be highly improved. Among these properties arethe density, viscosity, interfacial tension, breakdownvoltage, and neutralization value.The main step in the regeneration of transformeroil is carried out using the adsorption process, whichconsists of the removal of the acid components,water and oxidation products with an adsorbent.

Currently, activated bauxite is used as an adsorbentfor the recovery of aged oil in order to regenerate theoil, maintaining the properties of new oil with lowcost [11]. One of the problems of the regenerationprocess with bauxite is the great volume of wastethat is discarded in landfill sites [12].

Traditionally, mineral oil, synthetic esters and silicon oils have been used in transformers. More recently, the environmentally friendly sunflower oil hasbeen usedas transformer oil for special purposes [13-16]. The life time assessment and evaluation of the condition of a transformer is of high importance for the users and manufacturers. The end of life of the transformer is defined as the decrease in the tensile strength of the isolating paperto approx 50% of the starting value [17-21].

In this investigation, we wish to report on constructing and using a lab-scale refining unit containing kaolin as sorbent for treatment of aged transformer oil (more than ten years in service). The variations of acidity, breakdown voltage, viscosity, specific gravity, water content and some undesirable gases of the treated oil are measured.

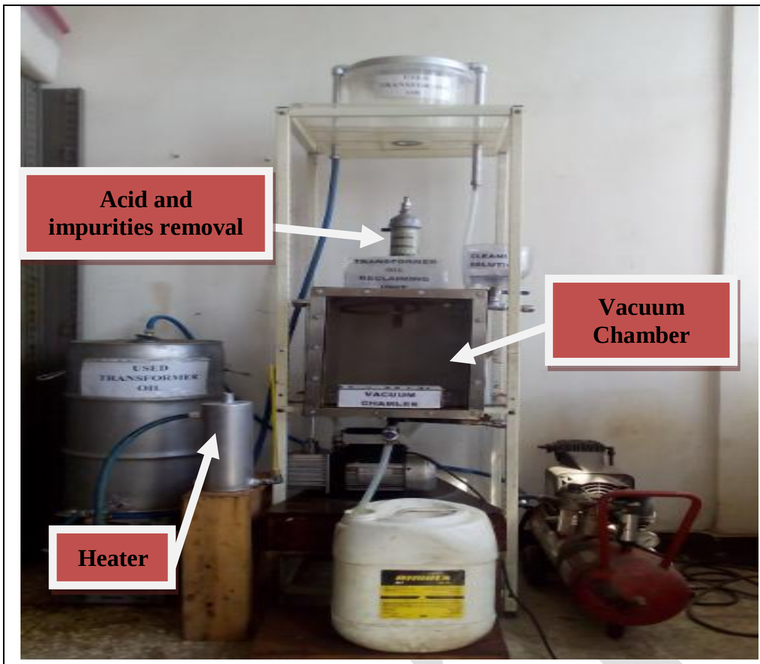
2. EXPERIMENTAL:

2.1- Refining unit:

The refining unit consists of three components;

1- Vacuum chamber and pump.
2- Acidity and impurities removal cartridge.
3- Fine filter.

All essential parts of the unit (vacuum pump, transfer pump, valves, fine and coarse filters and heaters) were handmade assembled as shown in Figure (1):



Figur(1): Typical photograph of the constructed refining unit.

The schematic diagram of refining unit is shown in Figure (2) as follow:

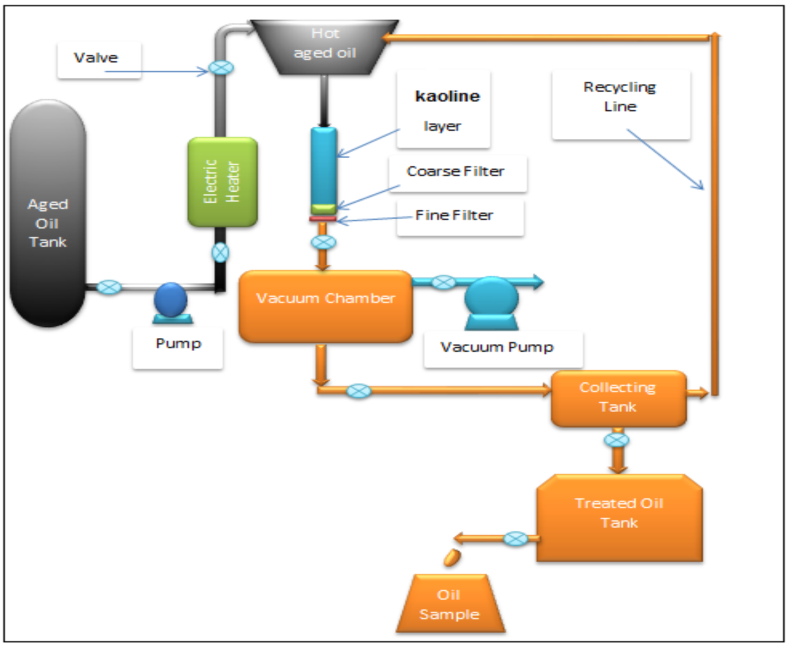


Figure (2): The schematic diagram of refining unit

2.2 Materials:

2.2.1 Aged Transformer Oil:

Aged Transformer oil was collected from high voltage transformer after more than ten years operation with the properties listed in Table (1).

Table (1) :physico-chemical characteristics of the used aged oil.

Exp.	Standard Method	Results	Limits[1]		
			≤ 72.5 K.V.	> 72.5 ≤ 170 K.V.	> 170 K.V.
Specific Gravity at 15ºC	ASTM D1298	0.866	≤ 0.91 [2]		
Color	ASTM D1500	> 8	< 2	Clear not turbid	
Water Contentppm at	BS 148 - IEC	48	< 25	< 15	< 10
Impurities	ASTM D1796	+Ve	NIL		
Total Acidity (mg KOH/g)	ASTM D974 -	0.31	< 0.3	< 0.2	< 0.15
Break down Voltage Kv	IEC 60156	15	> 30	> 40	> 50
Kinematics Viscosity (CST)	ASTM D445	10.45	≤ 12 [2]		
Flash Point openºC	ASTM D92	140	Maximum decrease 10%		
Copper Corrosion	ASTM D130	----	NIL		

(1) Acceptable limits for mineral insulating oils in-service: According to IEC 60422:2005.

(2) Acceptable limits for mineral insulating oils: According to ASTM D3487.

2.3. Kaolin clay:

Kaolin used in this investigation was collected from kalabsha quarry in Aswan City South Egypt, and mainly consists of Al, Si, Fe, Ti and other trace elements. The typical and grinded forms of kaolinare shown in Fig. (3).

Figure (3): Typical and grinded forms of kaolin.

2.4. Treatment process:

The treatment process was performed using one liter of the aged transformer oil with different doses of kaolin at different temperatures and time in the lab scale refining unit.

The amounts of kaolin used were put in acid and impurities removal cartridge. The aged oil samples were heated and passed through the cartridge for different time and temperature in stages of half an hour each. The oil was then introduced to vacuum chamber to remove undesirable gases after treatment. The treated oil was finally collected in the treated oil tank. Samples of the treated oil were then withdrawn and analyzed applying the standard methods of test.

3. Results and Discussion:

Experimental work revealed that kaolin has approximately the same constituents of bentonite and bauxite that are the most substances used in reclaiming the transformer oils [22]. Therefore the kaolin was chosen to use as reclaiming substance.

The electrical, chemical and physical properties of insulating oil can be considerably improved by its filtering, degassingand dehydration.

During its operation, transformer-insulating oil is absorbing moisture over itsfree surface in the expansion vessel and it becomes polluted by absorbingdirty particles, fibers, soot, undesired gases and aging products. Therefore, oil upgrading hasto eliminate these contaminants.

The abovementioned contaminants can be removed by filtering, degassing and dehydration of insulating oilto the extent depending on moisture content and reducing the acidity by an acid adsorbent agent.

3.1 Structure and chemical composition of kaolin:

3.1.1- X-ray analysis:

Kaolin collected fromkalabsha quarry in Aswan city South Egypt was analysed using; Energy Dispersive X-ray spectrometer (EDX) ISIS Link Instrument P/C. Oxford Co,which is attached to a SEM. Figure (4) shows the spectrum of kaolin sample.It is evident that kaolin sample was enriched by some inorganic elements whose amounts are represented by the peaks in Figure (4).

There are traces of (Fe) and small amount of titanium ions. Thepresence of (Al) and (Si) ions as indicated in Figure (4) confirms that the sample is enriched by these two elements .

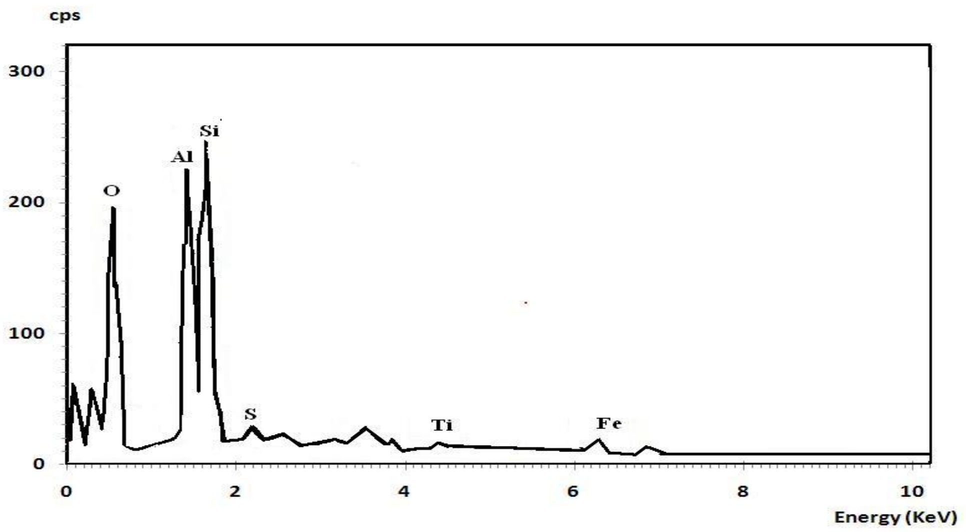


Figure (4): X-ray chart of kaolin sample

3.1.2- Thermogravimetric analysis (TGA):

Thermogravimetric analysis of kaolin sample was performed using ThermogravimetricdeterminatorLeco: Mac-500.ST.Joseph, Michigan-USA. This apparatus provides a continuousmeasurement of sample weight at a range oftemperatures between ambient and 900 ^oC. The samples were heated in an alumina cell to 900 ^oC at heating rate of 10^{o}C/min with nitrogen as the circulating gas.

The diagram obtained (Fig. 5) shows four characteristic stages of decomposition. The first stage starts at 55 °C and ends at 90°C with weight loss of 5.3 %. This could be recognized as due to the moisture content of kaolin sample. The second stage which related to the main decomposition of the sample occurs in one step of decomposition starts at 90°C and ends at 220°C with weight loss of 11% representing the hydrated hydroxide [$Al(OH)_3.xH_2O$] and others. The third stage of decomposition is related to the carbonization process which occurs up to 600 °C with a weight loss of 32%.The fourth stage is related to calcination stage which started at 600 ^oC and ended at 900^{o}C with weight loss of 37%.

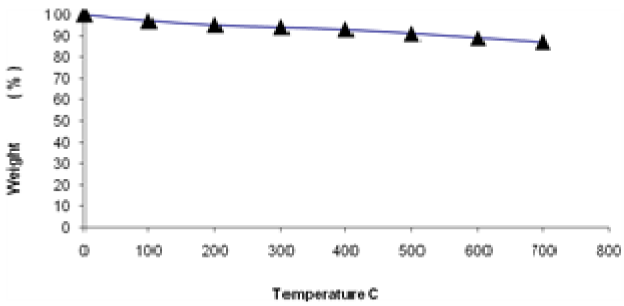


Figure (5) : TGA of kaolin.

3.2. Effect of kaolin treatment on acidity number of oil:

The degradation of oil produces some organic acids such as carboxylic acids that will either dissolve in the oil or volatilize into the headspace of transformer. Dissolved acids may cause damage to the paper and copper windings, while volatile acids corrode the top of the unit. As a result, all of the necessary conditions exist properly in a power transformer for the degradation of the oil.

The effect of kaolin on the removal of acidity is represented by Figures (6-9). These Figures indicate that the acidity decreases by increasing the amount of adsorbent material (kaolin) at different temperatures and stages of refining (stage time is ½ hour). The maximum decrease of acidity was at kaolin dose of 20% for 4 stages, it reached 0.02mg KOH /g of oil.

According to ASTM No. D 3487, the total acidity is 0.31mgKOH/g of oil maximum.aged transformer oil either before purification or before treatment has a total acidity of

0.31mgKoH/g of oil, which mean that it is over the ASTM limits but total acidity decreased to treated oil 0.02 mgKOH/g [23] .

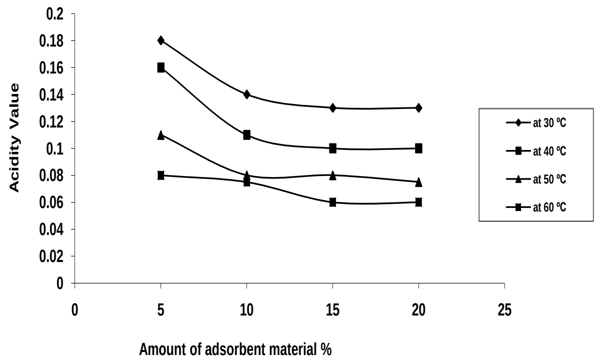


Figure (6) : Variation of total acid value with kaolin dose (1 stage)

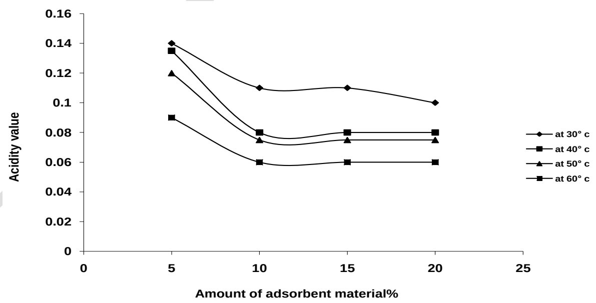


Figure (7) : Variation of total acid value with kaolin dose (2 stages)

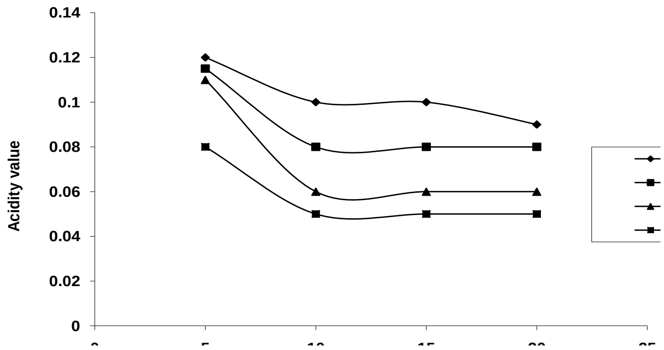


Figure (8) : Variation of total acid value with kaolin dose (3 stages)

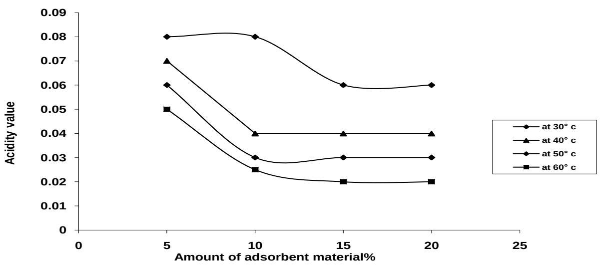


Figure (9) : Variation of total acid value with kaolin dose (4 stages)

3.2. Colour:

The colour of a sample is determined by direct comparison with a set of colour standards using "Colorimeter as colorimeter degree according to ASTMD1500/03".The colour of an oil sample is used mainly as a guide to thedegree of refinement of the oil when it is new. If the sample isfrom a transformer that has been in service then the colour canbe followed over a period of time to indicate the possible condition of the oil. It should be pointed out that the colour ofthe oil by itself should never be used to indicate the dielectricquality of the oil [5]. However it can be used to determinewhether more definitive tests should be done to determinespecific characteristics of the sample that are more related tothe performance of the oil .The clarity of the sample can also give possible suggestionsfor further tests. Cloudiness of the sample can indicate thepresence of water, which in turn will decrease the dielectricstrength of the sample.

Figures (10-13) represent the variation of oil colour with amount of adsorbent material (kaolin) at different temperatures through the four stages of treatment. There is a significant improvement in the colour of the treated oil resulting from increasing the amount of adsorbent material (kaolin), at the working temperatures. The colour of oil was changed from more than 8 degree of aged oil to 1 degree after 4 stages as can be seen from the Figures.

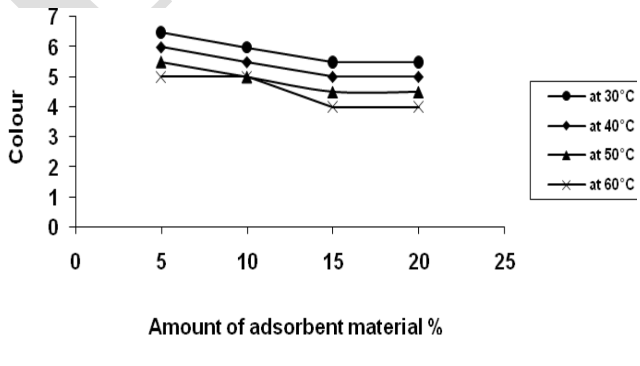


Figure (10) :Variation of colour with kaolin dose (1 stage)

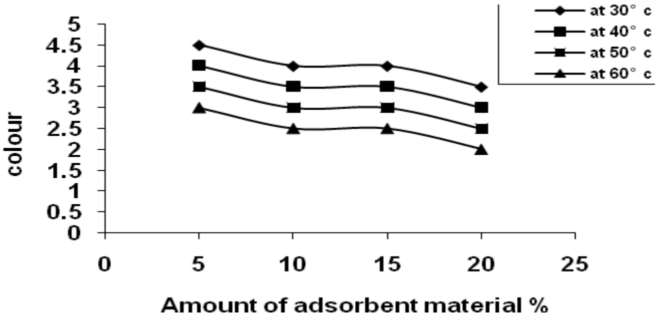


Figure (11) :Variation of colour with kaolin dose (2 stages)

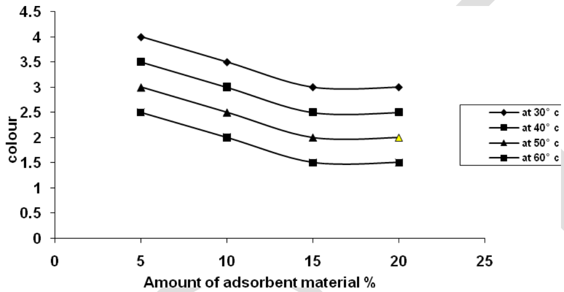


Figure (12) :Variation of colour with kaolin dose (3 stages)

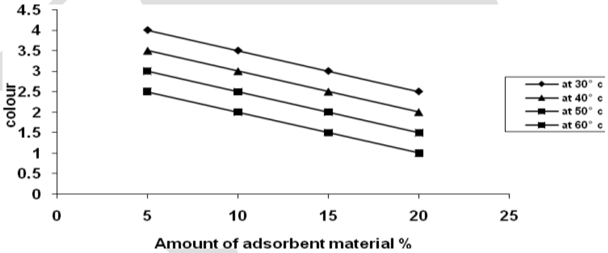
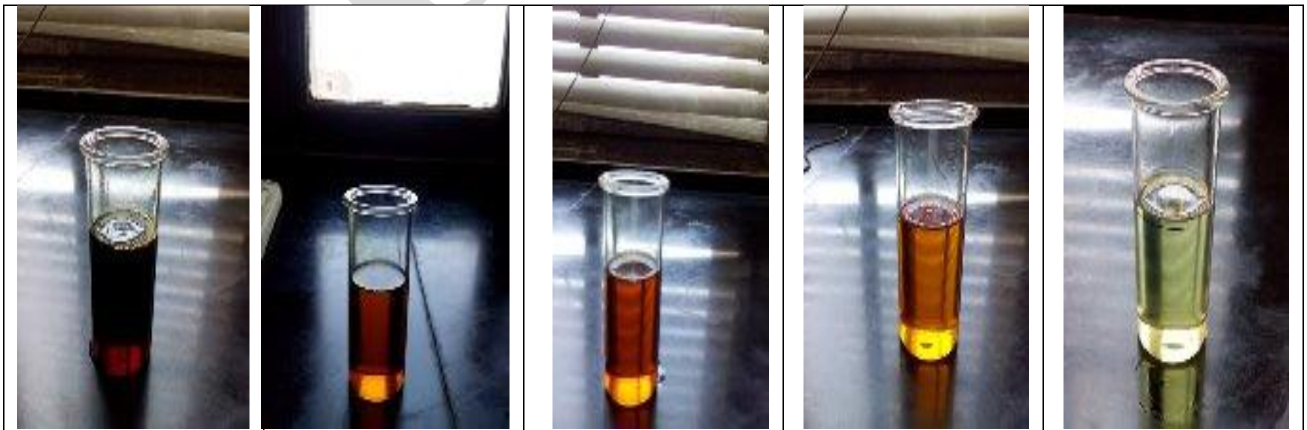


Figure (13): Variation of colour with kaolin dose (4 stages)

Also figure (14) show thecolour oil sample photograph of untreated and treated oil at different reclaiming stages



Untreated oil	Treated 1 stage	Treated 2 stage	Treated 3 stage	Treated 4 stage

Figure (14)Colour of treated and untreated transformer oil for different sages

3.3. BREAKDOWN VOLTAGE:

This characteristic is very significant and is usually investigated first and its value should be held at the highest possible level. The lowering of this value mainly indicates the growth of the water content in oil[24] .

The breakdown voltage of aged and reclaimed oil was measured by petrotestMegger OTS100AF according to IEC60156. Figures (15-18) show the variation of breakdown voltage of oil by the increasing the amount of adsorbent material. The value was changed from 15 Kvfor aged oil to 74Kvfor reclaimed oil by such material at temperature 60 ^{0}C after the four stages treatment.

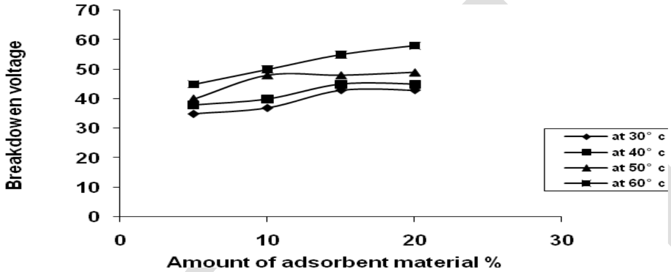


Figure (15) : Variation of breakdown voltage with kaolin dose (1 stage)

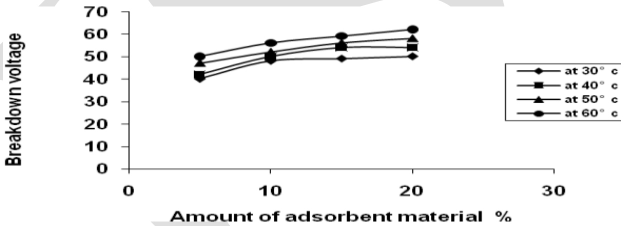


Figure (16) : Variation of breakdown voltage with kaolin dose (2 stages)

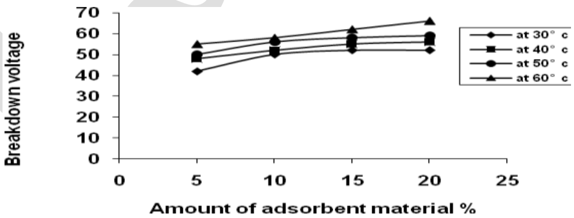


Figure (17) : Variation of breakdown voltage with kaolin dose (3 stages)

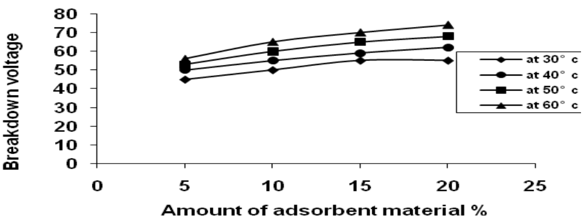


Figure (18): Variation of breakdown voltage with kaolin dose (4 stages)

3.4. Viscosity:

The viscosity of dielectric coolants within the range of normal operating temperatures is important because it can impact both the cooling and performance of some internal components. The oil closed to the windings in the field transformer flows up at higher temperature while the oil at lower temperature flows to bottom from the wall. The heat is scattered from windings in this way. So, transformer oil with lower viscosity has better cooling effect. The increase of viscosity, which has negative effect on load and efficiency, is adverse to the safe operation of the unit. Therefore, it is essential to control the viscosity of transformer oil in service. The viscosity of aged and treated oil was measured by "viscometer Koehler"K2337.Table (2) shows the variation of viscosity of oil during the four stages of treatment at 60 ^{0}C for 20% adsorbent material (kaolin).

Table (2) : Variation of oil viscosity during the four stages of treatment.

No. of Stage	1 Stage	2 Stages	3 Stages	4 Stages
Viscosity(CST)	11.1	10.9	10.8	10.8

3.5. Moisture:

Moisture is generated at temperatures over 80°C from deterioration of the oil and still generates above 170°C. Hydrogen is generated from degradation of the oil at temperatures above 120°C and still generates at temperatures over 140°C. Carbon monoxide and dioxide are generated significantly in the aged oil at temperatures greater than 110°C [5-7]. Figures (19-22) show the variation of water content of oil by the increasing the amount of adsorbent material. The value was changed from 48ppm for aged oil to 9 for reclaimed oil by such material at temperature of 60 ^{0}C during the four stages treatment.

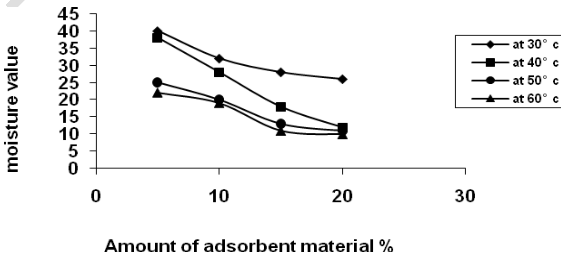


Figure (19) : Variation of moisture with kaolin dose (1 stage)

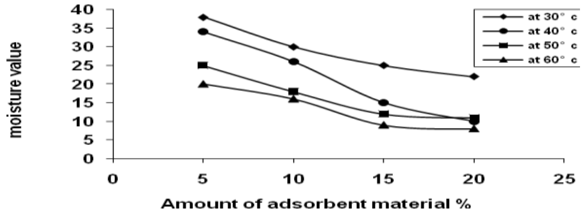


Figure (20) : Variation of moisture with kaolin dose (2 stages)

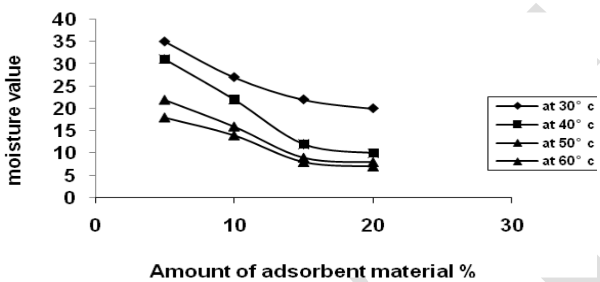


Figure (21) : Variation of moisture with kaolin dose (3 stages)

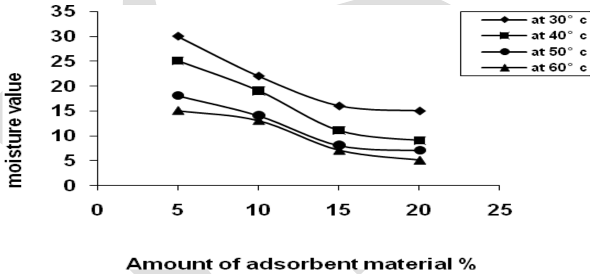


Figure (22) : Variation of moisture with kaolin dose (4 stages)

3-7-Dissolved Gas Analysis (DGA):ASTM D3612

The dissolved gases in the oil play an important role in the transformer operation because of the probability of explosion. There is a limit for every gas in the transformer oil according to its load.

The gases in the aged and treated oil were analyzed by Gas Chromatograph "DANI Auto sampler GC1000" and the results are listed in Table (3). It is obvious that the amounts of gases in the reclaimed oil are within the standard limits of operation.

Table (3): Analysis of gas in the aged and treated oil.

Gas	ppm					Alert limits
	Aged	1 Stage	2 stages	3 Stages	4 Stages	
Hydrogen (H_2)	23	22	23	23	23	100 – 700
Oxygen (O_2)	11971	14975	21241	23671	26374	-
Nitrogen (N_2)	75167	7334	70360	6998	68219	-
Carbon monoxide (CO)	318	235	122	0.0	0.0	350 – 570
Carbon dioxide (CO_2)	1829	1334	1267	1198	1185	2500 – 4000
Methane (CH_4)	754	11	2	0.0	0.0	120 – 400
Ethane (C_2H_6)	4223	245	94	0.0	0.0	65 – 100
Ethylene (C_2H_4)	10827	611	136	0.0	0.0	50 – 100
Acetylene (C_2H_2)	178	78	0.0	0.0	0.0	1 – 9
Total Dissolved Combustible Gas (TDCG) =	16324	967	377	23	23	720 – 1920

4- Elemental analysis of aged and reclaimed oil:

The elemental analysis of (C, H, N and S) were determined by LecoTruspect (CHN) Analyzer, Leco Corporation 3000 LAKE View AVE.ST. Joseph,MI-USA. The results are listed in Table (4).

Table (4)The elemental analysis of aged and reclaimed oil

Sample / Element %	Aged Oil	1 Stage	2 Stages	3 Stages	4 Stages
C	85.65	85.11	85.10	84.90	84.91
H	13.03	13.11	13.41	13.7	13.9
N	0.22	0.21	0.20	0.20	0.19
S	0.32	0.31	0.29	0.24	0.24

The data represented by Table (4) reveal that the carbon element in oil slightly reduced by the reclamation stages. The reduction in carbon element by the treatment may be attributed to the elimination of carbon impurities produced.The results indicate also that there is a significant reduction in sulphur content at the third and fourth stages of treatment.

5- Environmental Impacts:

Used transformer oil is considered as a hazardouswaste environmentally, because of its chemical reaction, toxicity, flammability, or ability of explosion.

Aged transformer oil contains some toxic chemicals resulting from additives which as used to improve oil properties such asheavy metals, organic materials (e.g. phenol). Specialsynthetic transformer oils, are very toxic, carcinogenic, soluble in water and penetrate in the soil andunderground water.

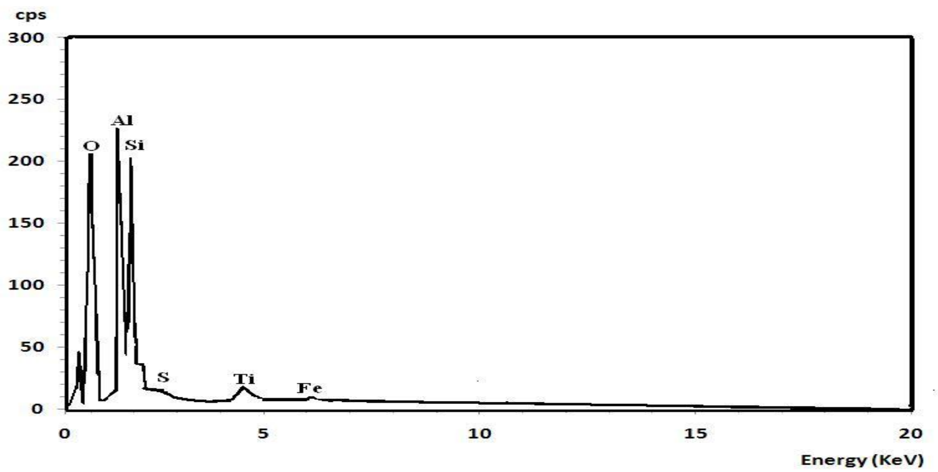
The reusing of transformer oil by reclaimation using kaolin can solve the above mentioned problems of aged oil disposal. Nevertheless, kaolin after reclaimation can be reused after ignition at 750 ^{0}C at which temperature kaolin returns back to its constituents. Figure (23) shows the typical image of kaolin after using and ignition.

A B

Figure (23): Typical image of kaolin after using (A) and ignition (B)

Also Figure (24) shows the X-ray spectrum of used kaolin after ignition. The spectrum shows the same peaks as kaolin before using. As can be seen from the spectrum of kaolin after using and ignition it contain Al, Fe and Ti elements which are the most elements used in the reclaiming of oil.

This indicates that the used kaolin can be recycled and used for further treatment processes.



Figure(24) : X-ray spectrum of kaolin after using and ignition.

6. CONCLUSION:

High improvement of breakdown voltage occurs after using kaolin reclaimed transformer oil and changed from 15 to 72 kV. Also some improvements have been achieved such as water content changed from 48 to 9 ppm and total acidity changed from 0.37 to 0.01mg/g of oil.

Economically the actual cost for treated oil is negligible with respect to oil price.

kaolin is available with no costs .

Environmentally, after kaolinreclamation process for the used transformer oil, the kaolin can be recycled by ignition and used in further treatment processes.

REFERANCES :

[1]-Ekosse G. (2000) The Makoro kaolin deposit, southeastern Botswana: its genesis and possible industrial applications. Applied Clay Science 16, (5-6) 301–320

[2]- Ekosse G. (2001) Provenance of the Kgwakgwe kaolin deposit in south eastern Botswana and its possible utilization. Applied Clay Science 20 (3) 137–152

[3]-Murray H. H. (1986) Clays. In: Ullman's encyclopedia of industrial chemistry. 5th Edition. 109-136 pp

[4] A. A. Al-Zahrani and M.A. Daous (2000) 'Recycling of spent bleaching clay', Process Safety and Environment Protection (78-B3), pp. 224–228.

[5] L. Nasrat, M. Abdelwahab and G. Ismail ,"Improvement of Used Transformer Oils with Activated Bentonite", Journal of Engineering, Vol. 3, pp 588-593 ,2011.

[6] A.C. Laurentino, A.L. Parize, M.C.M. Laranjeira, A.R. Martins, N.M. Mayer and V.T. De Fa´vere (2007)'Regeneration of insulating Mineral Oil by Carbonated Amorphous Calcium Phosphate-Chitosan Adsorbent',Process Safety and Environment Protection (85-B4), pp.327–331.

[7] A. F. Fitzgerald, C. Kingsley and S. Umans, "Electric Machinery", 6th edition, McGraw Hills.

[8]G.L. Goedde and A.P. Yerges (1998) 'Dielectric fluid for use in power distribution equipment', US patent 5,766,517. 1998.

[9]L. Nasrat, M. Abdelwahab and G. Ismail,"Improvement of Used Transformer Oils with ActivatedBentonite", Journal of Engineering, Vol. 3, pp 588-593,2011.

[10] R. Ferguson, A. Lobeiras and J. Sabau, "Suspended Particles in the Liquid Insulation of Power Transformers"IEEE Electrical Insulation Magazine, Vol. 18, No. 4, pp.17-23, August 2002.

[11] A.A. Al-Zahrani and M.A. Daous (2000) 'Recycling of spent bleaching clay', Process Safety and Environment Protection (78-B3), pp. 224–228.

[12] A.C. Laurentino, A.L. Parize, M.C.M. Laranjeira, A.R.Martins, N.M. Mayer and V.T. De Fa´vere (2007) 'Regeneration of insulating Mineral Oil by CarbonatedAmorphous Calcium Phosphate-Chitosan Adsorbent',Process Safety and Environment Protection (85-B4), pp.327–331.

[13]K. Longva, "Natural Ester Distribution Transformers Improved Reliability and Environmental Safety," Nordic Insulation Symposium, Trondheim, Norway, 13-15 June 2005.

[14] U. Gafvert, G. Frimpong and J. Fuhr, "Modeling of Di-electric Measurements on Power Transformers," Cigre, Paris, 1998.

[15] Z. T. Yao and T. K. Saha, "Separation of Aging and Moisture Impacts on Transformer Insulation Degradation by Polarization Measurements," Cigre, Paris, 2002.

[16] T. V. Oommen, "Vegetable Oils for Liquid Filled Transformers," IEEE Electrical Insulation Magazine, Vol. 18, No. 1, January-February 2002, pp. 6-11. doi:10.1109/57.981322

[17] R. Ferguson, A. Lobeiras and J. Sabau, "Suspended Par-ticles in the Liquid Insulation of Power Transformers," IEEE Electrical Insulation Magazine, Vol. 18, No. 4, Ju-ly-August 2002, pp. 17-23. doi:10.1109/MEI.2002.1019902.

[18] R. Blue, D. Uttamchandani and O. Farish, "Infrared De-tection of Transformer Insulation Degradation Due to Accelerated Thermal Aging," IEEE Transactions on Di-electrics and Electrical Insulation, Vol. 5, No. 2, April 1998, pp. 165-168. doi:10.1109/94.671924

[19] I. L. Hosier, A. S. Vaughan, S. J. Sutton and F. J. Davis, "Chemical, Physical and Electrical Properties of Aged Dodecylbenzene: Thermal Aging of Mixed Isomers in Air," IEEE Transactions on Dielectrics and Electrical Insulation, Vol. 14, No. 5, 2007, pp. 1113-1124. doi:10.1109/TDEI.2007.4339470

[20] I. L. Hosier, A. S. Vaughan and S. J. Sutton, "Aging Be-havior of Dodecylbenzene/Mineral Oil Blends," Annual Report - Conference on Electrical Insulation and Dielec-tric Phenomena (CEIDP 2007), Vancouver, 14-17 Octo-ber 2007, pp. 69-72.

[21] P. Aksamit, D. Zmarzly, T. Boczar and M. Szmechta, "Aging Properties of Fullerene Doped Transformer Oils," Conference Record of the 2010 IEEE International Sym-posium on Electrical Insulation (ISEI), San Diego, 6-9 June 2010.

[22]P. M. Balma, R. C. Degeneff, H.R.Moore and L.B .Wagenaar, ''The effects of long term operation and system conditions on the dielectric capability and insulation coordination of large power transformers'', IEEE Trans onPower Delivery, Vol.14 No.3, July 1999.

[23]L. Nasrat, M. AbdelwahabandG. Ismail ''Improvement of used transformer oils with activated bentonite'', Engineering, Vol.3, 2011, pp. 588-593 .

[24]I. Macuzic, B. Jeremic ''modern approach to problems of transformer oil purification '', Tribology in industry, Vol.24 No. 3&4, 2002 .