МЕМБРАНЫ И МЕМБРАННАЯ ТЕХНОЛОГИЯ / MEMBRANES AND MEMBRANE TECHNOLOGY

DOI: https://doi.org/10.60797/IRJ.2024.144.22

IMPROVING THE EFFICIENCY OF WASTEWATER TREATMENT CONTAINING PETROLEUM PRODUCTS

Research article

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Abstract

In order to increase the efficiency of the process of ultrafiltration of wastewater from motor transport enterprises containing petroleum products, their preliminary treatment with ozonation is proposed. Ozonation was carried out to enlarge impurities of petroleum origin. The required ozone concentration was provided by varying the power of the ozonator from 20 to 50 watts. Based on the analysis of literature sources, the most effective ratio of the concentration of ozone and the concentration of petroleum products contained in the test solution was selected, equal to 2.5 to 5% by weight. As a result of the analysis of literary sources and conducted experiments, it was found that the optimal time for ozonation is within 5-10 minutes before the formation of flakes. The resulting heterogeneous medium was then separated by ultrafiltration. Tubular single-channel polymer membranes based on fluoroplast and polysulfonamide with an average pore size of 0.05 microns were used as a separating element. The ultrafiltration process was carried out at a temperature of 323 K of the separated medium and an operating pressure of 0.4 MPa. As a result of the study, satisfactory indicators were obtained for the quality of wastewater treatment, which corresponded to the norms of the maximum permissible concentration of harmful impurities.

Keywords: wastewater, ozonation, ultrafiltration, polymer membranes.

ПОВЫШЕНИЕ ЭФФЕКТИВНОСТИ ОЧИСТКИ СТОЧНЫХ ВОД, СОДЕРЖАЩИХ НЕФТЕПРОДУКТЫ

Научная статья

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Аннотация

С целью повышения эффективности процесса ультрафильтрации сточных вод автотранспортных предприятий, содержащих нефтепродукты предлагается предварительная их обработка озонированием. Озонирование производилось для укрупнения примесей нефтяного происхождения. Нужная концентрация озона обеспечивалась варьированием мощности озонатора от 20 до 50 Вт. На основании анализа литературных источников было выбрано наиболее эффективное соотношение концентрации озона и концентрации нефтепродуктов, содержащихся в исследуемом растворе, равное от 2,5 до 5 мас.%. В результате анализа литературных источников и проведенных экспериментов установлено, что оптимальное время проведения озонирования находится в пределах 5-10 мин. до образования хлопьев. Затем полученная гетерогенная среда подвергалась разделению ультрафильтрацией. В качестве разделяющего элемента использовались трубчатые одноканальные полимерные мембраны на основе фторопласта и полисульфонамида со средним размером пор 0,05 мкм. Процесс ультрафильтрации проводился при температуре разделяемой среды 323 К, и рабочем давлении ΔP = 0,4 МПа. В результате исследования получены удовлетворительные показатели по качеству очистки сточных вод, которые соответствовали нормам предельно допустимой концентрации вредных примесей.

Ключевые слова: сточные воды, озонирование, ультрафильтрация, полимерные мембраны.

Introduction

Many industrial enterprises generate large volumes of wastewater containing petroleum products (WWPP) that do not comply with environmental regulations. The relevance of such wastewater treatment is due to several factors:

- reduction of pollution and prevention of negative impact on the environment;
- compliance with regulatory requirements for the maximum permissible concentration of petroleum products in wastewater for discharge into central sewers and reservoirs;
- reduction of water supply costs due to the use of recycled water and a closed consumption cycle;
- social responsibility of organizations involved in the treatment of WWPP;
- stimulating research and development of new technologies that can be further applied to other types of industrial and household wastewater.

Thus, treatment of wastewater from petroleum products and other impurities of man-made impact is important for environmental conservation, compliance with legal requirements, economic efficiency and social responsibility of organizations.

This type of waste is a direct emulsion in which the dispersed phase is oil (non–polar liquid) and the dispersed medium is water (polar liquid).

For the separation of petroleum products (PP) and water, there is a wide variety of technological methods based on chemical, biochemical, aerobic and anaerobic, thermal, electrochemical processes, flame neutralization, evaporation, distillation, oxidative processes, decomposition of reagents, as well as coalescence, flotation and sorption [1], [3], [5], [8]. Most of these methods consume a large amount of energy, require the use of reagents, the use of oil traps, and with a large volume of wastewater, an entire system of settling ponds that affect the ecological system around them.

Despite the large number of studies by domestic and foreign scientists in the field of biosphere protection, the problem of deep wastewater treatment from organic and inorganic compounds remains unresolved.

One of the main directions for the development of technology for wastewater treatment is the development of low-energy, non-reactive, low-waste processes [2], [9]. The analysis of scientific papers in a ten-year retrospective shows great interest in membrane technologies and wastewater treatment by ozonation [10], [12], [14], [15], [16].

In one of the works [17], a good result was obtained for the purification of a water-oil emulsion after two stages of ultrafiltration and nanofiltration. The retention of almost all impurities was in the range of 97-99%, the water after nanofiltration was transparent and met the requirements of permissible concentrations of pollutants in wastewater allowed to discharge into wastewater disposal systems.

The disadvantage of the proposed method was the complication of the technological process, a significant increase in energy consumption and a drop in the productivity of the installation as a whole. In addition, there remains the problem of reducing the influence of concentration and gel polarization on the membrane surface, which is the limiting factor of separation [18], [19].

In the study [20], spent coolant was neutralized at an installation with a capacity of 3.5 g/h of ozone at a concentration of an air-ozone mixture up to 33 mg/l. It turned out that ozonation is most effective in an alkaline environment at pH = 12. At pH = 10, 100% ozone absorption was observed for 30-45 minutes. During 1-1.5 hours, the surfactant was almost completely destroyed. Chemical Oxygen Demand (COD) decreased from 7.5 to 2-2.4 g/l, which is 70-72% of the potential. The ozone absorption was 90-96%.

After the destruction of surfactants, the loss of ozone increased sharply, which indicated the presence of difficult-to-oxidize substances. The minimum COD value (0.3-0.4 g/l) was observed after 2.5-3 hours, with a large loss of ozone. Complete oxidation of organic substances could not be achieved. Intermediate products of hydrocarbon decomposition remained in the ozonated water, which could not be further destroyed.

The advantage of ozonation is that ozone is effective against most organic compounds that are difficult to oxidize, which decompose to form safe substances. At the same time, unpleasant odors are eliminated and disinfection occurs due to the bactericidal properties of ozone [21].

Petroleum products in wastewater are in an emulsified state in the form of very fine particles. As shown in [22], the reaction of ozone with emulsified petroleum products has its own characteristics. As a result of the reaction contact of ozone and particles of petroleum products, the upper layer is rapidly oxidized. Then the oxidation process slows down sharply, as the rate of ozone diffusion deep into the emulsified particles of petroleum products decreases. The subsequent process of oxidation of petroleum products with ozone takes a long time, which reduces the effectiveness of this method of purification of oily water. However, numerous experiments on the use of ozone for the purification of oily wastewater have shown that partially oxidized particles of petroleum products intensively coagulate and pass into a floccular phase.

The phenomenon of coagulation of partially oxidized petroleum products has led to a hypothesis about the possibility of intensifying the process of ultrafiltration of wastewater containing petroleum products using ozone, due to a decrease in the formation of a gel polarization layer on the membrane surface.

Thus, the purpose of this work is to study the hybrid separation process of heterogeneous media containing petroleum products and water, based on the consistent application of ozonation and ultrafiltration.

Research methods and principles

Samples taken from stormwater wastewater from the truck maintenance station of the Yarkamp Group of companies in Yaroslavl, presented in Table 1, were used as WWPP.

The efficiency of oil-containing wastewater treatment depends on the ratio of the initial concentrations of ozone C_{oz} and petroleum products C_{PP}.

Complete oxidation of petroleum products occurs under the condition Coz ≥ CPP, under the condition when $C_{oz} > C_{PP}$ the highest oxidation rate is observed. However, the higher the ozone concentration, the higher the cost of the process. On the other hand, if there is a slight excess of ozone or if the concentrations of $C_{oz} = C_{PP}$ are equal, the ozonation time increases and the loss of expensive gas due to its natural decay is inevitable.

It is advisable not to bring oil products to complete decomposition during ozone oxidation, but to remove partially oxidized and coagulated particles by ultrafiltration.

Based on the analysis of theoretical and experimental studies presented in the literature [22], [23], [24], [25], [26], the optimal concentration ratio was determined to be equal C_{oz}/C_{PP}= 2.5-5% by weight.

The process of ozonation of WWPP samples was carried out at a temperature of 293 K and atmospheric pressure in a bubbling reactor. Oxygen was used as an ozone source at a gas flow rate of 120-150 ml/min. The required ozone concentration was obtained by changing an ozonator power in the range from 20 to 50 watts. The duration of ozone oxidation was carried out for 5-10 minutes, which led to abundant flocculation of oil-containing impurities in the samples.

The prepared heterogeneous system was then separated in a laboratory ultrafiltration unit [19]. In experimental studies, we used tubular polymer ultrafiltration membranes based on fluoroplast and polysulfonamide with an average pore size of 0.05 microns produced by LLC «Vladipor» in Vladimir city.

Main results

Figure 1 shows the results of the observed permeability parameters of the process of separation of WWPP from time during ultrafiltration and ultrafiltration with ozonation.

Analysis of the curves in Figure 1 shows the effectiveness of applying ozonation before ultrafiltration. The separation process reaches a plateau with a higher specific productivity. This effect can be explained by the coarsening of dirt particles and the formation of a floccular phase, and a smaller gel layer due to the action of tangential forces on it during the flow in the tubular channel.

Table 1 shows the results of chemical analysis of treated real effluents after ozonation followed by ultrafiltration and their comparison with standard indicators of the content of harmful impurities.

Table 1 - Comparison of the concentration of pollutants in the filtrate with permissible values

DOI: https://doi.org/10.60797/IRJ.2024.144.22.1

Indicator	The standard MPC	Spent WWPP	Ultrafiltration (fluoroplast)		Ozonation and ultrafiltration (fluoroplast)	
			Permeate pollutant concentration value	Degree clearances	Permeate pollutant concentration value	Degree clearances
		C±Δ mg/dm^3 P=0.95, n=2	C±Δ mg/dm^3 P=0.95, n=2	%	C±Δ mg/dm^3 P=0.95, n=2	%
	6.0-9.0	8.9±0.1	8.9±0.1	-	7.8±0.1	-
Suspended solids, mg/dm^3	300	**1554±233**	< 0.5	99.9	< 0.5	99.9
Dry residue, mg/dm^3	3000	**19900±3980**	**4700±470**	23.2	850±85	81.4
*BOD_5, mg/dm^3	300	**6305±1261**	**315±63**	80.2	8.8±1.8	97.0
COD, mg/dm^3	500	**18215±3643**	**1052±210**	76.2	23.4±4.7	97.6
Nitrate ion, mg/dm^3	-	54.6±11	47±7	13.9	3.15±0.63	92.1
Nitrite ion, mg/dm^3	-	2.91±0.58	2.1±0.42	27.8	<0.02	98.9
Sulfate ion, mg/dm^3	300	121±24	108±16	10.7	9.21±1.84	90.9
Phosphate ion, mg/dm^3	12	**54.6±11**	**20±4**	17.7	1.84±0.37	90.4
Chloride ion, mg/dm^3	1000	280±56	277±27.7	1.1	30.8±6.2	88.8
Petroleum products, mg/dm^3	10	**14400±2880**	**109±10.9**	93.2	<0.05	99.9
Anionic surfactants, mg/dm^3	10	3.15±0.79	2.6±0.5	10.3	<0.02	99.3
Non-ionic surfactant, mg/dm^3	-	4711±942	2974±446	31.2	1.12±0.22	99.9
Fat content, mg/dm^3	50	**10100±2525**	**149±29.8**	94.9	<0.01	99.9

*Note: * BOD_5 - Biochemical oxygen demand during 5 days of incubation at 20 °C*

According to the results of chemical analysis (Table. 1) it can be seen that the addition of the ozonation stage to the wastewater treatment process makes it possible to almost completely filter out fats and petroleum products, as well as increase the efficiency of neutralization of multivalent metal ions and surfactants.

Possible chemical reactions of wastewater components with ozone and mechanisms for improving filtration quality may include:

- reactions with hydrocarbons contained in petroleum products, which leads to the formation of lighter and less toxic compounds;
- decomposition of petroleum products into less toxic compounds such as acids, aldehydes and ketones;
- the formation of flake-like, larger particles, which simplifies their removal by ultrafiltration.

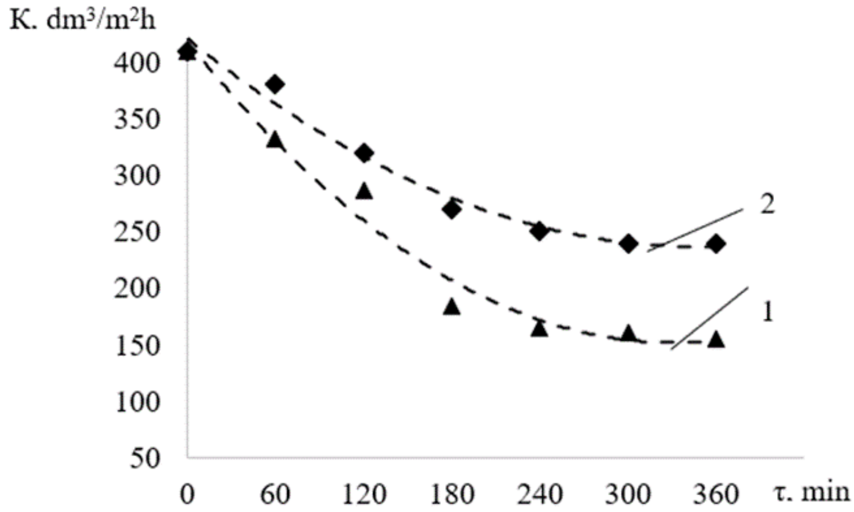

Figure 1 - Dependence of membrane permeability on time at t=323 K, ΔP = 0.4 MPa, membrane material - fluoroplast:
1 - ultrafiltration; *2* - ozonation with ultrafiltration
DOI: https://doi.org/10.60797/IRJ.2024.144.22.2

Conclusion

Based on the presented research results, the hypothesis of increasing the efficiency of the wastewater separation process containing petroleum products through the consistent application of ozonation and ultrafiltration was confirmed.

Further development of the proposed method of separation of WWPP should be carried out in the following directions:

- to obtain the most effective technological modes of ozone treatment, wastewater and stormwater in order to recommend them for practical use as a stage of preparation of solutions before ultrafiltration;
- synthesis of hardware design and its implementation.

Конфликт интересов

Не указан.

Рецензия

Все статьи проходят рецензирование. Но рецензент или автор статьи предпочли не публиковать рецензию к этой статье в открытом доступе. Рецензия может быть предоставлена компетентным органам по запросу.

Conflict of Interest

None declared.

Review

All articles are peer-reviewed. But the reviewer or the author of the article chose not to publish a review of this article in the public domain. The review can be provided to the competent authorities upon request.

Список литературы / References

1. Комарова Л.Ф. Инженерные методы защиты гидросферы / Л.Ф. Комарова, В.А. Сомин — Барнаул: АлтГТУ, 2019. — 283 с.

2. Pervov A.G. Application of membranes to treat wastewater for its recycling and reuse: new considerations to reduce fouling and increase recovery up to 99 percent / A.G. Pervov, A.P. Andrianov // Desalination and Water Treatment. — 2011. — 1. — p. 2-9. — DOI: 10.5004/dwt.2011.3133 .

3. Лукиных Н.А. Методы доочистки сточных вод / Н.А. Лукиных, Б.Л. Липман, В.П. Криштул — Москва: Стройиздат, 1974. — 96 с.

4. Семенов А.В. Современные решения аккумуляции и очистки дождевых и талых вод / А.В. Семенов, Н.С. Латышев, Р.В. Петрук // Водоснабжение и санитарная техника. — 2023. — 9. — с. 56-60. — DOI: 10.35776/VST.2023.09.09.

5. Kuyukina M.S. Oilfield wastewater biotreatment in a fluidized-bed bioreactor using co-immobilized rhodococcus cultures / M.S. Kuyukina, I.B. Ivshina, M.K. Serebrennikova et al. // Journal of Environmental Chemical Engineering. — 2017. — Vol. 5. — P. 1252–1260. — DOI: 10.1016/j.jece.2017.01.043.

6. Xue J. Tetradecylamine-MXene functionalized melamine sponge for effective oil/water separation and selective oil adsorption / J. Xue, L. Zhu, X Zhu et al. // Sep. Purif. Technol. — 2021. — Vol. 118106. — DOI: 10.1016/j.seppur.2020.118106.

7. Медведева И.В. Новые композитные материалы и процессы для химических, физико-химических и биохимических технологий водоочистки / И.В. Медведева, О.М. Медведева, А.Г. Студенок и др. // Известия высших учебных заведений. серия «Химия и химическая технология». — 2023. — Т. 66(1). — с. 6-27. — DOI: 10.6060/ivkkt.20236601.6538.

8. Pavselj N. Experimental Design of an Optimal Phase Duration Control Strategy Used in Batch Biological Wastewater Treatment / N. Pavselj, N. Hvala, J. Kocijanet al. // ISA Transactions. — 2001. — Vol. 40. — p. 41-56. — DOI: 10.1016/S0019-0578(00)00042-2.

9. Pervov A.G. Determination of optimal operation pressure values for ultrafiltration wastewater treatment / A.G. Pervov, K.V. Tikhonov, N.A. Makisha // Membranes and Membrane Technologies. — 2020. — Vol. 2. — № 3. — p. 159-168. — DOI: 10.1134/S2517751620030051.

10. Liu J. Recyclable magnetic graphene oxide for rapid and efficient demulsification of crude oil-in-water emulsion / J. Liu, H. Wang, X. Li et al. // Fuel. — 2017. — Vol. 189. — p. 79-87. — DOI: 10.1016/j.fuel.2016.10.066.

11. Roostaie T. Performance of biodegradable cellulose-based agents for demulsification of crude oil: Dehydration capacity and rate / T. Roostaie, M. Farsi, M.R. Rahimpour et al. // Sep. Purif. Technol. — 2017. — Vol. 179. — p. 291-296. — DOI: 10.1016/j.seppur.2017.01.036. .

12. Svarovskaya L.I. Bio-inert Interactions in an Oil—Microorganisms System. / L.I. Svarovskaya, A.Y. Manakov, L.K. Altunina et al. — Cham, Switzerland: Springer, 2020. — p. 195-205. — DOI: 10.1007/978-3-030-21614-6_49.

13. Dmitrieva E.S. Polymeric Membranes for Oil-Water Separation / E.S. Dmitrieva, T.S. Anokhina, E.G. Novitsky et al. // A Review. Polymers. — 2022. — Vol. 14(5). — p. 980-1005. — DOI: 10.3390/ polym14050980.

14. Tanudjaja H.J. Membrane-based separation for oily wastewater: A practical perspective / H.J. Tanudjaja, C.A. Hejase, V.V. Tarabara // Water Res. — 2019. — Vol. 156. — p. 347-365. — DOI: 10.10.1016/j.watres.2019.03.021.

15. Shalaby M.S. Recent Aspects in Membrane Separation for Oil/Water Emulsion / M.S. Shalaby, G. Sołowski, W. Abbas // Adv. Mater. Interfaces. — 2021. — Vol. 8. — p. 2100448. — DOI: 10.10.1002/admi.202100448.

16. Lee B. Review on oil/water separation membrane technology / B. Lee, R. Patel // Membr. J. — 2020. — Vol. 30. — p. 359-372. — DOI: 10.10.14579/membrane_journal.2020.30.6.359.

17. Фазуллин Д.Д. Оценка и устранение токсичности нефтесодержащих сточных вод / Д.Д. Фазуллин, Г.В. Маврин, И.Г. Шакиев // Вестник Технологического университета. — 2015. — № 11. — с. 213-216. — DOI: 10.1134/S2218117220030049.

18. Федосов С.В. Моделирование процесса ультрафильтрации с учетом образования осадка на поверхности мембраны / С.В. Федосов, Ю.П. Осадчий, А.В. Маркелов // Мембраны и мембранные технологии. — 2020. — Т.10. — №3. — с. 177-189. — DOI: 10.1134/S2218117220030049.

19. Markelov A.V. Regeneration of ultrafiltration membranes in the process of separating oil-water systems / A.V. Markelov, A.V. Sokolov // ChemChemTech. — 2023. — Vol. 66. — № 1. — p. 114-119. — DOI: 10.6060/ivkkt.20236601.6718.

20. Енаки Г.А. Последующая обработка отработанного ВМЭ Укринол-1 окислением / Г.А. Енаки, В.М. Ткаченко. — Москва: ЦНИИТЭнефтехим, 1977. — с. 122-129.

21. Григорьев Е.И. Использование озона для очистки сточных вод / Е.И. Григорьев, Н.Н. Шишкина, Л.Р. Заинуллина и др. // Вестник Казанского технологического университета. — 2012. — № 21. — с. 99-101.

22. Решняк В.И. Использование озона в процессах очистки маслянистой трюмной (подслойной) воды / В.И. Решняк, А.Е. Пластинин, В.С. Наумов и др. // Морские интеллектуальные технологии. — 2019. — № 4-2 (46). — с. 168-173.

23. Воюцкий С.С. Курс коллоидной химии / С.С. Воюцкий — Москва: Химия, 1975. — 512 с.

24. Фролов Ю.Г. Курс коллоидной химии / Ю.Г. Фролов — Москва: Недра, 1981. — 304 с.

25. Разумовский С.Д. Озон и его реакции с органическими соединениями / С.Д. Разумовский — Москва: Наука, 1974. — 322 с.

26. Патраков Ю.Ф. Расширение сырьевой базы флотационных реагентов за счет использования озонированных отработанных моторных масел / Ю.Ф. Патраков, С.А. Семенова, М.С. Клейн // Вестник Кузбасского государственного технического университета. — 2018. — № 1. — с. 164-168. — DOI: 10.26730/1999-4125-2018-1-164-168.

Список литературы на английском языке / References in English

1. Komarova L.F. Inzhenernye metody zaschity gidrosfery [Engineering methods of hydrosphere protection] / L.F. Komarova, V.A. Somin — Barnaul: AltGTU, 2019. — 283 p. [in Russian]

2. Pervov A.G. Application of membranes to treat wastewater for its recycling and reuse: new considerations to reduce fouling and increase recovery up to 99 percent / A.G. Pervov, A.P. Andrianov // Desalination and Water Treatment. — 2011. — 1. — p. 2-9. — DOI: 10.5004/dwt.2011.3133 .

3. Lukinyh N.A. Metody doochistki stochnyh vod [Methods of wastewater treatment] / N.A. Lukinyh, B.L. Lipman, V.P. Krishtul — Moskva: Strojizdat, 1974. — 96 p. [in Russian]

4. Semenov A.V. Sovremennye reshenija akkumuljatsii i ochistki dozhdevyh i talyh vod [Modern solutions for accumulation and purification of rain and meltwater] / A.V. Semenov, N.S. Latyshev, R.V. Petruk // Water supply and sanitary equipment. — 2023. — 9. — p. 56-60. — DOI: 10.35776/VST.2023.09.09. [in Russian]

5. Kuyukina M.S. Oilfield wastewater biotreatment in a fluidized-bed bioreactor using co-immobilized rhodococcus cultures / M.S. Kuyukina, I.B. Ivshina, M.K. Serebrennikova et al. // Journal of Environmental Chemical Engineering. — 2017. — Vol. 5. — P. 1252–1260. — DOI: 10.1016/j.jece.2017.01.043.

6. Xue J. Tetradecylamine-MXene functionalized melamine sponge for effective oil/water separation and selective oil adsorption / J. Xue, L. Zhu, X Zhu et al. // Sep. Purif. Technol. — 2021. — Vol. 118106. — DOI: 10.1016/j.seppur.2020.118106.

7. Medvedeva I.V. Novye kompozitnye materialy i protsessy dlja himicheskih, fiziko-himicheskih i biohimicheskih tehnologij vodoochistki [New composite materials and processes for chemical, physico-chemical and biochemical water treatment technologies] / I.V. Medvedeva, O.M. Medvedeva, A.G. Studenok et al. // News of higher educational institutions. The series "Chemistry and chemical technology". — 2023. — Vol. 66(1). — p. 6-27. — DOI: 10.6060/ivkkt.20236601.6538. [in Russian]

8. Pavselj N. Experimental Design of an Optimal Phase Duration Control Strategy Used in Batch Biological Wastewater Treatment / N. Pavselj, N. Hvala, J. Kocijanet al. // ISA Transactions. — 2001. — Vol. 40. — p. 41-56. — DOI: 10.1016/S0019-0578(00)00042-2.

9. Pervov A.G. Determination of optimal operation pressure values for ultrafiltration wastewater treatment / A.G. Pervov, K.V. Tikhonov, N.A. Makisha // Membranes and Membrane Technologies. — 2020. — Vol. 2. — № 3. — p. 159-168. — DOI: 10.1134/S2517751620030051.

10. Liu J. Recyclable magnetic graphene oxide for rapid and efficient demulsification of crude oil-in-water emulsion / J. Liu, H. Wang, X. Li et al. // Fuel. — 2017. — Vol. 189. — p. 79-87. — DOI: 10.1016/j.fuel.2016.10.066.

11. Roostaie T. Performance of biodegradable cellulose-based agents for demulsification of crude oil: Dehydration capacity and rate / T. Roostaie, M. Farsi, M.R. Rahimpour et al. // Sep. Purif. Technol. — 2017. — Vol. 179. — p. 291-296. — DOI: 10.1016/j.seppur.2017.01.036. .

12. Svarovskaya L.I. Bio-inert Interactions in an Oil—Microorganisms System. / L.I. Svarovskaya, A.Y. Manakov, L.K. Altunina et al. — Cham, Switzerland: Springer, 2020. — p. 195-205. — DOI: 10.1007/978-3-030-21614-6_49.

13. Dmitrieva E.S. Polymeric Membranes for Oil-Water Separation / E.S. Dmitrieva, T.S. Anokhina, E.G. Novitsky et al. // A Review. Polymers. — 2022. — Vol. 14(5). — p. 980-1005. — DOI: 10.3390/ polym14050980.

14. Tanudjaja H.J. Membrane-based separation for oily wastewater: A practical perspective / H.J. Tanudjaja, C.A. Hejase, V.V. Tarabara // Water Res. — 2019. — Vol. 156. — p. 347-365. — DOI: 10.10.1016/j.watres.2019.03.021.

15. Shalaby M.S. Recent Aspects in Membrane Separation for Oil/Water Emulsion / M.S. Shalaby, G. Sołowski, W. Abbas // Adv. Mater. Interfaces. — 2021. — Vol. 8. — p. 2100448. — DOI: 10.10.1002/admi.202100448.

16. Lee B. Review on oil/water separation membrane technology / B. Lee, R. Patel // Membr. J. — 2020. — Vol. 30. — p. 359-372. — DOI: 10.10.14579/membrane_journal.2020.30.6.359.

17. Fazullin D.D. Otsenka i ustranenie toksichnosti neftesoderzhaschih stochnyh vod [Assessment and elimination of toxicity of oily wastewater] / D.D. Fazullin, G.V. Mavrin, I.G. Shaikhiev // Bulletin of the Technological University. — 2015. — № 11. — p. 213-216. — DOI: 10.1134/S2218117220030049. [in Russian]

18. Fedosov S.V. Modelirovanie protsessa ul'trafil'tratsii s uchetom obrazovanija osadka na poverhnosti membrany [Modeling of the ultrafiltration process taking into account the formation of sediment on the membrane surface] / S.V. Fedosov, Ju.P. Osadchij, A.V. Markelov // Membranes and membrane technologies. — 2020. — T.10. — №3. — p. 177-189. — DOI: 10.1134/S2218117220030049. [in Russian]

19. Markelov A.V. Regeneration of ultrafiltration membranes in the process of separating oil-water systems / A.V. Markelov, A.V. Sokolov // ChemChemTech. — 2023. — Vol. 66. — № 1. — p. 114-119. — DOI: 10.6060/ivkkt.20236601.6718.

20. Enaki G.A. Posledujuschaja obrabotka otrabotannogo VME Ukrinol-1 okisleniem [Post-treatment of spent WOE Ukrinol-1 by oxidation] / G.A. Enaki, V.M. Tkachenko. — Moscow: TsNIITEneftekhim, 1977. — p. 122-129. [in Russian]

21. Grigor'ev E.I. Ispol'zovanie ozona dlja ochistki stochnyh vod [The use of ozone for wastewater treatment] / E.I. Grigor'ev, N.N. Shishkina, L.R. Zainullina et al. // Bulletin of the Kazan Technological University. — 2012. — № 21. — p. 99-101. [in Russian]

22. Reshnjak V.I. Ispol'zovanie ozona v protsessah ochistki masljanistoj trjumnoj (podslojnoj) vody [The use of ozone in the purification processes of oily bilge (sublayer) water] / V.I. Reshnjak, A.E. Plastinin, V.S. Naumov et al. // Marine intelligent technologies. — 2019. — № 4-2 (46). — p. 168-173. [in Russian]

23. Vojutskij S.S. Kurs kolloidnoj himii [Course of colloidal chemistry] / S.S. Vojutskij — Moskva: Himija, 1975. — 512 p. [in Russian]

24. Frolov Ju.G. Kurs kolloidnoj himii [Course of colloidal chemistry] / Ju.G. Frolov — Moskva: Nedra, 1981. — 304 p. [in Russian]

25. Razumovskij S.D. Ozon i ego reaktsii s organicheskimi soedinenijami [Ozone and its reactions with organic compounds] / S.D. Razumovskij — Moskva: Nauka, 1974. — 322 p. [in Russian]

26. Patrakov Ju.F. Rasshirenie syr'evoj bazy flotatsionnyh reagentov za schet ispol'zovanija ozonirovannyh otrabotannyh motornyh masel [Expansion of the raw material base of flotation reagents through the use of ozonated used engine oils] / Ju.F. Patrakov, S.A. Semenova, M.S. Klejn // Bulletin of the Kuzbass State Technical University. — 2018. — № 1. — p. 164-168. — DOI: 10.26730/1999-4125-2018-1-164-168. [in Russian]