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REGENERATION OF USED TURBINE OILS AND RECOVERY OF THEIR QUALITY PARAMETERS USING ACTIVATED BENTONITE

Bekhruz T. Salomatov[1], Nodir Sh. Panoev[1*], Jasur A. Safarov[1], Dildora M. Tilloeva[1,2], Saidakbar A. Turaxujaev[3], Muzafar S. Sharipov[4], Mumin R. Ibrokhimov[5]

[1]*Bukhara State Technical University, Q. Murtazaev street. 15, 200100 Bukhara, Uzbekistan*
[2]*Asia International University, Gijduvon Street. 74, 200100 Bukhara, Uzbekistan*
[3]*Chilon Lubricants LLC, Tashkent, Bektemir district st. Oltintopgan 14, 100033 Tashkent, Uzbekistan*
[4]*Bukhara State University, M. Ikbol str. 11, 200117 Bukhara, Uzbekistan*
[5]*Management office of Bukhara Oil Refinery LLC. Farg'ona yo'li 7B, 100011. Tashkent, Uzbekistan.*

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Abstract

This article covers the problem of regeneration of turbine oils used in the power engineering. The main attention is given to the process of purification and recovery of used Shell Turbo S4 GX46 mineral oil with usage of activated Navbahor bentonite as an adsorbent. The research analyzes the factors of oil degradation during operation (oxidation, contamination, mixing with water), and also studies the adsorption properties of bentonite using SEM (scanning electron microscopy), EDS (energy dispersive X-ray spectroscopy) and physicochemical analysis. The results show that due to the high content of SiO_2 (58.68 %) and Al_2O_3 (15.42 %), bentonite effectively removes contaminants, and the purified oil restores its kinematic viscosity, acid number and thermal stability. Considering the forecasts of global oil consumption, the use of bentonite is recommended as an economically and environmentally effective regeneration method. Gas chromatography-mass spectrometry analysis showed an increase in components such as tetratriacontane (26.53 %) and hexatriacontane (70.56 %) in the purified oil, confirming its improved stability and anti-corrosion properties. From an economic perspective, this method is efficient and gains importance in light of global projections suggesting a 3–4 % growth in oil consumption.

Keywords: Turbine oils; bentonite adsorbent; regeneration; oxide composition; physicochemical properties; adsorption; energy; montmorillonite; oxidative stability.

РЕГЕНЕРАЦІЯ ВІДПРАЦЬОВАНИХ ТУРБІННИХ ОЛИВ ТА ВІДНОВЛЕННЯ ЇХ ЯКІСНИХ ПОКАЗНИКІВ ІЗ ВИКОРИСТАННЯМ АКТИВОВАНОГО БЕНТОНІТУ

Бехруз Т. Саломатов[1], Нодір Ш. Панойов[1], Жасур А. Сафаров[1], Дільдора М. Тіллоева[1,2], Саїдакбар А. Турахуджаєв[3], Музаффар С. Шаріпов[4], Мумін Р. Іброхімов[5]

[1]*Бухарський державний технічний університет, вул. К. Муртазаєва, 15, 200100, Бухара, Узбекистан*
[2]*Азійський міжнародний університет, вулиця Гіждуванська, 74, 200100, Бухара, Узбекистан*
[3]*ТОВ «Чілон Лубрикантс», м. Ташкент, Бектемірський район, вул. Олтінтопган 14, 100033 Ташкент, Узбекистан*
[4]*Бухарський державний університет, вул. М. Ікбола, 11, 200117 Бухара, Узбекистан*
[5]*Офіс управління ТОВ «Бухарський нафтопереробний завод». Фаргона Йолі 7Б, 100011. Ташкент, Узбекистан.*

Анотація

У статті розглядається проблема регенерації турбінних олив, що застосовуються в енергетиці. Основну увагу приділено процесу очищення та відновлення відпрацьованої мінеральної оливи Shell Turbo S4 GX46 із використанням активованого навбахорського бентоніту як адсорбенту. В дослідженні проаналізовано фактори деградації оливи під час експлуатації (окиснення, забруднення, змішування з водою), а також вивчено адсорбційні властивості бентоніту за допомогою СЕМ (сканувальної електронної мікроскопії), ЕДС (енергодисперсійної рентгенівської спектроскопії) та фізико-хімічного аналізу. Результати показують, що завдяки високому вмісту SiO_2 (58.68 %) і Al_2O_3 (15.42 %) бентоніт ефективно видаляє забруднення, а очищена олива відновлює свої показники кінематичної в'язкості, кислотного числа та термічної стабільності. З огляду на прогнози світового споживання нафти, використання бентоніту рекомендується як економічно та екологічно ефективний метод регенерації. Газохромато-мас-спектрометричний аналіз показав збільшення вмісту таких компонентів, як тетратріаконтан (26.53 %) та гексатріаконтан (70.56 %) в очищеній олові, що підтверджує її покращену стабільність та антикорозійні властивості. З економічної точки зору, цей метод є ефективним і набуває значення з огляду на глобальні прогнози щодо зростання споживання нафти на 3–4 %.

Ключові слова: турбінні оливи; бентонітовий адсорбент; регенерація; оксидний склад; фізико-хімічні властивості; адсорбція, енергетика; монтморилоніт; окислювальна стабільність.

*Corresponding author: e-mail: panoyev89@mail.ru
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Journal of Chemistry and Technologies, 2025, *33*(4), 1055-1067

Introduction

With the grow of the economy of the country, the need for oil also increases. In economically and industrially developing countries, the demand for energy resources, particularly petroleum-based products, is consistently increasing. This growth is directly associated with the expansion of industrial production, transportation infrastructure, power generation, and other critical sectors. The stable and efficient performance of power facilities, especially impeller turbines in thermal power plants, is largely determined by the operational reliability of their lubrication systems. Turbine oils, as an essential component of these systems, fulfill a wide range of complex functions: they not only minimize friction and wear between moving parts but also facilitate heat dissipation, provide corrosion protection, and retain contaminant particles in suspension. Consequently, turbine oils represent advanced multicomponent materials capable of operating under elevated thermal, pressure, and oxidative stresses [1].

Under current conditions, particularly at elevated temperatures and under continuous mechanical loads, turbine oils progressively undergo deterioration of their initial physicochemical characteristics. The principal mechanisms contributing to this degradation include thermal decomposition, oxidative transformations, emulsification with water, catalytic interactions with metallic particles, and microbiological contamination. These processes lead to substantial alterations in viscosity, density, acid number, oxidation stability, color, and other critical quality parameters of the lubricant. Such changes diminish the operational reliability of turbine systems, accelerate corrosion phenomena, and significantly increase the probability of emergency failures [2].

The sustainable development of the energy and industrial sectors, accompanied by the intensive growth of thermal power generation, has resulted in a steady rise in the demand for turbine oils. Globally, turbine oil consumption demonstrated an average annual increase of 3–4 % during the period 2019–2024, reaching approximately 1.2 million tons by 2024. Projections indicate that this figure may rise to about 1.5 million tons in the subsequent five-year period, 2025–2030 [3].

Under operating conditions, complex processes (oxidation, thermal decomposition, mechanical contamination, mixing with water, dilution) reduce the properties of oils with various compositions, which in turn requires the recovery of oil quality indicators using various methods. When cleaning oils and recovering their quality indicators, technological operations are used to remove wear products from their composition by physical and chemical methods [4].

The novelty of this work lies in its experimental demonstration of the efficiency achieved by activating local bentonite from the Navbahor deposit and applying it as an adsorbent in the process of regenerating Shell Turbo S4 GX46 turbine oil. While previous literature includes studies conducted with generic bentonites (both natural and activated), this study specifically highlights the oxide composition of Navbahor bentonite (SiO_2 ~58.7 %, Al_2O_3 ~15.4 %, Fe_2O_3 ~8.1 %) and its effect on Shell Turbo S4 GX46 oil, thereby.

Object and methods of research. The object of research was pure mineral oil Shell Turbo S4 GX46, used and purified turbine oil, and samples from Navbahor bentonite. Modern physicochemical analysis methods, as well as methods for analyzing oil and oil products in accordance with state (GOST) and world standards, were used to conduct the research [5].

The main physicochemical properties of pure Shell Turbo S4 GX46 turbine oil are given in Table 1 [6].

Table 1

Main physicochemical properties of Shell Turbo S4 GX46 pure mineral oil

No.	Indicator	Method	Shell Turbo S4 GX 46
1.	Viscosity grade, ISO	ISO 3448	46
2.	Kinematic viscosity, 40 °C , mm^2/s	ASTM D445	43.5
3.	Kinematic viscosity, 100 °C , mm^2/s	ASTM D445	7.50
4.	Viscosity index	ASTM D2270	139
5.	Density, 15 °C , g/sm^3	IP 365	0.829
6.	Flash point	ASTM D92	245
7.	Pour point	ASTM D97	-21
8.	Acid number, mg KOH/g	ASTM D974	0.15
9.	Air separation, 50 °C, min	ASTM D3427	1
10.	Corrosion on copper plate, $3h/100$ °C	ASTM D130	1b
11.	Anticorrosion properties	ASTM D665 A & B	No corrosion

Journal of Chemistry and Technologies, 2025, *33*(4), 1055-1067

Continuation of Table 1

12.	Water separation, minutes to 3 ml of emulsion, minutes	ASTM D1401	15
13.	Demulsification (steam), seconds	IP 19	95
14.	Foaming, tendency stability, ml/ml	ASTM D892	
15.	Load-bearing capacity on FZG stand - withstands loading stages	DIN 51354	11
16.	Oxidative stability		
17.	RPVOT, minutes	ASTM D2272	1400
18.	Changed RPVOT, % RPVOT		95%
19.	TOST by service life, hours	ASTM D943	10 000+
20.	TOST 1000 h sludge, mg/kg	ASTM D4310	25
21.	TOST (dry), 120 °C	ASTM D7873	
22.	Sludge content 50% RPVOT, mg/kg		28.2
23.	Hours of 50% RPVOT, minutes		1433

The main elements and their oxide forms in the bentonite SEM sample are analyzed. Based on the results of the elemental analysis, the oxide masses are calculated and the presence of a layered silicate structure based on montmorillonite is proven [10–16].

The SEM and elemental analysis of Navbahor bentonite are given below [17–18]:

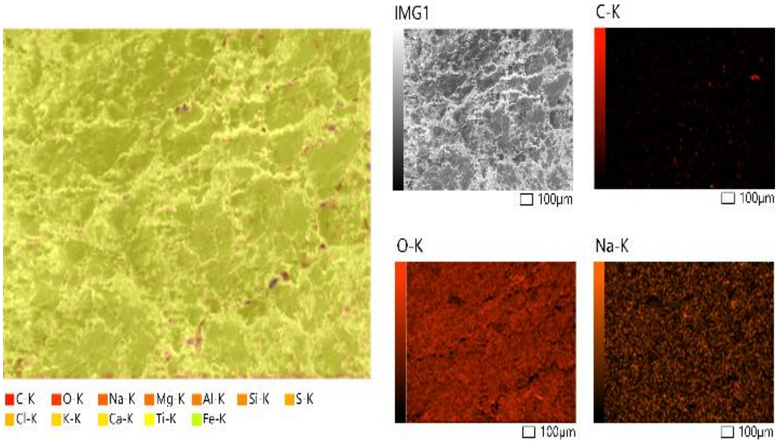


Fig. 1. Distribution of elements and microstructure on the surface of the sample by SEM (Scanning Electron Microscopy) and EDS (Energy Dispersive X-ray Spectroscopy) analysis of Navbahor bentonite.

The analysis shows that the sample contains high levels of SiO_2, Al_2O_3 and carbonate compounds, which expands its potential for use as an adsorbent [19–20].

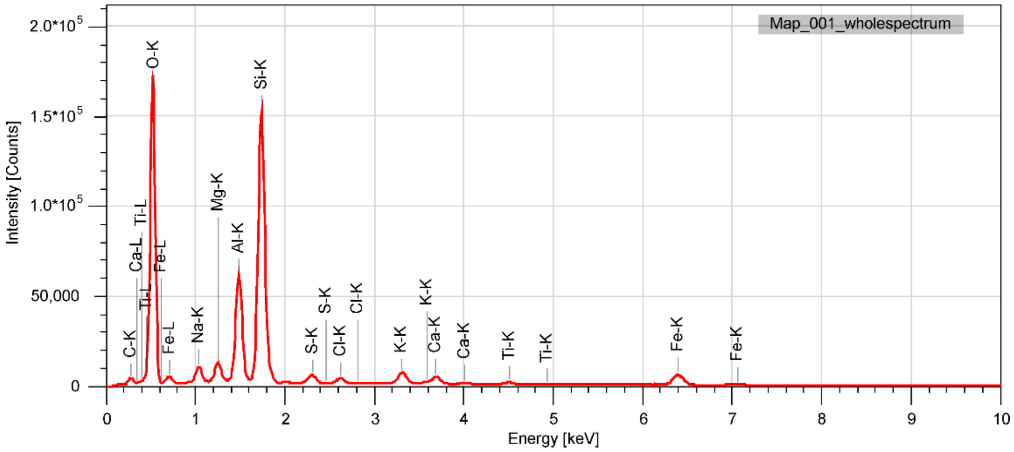


Fig. 2. SEM spectral image of Navbahor bentonite

The bentonite SM sample contains oxygen (O) – 51.80 %, silicon (Si) – 22.27%, aluminum (Al) – 8.45 %, iron (Fe) – 3.69 %, carbon (C) – 5.80 % and other elements (Table 2) [25]. Most of these elements are found in minerals in the form of various oxides. Based on the analysis, the corresponding oxide for each element was determined and the quantitative percentage in the substance was calculated. The data obtained reliably indicate the presence of a bentonite structure based on montmorillonite [21–24].

Table 2

Elemental oxide composition of Navbahor bentonite

№	Element	Mass%	Oxide formula	Oxide M (g/mol)	Element fraction (%)	Calculated oxide mass (%)
1	C	5.80	CO_2	44.1	27.3%	21.25
2	Na	1.94	Na_2O	61.98	74.2%	1.81
3	Mg	1.63	MgO	40.31	60.3%	2.70
4	Al	8.45	Al_2O_3	101.96	52.9%	13.96
5	Si	22.27	SiO_2	60.09	46.8%	47.48
6	S	0.91	SO_3	80.07	40.0%	2.28
7	Cl	0.61	Cl_2O_7	182.90	38.8%	1.57
8	K	1.52	K_2O	94.20	83.0%	1.83
9	Ca	0.99	CaO	56.08	71.5%	1.38
10	Ti	0.39	TiO_2	79.87	59.9%	0.65
11	Fe	3.69	Fe_2O_3	159.70	69.9%	4.28

SiO_2 (silicon dioxide) – 47.48 %. The most abundant oxide in bentonite, it is the main component of the silicate structure. SiO_2 forms tetrahedral layers and acts as a framework for the montmorillonite structure. High SiO_2 content: increases the adsorption capacity of bentonite, provides thermal stability, and is the main basis for ion exchange [26–29].

Al_2O_3 (aluminum oxide) – 13.96 %. The main oxide forming octahedral layers. Since aluminum is in high valence, these layers are structurally stable and mechanically strong. The ratio of Al_2O_3 to SiO_2 is ≈ 1 : 3.4, which corresponds to the classical montmorillonite structure [30].

CO_2 (carbon dioxide) – 21.25 %. This indicator indicates the presence of carbonates (for example, calcite ($CaCO_3$) or dolomite ($CaMg(CO_3)_2$)). Enrichment of bentonite with carbonate increases its stability in alkaline environments, but may reduce swelling properties [31–32].

The following physicochemical properties of the used oil (Shell Turbo S4 GX 46), selected as the object of the research, were analyzed at Chilon Lubricants LLC at room temperature of 22 °C, relative humidity of 58 % and atmospheric pressure of 720.059 mm Hg [33].

In the first stage of our research, some main physical parameters of the used oil were determined in laboratory conditions based on the above-mentioned GOST requirements. The results of the research are presented in Table 3.

Table 3

Experimentally determined parameters of the used oil

No.	Name of indicators	Actual data
1.	Kinematic viscosity at 40°C, mm^2/s	43.08
2.	Kinematic viscosity at 100°C, mm^2/s	7.40
3.	Viscosity index	137
4.	Flash point in the open crucible, °C	270
5.	Pour point, °C	-54
6.	Mass fraction of free organic acids, expressed in mg KOH per 1 g of the lubricant.	0.93
7.	Content of water-soluble acids and alkalis	none
8.	Acid number, mg KOH/g	0.088
9.	Alkaline number, mg KOH/g	-
10.	Water content, %	none
11.	Mass fraction of mechanical impurities, %	0.0065
12.	Ash content, %	0.0019
13.	Sulfate ash, %	0.0015
14.	Corrosive effect on metals (steel, copper)	1a
15.	Sulfur content by energy-dispersive X-ray fluorescence spectrometry	0.0007
16.	Density at 20°C, kg/m^3	826.1

In order to determine the hydrocarbon content of laboratory results obtained from used turbine oils, gas chromatograph-mass spectrometers with an accuracy of 80% or higher were selected. The gas chromatograph-mass spectrum of a sample taken from used Shell Turbo S4 GX46 turbine oil is shown in Fig. 3.

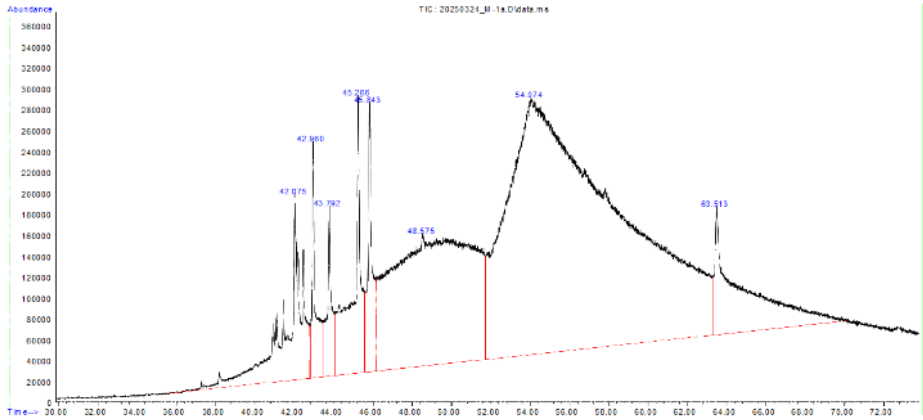


Fig. 3. Gas chromatographic mass spectrum of a sample of used Shell Turbo S4 GX46 turbine oil

The qualitative and quantitative composition of a sample of used Shell Turbo S4 GX46 turbine oil is presented in Table 4.

Table 4

Qualitative and quantitative composition of a sample of used Shell Turbo S4 GX46 turbine oil

No.	Components	Rf, min	Content, %
1	1-naphthalenecarboxamide	45.264	4.75
2	17-pentatriaconten	48.576	23.94
3	hexathriacontane	54.074	63.75
4	4,4-diamine-p-terphenyl	63.512	7.56

The percentage content of the four main components in a sample of Turbo S4 GX46 oil are shown. As can be seen, hexatriacontane has the largest share, followed by 17-pentatriacontane and the other two components in much smaller amounts.

1-Naphthalenecarboxamide usually increases the high-temperature resistance of the oil and provides stability. It is added as an acidity reducer and antioxidant.

17-pentatriacontane is an unsaturated hydrocarbon that controls the viscosity level of the oil and provides high lubricating properties.

The main component hexatriacontane is a saturated hydrocarbon and forms the main lubricating part of the oil. It provides high thermal stability, low evaporation rate and good lubricating properties.

4,4-Diamine-p-terphenyl is added as an antioxidant or stabilizer and also serves to increase thermal stability.

Using this information, we continued our research with activated bentonite. Bentonite obtained from the Navbahor deposit was dried in a muffle furnace at 550 °C for 2 hours to reduce the moisture and organic matter content and improve its absorption capacity, and the used turbine oil was filtered through this activated bentonite. The important physical parameters of the purified turbine oil were determined in laboratory conditions based on GOST requirements. The results of the research are presented in Table 5.

Table 5

Experimentally determined parameters of turbine oil purified with bentonite

No.	Name of indicators	Actual data
1.	Kinematic viscosity at 40°C, mm^2/s	42.79
2.	Kinematic viscosity at 100°C, mm^2/s	7.37
3.	Viscosity index	140
4.	Flash point in the open crucible, °C	265
5.	Pour point, °C	-44
6.	Mass fraction of free organic acids, expressed in mg KOH per 1 g of the lubricant.	1.14
7.	Content of water-soluble acids and alkalis	none
8.	Acid number, mg KOH/g	0.027
9.	Alkaline number, mg KOH/g	-
10.	Water content, %	none
11.	Mass fraction of mechanical impurities, %	0.0045
12.	Ash content, %	0.0016
13.	Sulfate ash, %	0.0014
14.	Corrosive effect on metals (steel, copper)	1a
15.	Sulfur content by energy-dispersive X-ray fluorescence spectrometry	0.0052
16.	Density at 20°C, kg/m^3	825.2

This oil is characterized by a high viscosity index, stable operation over a wide temperature range, high thermal stability, good corrosion protection properties and chemical purity. It is suitable for use in mechanisms operating under high loads, as well as in cold and hot climates. The low mechanical impurities and water content extend its service life.

According to the analysis results, Shell Turbo S4 GX46 oil has a high content of hexatriacontane, which makes it resistant to high temperatures, stable and effective for long-term use. Other components play an important role in improving the overall quality of the oil by performing additional functions.

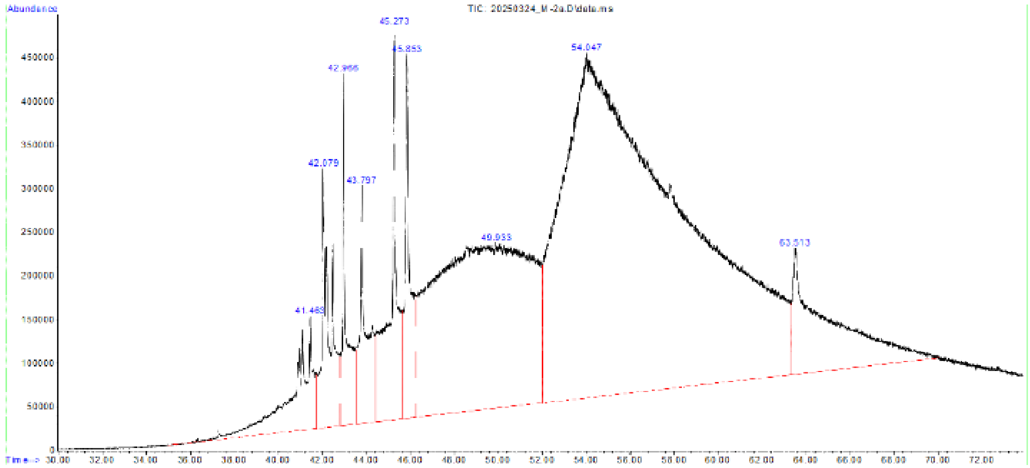


Fig. 4. Gas chromatographic mass spectrum of a sample of used Shell Turbo S4 GX46 turbine oil purified using bentonite

The qualitative and quantitative composition of the sample of used Shell Turbo S4 GX46 turbine oil purified using bentonite is presented in Table 6.

Table 6

Qualitative and quantitative composition of the sample of used Shell Turbo S4 GX46 turbine oil purified using bentonite

No	Components	Rf, min	Content, %
1	Tricosane	49.934	26.70
2	Hexathriacontane	54.048	65.95
3	Benzo[a]anthracene	63.512	7.35

The percentage content of the three main components in the sample after purification of Turbo S4 GX46 oil with bentonite can be seen to have changed. Initially, hexatriacontane accounted for the largest share, but after purification with bentonite, the composition changed and the amount of other components, such as tricosane and the aromatic compound Benzo[a]anthracene, increased.

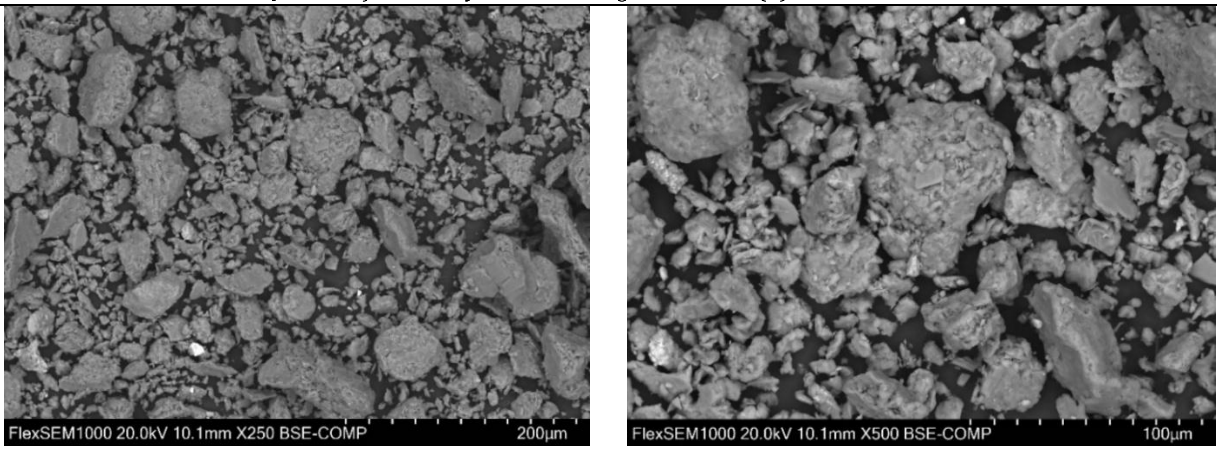
Tricosane is a medium-chain alkane that improves cold-running properties, provides fluidity, and balances viscosity.

Benzo[a]anthracene is an aromatic compound that provides stability at high temperatures, while at the same time, in small amounts, it helps to have dispersant and cleaning properties.

The potential for using bentonite adsorbent for the regeneration of used turbine oils is related to its natural properties, structure, and ability to remove contaminants. Bentonite, composed mainly of the mineral montmorillonite, has a high surface area (600–800 m^2/g), porous structure, and cation exchange capacity (CEC). These properties make bentonite a suitable material for the effective adsorption of organic compounds, metals, water, and other residues.

SEM images (Fig. 5, a and b) show the porous and layered structure of bentonite, which confirms that it has a high surface area and is effective in retaining contaminants.

Bentonite can be used as an effective adsorbent for the regeneration of used turbine oils. Its high surface area, porous structure and cation exchange capacity play an important role in the removal of contaminants such as oxidized products, metals and water. The EDS spectrum and SEM images confirm that the composition and structure of bentonite are suitable for this process. However, its effectiveness depends on the nature of the contaminants and the process parameters.



a X250 **b X500**

Fig. 5. Scanning electron microscope (SEM) image of activated bentonite adsorbent and microstructure of the sample surface

The EDS spectrum (Fig. 6) confirms that bentonite contains elements such as oxygen (O), silicon (Si), aluminum (Al), magnesium (Mg), sodium (Na), calcium (Ca) and iron (Fe). These elements indicate that bentonite has a high efficiency as an adsorbent. For example, high oxygen and silicon content indicates its silicate structure, while iron and vanadium indicate its ability to bind metals derived from oil.

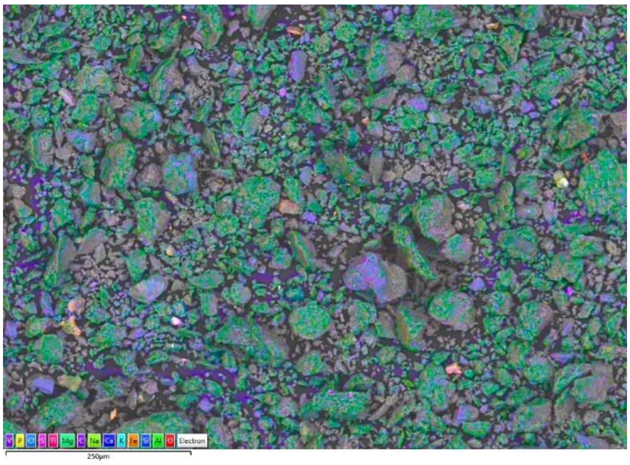


Fig. 6. Elemental distribution map (SEM-EDS) of the surface of the activated bentonite adsorbent and energy dispersive X-ray spectroscopy (EDS) spectrum of the sample composition

The energy dispersive X-ray spectroscopy (EDS) spectrum of the activated bentonite adsorbent composition is a spectral plot obtained using the energy dispersive X-ray spectroscopy (EDS) method, which shows the elements in the sample composition and their relative amounts. The X-axis represents the energy in kiloelectronvolts (keV) (0–20 keV), and the Y-axis represents the intensity in counts/electron-volt per second (cps/eV) (0–35 cps/eV). The peak with the highest intensity in the spectrum belongs to Si (silicon), with an intensity exceeding 30 cps/eV. In addition, elements such as Al (aluminum), C (carbon), O (oxygen) and Fe (iron) are also present in significant amounts.

The elemental distribution map (SEM-EDS) image of the sample surface is an elemental map obtained using scanning electron microscopy (SEM) and energy dispersive X-ray spectroscopy (EDS), which shows the location of elements on the sample surface through colors. Each color corresponds to a specific element, for example, O is yellow, Na, Mg and Al are green, C and V are purple, Ca and Si are blue, etc. (Fig. 7). The map clearly shows the heterogeneous distribution of elements, which can indicate the complex composition of the sample, for example, whether it is a geological or metallurgical material. The image has a scale bar of 250 micrometers (μm), confirming that this is a microscopic level analysis.

Journal of Chemistry and Technologies, 2025, *33*(4), 1055-1067

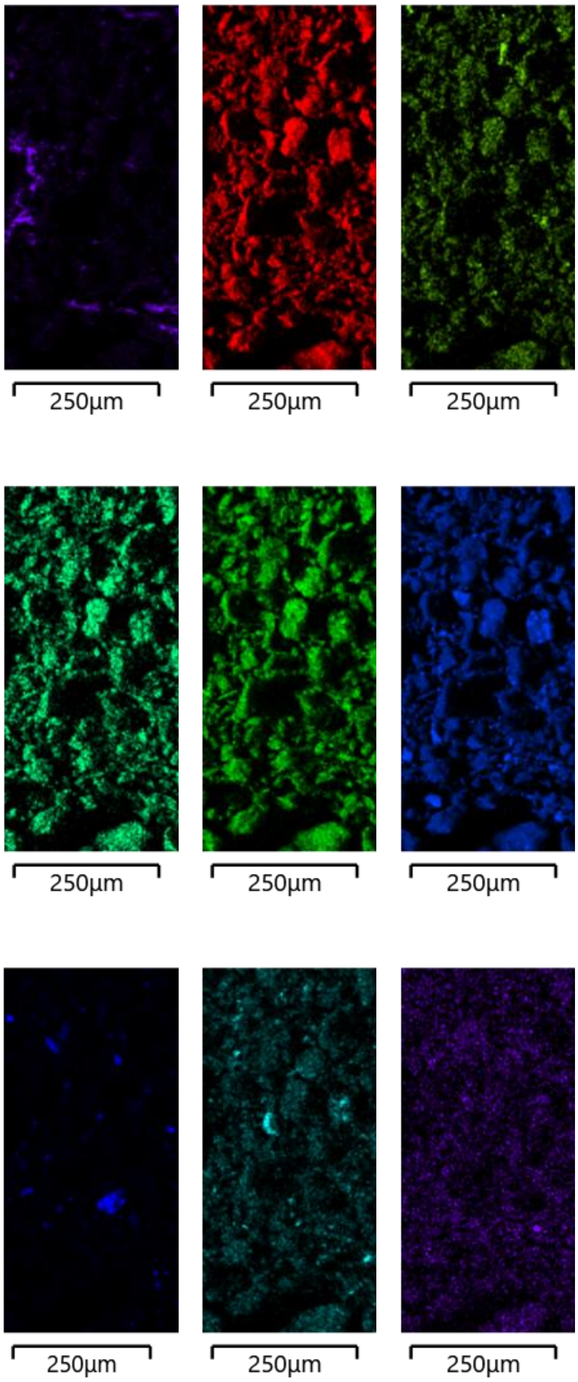


Fig. 7. Elemental distribution map and quantitative analysis of the surface of activated bentonite adsorbent (SEM-EDS).

This analysis not only serves to quantitatively analyze the composition of the sample but also shows the spatial distribution of elements.

The results of the analysis of the elements in the activated bentonite adsorbent using energy dispersive X-ray spectroscopy (EDS) show the mass percentage (mass%) and standard deviation (σ) of the elements (Table 7).

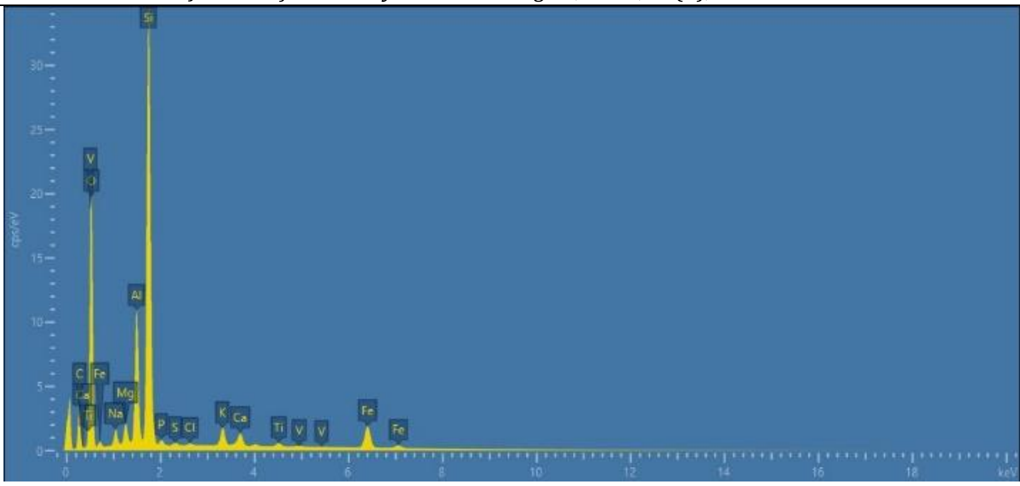


Fig. 8. Energy dispersive X-ray spectroscopy (EDS) of elements in activated bentonite adsorbent

Table 7

The mass percentage and standard deviation (σ) of the elements in the activated bentonite adsorbent

№	Element	Mass%	σ
1	O	51.04	0.07
2	Si	27.42	0.04
3	Al	8.16	0.02
4	Fe	5.68	0.03
5	Na	1.72	0.02
6	K	1.61	0.01
7	Mg	1.60	0.02
8	Ca	1.23	0.01
9	P	0.52	0.01
10	Ti	0.45	0.01
11	S	0.25	0.01
12	Cl	0.16	0.01
13	V	0.14	0.01
14	C	0.00	0.00
15	Total	100.00	

In the analysis of the composition of the substance, the conversion of elemental mass percentages to oxide mass percentages was determined using standard methods (Table 8).

Table 8

Mass percentages of oxides calculated based on elements

№	Element	Oxide	Molar mass (g/mol)	Calculated oxide mass (%)
1	Si	SiO_2	60.08	58.68
2	Al	Al_2O_3	101.96	15.42
3	Fe	Fe_2O_3	159.69	8.11
4	Na	Na_2O	61.98	2.32
5	K	K_2O	94.2	1.94
6	Mg	MgO	40.3	2.65
7	Ca	CaO	56.08	1.72
8	P	P_2O_5	141.94	1.19
9	Ti	TiO_2	79.87	0.75
10	S	SO_3	80.06	0.63
11	Cl	Cr_2O_7	182.9	1.22
12	V	V_2O_5	181.88	0.25

In this study, the physicochemical characteristics of turbine oil subjected to purification with activated bentonite were analyzed. According to the results obtained, the kinematic viscosity of the oil was 42.78 mm^2/s at 40 °C and 7.36 mm^2/s at 100 °C, the viscosity index was 139, which indicates the stability of the oil over temperature. Thermal parameters also gave positive results: the flash point in an open crucible was 265 °C, and the pour point was −44 °C. No water, water-soluble acids and alkalis were detected in the oil. The mass fraction of organic acids was 1.14 mg KOH/g, and the total acidity index was 0.024 mg KOH/g. The content of mechanical impurities (0.0044 %), ash content (0.0014 %) and sulfated ash (0.0013 %) were recorded at very low values. Also, the results for corrosion effects are class "1a", indicating that the oil does not have a harmful effect on metals. The sulfur content was 0.0052 % and the density was 825.1 kg/m^3 at 20 °C.

Results of the physicochemical evaluation demonstrate that the oil possesses a high viscosity index, maintains stability under varying thermal conditions, exhibits significant resistance to thermal degradation, provides reliable corrosion inhibition, and is distinguished by its chemical purity. The low mechanical impurities and water content of the oil extend its service life.

Table 9

Experimentally determined parameters of turbine oil purified with activated bentonite

No.	Name of indicators	Actual data
1.	Kinematic viscosity at 40 °C, mm^2/s	42.78
2.	Kinematic viscosity at 100 °C, mm^2/s	7.36
3.	Viscosity index	139
4.	Flash point in the open crucible, °C	265
5.	Pour point, °C	-44
6.	Mass fraction of free organic acids, expressed in mg KOH per 1 g of the lubricant.	1.14
7.	Content of water-soluble acids and alkalis	none
8.	Acid number, mg KOH/g	0.024
9.	Alkaline number, mg KOH/g	-
10.	Water content, %	none
11.	Mass fraction of mechanical impurities, %	0.0044
12.	Ash content, %	0.0014
13.	Sulfate ash, %	0.0013
14.	Corrosive effect on metals (steel, copper)	1a
15.	Sulfur content by energy-dispersive X-ray fluorescence spectrometry	0.0052
16.	Density at 20 °C, kg/m^3	825.1

In general, it was found that the turbine oil purified using activated bentonite has high quality indicators and can be effectively used in industrial machinery and equipment.

The gas chromatographic-mass-spectral image of a sample of used Shell Turbo S4 GX46 turbine oil purified using activated bentonite is presented in Fig. 9.

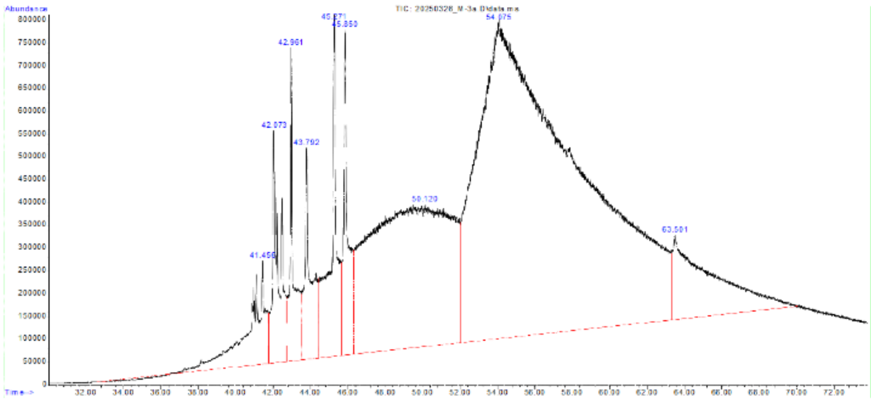


Fig. 9. Gas chromatographic mass spectrum of a sample of used Shell Turbo S4 GX46 turbine oil purified using activated bentonite

The qualitative and quantitative composition of the sample of used Shell Turbo S4 GX46 turbine oil purified using activated bentonite is presented in Table 10.

Table 10

Qualitative and quantitative composition of the sample of used Shell Turbo S4 GX46 turbine oil purified using activated bentonite

№	Components	Rf, min	Content, %
1	4-methyl-2-mercaptopyridine-1-oxide	43.789	2.91
2	Tetratriacontane	50.122	26.53
3	Hexatriacontane	54.074	70.56

After the purification process using activated bentonite, the compositional ratio of the three key components in Turbo S4 GX46 oil was found to be changed. In this case, after purification with

Journal of Chemistry and Technologies, 2025, *33*(4), 1055-1067

activated bentonite, which has the largest share of hexatriacontane, a change in the composition occurred, and an increase in the amount of tetratriacontane and 4-methyl-2-mercaptopyridine-1-oxide in the oil was observed.

Tetratriacontane is a high-molecular saturated alkane, which increases the viscosity of the oil and provides anti-friction properties. It also provides thermal and oxidative stability of the oil.

1,4-methyl-2-mercaptopyridine-1-oxide is a pyridine derivative, which contains a mercaptan (-SH) and an N-oxide group. The mercaptan group (-SH) binds well to metal surfaces, therefore this substance is used as an anti-corrosion additive. Due to the N-oxide group, it captures free radicals, therefore protecting oils from oxidation.

Comparison of Turbine Oil Cleaning Efficiency

The efficiency of cleaning used turbine oil using activated bentonite was studied by comparing, as shown in Table 11 below. The cleaning technology based on activated bentonite is an effective method for improving the quality of turbine oils and enabling their reuse.

Table 11

A comparative study on the efficiency of cleaning used turbine oil using bentonite

Parameters	Used Turbine Oil	Local Bentonite	Activated Bentonite	Change (%)
Viscosity at 40 °C, mm^2/s	43.080	42.790	42.780	–0.7
Viscosity at 100 °C, mm^2/s	7.400	7.370	7.360	–0.5
Viscosity Index	137.000	140.000	139.000	+1.5
Flash Point, °C	270.000	265.000	265.000	–1.9
Pour Point, °C	–54.000	–44.000	–53.000	–1
Acid Number, mg KOH/g	0.088	0.027	0.024	–72.7
Mechanical Impurities, %	0.007	0.005	0.004	–32.3
Ash Content, %	0.002	0.002	0.001	–26.3
Density at 20 °C, kg/m^3	826.100	825.200	825.100	–0.1

The provided data confirms the effectiveness of the process of cleaning used turbine oil using activated bentonite. The results show positive changes in the main physicochemical indicators:

Viscosity (at 40 °C and 100 °C) remained almost unchanged (–0.5 % to –0.7 %), indicating that the oil's operational stability has been maintained.

The Viscosity Index increased from 137 to 139–140 (+1.5 %), indicating an improvement in the oil's resistance to temperature variations.

The Acid Number decreased significantly (–72.7 %), indicating that oxidation products have been effectively removed.

Mechanical Impurities and Ash Content decreased by –32.3 % and –26.3 % respectively, indicating an improvement in the oil's cleanliness and performance quality.

No significant changes were observed in Density and Flash Point, indicating that the oil's general properties have been preserved.

Overall, turbine oil purification technology using activated bentonite produces effective results, improves key quality indicators, and allows oil to be reused.

The process of purifying used turbine oil with activated bentonite is described step by step using the technological scheme shown in Figure 10.

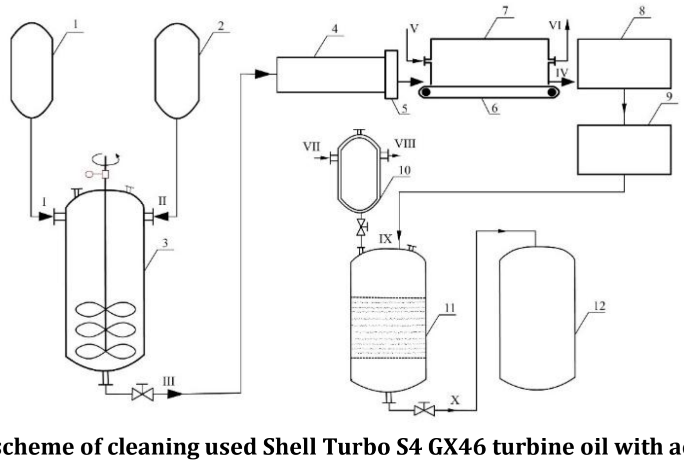


Fig. 10. Principal scheme of cleaning used Shell Turbo S4 GX46 turbine oil with activated bentonite

The technological scheme of cleaning used turbine oil consists of two stages:

1. Activation of local bentonite
2. Purification of oil using activated bentonite

For the activation of local bentonite, local bentonite from container 1 and water from container 2 are fed into reactor 3 through streams I and II. With the help of the mixing mechanism of the reactor, the mass is prepared under normal conditions and sent via stream III to pressing unit 4. Using cutter 5, the mass is cut into uniform pieces and dried with hot air through stream V in the belt drum 6 equipped with air dryer 7. Moisture-saturated air is released through stream VI. The dried bentonite is sent via stream IV to furnace 8. In the furnace, it is held for 60 minutes at a temperature of 400–450 °C for activation. The activated bentonite is collected in container 9 and cooled to room temperature.

In the next stage, the activated bentonite is placed into reactor 11 through stream IX. The jacketed container 10 is heated with water via streams VII and VIII up to 70 °C. The heated oil is then fed into reactor 11. In the reactor, the oil passes through the layer of bentonite, during which it is purified of excess additives that negatively affect its quality. The purified oil is collected in container 12 through stream X.

Economic assessment of regenerating used turbine oils with Navbahor bentonite

A. Inputs and Assumptions

Navbahor bentonite price (A): 1.950 UZS/kg

Activation cost (per kg bentonite): 206 UZS/kg

Market price of Shell Turbo S4 GX46 (calculated): ≈ 113,616 UZS/kg (based on $1.578.26 per 208.2 L; density = 0.829 kg/L; 1 USD ≈ 12.425 UZS)

Considered bentonite doses: 10 g, 50 g, 100 g per 1 kg oil.

Operational cost scenarios:

Minimal (mixing, filtration, labour): 650 UZS/kg_oil

Conservative (full industrial): 50,000 UZS/kg oil

B. Results Table (per 1 kg oil)

Table 12

Calculate the regeneration costs for 1 kg of Shell Turbo S4 GX46 turbine oil

S/n	Dose (g/kg)	Bentonite cost (UZS)	Activation cost (UZS)	Regen (materials) UZS/kg	Regen + Low proc UZS/kg	Regen + High proc UZS/kg	Saving (+low proc) UZS/kg	Saving, % (+low proc)
1.	10	19.5	2.1	21.6	671.6	50021.6	112944.5	99.41
2.	50	97.5	10.3	107.8	757.8	50107.8	112858.3	99.33
3.	100	195.0	20.6	215.6	865.6	50215.6	112750.5	99.24

Interpretation: 'Regen (materials)' includes only bentonite + activation costs. '+Low proc' adds minimal operational expenses (650 UZS/kg), while '+High proc' adds conservative industrial costs (50,000 UZS/kg).

C. Executive Summary

A simple economic assessment was performed for regenerating 1 kg of used Shell Turbo S4 GX46 oil using activated Navbahor bentonite. With bentonite at 1.950 UZS/kg and activation cost 206 UZS/kg of bentonite, the new oil replacement cost was ~113.616 UZS/kg. For bentonite doses of 10–100 g per kg oil, material costs are very low (22–216 UZS/kg). Even after adding minimal processing costs (650 UZS/kg), regeneration remains far cheaper than new oil (>99 % savings). With conservative industrial costs (50,000 UZS/kg), regeneration still offers ~56 % savings. Thus, activated Navbahor bentonite is economically attractive for industrial oil regeneration, provided operational costs are validated at scale.

Conclusion

According to the research results, activated Navbahor bentonite shows high efficiency in regenerating used Shell Turbo S4 GX46 turbine oil. The porous structure and high adsorbent capacity of bentonite (SiO_2 58.68 %, Al_2O_3 15.42 %, Fe_2O_3 8.11 %) allow for the effective removal of oxidized products, metal particles and water from the oil, as a result of which the kinematic viscosity of the oil (42.78 mm^2/s at 40 °C), flash point (265 °C) and acidity index (0.024 mg KOH/g) are restored close to the initial state. Gas chromatography-mass spectrometry analysis showed an increase in components such as tetratriacontane (26.53 %) and hexatriacontane (70.56 %) in the purified oil, confirming its improved stability and anti-corrosion properties. From an economic perspective, this method is efficient and gains importance in light of global projections suggesting a 3–4 % growth in oil consumption. Continued research is advised to optimize the process and promote the industrial-scale utilization of bentonite, with the aim of strengthening the reliability and sustainability of energy systems.

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