EURASIAN PHYSICAL TECHNICAL JOURNAL

2025, Volume 22, No. 4(54)

https://doi.org/10.31489/2025N4/94-100

Received: 07/10/2025 Revised: 13/11/2025 Accepted: 22/12/2025 Published online: 29/12/2025

Research Article

UDC 533.6:66.095:66.047

INVESTIGATION OF THE EFFECT OF ELECTROPHYSICAL PARAMETERS OF THE HIGH-VOLTAGE SHORT-PULSE ELECTROHYDRAULIC DISCHARGE SYSTEM AND A NANOCOMPOSITE CATALYST ON OIL SLUDGE DESTRUCTION

Satybaldin A.Zh.[1], Shaimerdenova K.M.[1], Zhandybaev B.B.[1], Bakibaev A.A.[2], Alpyssova G.K.[1], Seitzhan R.[1], Tyanakh S. [1]

[1] Buketov Karaganda National Research University, Karaganda, Kazakhstan
[2] Tomsk State University, Tomsk, Russian Federation
**Corresponding author:* zhandybaevb@gmail.com

Abstract. *This paper presents the results of a study on oil sludge processing using high-voltage short-pulse electrohydraulic discharge. The influence of key parameters, such as discharge voltage, capacitor bank capacitance, processing time, electrode gap, and catalyst concentration, on the yield of light and medium petroleum fractions is analyzed. Experiments have shown that the optimal conditions for achieving the maximum fraction yield (up to 36.4%) are: a processing time of 6 minutes, an electrode gap of 10 mm, a capacitor bank capacitance of 0.125 μF, and a nanocomposite catalyst concentration of 1%. It has been established that the use of a catalyst enhances the destruction of high-molecular compounds, while optimization of the electrophysical parameters improves the energy efficiency of the process. The obtained results can be used to develop energy-efficient technologies for oil waste disposal.*

Keywords: oil sludge, nanocatalyst, high-voltage short-pulse electrohydraulic discharge, light and middle fractions.

1. Introduction

Oil production, crude oil processing, and its transportation through main pipelines are accompanied by the accumulation of large amounts of petroleum-containing waste, among which oil sludge (OS) occupies a significant place. Oil sludge formed during the operation of enterprises in the oil industry is a multicomponent system that includes water, organic compounds, and mineral impurities. Due to the presence of pathogenic microorganisms, parasites, and heavy metals, such waste has a negative impact on ecosystems and poses a threat to human health. Oil sludge also contains a solid inert fraction. According to estimates, the annual global volume of oil sludge generation exceeds one billion tons, meaning that up to seven tons of such contaminated material may be produced per ton of extracted crude oil [1]. Traditional methods of handling oil sludge—such as storage in sludge pits or subsequent incineration—lead to the loss of a significant portion of valuable hydrocarbons and are accompanied by harmful effects on ecosystems. Therefore, the processing of oil sludge with the aim of recovering oil for further economic use is considered a more efficient, economical, and environmentally justified option. Various technologies for extracting oil from oil sludge have been studied to date, including freezing methods [2], solvent extraction [3], microwave irradiation [4], centrifugation [5], ultrasonic treatment [6], and pyrolysis [6, 7]. However, most existing methods thermal, biological, mechanical, chemical, and physicochemical are unable to ensure sufficient environmental safety and a high degree of recovery of petroleum products from sludge. An additional challenge is that these technologies rely on expensive, fully imported equipment requiring skilled technical maintenance, as well as significant reagent costs (polyurethane compositions, various resins, liquid glass, cement materials). As a result, the overall environmental burden associated with oil sludge processing remains high. One of the most promising approaches to minimizing harmful impacts is the extraction of valuable hydrocarbon components from oil sludge followed by their processing into commercial products, which significantly reduces the amount of residual waste. In recent years, companies in the oil production sector have been actively implementing new technological solutions aimed at more efficient utilization of waste generated at the stages of oil extraction and refining. However, as follows from the conducted analysis of published studies [1–7], to date there is no universal technology for neutralizing and processing oil sludge that simultaneously meets all environmental, technical, and economic requirements. Centrifuges and separation units used in industry—both foreign and domestic—allow effective water removal and reduce the impact of solid mechanical impurities while practically preserving the hydrocarbon fraction of the raw material. According to study [8], combined oil sludge processing technologies based on mechanical and physicochemical methods followed by a biological post-treatment stage are considered more environmentally safe and provide enhanced efficiency in the treatment of petroleum waste. Such processing methods require significantly lower costs compared to direct incineration of oil sludge, and their efficiency is considerably higher. An additional challenge is that these technologies rely on expensive, fully imported equipment that requires qualified technical maintenance, as well as substantial expenditures on reagents (polyurethane compounds, various resins, liquid glass, cement materials). As a result, the overall environmental burden of oil sludge processing remains high.

Consequently, a global trend has emerged toward a decline in the growth rate of conventional hydrocarbon reserves, including crude oil. In this regard, special attention is being paid to the rational use of petroleum resources and the active search for alternative and unconventional sources of hydrocarbons. The search for efficient technologies for oil sludge processing and utilization is therefore an urgent scientific and practical challenge. This issue becomes increasingly important as the availability of conventional hydrocarbon resources decreases and the need to expand the raw material base through unconventional sources grows. However, the processing of such feedstocks is associated with several difficulties due to their high viscosity, the presence of resin–asphaltene compounds, metals, and other impurities, which significantly complicate the treatment process [9, 10]. One of the most promising methods for processing petroleum waste is the application of high-voltage short-pulse electrohydraulic discharge (HVED) to heavy hydrocarbon organic matter. This method is based on the generation of high-energy pulses in a liquid medium, which produce shock-wave effects and create localized extreme conditions—high temperatures, pressures, and cavitation. As a result, complex hydrocarbon structures are destroyed, leading to the formation of lighter fractions [11, 12]. The use of HVED technology improves the physicochemical properties of petroleum residues, reduces their viscosity, enhances fluidity, and increases the yield of light and middle hydrocarbon fractions that are in demand as fuels and petrochemical feedstocks. Additional advantages of this method include its relative energy efficiency, environmental friendliness (due to the absence of aggressive chemical reagents), and the possibility of integration with catalytic processes. In our previous studies [13, 14], the effectiveness of the developed nanocomposite catalyst based on bentonite coated with nickel, in combination with the impact of HVED, was examined. It was shown that the introduction of the catalyst contributes to the intensive destruction of chemical bonds in heavy hydrocarbon C-C compounds and leads to an increased yield of light and middle fractions. The obtained results confirmed the feasibility of using the developed nanocomposite catalysts based on nickel-coated bentonite to enhance the efficiency of oil sludge processing.

A promising direction for further research is the study of the effect of HVED discharges and the addition of the nanocomposite catalyst based on zeolite, coated with nickel as developed by the authors, in order to increase its catalytic activity. Zeolites, due to their unique crystalline structure and surface properties, provide high efficiency in processing heavy hydrocarbon feedstocks and contribute to the increased yield of low-molecular-weight products. Additionally, zeolites exhibit significant thermal stability, which allows their use in the treatment of petroleum residues under high-temperature conditions [15].

The application of HVED in combination with nanocomposite catalysts based on zeolites opens up new possibilities for the efficient processing of oil sludge. In particular, studying the effect of a catalyst composed of a mixture of activated zeolite and bentonite clay impregnated with nickel on the oil sludge treatment process can serve as a foundation for the development and implementation of new nanocatalysts for the thermal cracking of heavy hydrocarbon feedstocks. This approach enhances processing efficiency, increases the yield of target products, and simultaneously contributes to solving the problem of industrial waste utilization.

2. Materials and methods of research

The oil sludge used in this study was obtained from the inner surfaces of the Atasu–Alashankou main oil pipeline. To increase the processing efficiency, a nickel-coated zeolite catalyst was additionally introduced into the oil sludge. The catalyst concentration in the treated sludge varied from 0.0 to 1.5% (0.5%, 1.0%, and 1.5%). The catalyst was introduced in the form of a fine powder immediately before the start of the electrohydraulic treatment. The fractional composition of the processed products was determined by thermal distillation. The main criterion for evaluating process efficiency was the percentage yield of light and middle hydrocarbon fractions at temperatures up to 200 °C and 300 °C, respectively, for the analyzed oil sludge.

To determine the optimal parameters and develop a mathematical model of the oil sludge processing process formed on the inner surfaces of the Atasu–Alashankou oil pipeline under the influence of HVEDs, laboratory experiments were carried out using the probabilistic–deterministic experimental design method. The applied methodological approach made it possible to evaluate the combined effect of the key parameters of the HVED system and the nanocatalytic additive. The list of the studied factors and their levels is presented in Table 1. Since the dependence of the yield of target products from oil sludge on the considered parameters exhibits a nonlinear character, the experimental data were processed using the method of experimental design based on the principles of nonlinear multiple correlation. The design matrix is presented in Table 2. Each row of the matrix corresponds to a specific set of experimental conditions. The matrix structure was developed in such a way that, in the full set of experiments, each level of any factor is combined exactly once with every level of the remaining parameters.

Table 1. Studied electrophysical parameters of the HVED system and the added nanocomposite catalyst

X1 (%)	0	0,5	1	1,5
X2(μF)	0,125	0,25	0,5	0,75
X3(min)	5	6	7	8
X4(mm)	7	8	9	10

Note: The variable X_1 represents the amount of added nanocomposite catalyst (%), X_2-the capacitance of the capacitor bank in the HVED system (μF), X_3-the treatment time (min) under electrohydraulic discharges, and X_4-the electrode gap (mm).

Table 2. Experimental design matrix and the influence of various HVED system factors and added catalyst on the yield of light and middle fractions after treatment.

No.	X_1, %	X_2, μF	X_3, min	X_4, mm	y_{avg}, %
1	0	0,125	5	7	20,3
2	0,5	0,25	6	8	29,9
3	1	0,5	7	9	24,9
4	1,5	0,75	8	10	21,3
5	0	0,25	7	10	18,1
6	0,5	0,125	8	9	21,1
7	1	0,75	5	8	13,33
8	1,5	0,5	6	7	29,61
9	0	0,5	8	8	21,46
10	0,5	0,75	7	7	15,4
11	1	0,125	6	10	36,4
12	1,5	0,25	5	9	30,09
13	0	0,75	6	9	9,18
14	0,5	0,5	5	10	23,68
15	1	0,25	8	7	25,8
16	1,5	0,125	7	8	20,9

3. Results and discussion

Based on the constructed experimental design matrix, histograms were plotted to illustrate the influence of the main parameters on the yield of light and middle hydrocarbon fractions. Figure 1 shows the dependence of the yield of these fractions on the duration of the HVED treatment and the electrode gap during the processing of oil sludge formed on the inner surface of the Atasu–Alashankou oil pipeline. As shown in Figure 1, the highest yield of light and middle fractions is achieved at a treatment duration of 6 minutes and an electrode gap of 10 mm. Under these conditions, the yield reaches 36.4% of the initial oil sludge mass. This result can be explained by the combined effect of two factors-the optimal duration of the HVED treatment and the interelectrode distance-which ensure the most stable formation of the pulsed discharge, thereby promoting the destruction of high-molecular-weight hydrocarbon compounds.

When the treatment time exceeds 6 minutes (up to 7–8 minutes), a decrease in the yield of target fractions is observed, which is associated with the redistribution of discharge energy and possible secondary compaction of the reaction products. Similarly, reducing the electrode gap below 10 mm decreases process efficiency due to discharge channel instability and local overheating of the medium. Figure 2 shows the influence of the capacitor bank capacitance of the HVED system and the treatment duration on the yield of light and middle fractions from the oil sludge. The highest yield of light and medium fractions is observed at the minimum capacitance of the capacitor bank - 0.125 μF. Under six minutes of exposure, the yield reaches its maximum value of 36.4 %.

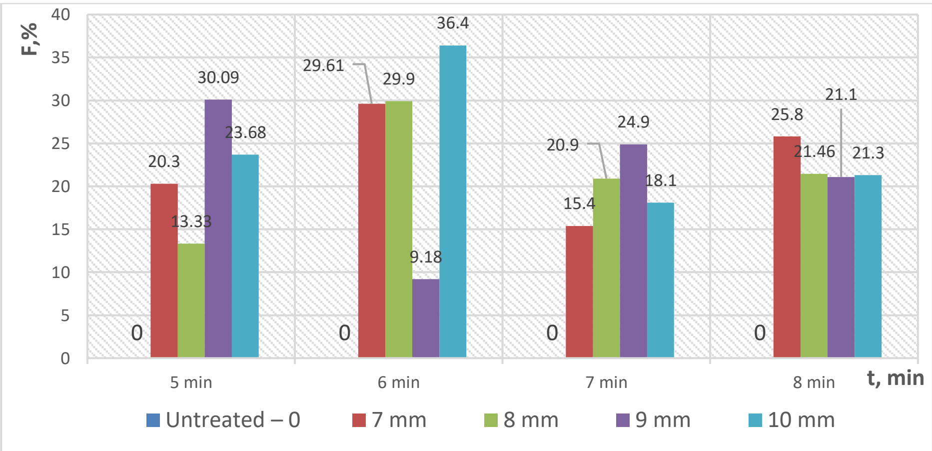


Fig.1. Influence of HVED treatment time and electrode gap on the yield of light and middle fractions

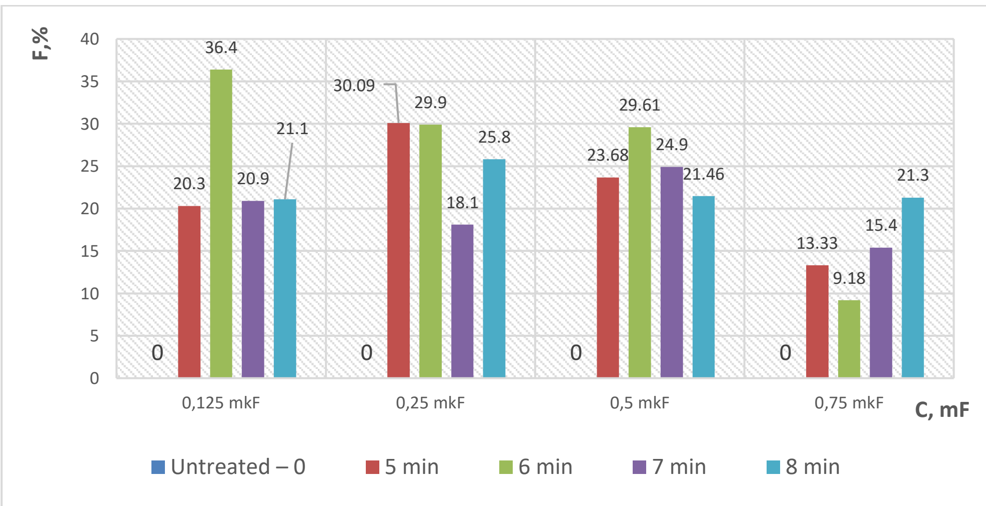


Fig.2. Influence of the capacitor bank capacitance of the HVED system on the yield of light and middle fractions

This result indicates that at low capacitance values, more powerful and concentrated discharge pulses are formed, providing effective destruction of complex hydrocarbon structures. With an increase in capacitance (0.25–0.75 μF), a gradual decrease in yield is observed, which is associated with the elongation of the pulse over time and a reduction in the specific energy transferred to the reaction zone. At the same time, the influence of treatment duration also becomes evident: increasing the exposure time to 7–8 minutes leads to stabilization of the results; however, a significant increase in yield is not observed. Experimental data showed that the maximum yield of light and medium fractions is achieved at a nanocatalyst concentration - zeolite impregnated with nickel - of 1% and a treatment duration of 6 minutes (Fig. 3).

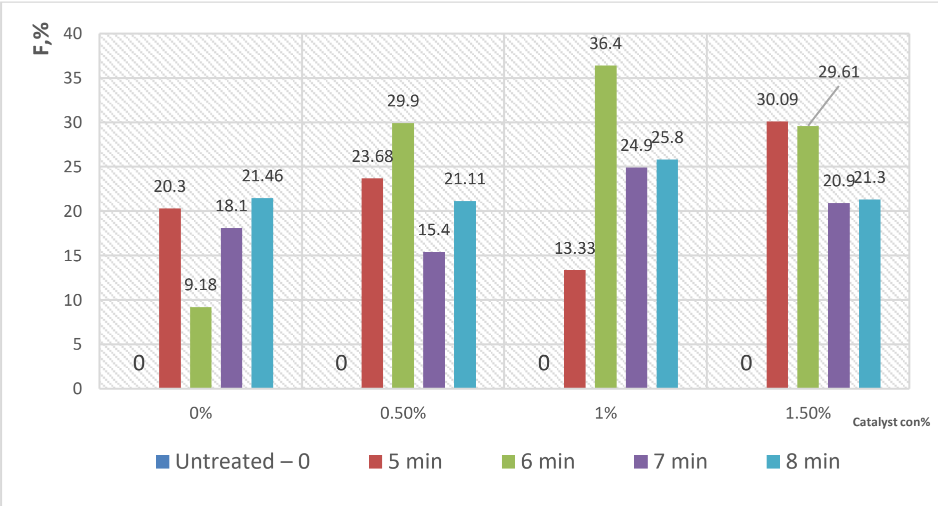
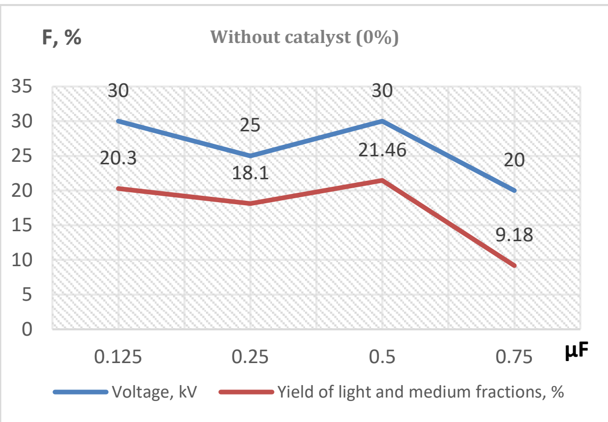
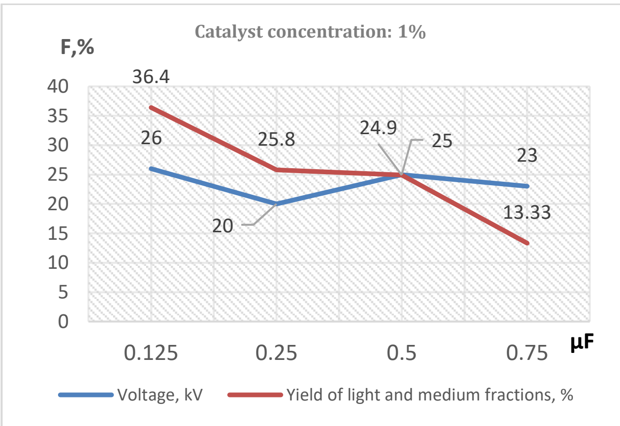


Fig.3. Influence of the amount of nickel-coated zeolite nanocatalyst on the yield of light and medium fractions

Further increase in the amount of catalyst leads to a decrease in the yield of target products, which may be associated with the sorption of active components or the restriction of mobility in the organic medium. This confirms the necessity of accurately determining the optimal catalyst content to achieve maximum process efficiency. As shown in Fig. 4, the following graphs illustrate the influence of discharge voltage (kV) and capacitor bank capacitance (μF) on the yield of light and medium oil sludge fractions (%) during processing by the HVED method.





a) b)

Fig. 4. Influence of discharge voltage on the yield of light and medium fractions from oil sludge:
(a) without catalyst; (b) with 1% catalyst content.

In experiments conducted without the use of a catalyst (0%), it was found that increasing the capacitance of the capacitor bank from 0.125 to 0.25 μF leads to a decrease in discharge voltage, recorded by the kilovoltmeter, from 30 to 25 kV. This is accompanied by a reduction in the yield of light and medium fractions — from 20.3% to 18.1%. With a further increase in the capacitance of the HVED system up to 0.5 μF, the opposite trend is observed: the voltage rises to 30 kV, and the proportion of light and medium fractions increases to 21.46%. Thus, the capacitance of the capacitor bank has a significant effect on the intensity of the destruction of high-molecular-weight hydrocarbon compounds present in oil sludge.

At a catalyst content of 1%, the dependence becomes more pronounced: the maximum yield (36.4%) is observed at a capacitance of 0.125 μF, while the kilovoltmeter reading is 26 kV. When the capacitance increases to 0.5 μF, the voltage drops to 20 kV, and the yield of target fractions decreases from 36.4% to 25.8%. This behavior can be explained by the fact that at lower capacitance values of the capacitor bank, higher pulse voltages are generated in the system, ensuring the intensive occurrence of physical-chemical destruction processes. In the presence of a catalyst, these processes proceed more efficiently due to the accelerated breaking of molecular C–C bonds in heavy hydrocarbons.

4. Conclusion

As a result of the experimental studies, it was established that the use of HVED technology in combination with a nickel-coated zeolite nanocatalyst enhances the efficiency of processing oil sludge formed on the inner surfaces of the Atasu–Alashankou oil pipeline. It was determined that the yield of light and medium hydrocarbon fractions is significantly influenced by the electrophysical parameters of the process: the capacitance of the HVED system's capacitor bank, the interelectrode gap, the treatment duration, and the catalyst content.

The kilovoltmeter readings, which reflect the actual discharge voltage, together with the capacitance of the HVED capacitor bank and the catalyst concentration, determine the efficiency of the electrohydraulic destruction process of high-molecular-weight compounds in oil sludge.

The maximum fraction yield of 36.4% is achieved under optimal conditions: treatment duration of 6 minutes, interelectrode distance of 10 mm, capacitor capacitance of 0.125 μF, and catalyst concentration of 1.0%. The introduction of the zeolite-based catalyst increases the energy efficiency of the process, confirming the potential of combining HVED technology with catalytic methods for oil waste processing.

Conflict of interest statement

The authors declare that they have no conflict of interest in relation to this research, whether financial, personal, authorship or otherwise, that could affect the research and its results presented in this paper.

CRediT author statement

Satybaldin A. Zh.: Supervision, Funding acquisition, Writing – review & editing, **Shaimerdenova K. M.**: Methodology, **Zhandybaev B.B.**: Writing –original draft, Investigation, **Bakibayev A.A.**: Formal analysis, **Seitzhan R.**: Data curation, **Berdibayev D.N.**: Investigation, **Alpysova G.K.**: Data curation. The final manuscript was read and approved by all authors.

Funding Information

This research was funded by the Science Committee of the Ministry of Science and Higher Education (Grant No. AP23483556).

References

1. Niu A., Sun X., Lin C. (2022) Trend in research on characterization, environmental impacts and treatment of oily sludge: A systematic review. *Molecules*, 27, 7795. https://doi.org/10.3390/molecules27227795

2. Lin C., He G., Li X., Peng L., Dong C., Gu S., Xiao G. (2007) Freeze/thaw induced demulsification of water-in-oil emulsions with loosely packed droplets. *Separation and Purification Technology*, 56, 175–183. https://doi.org/10.1016/j.seppur.2007.01.035

3. Al-Zahrani S.M., Putra M.D. (2013) Used lubricating oil regeneration by various solvent extraction techniques. *Journal of Industrial and Engineering Chemistry*, 19, 536–539. https://doi.org/10.1016/j.jiec.2012.09.007

4. Fortuny M., Oliveira C.B.Z., Melo R.L.F.V., Nele M., Coutinho R.C.C., Santos A.F. (2007) Effect of salinity, temperature, water content, and pH on the microwave demulsification of crude oil emulsions. *Energy & Fuels*, 21, 1358–1364. https://doi.org/10.1021/ef0603885

5. Cambiella A., Benito J. M., Pazos C., Coca J. (2006) Centrifugal separation efficiency in the treatment of waste emulsified oils. *Chemical Engineering Research and Design*, 84, 69–76. https://doi.org/10.1205/cherd.05130

6. Shishkin Y.L. (2006) Fractional and component analysis of crude oils by the method of dynamic microdistillation–differential scanning calorimetry coupled with thermogravimetry. *Thermochimica Acta*, 441, 162–167. https://doi.org/10.1016/j.tca.2005.12.011

7. Chen J. B., Mu L., Jiang B., Yin H., Song, X., Li A. (2015) TG/DSC-FTIR and Py-GC investigation on pyrolysis characteristics of petrochemical wastewater sludge. *Bioresource Technology*, 192, 1–10. https://doi.org/10.1016/j.biortech.2015.05.031

8. Hu G.J., Li J. B., Zeng G.M. (2013) Recent development in the treatment of oily sludge from petroleum industry: A review. *Journal of Hazardous Materials*, 261, 470–490. https://doi.org/10.1016/j.jhazmat.2013.07.069

9. Zhukova E.M. (2008) Effect of high-voltage electrohydraulic discharge on the physicochemical properties of oil and petroleum products. Doctoral Dissertation, Saratov State University named after N.G. Chernyshevsky. Saratov, Russia. 145. Available at: https://www G.K..dissercat.com/content/vozdeistvie-vysokovoltnogo-elektrogidravlicheskogo-razryada-na-fiziko-khimicheskie-svoistva [in Russian]

10. Nikolaev A. I., Peshnev B. V., Ismail A.M.H. (2022) Cavitation treatment of water-containing petroleum products. *Izvestiya Vysshikh Uchebnykh Zavedenii. Series Chemistry and Chemical Technology*, *65*(7), 94–99. https://doi.org/10.6060/ivkkt.20226507.6611 [in Russian]

11. Balakaeva G., Kalmenova G. (2023) Development of an application for thermal processing of oil sludge to prevent environmental pollution in the industrial oil and gas sector. *Bulletin of Abai Kazakh National Pedagogical University. Series of Physical and Mathematical Sciences*, *81*(1), 136–144. https://doi.org/10.51889/2959-5894.2023.81.1.015

12. Bodykov D. U., Salakhov R.Kh. (2020) Oil processing using the electrohydraulic effect. *Combustion and Plasma Chemistry*, *18*, 29–36. https://doi.org/10.18321/cpc343

13. Satybaldin A. Zh., Shaimerdenova,K. M., Baikenov,M. I., Zhandybayev,B. B., Tyanakh S. (2025) Influence of nanocatalyst and HVED on the yield of fractions from oil sludge. *Bulletin of Toraighyrov University*, *2*, 289–302. https://doi.org/10.48081/BMGX4755

14. Satybaldin A., Zhakipbaeyev B., Tusipkhan A., Baykenov M., Khalikova Z., Alpyssova G. (2021) The influence of a high-voltage discharge on the oil bottom sediments formed at the oil storage facilities of the atasu-alashankou station. *Eurasian Physical Technical Journal*, *18*(3(37), 71–75. https://doi.org/10.31489/2021No3/71-75

15. Ivanova I.I. (2017) Zeolite catalysts: Synthesis, activation, catalysis, and deactivation. In *International Symposium "Diffraction Methods in the Characterization of New Materials"* (May 31 – June 2, 2017). Conference presentation [Electronic resource]. Available at: https://istina.msu.ru/conferences/presentations/607587

AUTHORS' INFORMATION

Satybaldin, Amangeldy Zharlygassynovich – Candidate of Chemical Sciences, Associate Professor, Faculty of Physics and Technology, Buketov Karaganda National Research University, Karaganda, Kazakhstan; https://orcid.org/0000-0002-0846-4665; satybaldin.1975@mail.ru

Shaymerdenova, Kulzhan Meiramovna - Candidate of Technical Sciences, Professor, Faculty of Physics and Technology, Buketov Karaganda National Research University, Karaganda, Kazakhstan; https://orcid.org/0000-0002-9588-4886; gulzhan.0106@mail.ru

Zhandybayev, Beken Bakhytbekuly - PhD student, Faculty of Physics and Technology, Buketov Karaganda National Research University, Karaganda, Kazakhstan; https://orcid.org/0000-0001-5719-9549; zhandybaevb@gmail.com

Bakibayev, Abdigali Abdimanapovich – Doctor of Chemical Sciences, Professor, Faculty of Chemistry, Tomsk State University, Tomsk, Russian Federation; https://orcid.org/0000-0002-3335-3166 ; bakibaev@mail.ru

Alpyssova, Gulnur Kenzhebekovna – PhD, Associate Professor, Faculty of Physics and Technology, Buketov Karaganda National Research University, Karaganda, Kazakhstan; https://orcid.org/0000-0002-7164-218; gulnur-0909@mail.ru

Seitzhan, Raikhan – Master, Senior Lecturer, Faculty of Chemistry, Buketov Karaganda National Research University, Karaganda, Kazakhstan; https://orcid.org/0000-0003-2362-6383; Raikhan.Seitzhan@mail.ru

Tyanakh, Sairagul – PhD, Senior Lecturer, Faculty of Chemistry, Buketov Karaganda National Research University, Karaganda, Kazakhstan; https://orcid.org/0000-0001-5343-4695 ; Saika_8989@mail.ru