Simulation of oil products separation from fibrous sorbent material centrifugally

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The paper deals with ecotechnology on the example of the process of separating the fibre sorbent material from oil products by the centrifugal method for the mining industry. For mathematical modelling of the process of centrifugal separation of oil-containing products from fibrous sorbent unit, a problem of finding how the productivity of the process depends on the radius of the centrifuge perforated drum, transverse dimensions of sorbent units, drum angular speed, a viscosity of the fluid and nominal diameter of a capillary, was solved. The basic assumption in the problem solution was that the fibrous sorbent units are considered as a set of cylindrical capillaries of a certain length and diameter arranged radially. It is also believed that every capillary is initially completely and uniformly filled with a liquid. It is found that the productivity of the process significantly increases with increasing the average diameter of the fibres forming the fibrous sorbent article, and also with increasing radius and angular speed of the centrifuge perforated drum and reducing the transverse dimension of the fibrous sorbent unit. It was made an experimental stand of centrifugal separation plant for oil products from fibrous sorbent material. The use of this method will increase the efficiency of combating oil pollution for the mining industry.

Key words: *ecotechnology, oil products, sorbent units; separation of liquid; centrifugal method; regeneration process*

1. Introduction

Crude oil has a noticeable negative impact on the ecosystems of the geosphere and the hydrosphere. The effect is mainly related to the extraction, transporting and processing of oil. Regardless of the development and employment of low-waste technologies in oil refineries; upgrading of petroleum production technology; improvement of the processes for storage and transportation of oil and petroleum products; advanced activities for localization and elimination of accidental spills, as a whole pollution of water reservoirs with crude oil remains dangerously high (Angelova, 2011).

Oily wastewater is one of the environmental concerns today. As one of the most important global sources of energy and raw material for industries, any oil spillage or inefficient extraction implies not only environmental issues but also an economic loss (Akhzat et al., 2006). By now, various technologies, such as absorption, filtration, membrane technology and physical, mechanical, biological and photochemical method were proposed for oily wastewater treatment (Yim et al., 2012) and (Han et al., 2015). The most common way is done by absorption or filtration using porous sorbents (Zhang et al., 2014). A large number of synthetic polymers including polypropylene, polyester, polyurethane and various acrylic and olefin resin have been reported as the oil sorbents with high capacity of oil absorption (Sabir, 2015) and (Haoyi et al., 2014).

The use and transport of crude petroleum and petroleum products have led to an increasing amount of spillages of various scales. Petroleum-spills may contaminate large areas of the sea, as well as the shores where it is eventually washed up. This can cause major environmental problems due to the toxicity of many compounds in petroleum to aquatic organisms, birds and humans (Lin et al., 2012) and (Wu et al., 2014). Moreover, the toxic volatile constituents of petroleum spills can evaporate and as a consequence, cause atmospheric pollution. Thus, clean-up of petroleum spills from the water surface is an important task. Different methods can be used for the removal of petroleum from the water surface, for example, thermal, biological, mechanical and physicochemical (using coagulants and adsorbent materials) techniques (Sayed, Zayed, 2006) and (Gammound et al., 2007). So far, removing of petroleum spills by adsorbent materials is the most safety and effective processes (Ray et al., 2008) and (Flegner et al., 2015).

Environmental contamination occurs during oil and gas production as oil is transferred to the environment by transportation, refining, and use (Ibrahim, Wang, 2010) and (Banerjee et al., 2006). Oil is usually removed

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from wastewater before discharge to the environment to meet the maximum allowable limit of oil and grease in water as required by local enforcing agency (Šoltés, Harčáriková, 2015).

Topical issue of ecotechnology is the collection of oil pollution, and then separating the fibrous sorbent material from oil products. The process of regeneration of fibrous sorbent units by the use of a centrifugal method is described as follows. Saturated with oil or oil product fibrous sorbing material shaped like a boom cylinder or pad is placed in a perforated cylindrical drum (Sviatskii et al., 2015) and (Sviatskii et al., 2016). Depending on the size of the drum, several units can be loaded as one portion. The drum, which axis is placed vertically, is rotated. Because of centrifugal forces the liquid, seeping between elementary fibres, moves toward the peripheral surface of the drum and leaves the drum through the formed therein set of small-diameter holes, accumulating in a reservoir.

To establish engineering methods for calculation and design of arrangements for the regeneration of oil-saturated fibrous sorbent units by means of the centrifuging process, it is necessary to relate the main technical characteristics of the centrifugal arrangements with the properties of the fibrous sorbent units and liquids subjected to separation.

A similar problem, how to evaluate the effectiveness of a centrifugal drying of timber, has been solved by Oti Moto P.M. (Oti Moto, 2006), (Oti Moto, 2007) and (Oti Moto, 2014). In the recent research the structure of a real unit, moisture from which removes under the action of centrifugal force, is simulated by a set of cylindrical capillaries, which greatly simplifies the solution of our problem. In our case, the sorbing elementary fibres are randomly intertwined. Hence the openings between them, filled with a liquid during the adsorption process, are of not regular geometry. This will require making some assumptions that simplify the rigour analytical solution but will lead to greater, than in (Sviatskii et al., 2015), (Sviatskii et al., 2016) and (Oti Moto, 2007) calculation error compared with the experimental data.

The paper (Straka, 2014) investigated potential reactive materials for the removal of heavy metals from contaminated water.

In the most widespread technologies existing today, the spinneret way is used for fibre creation. This method manages to get a fibre diameter of approximately 0.05 mm, but their weak point is the high production costs. Patented production method allows to obtain a fibre diameter of 0,01 - 0,02 mm and thinner for a fraction of the traditional cost (Inotomsk.ru, 2016). Therefore, the proposed sorbent is composed of finer fibres, having a very high surface area and, respectively, higher absorption capacity. He surpasses the existing Russian and world analogues in oil intensities and health.

The proposed highly effective sorbent - a synthetic fibrous material made on TU-2282-001-49396305-99 from the source of raw materials: goods polypropylene, polyethene terephthalate, waste products of polypropylene and polyethene terephthalate. The sorbent is a fine-fibred such vata mass. Colour from light grey to dark grey (colourless raw materials). The bulk density of the sample fibrous materials is between 160 and 174 kg/m at porosity from 81 % to 81.5%.

It is designed for the production of filter materials and other products for cleaning of water, air and soil from pollution with oil products, heavy metals. The material is recovered, its properties are completely restored after mechanical pressing, which can be repeated up to 50 times. Collects amount of pollution, by mass up to 12 times of its weight. Much easier to water and floats on its surface. Unlike similar materials can be used at temperatures below zero.

Installation for producing fibrous polymeric sorbent contains extruder with a rotating fibre maker, site of deposition of the finished product and a receiving device that allows you to implement a «melt blowing» - drag dispersion of polymer melt from a number of polypropylene, polycarbonate, polyethylene terephthalate.

The patented production method involves 90% use standard equipment for processing waste, which results in a considerably lower cost of production and allows to offer this product to the end consumer at a relatively cheap price. So here is an opportunity to save costs and to preserve competitive advantages. Sorbents can be manufactured in various forms: in the form of rolls, cushions, bags, mats and so on, depending on the characteristics and needs of the customers. When placing sorbent on the contaminated surface water, oil is absorbed by the structure of the fibres and the water starts, thus, the buoyancy of the sorbent is improving.

Adsorbent on base of fibrous polymer materials (VPM) is intended for manufacturing of filtering and absorbing elements for purification of water, collect petroleum products from the surface of water basins and polluted by oil and petroleum areas. As the material is hydrophobic, it will absorb oil, repelling water, and will always remain afloat, which is important when collecting oil from the water area. Adsorbent can be applied as a constituent element of the boom, able not only to solve the problem of localization of oil spill and oil products on water surface, but also prevent their loss due to the absorption capacity of the adsorbent and the possibility of subsequent separation of hydrocarbons by the method of mechanical squeezing or centrifugation. The advantages of this product include low cost, high sorption capacity and full utilization when used in road construction without causing damage to the environment. Adsorbent can also be used as a highly efficient filtration component in the structure of complete devices in the systems of circulating water supply (Inotomsk.ru, 2016).

The research results will help to deal effectively with the removal of oil products from water pumped from the mine during mining operations, with industrial water purification, used in the repair and production of mineral resources and the refining of surface water and groundwater when accidents occur, etc.

2. Material and methods

A graphical model of fibrous sorbent units regeneration by the centrifugal method is shown in Figure 1. At this stage of our research, the task was to determine the dependence of the process productivity G of separation of liquid from the fibrous sorbent unit centrifugally in terms of effective radius R_2 of centrifuge perforated drum, the transverse dimension of the sorbent unit $L = R_2 - R_1$, drum angular speed ω, the viscosity of the sorbed fluid η, and capillary diameter d_c.

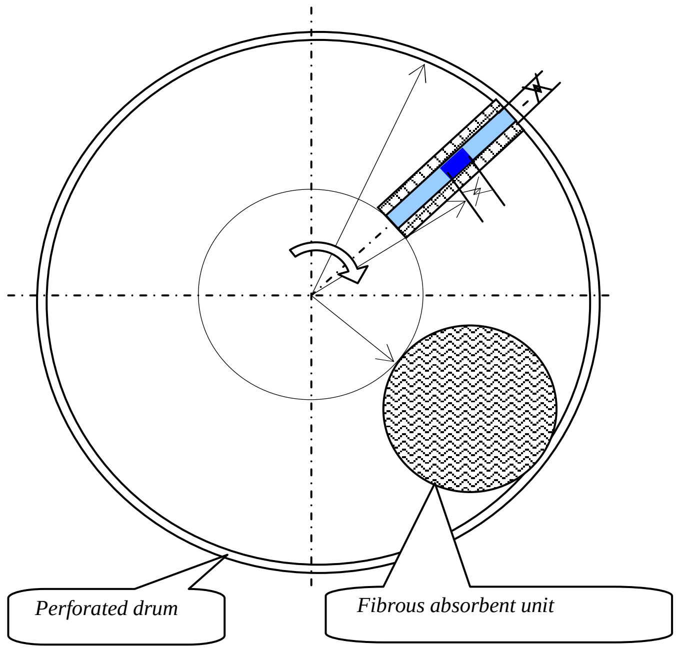

Fig. 1. Graphical model of regeneration process.

The basic assumption in the problem solution is that the fibrous sorbent unit under regeneration is considered as a set of cylindrical capillaries of length L and diameter d_c, arranged radially. We also assume that initially every capillary is completely and uniformly filled with liquid.

Considering an elementary liquid column of diameter d_c and height d_r taken at a distance r from the axis of rotation of the drum, we determine the centrifugal force acting on it:

$$dF_c = dm_l \omega^2 r \tag{1}$$

where mass dm_l of an elementary column of liquid is defined as the product of its volume by the density ρ_l of liquid

$$dm_l = 0.25 \rho_l \pi d_c^2 dr \,. \tag{2}$$

Substituting (2) in (1), we have:

$$dF_c = 0.25 \rho_l \pi d_c^2 \omega^2 r dr \,. \tag{3}$$

After integration of the expression (3) in the limits R_1 and R_2 we find centrifugal force acting on the column of liquid contained in the capillary:

$$F_c = 0.125 \rho_l \pi d_c^2 \omega^2 (R_2^2 - R_1^2) \,. \tag{4}$$

Under the action of this force, the fluid moves through the capillary and leaves the drum. Consequently, the pressure drop, which affects the expiring of liquid, can be determined as the ratio of the force to the area of a capillary:

$$\varDelta P = 4F_c/\pi\pi_c^2 . \tag{5}$$

From expressions (5) and (4) we have:

$$\varDelta P = 0.5\rho_l\omega^2(R_2^2 - R_1^2) . \tag{6}$$

With angular speed ω expressed in terms of the number n of the drum revolutions, $\omega=2\pi n$, expression (6) becomes:

$$\varDelta P = 2\pi^2 n^2 \rho_l(R_2^2 - R_1^2) . \tag{7}$$

The volume of liquid of viscosity η, squeezing through a capillary of length $L = R_2\text{-}R_1$ and the radius $rc = d_c/2$ during time t under the action of pressure drop ΔP, is determined by the Poiseuille's formula:

$$V = \frac{\pi r_c^4 \varDelta Pt}{8\eta(R_2^2 - R_1^2)} . \tag{8}$$

Note that the validity of the use of formula (8) in the considering case of expiry of liquid through the capillary may require further discussion. The fact is that as the liquid outflow from the capillary, the centrifugal force acting on the liquid remaining in the capillary, decreases, and therefore the pressure drop ΔP in the numerator of the formula (8) in reality is not constant but decreases from the maximum value ΔP to zero. Placed in the denominator of formula (8), the capillary length L also is not constant - it decreases as the liquid expires, from the maximum value of $L = R_2 - R_1$ to zero. However, laws of change of these values are different, although they have similar limits. Therefore, the validity of the formula (8) will be considered as conditionally proven.

If we assume that a capillary is completely filled with liquid before the centrifugation process, the volume of the liquid is:

$$V = \pi r_c^2(R_2^2 - R_1^2) . \tag{9}$$

Equating the right-hand sides of the expressions (8) and (9), we obtain a formula for the determination the full-time t of the expiry of liquid through the capillary, which can be regarded as duration of a liquid separation process from the fibrous sorbent units:

$$t = \frac{8\eta(R_2 - R_1)^2}{r_c^2 \varDelta P} . \tag{10}$$

From expressions (10) and (7) we have:

$$t = \frac{4\eta(R_2 - R_1)}{\pi^2 n^2 r_c^2 (R_2 + R_1)\rho_l} . \tag{11}$$

The effective capillary radius r_c in formula (11) depends on the average diameter d_f of an elementary fibre of which the fibrous sorbent is composed, and is determined by the use of previously obtained experimental data of Table 1.

Tab. 1. The dependence of the radius r_c of the capillary cells from the fibre diameter d_f.

Test number	d_f, diameter of fibre [m]	m_{oil}, mass of collected oil [kg]	m_f, mass of fibre [kg]	K_s, sorption coefficient (determined experimentally)	r_c, effective capillary radius [m]
1	0.000010	0.0723	0.00270	26.78	0.000034
2	0.000030	0.093	0.00301	31.23	0.00011
3	0.000051	0.10138	0.00262	38.7	0.00021
4	0.000130	0.03671	0.00429	8.56	0.00025

Productivity G of the centrifugal process of separation of liquid from the fibrous sorbent units is determined by the formula:

$$G = \frac{V_l K_{sep}}{t}, \quad (12)$$

where K_{sep}= 0.9 - 0.95 – determined experimentally separation factor, which indicates what part of the liquid is separated from the fibrous sorbent units in the process of centrifugation; V_l - the volume of liquid separated from the fibrous sorbent units during centrifugation, which depends on the sorption coefficient K_s:

$$m_l = K_s m_f \qquad \text{or} \qquad V_l \rho_l = K_s V_f \rho_f \,, \quad (13)$$

where ρ_f =10 - 30 kg/m^3 – density of fibrous sorbent unit, V_f= $\pi H(R_2\text{-}R_1)^2$ – volume of fibrous sorbent unit, placed in the centrifuge drum of height H.

From (13) we have:

$$V_l = K_s \pi H(R_2 - R_1)^2 \rho_f / \rho_l \,. \quad (14)$$

Substituting values for V_l (14) and t (11) in (12), after simplifications we obtain a formula for the productivity G (m^3. s^{-1}) of the centrifugal process of separation of liquid from the fibrous sorbent units with specified characteristics:

$$G = \frac{\pi^3 K_s K_{sep} H(R_2 + R_1)^2 \rho_f n^2 r_c^2}{4\eta}. \quad (15)$$

3. Results and discussion

Analysing the formula (15), we note that the productivity of the oil separation from the fibrous sorbent units depends on the dynamic viscosity η of the oil, which can vary from 2 to 8 mPa.s, depending on the field and temperature. Apparently, the productivity of the process significantly increases with increasing the average diameter of the elementary fibres forming the fibrous sorbent units. A significant increase in process productivity can be achieved by increasing the radius and angular speed of the perforated drum of a centrifuge and reducing the transverse dimensions of the fibre sorbent units.

It was made an experimental stand of centrifugal separation plant for oil products from fibrous sorbent material to verify the results of the above simulation. Due to the fact that the experimental study of the separation of oil liquids from fibrous sorbent material is made in the laboratory at room temperature using a small sample of sorbent articles has been simplified experimental stand construction. Perforated drum experimental stand is cylindrical - shaped without cells to accommodate large items in the form of cylindrical booms and without nozzle arrangements for the supply of steam or hot air. This simplified experimental design of the stand will perform an experimental verification of the results of mathematical modelling of the process of separation of oil liquids from fibrous sorbent material with minimal cost and without compromising the reliability of the results (Straka, 2014).

The base unit of experimental stand centrifugal separation plant for oil products from fibrous sorbent material used a household centrifugal juicer. Driving test bench and its general form are shown in Figure 2.

Experimental stand centrifugal separation plant for oil liquids from fibrous sorbent products includes plastic housing 1 with quick cover 2. The housing 1 is placed an electric motor 6 on the shaft 5 which is rigidly fixed perforated drum 5. Quick release cover 2 is fixed to the guard member 7 Tray draining. The kit also includes a stand for collecting liquid container 8, which is not shown in general form.

View of test bench top and bottom, with the removed protecting elements, are shown in Figure 2. At the bottom of the experimental stand has three self-aligning bearings, made of rubber, which are intended to limit the transmission of vibrations from the operating stand of the surrounding devices and equipment. Fixing enclosing member 7 is provided on the housing 1 by means of three guide members shown in Figure 2 right. Securing the enclosing member 7 on the housing 1 is made by a hinged bracket.

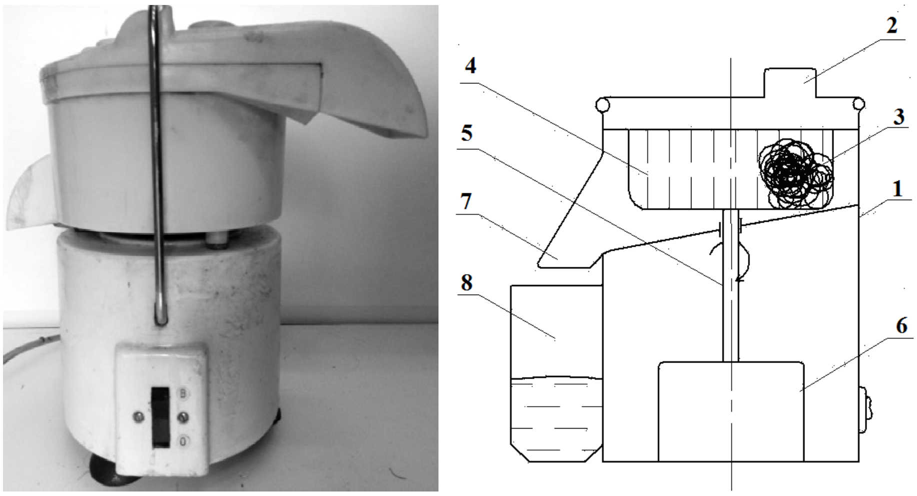

Fig. 2. General view and the diagram of the experimental stand centrifugal installation.

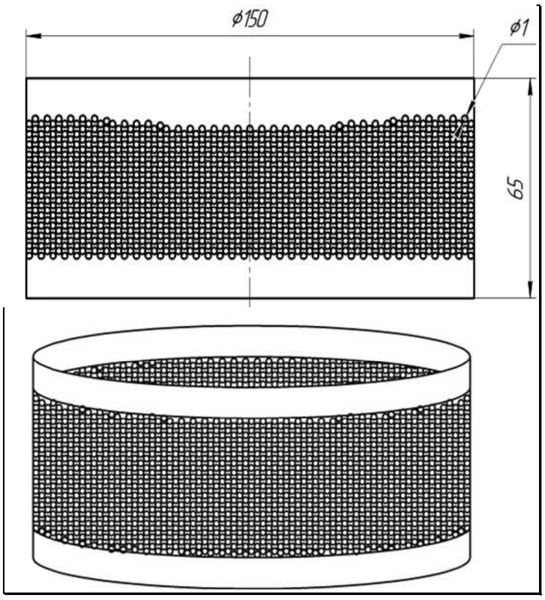

Fig. 3. The perforated drum.

The main element of the experimental stand is a cylindrical centrifugal installed perforated drum, a section of which the general form shown in Figures 4 - 5. The perforated drum is made of lightweight aluminium alloy and has an outer diameter 150 mm and height 65 mm. The cylindrical surface drum has 5887 holes of 1 mm diameter with a pitch of 2 mm. The internal cavity of the drum was 1000 cm^3. The perforated drum was balanced to reduce vibration during its rotation.

Fig. 4. General side view of the perforated drum.

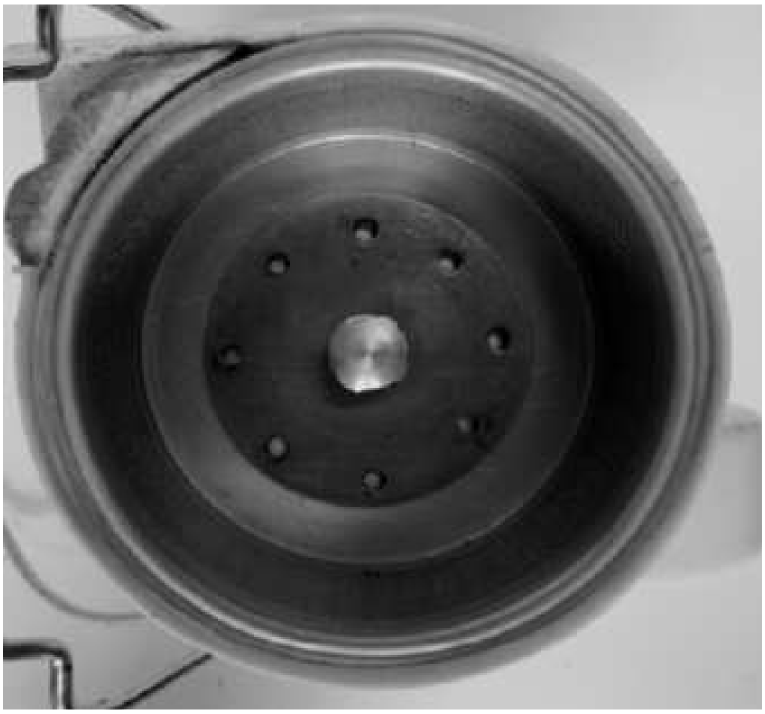

Fig. 5. General view of the perforated drum assembly removed from the experimental stand cover.

Experimental stand centrifugal installation works as follows. Saturated liquid petroleum product a sample fibrous sorbent that is placed through a hole in the top cover of the stand into the inner cavity of the perforated drum. The drum is rotationally driven. Under the influence of centrifugal forces of the moving liquid petroleum sample fibrous sorbent on the peripheral surface of the drum and the through-holes on the surface are moving into the inner cavity enclosing element and further - into the receptacle.

During the debugging of experimental stand, it was found that perforated drum acceleration period up to the steady rotational speed 800 rpm is 3 - 6 seconds, depending on the volume of the loaded sorbent therein fibrous specimen. It is found that efficient loading volume perforated drum is 50 - 150 cm^3 - a decrease of load leads to an increase in estimation error squeezing ratio and magnification - to substantially stand vibration during operation due to the violation of the stand balancing induced increase unbalanced mass of the sample, as shown in Figure 6.

Fig. 6. A typical violation of the perforated drum balancing.

4. Conclusion

The problem of determining the dependence of performance liquid separation process from the fibrous sorbent articles, operating radius perforated centrifuge drum, the transverse dimension of the sorbent articles angular drum speed, viscosity sorbed liquid and the nominal diameter of the capillary was solved by the mathematical modeling process of separating oil from the fibrous sorbent articles by the centrifugal method. It is found that the productivity of the process significantly increases with increasing the average diameter of the filaments forming the fibrous sorbent article, and also with increasing radius and frequency of rotation of the perforated basket centrifuge and reducing the transverse dimension of the fibrous sorbent products. The use of this method will increase the efficiency of combating oil pollution for the mining industry.

References

Akhtar M., Bhanger M.I., Iqbal, S., Hasany S.M.: Sorption potential of rice husk for the removal of 2,4-dichlorophenol from aqueous solutions: Kinetic and thermodynamic investigations, *J. Hazard. Mater. B 128, pp. 44-52, 2006*

Angelova D., Uzunov I., Uzunova S., Gigova A., Minchev L.: Kinetics of oil and oil products adsorption by carbonized rice husks, *Chem. Eng. J. 172 (1), pp. 306 – 311, 2011*

Banerjee, K., Joshi, M., Jayaram, R.: Treatment of oil spill by sorption technique using fatty acid grafted sawdust, *Chemosphere 64 (6), pp. 1026–1031, 2006*

Flegner, P., Kačur, J., Durdán, M., Laciak, M.: Application of adaptive filters in rock separation by rotary drilling process identification. *Acta Montanistica Slovaca, Volume 20 (2015), number 1, pp. 38-48, ISSN 1335-1788, 2015*

Gammoun, A., Tahiri, S., Albizane, A., Azzi, M., Moros, J., Garrigues, S., de la Guardia, M.: Separation of motor oils, oily wastes and hydrocarbons from contaminated water by sorption on chrome shavings, *J. Hazard. Mater. 145, pp. 148-153, 2007*

Han, G., de Wit, J.S., Chung, T.S.: Water reclamation from emulsified oily wastewater via effective forward osmosis hollow fiber membranes under the PRO mode. *Water Res., 81, pp. 54–63, 2015*

Haoyi, L., Weifeng, W., Bubakir, M.M., Hongbo, C., Xiangfeng, Z., Zhaoxiang, L., Yumei, D., Weimin, Y.: Polypropylene fibers fabricated via a needleless melt-electrospinning device for marine oil-spill cleanup, *J. Appl. Polym. Sci., 131, pp. 40080 (1–9), 2014*

http://inotomsk.ru/en/products/vysokoeffektivnyy-sorbent-na-osnove-voloknistykh-polimernykh-materialov/

Husseien, M., Amer, A.A., El-Maghraby, A., Taha, N.A.: Availability of barley straw application on oil spill cleanup, *Int. J. Environ. Sci. Tech. 6 (1), pp.123-130, 2009*

Ibrahim, S., Wang, S.: Ang, H.M. Removal of emulsified oil from oily wastewater using agricultural waste barley straw, *Biochem. Eng. J., 49 (1), pp. 78–83, 2010*

Lin, J., Shang, Y., Ding, B., Yang, J., Yu, J., Al-Deyab, S.S.: Nanoporous polystyrene fibers for oil spill cleanup, *Mar. Pollut. Bull., 64, pp. 347–352, 2012*

Oti Moto P.M.: Analysis existing methods of drying and removing moisture from the timber, Proceedings of the St. Petersburg Forestry Academy. Collection of reports of young scientists at the annual scientific conference of the St. Petersburg Forestry Academy: *Vol. 11. St. Petersburg; SPbGLTA, pp. 98-102, 2006*

Oti Moto P.M.: Study of quality of dehydrated timber during storage, Proceedings of the St. Petersburg Forestry Academy. Articles of young scientists, selected on the basis of annual scientific conference of the St. Petersburg Forestry Academy number 13: *Vol. 181 - St. Petersburg; SPbGLTA, pp. 145-150, 2007*

Oti Moto P.M.: The economic efficiency of the centrifugal method of timber dehydration, Proceedings of the St. Petersburg Forestry Academy. *St. Petersburg; SPbGLTA 2008, 2008*

Ray, F., Onuma, C., Serge, K., Yunfei, X.: Selected adsorbent materials for oil spill cleanup – a Thermoanalytical study, *J. Therm. Anal. Calorim. 91(3) pp. 809-816. 2008*

Sabir, S.: Approach of Cost-Effective Adsorbents for Oil Removal from Oily Water, *Crit. Rev. Environ. Sci. Technol., 45, pp. 1916–1945, 2015*

Sayed, A., Zayed, A.M.: Investigation of the effectiveness of some adsorbent materials in oil spill clean-ups, *Desalination 194, pp. 90-100, 2006*

Šoltés, M., Harčariková, M.: Analysis of Nova 1 strategy formed by barrier options and its application in hedging against a price drop in oil market. *Acta Montanistica Slovaca, Volume 20 (2015), number 4, pp. 311-318. ISSN 1335-1788, 2015*

Straka, M., Bindzár, P., Kaduková, A.: Utilization of the multicriteria decision-making methods for the needs of mining industry. *Acta Montanistica Slovaca, Volume 19 (2014), number 4, pp. 199-206, ISSN 1335-1788, 2014*

Sviatskii V.M., Sentyakov B.A., Sviatskii M.A., Sentyakov K.B., Garayev S.A.: Simulation of the process of fabrication canvas with fibrous materials, *Vestnik ISTU, No. 2., Izhevsk 2015, pp.17-20, 2015*

Sviatskii V.M., Sentyakov B.A., Sviatskii M.A., Tcherezov A.R.: Tests fibrous sorbent booms. *Safety of vital functions, No. 4, p. 27-29, 2015*

Wu, L., Zhang, J., Li, B., Wang, A.: Mechanical- and oil-durable superhydrophobic polyester materials for selective oil absorption and oil/water separation, *J Colloid Interface Sci., 413, pp. 112–117, 2014*

Yim, U.H., Kim, M., Ha, S.Y., Kim, S., Shim, W.J.: Oil Spill Environmental Forensics: the Hebei Spirit Oil Spill Case, *Environ. Sci. Technol, 46, pp. 6431–6437, 2012*

Zhang, S., Wang, P., Fu, X., Chung, T.S.: Sustainable water recovery from oily wastewater via forward osmosis-membrane distillation (FO-MD), *Water Res., 52, pp. 112–121, 2014*