Approximation of the filtration flow curve through the layers of sorbents and ionites in petrochemical and environmental mass transfer equipment

N A Merentsov1,4, V A Balashov1, A B Golovanchikov1, M V Topilin2 and A V Persidskiy3

1 Volgograd State Technical University, Volgograd 400005, Russia
2 Branch of LUKOIL-Engineering VolgogradNIPImorneft, Volgograd 400078, Russia
3 JSC Federal Scientific and Production Centre «Titan - Barricady», Volgograd 400071, Russia

4 E-mail: steeple@mail.ru

Abstract. A modified equation is presented for approximating experimental filtration flow curves through layers of sorbents and ionites in petrochemical and environmental mass transfer equipment, which makes it possible to decipher the contribution of the increasing inertial component of the filtration flow structure and to estimate the intensity of the upgrowth of filtration flow turbulence. The prospects of using the modified equation for solving spatial filtration problems are shown, since it ensures the continuity of the velocity fields and pressure gradients with successive changes in the filtration flow mode.

1. Introduction
Filtration flows are used in many industrial technological processes and products of various branches of mechanical engineering, in technologies and equipment of the chemical industry and related industries [1-36]. Filtration is used in water treatment processes and in environmental technologies [37-57]. Filtration processes are an integral part of the hydrology and technologies of oil and gas production. Filtration flows are also implemented in a wide range of environmental mass transfer equipment, in such processes as adsorption, desorption, ion exchange, etc. [58-110]. A detailed analysis of the structure of filtration flows in wide and narrow operating made ranges through the layers of sorbents and ionites can provide unique data and classifying tools for selecting the sorbent and its specific dispersion composition, based on the structure of the porous layer and the associated hydrodynamic flow modes developed through sorbent layers, based on the requirements of a specific mass-exchange petrochemical and environmental process and equipment. The goal of the work is to derive an equation for approximating experimental filtration flow curves through layers of sorbents and ionites, which makes it possible to recognize the pure inertial component of the filtration flow structure and to obtain unique tools for automatic control of the hydrodynamics of sorption mass transfer devices. This kind of tool can be the turbulization intensity coefficient $I_m$ (turbulization index $I_m$), obtained from the analysis of the filtration curve of the flow through the layers of sorbents and ionites in a specific operating range for gas or liquid flow rates due to the technological requirements of the mass transfer process. Moreover, owing to this tool, the modified equation for approximating
the curves of filtration flows and the turbulence index $I_m$ obtained from it, we can recognize the most effective hydrodynamic mode ranges, that have the highest contribution of the inertial components of the overall structure of the filtration flow (the momentum transfer mechanism), which are responsible for the intensive washing of sorbent granules and adjacent external diffusion layers, which leads to an intensification of mass transfer processes and increases the degree of capture of the extracted components by sorbents from liquids and gases. This article is devoted to the method of obtaining and deciphering the physical meaning of this classifying tool, the modified approximating equation and the turbulence index $I_m$ included in it.

2. Methods and materials

A detailed analysis of the filtration curves in the estimation of flows through porous layers has already yielded results. The authors obtained a universal criterion dependence of the hydraulic resistance coefficient and the modified Reynolds criterion $\lambda=f(Re_m)$ [111-115], allows, after the experimental removal of single-phase filtration curves through the layers of packing contact heat and mass transfer devices, to generalize huge amounts of experimental data using a single universal criterion equation, and especially in cases of incomparable experimental data (for absolutely different porous layers of heat and mass transfer contact devices) and to recognize the operating mode ranges of contact devices inherent in the entire spectrum of mass transfer processes and devices [111-115].

![Figure 1. Classifying criterion dependence $\lambda=f(Re_m)$ for the analysis of experimental data and classification of operating ranges of heat and mass transfer packing contact devices.](image_url)

Before proceeding to a detailed review, let’s clarify the basic concepts. The filtration curve is an experimentally obtained dependence $\Delta P/H=f(\nu f)$ without specifying the range of this dependence of the filtration rate. The full filtration curve is a filtration curve ($\Delta P/H=f(\nu f)$) constructed over a wide range of changes in filtration rates, ranging from $\nu f=0$ to the developed turbulent mode, when the quadratic filtration law is reached.

The experimentally obtained filtration curve can be conditionally divided into several modes according to filtration rates, pre-laminar, laminar, intermediate transition region of turbulent filtration, and developed turbulent filtration. Laminar filtration with the predominant influence of the viscous component of the filtration flow structure and a negligible inertial component, which is certainly present, since the liquid and gas penetrating through the sorbent layers move along different paths and channels, washing the sorbent granules. The intermediate transitional region of turbulent filtration
occupies the intermediate mode range between laminar filtration and the developed turbulent filtration mode (when the quadratic law is reached). At the same time, there is a significant contribution of both the viscous and inertial components of the filtration flow structure, and it should be noted that many mass-exchange petrochemical and environmental sorption processes occur precisely in the transient filtration mode. The intermediate transition region of turbulent filtration is followed by a developed turbulent filtration mode, when the quadratic filtration law is reached. In the developed turbulent filtration region, the contribution of the inertial component of the filtration flow structure, with a relatively low viscosity component, prevails. As we can see, the «full» filtration curve, due to the constant contribution of the viscous and inertial components to the overall structure of the filtration flow, is always nonlinear, and the nonlinearity of each individual section and a narrow operating range can be described using a modified equation. This modified equation for approximating the filtration curve in the required narrow mode range with the accompanying turbulization index \( I_m \), is particularly informative in the transition region, turbulent and developed turbulent filtration. This modified equation and its constituent coefficients of the intensity of turbulence development \( \langle I_m \rangle \) (turbulence index) for filtration flows through the sorbent layers are a direct reflection of the contribution of the inertial component of the filtration flow structure, which is responsible for the intensification of mass transfer processes and the intensity of washing of the external diffusion layer of the surface of sorbents and ionites.

The intensity of the sorption mass-exchange processes depends on the quality of the organization of the advanced filtration of flow of liquids and gases through the layers of sorbents, active washing surfaces of sorbents and access the extracted components to external diffusion absorbing layers of sorbents. These processes occur with varying intensity, starting with laminar filtration and up to the developed turbulent and fluidization of the sorbent layers.

Let us consider an applied example of obtaining this classifying index (turbulization index) for estimating the contribution of the inertial component of the structure of a single-phase filtration flow through layers of sorbents and ionites. An example of an experimentally determined filtration curve \( \Delta P/H=f(\nu_f) \) for single-phase filtration flows through layers of sorbents (adsorbents) is shown in figure 2.

One of the main problems of approximation of filtration curves is a smooth transition from laminar filtration to the transition section of the filtration curve without breaking the velocity fields and pressure gradient.

The solution to the problem of continuity of the filtration curve is to use the Kozeni-Karman equation and the power dependence for its description of the articulation of its linear and nonlinear sections, as shown in figure 2.

However, in this case, the problem of the continuity of the filtration curve is only partially solved, since if the pressures at the junction points of the adjacent linear and nonlinear sections are equal, the requirement of equality of the gradients \( dP/d\nu \), calculated for the neighboring sections at the speed corresponding to their intersection point, is not met, which indicates the presence of a field rupture speeds at this point. This approximation of the filtration curve is often used in obtaining criterion equations for determining the coefficients \( \lambda, \alpha \) and \( \beta x,y \), since it does not lead to a discontinuity of \( \lambda, \alpha \) and \( \beta x,y \) in monodimensional flows. For solving spatial problems, such an approximation of the filtration curve is not applicable due to the inequality of the velocity gradients at the junction point of the linear and nonlinear sections. The condition for the continuity of the filtration curve and its smooth transition from the linear to the nonlinear area is the equality at the point «a» of the gradients \( (dP/dH)/d\nu \), determined along the filtration curve both in the direction of increasing the filtration rate and in the opposite direction. The equation approximating the nonlinear section of the filtration curve in the area of the interface of its linear and nonlinear sections must meet this condition. Consider obtaining such an equation.
Figure 2. Filtration curve.

Figure 3 shows the filtration curve «0ab», consisting of a linear section «0a» and part of its nonlinear section «ab» of the transient turbulent filtration region. The point «a», which corresponds to the critical filtration rate of «υсr», determines the junction of both sections. From this moment, the experimentally observed smooth deviation of the filtration curve from its linear state begins in the direction of increasing the hydraulic resistance of the porous layer at a more intense rate than in the linear region, and the extension of the straight linear section «ax» becomes tangent to its nonlinear part at the point «a».

Figure 3. Filtration curve for single-phase filtration flow through the sorbent layer.
Let the coordinates of a certain point «e» on the filtration curve be determined by the filtration rate \( \nu_f \) and the pressure gradient \( dP/dH \), equal to the sum of the losses from the action of the viscous friction forces \( \Delta P_{\text{visc}}/H \) and the inertia forces \( \Delta P_{\text{inert}}/H \)

\[
\frac{\Delta P}{H} = \frac{\Delta P_{\text{visc}}}{H} + \frac{\Delta P_{\text{inert}}}{H}.
\]

Let's introduce an oblique coordinate system «\( \zeta-x \)» with the origin at point «a», taking the tangent to the nonlinear section at point «a» as the axis «\( x \)».

In this coordinate system, the position of the point \( e(x,z) \) is determined by the following coordinate value:

\[
x = \frac{\nu_f - \nu_{cr}}{\cos \alpha},
\]

\[
z = \frac{\Delta P_{\text{inert}}}{H}.
\]

Let us introduce a orthogonal axis system «\( y-x \)» with the origin at point «a» and build a new curve «\( ab1 \)» in it, so that the coordinates \( y \) and \( z \) of curves «\( ab \)» and «\( ab1 \)» for points with the same value «\( x \)» on their common coordinate axis «\( x \)» were related by the relation

\[
y = z \cdot \cos \alpha.
\]

Relation (4) does not violate the tangency condition and the curve «\( ab1 \)» is only one of the possible set of their curves going from point «\( a \)» similar to the curve «\( ab \)». Therefore, the curve «\( ab1 \)» in the coordinate system «\( x-y \)» can be described by a power function

\[
x = B_1 y^{\frac{1}{n}}.
\]

Taking into account the expression (4), equation (5) is written in the form of a dependency as

\[
x = B_1 (z \cdot \cos \alpha)^{\frac{1}{n}},
\]

which is the equation of the curve «\( ab \)» in the oblique coordinate system, connected by the relation (2) and (3) with the dependence \( \Delta P/H = f(\nu_f) \).

Substituting in (6) the values «\( x \)» and «\( z \)» as (2) and (3) after a series of transformations, we get

\[
\left( \frac{\nu_f - \nu_{cr}}{B_2} \right)^{1/n} = \frac{\Delta P_{\text{inert}}}{H},
\]

where

\[
B_2 = B_1 (\cos \alpha)^{\frac{1}{n}}.
\]

Based on Darcy’s law

\[
\frac{\Delta P_{\text{visc}}}{H} = \frac{\mu}{k} \nu_f
\]

and then according to the dependency (1)
Substituting this value of the pressure gradient \( \Delta P_{\text{visc}}/H_{\text{inert}} \) into equation (7), we obtain

\[
\left( \frac{v_f - v_{cr}}{B_2} \right)^{I_m} = \frac{\Delta P}{H} - \frac{\mu}{k} v_f,
\]

from where

\[
\frac{\Delta P}{H} = \frac{\mu}{k} v_f + \left( \frac{v_f - v_{cr}}{B_2} \right)^{I_m},
\]

where \( I_m \) – is an exponent called the turbulence index (for layers of sorbents and ionites), \( B_2 \) – is a coefficient determined by the structure of the porous environ.

3. Conclusions

Equation (8) approximates the filtration curve in the nonlinear area when \( v_f > v_{cr} \). When \( v_f = v_{cr} \), it turns into the equation of Darcy’s law, but at the same time, in contrast to the Ergun equation, a discontinuity of the pressure field is excluded when performing calculations of one-dimensional filtration flows and a discontinuity of the velocity field in the case of using a power law to approximate the nonlinear section of the filtration curve.

Thus, the resulting modified approximating equation and the turbulization index \( I_m \) included in it reflect exclusively the inertial component of the filtration flow structure in any operating mode range of interest in terms of filtration rates, minus the contribution of the viscous component of resistance.

This deduction of components in assessing the development of turbulization is required when considering any filtration flows (whether contact packed mass transfer devices or the flow of liquids and gases through porous layers of sorbents and ionites), especially in cases of a significant contribution of viscous components (in filtering through layers of sorbents – this is necessary) and necessarily in cases where initially the filtration curves to be compared and subsequent classification developed according to an incomparable script.

In addition to the analytical, laboratory and calculation practice in the research of the structure of the fluid flows through the layers of sorbents and ionites obtained modifying equation and index of the turbulence included in it play a crucial role as one of the tools of automatic control modes of mass transfer sorption apparatus adsorption and electrodosorption, ion exchange in an electric field, drying of dispersed materials and is determined by the program in automatic mode during the autocalibration process parameters mass transfer devices [116-124]. In our opinion, this approach is a promising direction that can be developed, for example, the imposition of controlled electric fields on sorption mass transfer processes, which will increase the capacity of sorbents, intensify mass transfer processes, increase the protective action time, and the degree of purification of liquid and gas emissions [123-126]. But all this is possible only under conditions of advanced hydrodynamics and high-quality washing of the mass-exchange surfaces of sorbents and high-quality access of molecules and ions of the extracted components to the surfaces of sorbents and ionites. Therefore, along with the automated control of the main technological parameters, the electric field intensity, and others, the decoding of the contribution of the inertial component of the filtration flow structure (the pulse transfer mechanism) comes to the fore as the main tool for automatic recognition and maintenance of optimal hydrodynamic modes of mass-exchange sorption devices, while the turbulence index is automatically recognized by the control program during the automatic calibration of the device at the stage of commissioning, by analogy with [116-124].

From the point of view of the washability of the external diffusion layers of sorbent granules by continuous flows of gases or liquids in conditions of preservation of sorbent granules from abrasion,
according to the turbulization index «I_m»), in the process of automatic calibration of the sorption devices (at the stage of commissioning or during current operation), the authors are able to recognize the optimal operating modes, that is, to ensure the operation of the sorption devices in the mode preceding the start of fluidization, or in the mode of the start of fluidization on demand. Thus ensuring the safety of the sorbent granules, preventing the clogging of the sorbent micropores at the highest available indicators of the inertial components of the filtration flow structure under conditions of intensification of mass transfer processes.

Acknowledgements
This work was supported by a grant from the President of the Russian Federation (MK-1287.2020.8) «Modelling of control processes in mass transfer environmental and petroleum processing equipment».

References
[1] Pokusaev B G, Tairov E A, Khan P V and Khramtsov D P 2018 Numerical and analytical approaches to modeling critical two-phase flow with granular layer Journal of Engineering Thermophysics 27(1) 20-9
[2] Khramtsov D P, Vyazmin A V, Pokusaev B G, Karlov S P and Nekrasov D A 2016 Numerical simulation of slug flow mass transfer in the pipe with granular layer Chemical Engineering Transactions 52 1033-8
[3] Merentsov N, Balashov A, Golovanchikov A and Topilin M 2020 The determination of hydraulic resistance during laminar filtration through layers of sorbents and ion-exchange granules in environmental mass exchange equipment E3S Web of Conferences 193 02002
[4] Soloveva O 2021 Study of aerosol motion in granular and foam filters with equal porosity of the structure Advances in Intelligent Systems and Computing 1259 638-49
[5] Solovev S, Soloveva O, Khusainov R and Lamberov A 2021 Numerical investigation of the catalyst granule shapes influence on dehydrogenation reaction Advances in Intelligent Systems and Computing 1259 383-90
[6] Soloveva O, Solovev S, Khusainov R and Yafizov R 2021 Mathematical modelling of heat transfer in open cell foam of different porosities Advances in Intelligent Systems and Computing 1259 371-82
[7] Soloveva O V, Solovev S A and Khusainov R R 2019 Evaluation of the efficiency of prefilter models using numerical simulation Journal of Physics: Conference Series 1399(2) 022059
[8] Solovev S A, Soloveva O V, Gilmurahmanov B S and Lamberov A A 2019 Numerical investigation of the ethylbenzene dehydrogenation reaction in a fixed bed reactor with catalyst granules of various sizes Journal of Physics: Conference Series 1399(5) 055022
[9] Solovev S A, Antipin A V, Soloveva O V and Khusainov R R 2019 Determination of effective diameter of solid particles for the eulerian-eulerian modelling approach of fluidized bed Journal of Physics: Conference Series 1210(1) 012133
[10] Soloveva O V, Solovev S A, Khusainov R R, Shubina A S and Antipin A V 2019 Numerical simulation of gas flow in porous structures of various geometries Journal of Physics: Conference Series 1210(1) 012134
[11] Solovev S A, Soloveva O V and Antipin A V 2019 Investigation of the influence of fine particles on the discrete phase density in the numerical modelling of a fluidized bed Journal of Physics: Conference Series 1158(4) 042022
[12] Soloveva O V, Solovev S A, Khusainov R R and Shubina A S 2019 Investigation of the effect of material's cell size with the fixed porosity on the efficiency of aerosol particle deposition Journal of Physics: Conference Series 1158(4) 042023
[13] Soloveva O V, Solovev S A, Egorova S R, Lamberov A A, Antipin A V and Shamsutdinov E V 2018 CFD modeling a fluidized bed large scale reactor with various internal elements near the heated particles feeder Chemical Engineering Research and Design 138 212-28
[14] Solovev S A, Soloveva O V and Popkova O S 2018 Numerical simulation of the motion of aerosol particles in open cell foam materials Russian Journal of Physical Chemistry A 92(3) 603-6

[15] Akhmadiev F G, Bekbulatov I G, Farakhov M I and Isyanov C K 2016 Mathematical modeling of filtering process of two-phase suspensions in tubular filters under nonisothermal conditions Theoretical Foundations of Chemical Engineering 50(1) 41-51

[16] Merentsov N A, Balashov V A, Bokhan S A, Nefed'eva E E, Tezikov D A and Groshev V V 2019 Modeling and calculation of flow filter IOP Conference Series: Earth and Environmental Science 224 012041

[17] Sokovnin O M and Zagoskin S N 2004 Kinetics of sorption of particles on granular filter Theoretical Foundations of Chemical Engineering 38(4) 399-403

[18] Shiryaeva E V, Gutin Yu V and Aksenov A A 2008 Determination of filtration and dewatering parameters of sediments in industrial filters Chemical and Petroleum Engineering 44(11-2) 611-21

[19] Dyachenko E N and Dyachenko N N 2013 Numerical modeling of filtration of liquid through layer of bulk filter Theoretical Foundations of Chemical Engineering 47(3) 262-5

[20] Solovev S A, Soloveva O V, Antipin A V and Shamsutdinov E V 2018 Investigation of internal elements impaction on particles circulation in a fluidized bed reactor Journal of Physics: Conference Series 944(1) 012114

[21] Soloveva O V, Solovev S A, Khusainov R R, Popkova O S and Panenko D O 2018 Investigation of the influence of the open cell foam models geometry on hydrodynamic calculation Journal of Physics: Conference Series 944(1) 012113

[22] Soloveva O V, Solovev S A and Popkova O S 2018 Modeling of the three-dimensional structure of open cell foam and analysis of the model quality using the example of pressure drop calculation Uchenye Zapiski Kazanskogo Universiteta Seriya Fiziko-Matematicheskie Nauki 160(4) 681-94

[23] Solovev S A, Soloveva O V, Antipin A V and Arzamasova A G 2017 Numerical investigation of the isoparaffins dehydrogenations in large fluidized bed reactor Astra Salvensis 2017 311-21

[24] Mardanov R F, Soloveva O V and Zaripov S K 2016 Flow past a porous cylinder in a rectangular periodic cell: Brinkman and Darcy models comparison IOP Conference Series: Materials Science and Engineering 158(1) 012065

[25] Soloveva O V and Solovyev S A 2016 Investigation of the influence of heated catalyst feeding system on the intensity of temperature-dependent chemical reaction in the fluidized bed apparatus IOP Conference Series: Materials Science and Engineering 158(1) 012086

[26] Soloveva O V, Solovev S A, Yafizov R R and Khusainov R R 2019 Determination of the effective thickness of an open cell foam filter using numerical simulation IOP Conference Series: Materials Science and Engineering 560(1) 012045

[27] Solovev S A, Soloveva O V and Sheshukov E G 2019 Influence of internal grids on particle motion in the fluidized bed reactor IOP Conference Series: Materials Science and Engineering 560(1) 012092

[28] Solovev S A and Soloveva O V 2019 Mathematical modeling of isoparaffins dehydrogenation in fluidized bed reactor IOP Conference Series: Materials Science and Engineering 537(6) 062073

[29] Soloveva O V, Solovev S A, Misbahkov R Sh and Yafizov R R 2019 Investigation of the aerosol particle deposition formation due to the capture of the filter fiber IOP Conference Series: Earth and Environmental Science 288(1) 012120

[30] Soloveva O V, Khusainov R R, Sheshukov E G and Yafizov R R 2019 Investigation of the effect of porosity on the particle deposition efficiency in the model of an open cell foam filter IOP Conference Series: Materials Science and Engineering 618(1) 012094

[31] Soloveva O V, Solovev S A, Shamsutdinov E V and Sheshukov E G 2019 Investigation of the
multi-layer open cell foam filter model using numerical simulation and experimental studies

IOP Conference Series: Earth and Environmental Science 337(1) 012059

[32] Soloveva O V, Solovev S A and Yafizov R R 2020 Determination of the particle deposition efficiency value in a granular and open cell foam filter IOP Conference Series: Materials Science and Engineering 709(3) 033064

[33] Soloveva O V 2020 Comparison of granular and open cell foam filter models by numerical simulation IOP Conference Series: Earth and Environmental Science 421(6) 062038

[34] Khusainov R R, Solovev S A, Soloveva O V and Ilyasov I R 2020 Numerical simulation and experimental study of the acetylene hydrogenation reaction IOP Conference Series: Materials Science and Engineering 734(1) 012205

[35] Soloveva O V, Khusainov R R and Yafizov R R 2020 CFD modeling of aerosol flow through a granular filter with porous granules IOP Conference Series: Materials Science and Engineering 734(1) 012180

[36] Khusainov R R, Soloveva O V, Solovev S A and Akhmetvaleeva L V 2020 Analysis of pre-filter models using numerical simulation IOP Conference Series: Materials Science and Engineering 862(6) 062103

[37] Fomenko A and Sokolov L 2015 Sorption removal of oil products from waste water Ecology and Industry of Russia 19(5) 8-12

[38] Sheldaisov-Meshcheryakov A A, Solmanov P S, Maximov N M, Mozhaev A V, Ishutenko D I, Nikul’shin P A and Pimerzin A A 2019 Influence of the pore structure of a catalyst for demetallization of petroleum feedstock on the process results Russian Journal of Applied Chemistry 92(10) 1392-8

[39] Dremicheva E 2019 Use of agricultural waste for wastewater treatment of industrial enterprises Ecology and Industry of Russia 23(4) 16-9

[40] Prolejchik A, Gaponenkov I and Fedorova O 2018 Extraction of heavy metal ions from inorganic wastewater Ecology and Industry of Russia 22(3) 35-9

[41] Nikolaeva L A, Golubchikov M A and Minneyarova A R 2018 Research on the mechanism and kinetics of oil-product adsorption from industrial wastewater by a modified hydrophobic carbonate sludge Chemical and Petroleum Engineering 53(11-2) 806-13

[42] Sokolov L I 2013 Use of wastes of grinding industry for cleaning of chromium containing effluent waters World Applied Sciences Journal 22(5) 690-6

[43] Merentsov N A, Bokhan S A, Lebedev V N, Persidskiy A V and Balashov V A 2018 System for centralised collection, recycling and removal of water pickling and galvanic solutions and sludge Materials Science Forum 927 183-9

[44] Alexandrov R, Feklistov D, Laguntsov N and Kurchatov I 2019 Mobile installation of water treatment in the aftermath of emergency situations Ecology and Industry of Russia 23(1) 4-10

[45] Dremicheva E 2019 Use of agricultural waste for wastewater treatment of industrial enterprises Ecology and Industry of Russia 23(4) 16-9

[46] Dremicheva E S and Laptev A G 2019 Modeling the process of sorption for the purification of waste water from petroleum products and heavy metals Theoretical Foundations of Chemical Engineering 53(3) 355-63

[47] Dremicheva E S and Shamsutdinov E V 2018 Intensification of sedimentation treatment of wastewater from oil products Water and Ecology 1 3-8

[48] Nikolaeva L A and Iskhakova R Y 2019 Integrated Wastewater Treatment for a GRES Thermal Engineering 66(8) 587-92

[49] Nikolaeva L A and Iskhakova R Ya 2019 Adsorption of industrial wastewater from oil products with application of mathematical modeling IOP Conference Series: Earth and Environmental Science 288(1) 012017

[50] Nikolaeva L A and Khamzina D A 2019 Purification of water sources from oil contamination by hydrophobic carbonate sludge IOP Conference Series: Earth and Environmental Science
Mathematical modeling of wastewater treatment by adsorption of petroleum products. 

Chemical and Petroleum Engineering. 55(1-2) 68-75

Nikolaeva L A and Iskhakova R Y 2019

Adsorption treatment of reverse-osmosis concentrate from water-treatment units at thermal power stations. 

Thermal Engineering. 66(5) 372-6

Nikolaeva L A and Aikenova N E 2021

Study of the sorption of oil products of power station wastewater modified with a TPP illuminator slurry. 

Thermal Engineering. 59(5) 404-7

Nikolaeva L A and Nedzvetskaya R Ya 2012

Comparison of Powdered and PVC-Bound Todorokite Media for Heavy Metal Removal from Acid Mine Drainage Tailings. 

Industrial and Engineering Chemistry Research. 57(42) 14315-24

Outram J G, Couperthwaite S J and Millar G J 2018

Enhanced removal of high Mn(II) and minor heavy metals from acid mine drainage using tunnelled manganese oxides. 

Journal of Environmental Chemical Engineering. 6(2) 3249-61

Outram J G, Couperthwaite S J and Millar G J 2018

Investigation of manganese greensand activation by various oxidants. 

Journal of Environmental Chemical Engineering. 6(4) 4130-43

Outram J G, Couperthwaite S J and Millar G J 2017

Ferrous poisoning of surface MnO2 during manganese greensand operation. 

Journal of Environmental Chemical Engineering. 5(3) 3033-43

Outram J G, Couperthwaite S J and Millar G J 2016

Comparative analysis of the physical, chemical and structural characteristics and performance of manganese greensands. 

Journal of Water Process Engineering. 13 16-26

Millar G J, Miller G L, Couperthwaite S J, Dalzell S and Macfarlane D 2017

Determination of an engineering model for exchange kinetics of strong acid cation resin for the ion exchange of sodium chloride & sodium bicarbonate solutions. 

Journal of Water Process Engineering. 17 197-206

Pepper R A, Couperthwaite S J and Millar G J 2018 A novel akaganeite sorbent synthesised from waste red mud: Application for treatment of arsenate in aqueous solutions.

Journal of Environmental Chemical Engineering. 6(5) 6308-16

Millar G J, Couperthwaite S J and Papworth S 2016

Ion exchange of sodium chloride and sodium bicarbonate solutions using strong acid cation resins in relation to coal seam water treatment. 

Journal of Water Process Engineering. 11 60-7

Pember N, Millar G J, Couperthwaite S J, De Bruyn M and Nuttall K 2016

BDST modelling of sodium ion exchange column behaviour with strong acid cation resin in relation to coal seam water treatment. 

Journal of Environmental Chemical Engineering. 4(2) 2216-24
[69] Millar G J, Schot A, Couperthwaite S J, Shilling A, Nuttall K and De Bruyn M 2015 Equilibrium and column studies of iron exchange with strong acid cation resin Journal of Environmental Chemical Engineering 3(1) 373-85

[70] Golovanchikov A and Merentsov N 2019 Modelling of absorption process in a column with diffused flow structure in liquid phase Advances in Intelligent Systems and Computing 983 635-44

[71] Golovanchikov A and Merentsov N 2019 Ion exchange in continuous apparatus with diffused flow structure in liquid Advances in Intelligent Systems and Computing 983 645-52

[72] Golovanchikov A B, Merentsov N A and Topilin M V 2019 Modeling of adsorption process in continuous counter current column having diffused flow structure in gaseous phase Journal of Physics: Conference Series 1278 012023

[73] Prolechik A, Gaponenkiv I and Fedorova O 2018 Extraction of heavy metal ions from inorganic wastewater Ecology and Industry of Russia 22(3) 35-9

[74] Fomenko A I and Sokolov L I 2019 Study of sorption properties of bog ores for extraction of manganese and iron ions from ground water Russian Journal of Applied Chemistry 92(2) 288-94

[75] Rachkova N G and Shuktomova I I 2010 Sorption of uranium, radium, and thorium by analcym-containing rock and sorbents based on plant tissue Russian Journal of Applied Chemistry 83(4) 620-4

[76] Zaporozhskikhik T A, Tret' yakova Ya K, Grabel'nykh V A, Russavskaya N V, Vshitsev V Yu, Levanova E P, Sukhomazova E N, Korabel I V and Korchevin N A 2008 Granulated sulfur-containing sorbents for recovery of heavy metal ions from aqueous solutions Russian Journal of Applied Chemistry 81(5) 866-8

[77] Fomenko A I and Sokolov L I 2019 Sorption properties of fly ash microspheres of thermal power plants Ecology and Industry of Russia 23(1) 50-4

[78] Smirnov V G, Dyrdin V V, Manakov A Y, Fedorova N I, Shikina N V and Ismagilov Z R 2019 Physicochemical and sorption properties of natural coal samples with various degrees of metamorphism Russian Journal of Applied Chemistry 92(10) 1410-21

[79] Fomenko A I and Sokolov L I 2017 Ash of incineration plants as industrial resource for extracting rare earth elements Ecology and Industry of Russia 21(12) 28-31

[80] Merentsov N, Persidskiy A, Lebedev V and Golovanchikov A 2020 Automatic control of operating modes of packed apparatus for selective gas emissions cleaning Ecology and Industry of Russia 24(2) 10-6

[81] Merentsov N, Persidskiy A, Lebedev V, Topilin M and Golovanchikov A 2019 Modelling and calculation of industrial absorber equipped with adjustable sectioned mass exchange packing Advances in Intelligent Systems and Computing 983 560-73

[82] Golovanchikov A B, Merentsov N A, Topilin M V and Persidskiy A V 2019 Dynamic packing for heat and mass exchange processes IOP Conf. Ser.: Earth and Environmental Science 288 012089

[83] Merentsov N, Golovanchikov A, Lebedev V and Gendler A 2020 Modelling and calculation of a small-size evaporation cooling apparatus for industrial recirculated water with a heat-and-mass exchange packing based on wastes from metal-working machinery E3S Web of Conferences 193 02003

[84] Golovanchikov A B, Merentsov N A and Balashov V A 2013 Modeling and analysis of a mechanical-draft cooling tower with wire packing and drip irrigation Chemical and Petroleum Engineering 48 595-601

[85] Merentsov N, Persidskiy A, Lebedev V, Prokhorenko N and GolovanchikovA2019 Heat and mass exchange packing for desinfection of circulation water in electric field Advances in Intelligent Systems and Computing 983 547-59

[86] Dmitriev A V, Madyshev I N, Kharkov V V, Dmitrieva O S and Zinurov V E 2021 Experimental investigation of fill pack impact on thermal-hydraulic performance of
evaporative cooling tower Thermal Science and Engineering Progress 22 100835

[87] Madyshev I, Kharkov V and Dmitriev A 2020 Cooling efficiency of filler unit in non-chemical cooling tower with advanced contact surface E3S Web of Conferences 193 01044

[88] Zinurov V E, Dmitriev A V, Ruzanova M A and Dmitrieva O S 2020 Classification of bulk material from the gas flow in a device with coaxially arranged pipes E3S Web of Conferences 193 01056

[89] Madyshev I, Dmitriev A and Kharkov V 2020 Determination of Volumetric Heat and Mass Transfer Coefficients in Filling Unit of Evaporative Cooling Tower 2020 International Multi-Conference on Industrial Engineering and Modern Technologies FarEastCon 9271292

[90] Dmitriev A V, Madyshev I N, Khafizova A I, Kharkov V V and Vakhitov M R 2020 Heat and mass transfer in unit of cooling tower filler with advanced gas-liquid contact surface IOP Conference Series: Materials Science and Engineering 862(6) 062099

[91] Merentsov N A, Lebedev V N, Persidskiy A V and Balashov V A 2019 Cascade bowl-type heat and mass exchange packing with dripping irrigation mode IOP Conference Series: Earth and Environmental Science 288 012106

[92] Merentsov N A, Lebedev V N, Golovanchikov A B, Balashov V A and Nefed'Eva E E 2018 Experimental assessment of heat and mass transfer of modular nozzles of cooling towersIOP Conference Series: Earth and Environmental Science 115 012017

[93] Persidskiy A V, Merentsov N A, Lebedev V N and Golovanchikov A B 2019 Heat and mass exchange packing with adjustable parameters for absorption and evaporation cooling IOP Conference Series: Earth and Environmental Science 288 012110

[94] Fomenko A I and Sokolov L I 2015 A study of sorption of phosphate ions from aqueous solutions by wood ash Russian Journal of Applied Chemistry 88(4) 652-6

[95] Dremicheva E S 2017 Studying the sorption kinetics on peat ions of iron(III) and copper(II) from wastewater Moscow University Chemistry Bulletin 72(4) 196-9

[96] Nikolaeva L A and Khamitova É G 2019 The use of energy industry waste as sorption material in the purification of reverse osmosis concentrate Chemical and Petroleum Engineering 55(5-6) 427-32

[97] Nikolaeva L A, Zainullina É R and Al’-Okbi A K 2019 Adsorption drying of natural gas by carbonate sludge Chemical and Petroleum Engineering 54(11-2) 919-25

[98] Nikolaeva L A and Khusnutdinov A N 2018 A Study of the absorption of nitrogen oxides from the boiler flue gases Thermal Engineering 65(8) 575-9

[99] Nikolaeva L A and Khusnutdinov A N 2018 Purification of gas emissions of chemical industry enterprises by carbonaceous cutting Ecology and Industry of Russia 22(8) 14-8

[100] Nikolaeva L A 2013 Research of sorption processes using chemical water purification sludge for nitrogen and sulfur oxides contained in smoke gases emitted from a thermal power station Thermal Engineering 60(4) 244-7

[101] Smirnov V, Dyrdin V, Kim T, Manakov A and Khoreshok A 2017 Experimental study of methane hydrates in coal E3S Web of Conferences 15 01020

[102] Smirnov V G, Dyrdin V V, Manakov A Y, Shikina N V and Ismagilov Z R 2019 Physicochemical and sorption properties of natural coal samples with various degrees of metamorphism Russian Journal of Applied Chemistry 92(10) 1410-21

[103] Dmitriev A, Madyshev I and Dmitrieva O 2018 Cleaning of industrial gases from aerosol particles in apparatus with jet-film interaction of phases Ecology and Industry of Russia 22(6) 10-4

[104] Dmitriev A, Madyshev I and Dmitrieva O 2020 Experimental study of hydraulic and heat and mass transfer parameters of inclined-corrugated contact elements of cooling tower sprinkler Ecology and Industry of Russia 24(1) 4-8

[105] Madyshev I N, Khafizova A I and Dmitrieva O S 2019 The study of gas-liquid flow dynamics in the inclined-corrugated elements of cooling tower filler unit E3S Web of Conferences 126 00031
[106] Dmitrieva O S, Nguyen V L, Yakimov N D and Sheshukov E G 2019 Evaluation of the efficiency of rectangular separators to collect the particles from the gas flows IOP Conference Series: Earth and Environmental Science 337(1) 012057
[107] Zinurov V E, Popkova O S and Nguyen V L 2019 Separator design optimization for collecting the finely dispersed particles from the gas flows E3S Web of Conferences 126 00043
[108] Dmitriev A V, Zinurov V E and Dmitrieva O S 2018 Influence of elements thickness of separation devices on the finely dispersed particles collection efficiency MATEC Web of Conferences 224 02073
[109] Dmitriev A V, Zinurov V E and Dmitrieva O S 2018 Intensification of gas flow purification from finely dispersed particles by means of rectangular separator IOP Conference Series: Materials Science and Engineering 451(1) 012211
[110] Dmitriev A V, Zinurov V E and Dmitrieva O S 2019 Collecting of finely dispersed particles by means of a separator with the arc-shaped elements E3S Web of Conferences 126 00007
[111] Golovanchikov A B, Balashov V A and Merentsov N A 2017 The filtration equation for packing material Chemical and Petroleum Engineering 5310-3
[112] Merentsov N A, Balashov V A, Bunin D Y, Lebedev V N, Persidskiy A V and Topilin M V 2018 Method for experimental data processing in the sphere of hydrodynamics of packed heat and mass exchange apparatuses MATEC Web of Conferences 243 5
[113] Merentsov N, Persidskiy A, Lebedev V and Golovanchikov A 2019 The use of industrial wastes from machine-building enterprises as packing materials for small-sized absorbers for gas emissions purification MATEC Web of Conferences 298 00031
[114] Merentsov N A, Persidskiy A V and Lebedev V N 2020 Use of wastes from metalworking machining for packings in contact heat-and-mass exchange devices Proceedings of the 5th International Conference on Industrial Engineering (ICIE 2019) Lecture Notes in Mechanical Engineering II 1443-54
[115] Merentsov N A, Persidskiy A V, Topilin M V, Lebedev V N, Balashov V A and Golovanchikov A B 2019 Experimental plant for studying hydrodynamics and heat and mass exchange processes in packing contact devices Journal of Physics: Conference Series 1278 012024
[116] Merentsov N A, Lebedev V N, Persidskiy A V and Golovanchikov A B 2020 Automatic control system for operation modes and calibration of technological parameters of evaporation cooling apparatuses Journal of Physics: Conference Series 1515 022004
[117] Merentsov N A, Persidskiy A V, Groshev V V, Kozlovtsiev V A and Golovanchikov A B 2019 Self-organization of processes in gas and liquid-phase catalytic reactors Journal of Physics: Conference Series 1399 044041
[118] Merentsov N, Persidskiy A and Topilin M 2019 Description of the process and packing materials for pulse liquid extraction Materials Today: Proceedings 19(5) 1908-12
[119] Merentsov N, Persidskiy A and Lebedev V 2019 Automatic parameter adjustment system for packing materials and control of flow modes in mass exchange columns Materials Today: Proceedings 19(5) 1899-903
[120] Merentsov N, Persidskiy A, Topilin M and Golovanchikov A 2019 Sectional automatic adjustment of catalyst layers in gas and liquid phase reactors MATEC Web of Conferences 298 00030
[121] Merentsov N, Persidskiy A, Lebedev V and Golovanchikov A 2020 Elastically deformable packing materials based on the waste of metalworking machines and hydrodynamic adjustment of contact blocks in mass-exchange apparatuses Materials Today: Proceedings 38(4) 1530-4
[122] Merentsov N, Persidskiy A, Lebedev V and Golovanchikov A 2020 Calibration of technological parameters of adjustable elastically deformable blocks of packed materials in mass exchange apparatuses Materials Today: Proceedings 38(4) 1545-50
[123] Merentsov N A, Persidskiy A V, Topilin M V and Golovanchikov A B 2020 Calibration of technological parameters of an electroadsorption apparatus with a fixed layer of adsorbent
[124] Merentsov N A, Persidskiy A V, Topilin M V and Golovanchikov A B 2020 Control of operating modes of an electroadsorption apparatus with a fixed layer of adsorbent *Journal of Physics: Conference Series* **1679**(5) 052096

[125] Merentsov N A, Golovanchikov A B, Topilin M V, Persidskiy A V and Tezikov D A 2019 Mass transfer apparatus for a wide range of environmental processes *Journal of Physics: Conference Series* **1399** 055028

[126] Merentsov N A, Persidskiy A V, Topilin M V and Golovanchikov A B 2020 Designs of electroadsorption mass transfer apparatuses *Journal of Physics: Conference Series* **1679**(5) 052021