Equipment for Oilfield Wastewater Treatment Using Swirling Flows

Oleksandr Liaposhchenko[1] (✉), Viktor Moiseev[2], Oleksandr Starynskyi[1], Eugenia Manoilo[2], and Houssein Seif[1,3]

[1] Sumy State University, 2, Rymskogo-Korsakova Street, Sumy 40007, Ukraine
o.liaposhchenko@pohnp.sumdu.edu.ua
[2] National Technical University «Kharkiv Polytechnic Institute», 2, Kyrpychova Street, Kharkiv 61002, Ukraine
[3] AlKhorayef Company For Sale, Maintenance & Repair of Oil Production Equipment LLC, Yaal Tower & Mall, 16th Floor, P.O. Box 46813, 64019 Fahaheel, Kuwait

Abstract. Installations for the treatment of oilfield wastewater have been developed. The article presents a solution to hydrocyclone installations for the treatment of oilfield wastewater based on the use of swirling flows. Due to the centrifugal forces in the hydrocyclone and the turbulent water movement, the armor shells of oil droplets are destroyed, enlarged, and the monodispersity increases. The forces acting in the hydrocyclone are considered, and the efficiency of centrifugal forces in separating solid particles is estimated. The main parameters and requirements for the quality of oilfield wastewater are given, recommended for calculation in developing new and improving existing oilfield wastewater treatment plants for oil reservoir flooding, which allows increasing oil recovery by 1,5–2 times. Improving the systems of field preparation of products includes developing new effective technical means, including hydrocyclones and the improvement of traditionally used equipment. Hydrocyclone can be used as the main element in the wastewater treatment system. The regime is observed, in which there is no over-dispersion of the remaining oil in the water (water in oil). Thus, the device implements a mechanism for separating light (oil, gas) and heavier fractions (sediment, water, oil).

Keywords: Oilfield wastewater · Hydrocyclone · Separation · Swirling stream · Hydrodynamic treatment · Filter

1 Introduction

The oil and gas industry is one of the most environmentally dangerous subsurface use industries and causes huge damage to the environment. It is characterized by a high energy intensity and significant pollution of vast territories. Subsurface protection provides for implementing a set of measures to prevent oil and gas losses, ensure the population's safety, rational use of surface and underground waters, and prevent their pollution. Petroleum products and reservoir water are the main environmental pollutants

V. Ivanov et al. (Eds.): DSMIE 2021, LNME, pp. 237–246, 2021.
https://doi.org/10.1007/978-3-030-77823-1_24

in this area. Reservoir water released to the surface changes the microrelief of the territory and is a source of secondary salinization of soils around oil wells. They have high geochemical activity and toxicity. They contain petroleum hydrocarbons, various salts, and mechanical impurities, which, being absorbed by the soil and entering the groundwater, dramatically change their chemical and physical properties – salt composition, alkalinity, the reaction of soil suspensions, soil-absorbing complex, disrupt the water-air regime and carbon-nitrogen balance.

2 Literature Review

The environmental consequences of oil spills are always difficult to predict. It is impossible to consider all the ecological consequences that disrupt all-natural processes and relationships in the environment.

Based on [1, 2] in oil and gas deposits, the distribution of liquids occurs according to their densities. The topmost part of the reservoir is occupied by free gas; just below lies oil, and the lowest layer of the reservoir is reservoir water, which in its own way supports the oil reservoir. In nature, reservoir mineralized water in deposits is located in the water zone and other layers, thereby saturating the productive rocks of the deposit [3].

In oil fields, in the process of oil production, the extracted reservoir water is separated from the oil at oil treatment plants and is a liquid oil-containing waste. Reservoir water (80–95%), rainwater runoff (1–3%), and industrial runoff (4–15%) form oilfield wastewater. Oil in oilfield wastewater is in the dissolved, emulsified, and free (floating) states. In addition to oil, oilfield wastewater contains mechanical impurities (drilled rock, corrosion products, etc.) and dissolved gases (nitrogen, hydrogen sulfide, methane, oxygen). In the process of wastewater cleaning, mechanical impurities (suspended solids), floating and emulsified oil, and substances used in oil extraction technology from the well are removed. Dissolved oil practically does not have any effect on the pick-up rate of injection wells.

When developing oil wells, the technology of injecting produced water into the well to maintain pressure is used. More than 90% of oilfield wastewater is used for flooding oil reservoirs. Flooding of oil reservoirs allows increasing oil recovery by 1,5–2 times. [4, 5].

The current scheme of pumping wastewater back into the reservoir at oil fields with the addition of reagents to increase oil recovery leads to a significant change in the chemical composition of reservoir waters, which affects the subsurface state. It creates a threat of spreading pollution to other aquifers.

In solving this problem, one of the main tasks is to purify oil-containing reservoir wastewater to achieve stable characteristics of the natural environment with acceptable parameters of contamination and possible extraction of valuable commodity components from recycled water.

Oilfield wastewater has a suspension-emulsion character. They contain a significant amount of dissolved mineral salts, which can pass into the oil phase. Studies on the mineral composition of reservoir waters show that mainly sodium, calcium, and magnesium chloride are distributed among the dissolved substances. Depending on the deposits, the formation water contains salts of alkaline and alkaline earth metals, particularly iodic and bromide, iron, sodium, calcium sulfides, and others.

As dispersed phases of wastewater, oil droplets and solid rock suspensions removed from the formation can serve as droplets of oil and solid rock suspensions. When extracted from the subsurface, reservoir water in an emulsified state practically does not contain any contamination (impurities do not exceed 10–20 mg/L).

After the separation of the emulsion into oil and water, the content of dispersed particles in the separated water increases significantly - oil up to 4–5 g/L, mechanical impurities up to 0,2 g/L. The gas content of reservoir water does not exceed 1,5–2.0 mg/t, it is usually equal to 0,2–0,5 mg/t. Methane, nitrogen, carbon dioxide, methane homologues, helium, and argon are mainly represented as water-soluble gases in reservoir water [6]. The condition of the armoring shells on oil droplets determines the methods of their destruction and cleaning of the oilfield wastewater. More clearly, all physical properties are determined by depth samples. In the absence of deep samples, these physical properties are determined by reference books and graphs.

When extracting oil from the reservoir, the properties and parameters of fluids, reservoir water quality, and the state of the oilfield equipment change. After oil treatment plants, oilfield wastewater is pre-treated from oil and mechanical impurities and is pumped into the oil reservoir, without disturbing its pick-up rate, through injection wells.

The biggest problem in the oil and gas industry remains the treatment of reservoir water and oilfield wastewater. Their disposal is an urgent problem for all production facilities of the oil and gas industry. The relevance is because reservoir water as an aggressive component causes intense corrosion of oil production equipment, accompanied by the spillage of reservoir water, causing salinization of the soil cover and groundwater during seepage and the death of vegetation. As a result of a reservoir water spill, a certain amount of oil is also received along the way, amounting to tens of tons per year. Reservoir waters have many toxic components in their composition.

3 Research Methodology

The difficulty of cleaning up oilfield wastewater at the leaching site is that mechanical impurities and oil exist together and not separately. All mechanical impurities are wetted with oil. At the oil-water interface, a highly concentrated coarse-dispersed intermediate layer emulsion is formed. The concentration of mechanical impurities is many times higher than their concentration in oil or water. When this layer is destroyed, depending on the density of the coagulated complex, either its deposition or surfacing will occur in the settling tank; when pumping purified water into injection wells, the impurities remaining in the water after purification are emulsified films of destroyed structures of intermediate layers. Thus, oilfield wastewater is polydisperse, multiphase, and represents a suspension-emulsion system.

Under the treatment of waste, reservoir water is the treatment of reservoir water to destroy or remove harmful substances from them. In turn, treating waste formation mineralized water from pollutants is a very complex production and a serious problem. In this production, as in any other production, there are raw materials (reservoir mineralized water) and finished products (purified water).

Mechanical and hydro-mechanical processes carry out oilfield wastewater purification: mixing, settling, centrifugation, and filtration to destroy the armor shells on oil droplets, a coalescence of oil droplets, and removal of a partially concentrated oil phase and sediment (mechanical impurities) [7, 8]. For the treatment of reservoir wastewater [9] in the oil industry, the method of settling in settling tanks is used. But this method often does not provide the necessary degree of cleaning. Therefore, tanks with agitators, settling tanks, separators, centrifuges, hydro-cyclones, drop-forming units, flotators, and filters are also used as equipment [10].

To successfully purify oilfield wastewater to quickly reduce the aggregative and kinetic stability of oil droplets, oilfield wastewater purification units and devices are developed that increase the effect, depth, and speed of the purification process [11, 12]. Due to this, oil droplets are rapidly enlarged, the coalescence process - a polydisperse system turns into a monodisperse one.

These processes are carried out most fully and intensively with a pre-determined degree of turbulization of the flow of oilfield wastewater in the cavities of various hydrodynamic droplet generators with subsequent settling. A high and stable effect of cleaning oilfield wastewater can be achieved by pre-hydrodynamic treatment in a swirling stream.

For effective destruction, consolidation, reduction of polydispersity, and increase of monodispersity of oil droplets, oilfield wastewater treatment plants are being created due to hydrodynamic treatment of wastewater in swirling streams [13, 14]. One of the promising directions for improving water treatment systems is hydrocyclones in them [15, 16].

In separation equipment, the armor shells are destroyed, the oil droplets are fragmented and coalesced, i.e., the monodispersity increases. Due to hydrodynamic treatment of the swirled flow, a high and stable effect of swirling cleaning is achieved in all areas of the swirled flow, i.e., the swirling flow is expanded, the swirled flow is properly damped, etc. The flow energy is used for the most effective implementation of the mechanism of destruction of oil emulsions.

But it should be noted that non-pressure hydrocyclones are intended only for the separation of oil from the water, which is in the form of a film or layer on a free surface, i.e., they perform the functions of collecting oil from the surface. Separation of oil droplets from water in an emulsified state is performed in cylindrical counter-current hydrocyclones of small-diameter [17, 18].

The treated water, entering the hydrocyclone through the tangential inlet, receives a rotational movement. Under the influence of the resulting centrifugal force, which exceeds the force of gravity by hundreds or thousands of times, the particles of impurities are thrown into the external downward flow, which moves in a spiral to the lower discharge port.

The use of hydrocyclones as stages for wastewater treatment can significantly increase the compactness of the entire treatment scheme and facilitate its operation. For water purification from oil and suspended substances, depending on the required degree of purification, the devices shown in Fig. 1 are used:

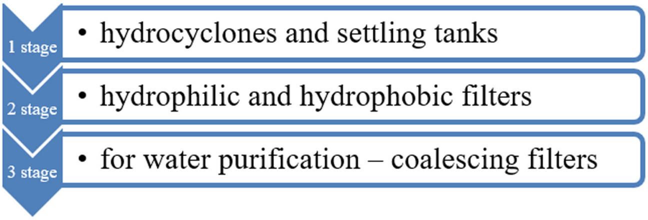

Fig. 1. The water purification devices.

The separation mechanism of the three-phase system in hydrocyclones is as follows: solid particles under the action of centrifugal force move to the walls of the hydrocyclone and along a helical trajectory move down to the lower outlet, through which they are removed from the hydrocyclone. The efficiency of water purification from oil depends on the design of the hydrocyclone and varies from 84 to 89%. Recommended parameters of the hydrocyclone: diameter of the cylindrical part 75 mm; diameter of the inlet port 15 mm; diameter of the axial port 10 mm; diameter of the discharge port 20 mm; taper angle 10 °C; inlet liquid pressure 0,17 MPa.

The productivity of a hydrocyclone is determined by the formula [19]:

$$Q = 28{,}5 d_0 d\sqrt{P/\alpha^{0,1}} \tag{1}$$

where $d_{o,}d$ – diameters of the feed and discharge pipes; P – pressure at the inlet to the hydrocyclone; $\alpha\alpha$ – the angle of taper.

Hydrocyclones operate with a higher hydraulic load than gravity settling tanks, but their productivity is low. Therefore, they are combined into batteries or multicyclones.

Separation of liquid suspensions by precipitation of mechanical impurities in a centrifugal field is carried out in cases when the density difference between the solid and liquid phases is positive ($\Delta\rho = \rho_S - \rho > 0$). Suppose a complex system contains, in addition to liquid (water) and solid phases, light floating components (oil, oils, gas bubbles), then for such a system. In that case, the density difference of the liquid and light phases is also positive ($\Delta\overline{\rho} = \rho - \rho_L > 0$). The centrifugal force is created either a due tangential injection of the suspension (hydrocyclones, vortex separators), r by untwisting a liquid located in a rotating rotor (centrifuges).

On a solid phase particle located in a centrifugal field at the current (selected) radius r, except for the gravitational force $F_g = m_S g$, and the Archimedean force:

$$F_a = m\omega^2 r = \rho\omega^2 r \cdot \frac{\pi d^3}{6}, \tag{2}$$

the centrifugal force acts

$$F_{cen} = m_s\omega^2 r = \rho_s\omega^2 r(\pi d^3/6) \tag{3}$$

Here $m_S = (\pi d^3 \rho_S)\backslash 6$ – the mass of the solid particle; m – the group of the liquid; d – the diameter of the solid particles; ω – the angular velocity of rotation of the particle.

Moreover, $\omega^2 r = a_r$ is the radial acceleration in the field of centrifugal forces.

The gravitational force is significantly less than the centrifugal force, as can be seen from the ratio

$$K_p = \frac{F_{cen}}{F_g} = \frac{mV_\tau^2}{r} : mg = \frac{V_\tau^2}{gr} = \frac{4(\pi n)^2 r}{g} \tag{4}$$

where K_p is the separation factor, which characterizes the ratio of centrifugal force to gravity; $V_\tau = 2\pi nr$ – circumferential (tangential) speed of the particle at the radius of rotation r; n – rotational frequency (rpm) of a particle in 1 s around the axis of rotation.

The multihydrocyclone can be used as the main element in the wastewater treatment system, provided that the regime is observed, in which there is no over-dispersion of the remaining oil in the water (water in oil), i.e., the acceleration of movement does not exceed the value of 1000 g. The device implements a mechanism for separating light (oil, gas) and heavier fractions (water, oil).

4 Results

Two main mechanisms are implemented separately or in combination in the currently used wastewater treatment units and devices in the fisheries: separation in the natural field of gravity or centrifugal forces and the flotation effect.

Both mechanisms are relatively low-cost because they use natural energy (flow or phase interaction), which is especially important in the conditions of a large volume of the processed medium. Hydrocyclones allow achieving a sufficient degree of wastewater treatment for their use in the reservoir pressure maintenance system.

The necessary deep-water purification can be achieved using multi-stage technology, including coarse and fine cleaning, post-treatment, and disinfection. Technological schemes of oilfield water treatment for use in the pressure maintenance system include the following main elements: settling tanks, coalescing-hydrophobic filter, arc discharge chamber, granular filter, electrochemical filter, UV emitters, hydrophobic filter [20, 21], which indicates a wide variety of technical means and methods. This characterizes the ways of development of cleaning systems, which include both the development and implementation of new technologies and equipment, including multihydrocyclone designs that serve for fine and coarse cleaning. Multihydrocyclones make it possible to achieve a deep degree of purification. Their use is promising both in the system of field wastewater treatment and in systems of preliminary water discharge.

Hydrocyclones have wide possibilities of using them in the good product preparation system as devices that intensify the process at the stages of primary separation of oil gas and water, stabilization and purification of oil from dissolved gases mercaptans, and wastewater treatment cannot become the only device used. Therefore, improving the systems of field preparation of oil well products includes developing new effective technical means, including multihydrocyclones, and the improvement of traditionally used equipment.

It is advisable to treat oil-containing wastewater for reuse following the scheme below.

The oil-containing wastewater flows into a receiving tank (sometimes into a pre-sump). The wastewater is then sent for treatment by pumps, particularly to pressure hydrocyclone, in which large (mechanical) impurities are separated and dumped into a hopper. After passing through cylindrical-conical hydrocyclones, thin-layer settling tanks, wastewater enters cylindrical hydrocyclones for purification from petroleum products. After hydrocyclones, the purified water is sent to flotators, coalescing, or sorption filters. If necessary, the final purification of water in the sorption filter to the content of petroleum products of 0.05 mg/L is possible (Fig. 2).

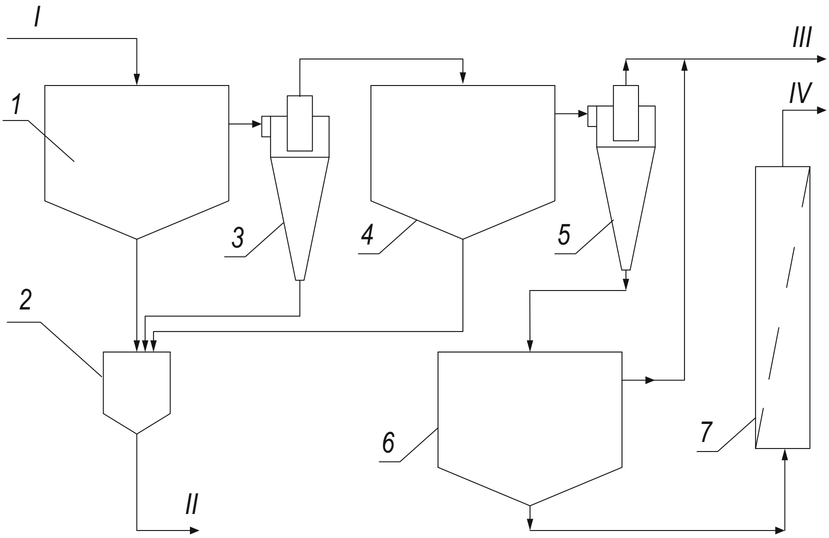

Fig. 2. The wastewater unit principal scheme: 1 – reservoir sump; 2 – sediment collector; 3 – hydrocyclone for separation of suspended solids; 4 – thin-layer sump; 5 – hydrocyclone for oil separation (SPR-separator); 6 – sump; 7 – fine filter. I – oil-containing wastewater; II – sediment; III – petroleum products; IV – treated water to the pressure maintenance system.

The treated water is returned to the well to maintain reservoir pressure. The cleaner the water being pumped into the formation, the greater the injection capacity of the injection well and the lower the required amount of water. The lower the costs associated with the pressure maintenance system (Fig. 3).

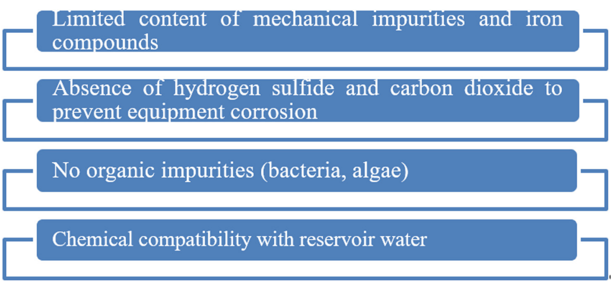

Fig. 3. The general requirements for pumped water.

The degree of oilfield wastewater purification is determined individually for each oil well. As discussed above, the difficulty lies in separating emulsified oil and coarse-dispersed emulsion from water. The content of oil and mechanical impurities in the treated wastewater of oil fields exceeds the standards defined by industry standards, which set out the requirements for the quality of water used for flooding oil reservoirs, depending on the properties of the reservoir. The increased content of oil and suspended substances in the water injected into the formation leads to incomplete oil recovery from the well. The permissible content of mechanical impurities is 3 mg/dm^3, and petroleum products - 5 mg/dm^3. The presence of mechanical impurities is one of the main factors that cause a decrease in the permeability of the bottom hole formation zone when using both fresh and reservoir waters.

Intense hydrodynamic regime creation can avoid the separation of emulsified oil problems [22]. In addition, in this case, such effects as the film formation on the separation surfaces, etc., may occur [23]. The SPR-separator with a spiral packing (turbo-spiral), which ensures a high intensity of the separation process, was considered in [24]. The turbo-spiral is designed to direct the incoming flow in the radial direction by centrifugal forces. As a result of the study, a method of the SPR separator numerical simulation was proposed. It allows determining the main hydrodynamic parameters of the separation process, separation efficiency, hydraulic resistance, the magnitude, and direction of the dispersed phase velocities, etc. The results of the numerical simulation point out that the action of centrifugal forces are provided separation efficiency. The separation efficiency was calculated using the dependence and its compounds. The usage of this separators type at the separating oil products stage may significantly increase the degree of wastewater treatment and the intensity of the presented unit.

5 Conclusions

Modern industrial methods of oil field development require new equipment with a high cleaning effect and a single capacity, tightness, and ease of factory manufacture and installation. As shown by technical and economic comparisons, the introduction of cylindrical counter-current hydrocyclones can produce a significant economic effect. Simultaneously, the amount of capital investment for the construction of treatment facilities is reduced several times, and operating costs are reduced by 15%, improving the sanitary and environmental conditions of operation of the plant.

No less important advantage of the scheme with hydrocyclones is significant space savings. In this case, the area occupied by the hydrocyclone installation is 10 times less than the area that would be required for the placement of settling tanks for a similar purpose. This indicator is often the main and determining factor when choosing a particular method of wastewater treatment.

Thus, to protect the environment from reservoir water pollution, the following measures are necessary: ensuring deep treatment of oilfield wastewater; extensive use of anti-corrosion coatings and chemical reagents for corrosion protection of oil-producing equipment; full sewage use obtained in the field in the reservoir pressure maintenance system; monitoring of the state of surface water and the quality of wastewater used in the reservoir pressure maintenance system.

The future is to conduct numerical and physical studies of hydrocyclone equipment to aim for technological and design optimization. Optimal operating parameters determination of a hydrocyclone for wastewater treatment and implementation of the results into production.

Acknowledgment. The developed methodology was realized within the research projects "Development and Implementation of Energy Efficient Modular Separation Devices for Oil and Gas Purification Equipment" (State reg. No. 0117U003931), and "Creation of new granular materials for nuclear fuel and catalysts in the active hydrodynamic environment" (State reg. No. 0120U102036) ordered by the Ministry of Education and Science of Ukraine.

References

1. Baklouti, S., et al.: Surface geochemical prospection for hydrocarbons in the oriental platformmath semicolon the case of Guebiba oilfield, Sfax region, Tunisia. J. Petrol. Sci. Eng. **159**, 830–840 (2017)
2. Machowski, R., Rzetala, M.A., Rzetala, M., Solarski, M.: Anthropogenic enrichment of the chemical composition of bottom sediments of water bodies in the neighborhood of a nonferrous metal smelter (Silesian Upland, Southern Poland). Sci. Rep. **9**(1) (2019)
3. Arefieva, O., Nazarkina, A.V., Gruschakova, N.V., Skurikhina, J.E., Kolycheva, V.B.: Impact of mine waters on the chemical composition of soil in the Partizansk Coal Basin, Russia. Int. Soil Water Conserv. Res. **7**(1), 57–63 (2019)
4. Muggeridge, A., et al.: Recovery rates, enhanced oil recovery and technological limits. Philos. Trans. Royal Soc. A Math. Phys. Eng. Sci. **372**(2006), 20120320 (2014)
5. Ding, L., Wu, Q., Zhang, L., Guérillot, D.: Application of fractional flow theory for analytical modeling of surfactant flooding, polymer flooding, and surfactant/polymer flooding for chemical enhanced oil recovery. Water **12**(8), 2195 (2020)
6. Du, J.F., Xiao, C., Guo, P., Shen, X.Y.: Study of gas-water properties under high temperature and pressure for water-soluble gas reservoirs. Toxicol. Environ. Chem. **97**(3–4), 306–313 (2015)
7. Vehmaanperä, P., Safonov, D., Kinnarinen, T., Häkkinen, A.: Improvement of the filtration characteristics of calcite slurry by hydrocyclone classification. Miner. Eng. **128**, 133–140 (2018)
8. Pecarevic, M., Mikus, J., Prusina, I., Juretic, H., Bratos, A., Cetinic, Brailo, M.: New role of hydrocyclone in ballast water treatment. J. Clean. Prod. **188**, 339–346 (2018)
9. Huliienko, S.V., Korniienko, Y.M., Metlina, M.S., Tereshenko, I.Y., Kaminskyi, V.S.: The correction of the dimensionless equation for the mass transfer coefficient estimation during the membrane modules regeneration. J. Eng. Sci. **7**(2), F24–F29 (2020). https://doi.org/10.21272/jes.2020.7(2).f4
10. Kharoua, N., Khezzar, L., Nemouchi, Z.: Hydrocyclones for de-oiling applications - a review. Pet. Sci. Technol. **28**(7), 738–755 (2010)
11. Sabbagh, R, Lipsett, M.G., Koch, C.R., Nobes, D.S.: Theoretical and experimental study of hydrocyclone performance and equivalent settling area. In: Proceedings of the ASME 2014 International Mechanical Engineering Congress and Exposition, vol. 7: Fluids Engineering Systems and Technologies, Montreal, Quebec, Canada (2014)
12. Yang, Q., Wang, H., Liu, Y., Li, Z.: Solid/liquid separation performance of hydrocyclones with different cone combinations. Sep. Purif. Technol. **74**(3), 271–279 (2010)

13. Lv, W., Chen, J., Chang, Y., Liu, H., Wang, H.: UU-type parallel mini-hydrocyclone group separation of fine particles from methanol-to-olefin industrial wastewater. Chem. Eng. Process. Process Intensification **131**, 34–42 (2018)
14. Lv, W., et al.: UU-type parallel mini-hydrocyclone group for oil-water separation in methanol-to-olefin industrial wastewater. Chem. Eng, Process. Process Intensification **149**, 107846 (2020)
15. Syarifah, I., Nazirah, W., Norhaniza, Y., Farhana, A., Nurasyikin, M.: A review of oilfield wastewater treatment using membrane filtration over conventional technology (2017)
16. Ghnainia, L., Eloussaief, M., Zouari, K., Abbes, C.: Wastewater treatment in petroleum activities: example of "SEWAGE" unit in the BG Tunisia Hannibal plant. Appl. Petrochem. Res. **6**(2), 155–162 (2016). https://doi.org/10.1007/s13203-015-0143-9
17. Jiang, L., et al.: Effect of overflow pipe on the internal flow fields and separation performance of W-shaped hydrocyclones. Minerals **10**(4), 329 (2020)
18. Yu, J., Fu, J.: Separation performance of an 8 mm mini-hydrocyclone and its application to the treatment of rice starch wastewater. Sep. Sci. Technol. **55**(2), 313–320 (2019)
19. Bauman, A.V.: Hydrocyclones. Theory and practice. B29 Agency «Sibprint», Novosibirsk (2020)
20. Liu, Z., et al.: Facile method for the hydrophobic modification of filter paper for applications in water-oil separation. Surf. Coat. Technol. **352**, 313–319 (2018)
21. Du, Y., Li, Y., Wu, T.: A superhydrophilic and underwater superoleophobic chitosan-TiO2 composite membrane for fast oil-in-water emulsion separation. RSC Adv. **7**(66), 41838–41846 (2017)
22. Liaposhchenko, O., Pavlenko, I., Ivanov, V., Demianenko, M., Starynskyi, O., Kuric, I., Khukhryanskiy, O.: Improvement of parameters for the multi-functional oil-gas separator of "HEATER-TREATER" Type. In: 2019 IEEE 6th International Conference on Industrial Engineering and Applications (ICIEA), pp. 66–71 (2019). https://doi.org/10.1109/IEA.2019.8715203.
23. Pavlenko, I., et al.: Three-dimensional mathematical model of the liquid film downflow on a vertical surface. Energies **13**(8), 1938 (2020). https://doi.org/10.3390/en13081938
24. Liaposhchenko, O., Pavlenko, I., Demianenko, M., Starynskyi, O., Pitel, J.: The methodology of numerical simulations of separation process in SPR-Separator. In: CEUR Workshop Proceedings, pp. 822–832 (2019)