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The application of the radiotracer method for the investigation of the cake layer formation on the membrane surface in the cross-flow flat-sheet membrane module

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ABSTRACT

The application of the radiometric method with the use of radiotracers for the investigation of membrane fouling was tested. The radiotracer method allows for a more complete control of membrane modules' performance, which may contribute to a longer working time due to the reduction of a frequency and an intensity of a periodic cleaning. The experiments were carried out with the cross-flow membrane module equipped with flat-sheet ultrafiltration membranes made of polyether sulfone. A suspension of the bentonite labeled by the radioactive isotope of lanthanum – ^{140}La was used as a feed solution. The influence of process parameters such as cross-flow velocity and pressure as well as feed concentration on the rate of membrane blocking indicated by the change in the specific radioactivity of deposit formed on the membrane surface was tested. The performed studies demonstrated that radiometric method enabled to estimate the thickness of the cake layer deposited on the membrane during the filtration process. It was noticed that thickness of the bentonite layer formed on the membrane surface increased with the increasing concentration of the feed solution and decreased with the increasing flow velocity and applied pressure. Experiments also showed the ability of applied method for in situ determination of both kinetics of the deposit formation on the membrane as well as the permeability of the deposit layer and its resistance.

Keywords: Ultrafiltration; Membrane fouling; Radiotracers

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1. Introduction

A deposit build-up on the membrane surface is a severe problem of membrane filtration systems, especially in pressure-driven processes. Membrane fouling is a permanent and often irreversible change in permeability; it causes increase in flow resistance, and in consequence, a decrease in filtration efficiency. These effects result from blocking of the membrane due to deposition of particulates, colloids, and other macromolecular compounds. They occur primarily in the case of pressure-driven membrane processes, such as microfiltration, ultrafiltration, nanofiltration, and reverse osmosis [1,2], but such effects can also be present in processes involving other driving forces, for example, membrane distillation or electrodialysis. The elimination of membrane fouling by all available means is important for efficient operation of membrane apparatuses. Understanding the nature of phenomena that cause membrane fouling by using carefully selected methods of surface analysis is equally vital.

There are many methods, which are widely used for membrane fouling investigation [3–7]. Some of those methods can be applied in situ without process interruption. Online monitoring techniques can play a major role in controlling the build-up of a deposit layer on a membrane and understanding mechanisms of fouling in membrane filtration systems. One of those techniques is an electrical

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impedance spectroscopy, which has already been employed to in situ monitoring of biofilm formation on the membrane surface [5]. Tung et al. [6] have discussed the application of an in situ optical method to monitor the growth of a fouling layer using a photointerrupt sensor array. Membrane fouling has also been studied using a novel method such as optical coherence tomography [7]. This technique has been explored to quantitatively interpret the formation of a cake layer during membrane process. The performed quantitative analysis has been based on a novel image processing method that was able to precisely resolve the 3D structure of the cake layer in a micrometer scale. There are also many studies on the examination of membrane blocking phenomenon, which demonstrate the utility of spectroscopic methods such as attenuated total reflection Fourier transform infrared (ATR-FTIR) spectroscopy [8,9]. This technique provides insight view into the chemical nature of deposits on membranes after filtration and enables characterization of the membrane surface, when testing the effectiveness of membrane cleaning [8]. Furthermore, it has been demonstrated that this technique enables fast evaluation of an average thickness of polymeric coatings (up to several micrometers thick) applied on nanofiltration and ultrafiltration membranes [9]. Unfortunately, ATR technique suffers from a lack of a good contact between the sample and the refractive ATR crystal, which can lead to nonaccurate results.

One of the mechanism manifestations of fouling phenomenon occurring in membrane processes is a filter cake formation. The mechanisms of formation of a filter cake are intensively explored, especially using optical methods, for example, photointerrupt sensors [10] or He-Ne laser beam [11]. These techniques have been applied to in situ measure of the cake layer thickness distribution across flat membranes during a cross-flow microfiltration process. The analysis of the deposit characteristics have allowed for better understanding of the mechanisms of membrane surface fouling. Another method, which can be applied for in situ detection of the layer thickness is a fluid dynamic gauging (FDG) method [12]. This technique has been used to track, in situ and in real time, the build-up of a filter cake during microfiltration of a suspension of hollow glass microspheres. FDG has been successfully applied to study deposits on surfaces of mixed cellulose ester membranes in cross-flow systems, at various transmembrane pressures. The simultaneous measurement of a permeate flux has given good agreement with the thickness detection by using this method.

The method of radiolabeled atoms used for testing various technological processes and apparatuses seem to be suitable for tracking phenomena occurring in the membrane zone. In the paper, an approach of the application of the radiometric method for study of cake layer formation on the membrane surface is presented. The main goal of the research was to identify the membrane blocking process and to assess its intensity. A quantification of the scale of membrane blocking allows for the better understanding of this phenomenon, which is of fundamental importance for reducing its impact on filtration efficiency. The radiometric technique used in the research described in the paper is noninvasive method, that can be an alternative to methods for the study of processes proceeded inside the membrane apparatus. The tracer method is based on introducing into the system a specific substance, and tracking the behavior of this substance, which allows to obtain information on this system [13]. As a tracer, radiolabeled compounds can be successfully used [14]. They have an advantage over nonradioactive tracers because of a very high sensitivity of detection, which gives the opportunity to use a very low concentration of the tracer, as well as for a remote detection of a radiation through layers of other materials present in the apparatus. Radioactive compounds can be added to the feed solution in a very small amount and due to the specifics of gamma radiation, which simply penetrates most of materials used for membrane module production, the radioactivity can be easily detected by a scintillation probe placed near the module. The increase in a specific radioactivity is related to the progress of formation of a sediment layer on the membrane and can be converted to the intensity of membrane fouling.

The literature indicates on this method as being useful, when studied phenomena occurring inside the membrane modules are quite scarce [15,16]. The papers are mainly focused on the study of mass transport through the ion-exchange membranes. A phenomenon of membrane blocking investigation using radiotracers was the subject of the paper [17], where the accumulation of radiolabeled macromolecules on the membrane surface due to concentration polarization was detected as an increase in voltage by a scintillation detector. The application of radioisotopes in the studies of the membrane processes was also described by Miskiewicz and Zakrzewska-Trznadel [18,19]. It was proven, that tracer method with an application of a short-lived radionuclides, could be a suitable tool for the study of kinetics of the particle deposition and the layer formation on the membrane surface, as well as hydrodynamic conditions in membrane apparatus.

2. Materials and methods

2.1. Materials

All chemicals used in the experiments were of analytical reagent grade. Bentonite of average particle size = 5.45 μm supplied by Sigma-Aldrich, USA (Cat. no. 285234) was used in experiments as a model medium. Lanthanum oxide (La_2O_3) used in the experiments as the carrier and the material for production of the radiotracer by irradiation in nuclear reactor was supplied by Fluka, Switzerland. Solutions of nitric acid and sodium hydroxide with concentrations of 1 and 0.1 M were used for pH adjustment. Distilled water was used for preparation of all solutions in the experiments.

Radioisotope of lanthanum – ^{140}La ($\tau_{1/2}$ = 40.3 h) was obtained by irradiation of lanthanum oxide (70×10^{-3} g) in the neutron flux (5×10^{13} neutrons/s m^2 for 2 min) in the Maria Research Reactor, Świerk, Poland. Total radioactivity of the sample after the exposure was 110 MBq. The obtained $^{140}La_2O_3$ was dissolved in 1 M nitric acid and the solution of $^{140}La(NO_3)_3$ was used as a tracer solution of an inactive carrier.

2.2. Methods

2.2.1. Membrane installation

Experiments described in the paper were performed using the membrane installation equipped with the flat sheet membrane module, the scheme of which is illustrated in Fig. 1. The system was composed of the cylindrical membrane module made of Plexiglas (self-made, INCT), the feed tank with volume of 3 L, the screw pump, as well as the control and the measuring equipment composed of manometers and flowmeter. An effective area of the membrane used was 2.12×10^{-3} m^2. The operating pressure difference was stabilized at the level of 0.15 and 0.3 MPa. All membranes used in the experiments were made of polyether sulfone with nominal pore size of 0.03 μm and they were purchased from GE Water & Process Technologies, USA.

2.2.2. Preparation of the feed solution

The feed solution for the membrane installation was a bentonite suspension radiolabeled with isotope of lanthanum – ^{140}La. This radionuclide was chosen due to its characteristics, namely short half-life, high energy of emitted gamma radiation (E_1 = 0.8 MeV, E_2 = 1.6 MeV), which could be easily detected as well as due to high ability to permanent binding to bentonite, which had been identified in the preliminary research.

The optimal conditions for the adsorption of lanthanum on bentonite determined experimentally in preliminary studies were as follows: pH was in the range from 5 to 7; the time required to reach equilibrium was 5 min.

A portion of a suspension for each filtration experiment was prepared in the following way: the appropriate mass of bentonite (1, 4, or 10 g) was mixed with 0.025 L of distilled water and then a few drops of the ^{140}La solution in 1 M HNO_3 were added. The pH of the sample was adjusted using 1 M NaOH or 1 M HNO_3. Such suspension was mixed for 30 min and then centrifuged (for 3 min at 12,000 rpm), then it was filtered using syringe filters (NY, 0.2 μm). Bentonite was then separated from the solution containing unreacted radionuclides and rinsed three times with 0.025 L of distilled water to remove residual radionuclides. Such radiolabeled bentonite was used to prepare a suspension, which served as a feed solution in the ultrafiltration system (Fig. 1).

2.2.3. The experimental procedure

In order to determine a rate of membrane fouling and to assess an influence of process parameters on this phenomenon, a series of experiments with different concentration of the filtered liquid c (0.5, 2, and 5 g/L), cross-flow velocity u (0.0075, 0.012, and 0.021 m/s) as well as operating pressure Δp (0.15 and 0.3 MPa) was conducted.

The radiolabeled suspension was introduced into the examined unit (Fig. 1) and filtered in a closed system (permeate and retentate streams were recirculated) for 5–7 h. The formation of the deposit layer on the membrane surface was recorded on the basis of the measurement of the increasing radioactivity of the sediment using a scintillation probe placed below the membrane module. The change of the radioactivity during experiments was monitored with the radiometer (FIR-1, INCT, Poland).

2.2.4. Calibration for thickness measurements

Thickness measurements were made by interpolating a calibration plot of thickness of the cake layer deposited

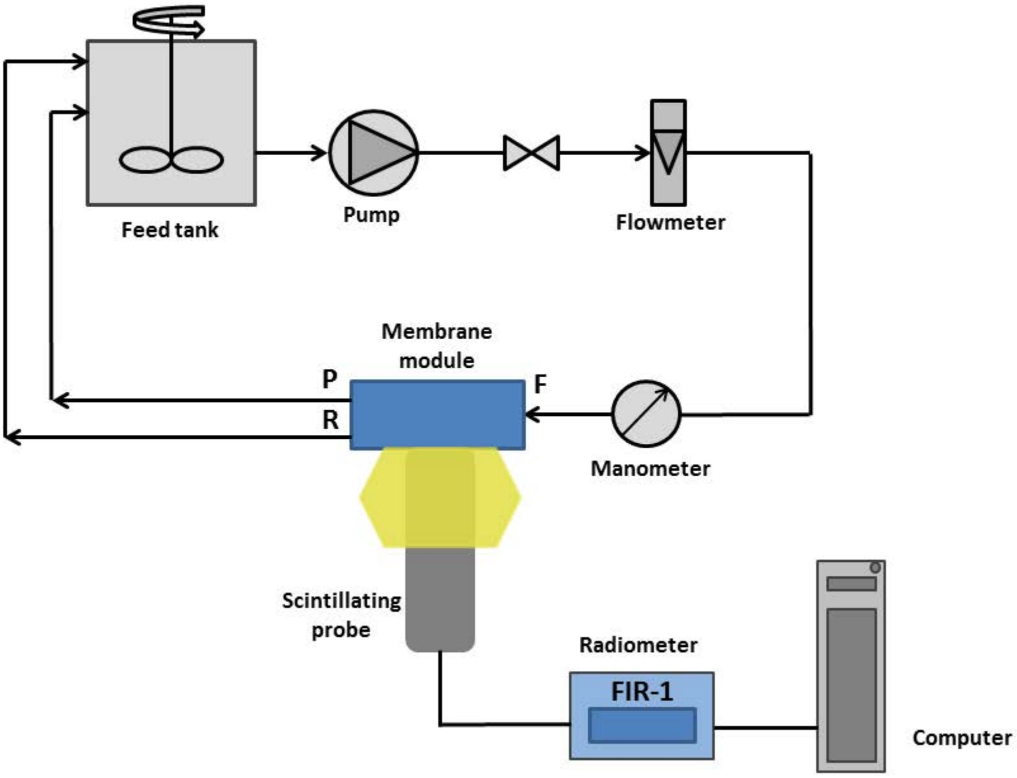

Fig. 1. The scheme of the installation with the flat sheet membrane module, F – feed, P – permeate, R – retentate.

on the membrane surface (δ) versus relative radioactivity of the bentonite layer (*A*). The relative radioactivity was determined according to the following relation (Eq. 1):

$$A = \frac{A_m}{A_t} \tag{1}$$

where A_m – specific radioactivity of the bentonite accumulated on the membrane (imp/s), A_t – total activity of the radiolabeled bentonite used in the experiment (imp/s).

In order to determine the thickness of the deposit, it was assumed that the sediment was distributed uniformly on the membrane surface and formed a layer of cylinder shape; the height of the cylinder corresponded to the thickness of the layer (δ). Therefore, a thickness of the bentonite layer on the membrane surface (δ) could be determined from the following relation:

$$\delta = \frac{m}{\rho \times \pi r_m^2} \tag{2}$$

where *m* – mass of the radiolabeled bentonite (kg); ρ – density of the bentonite (kg/m^3); r_m – radius of the membrane (m).

It was assumed, that density of the bentonite (ρ) was 2.7 × 10^3 kg/m^3 [20]. The calibration curve developed in the manner described earlier was used for in situ determination of the thickness during radiotracer experiments.

3. Results and discussion

3.1. Study on the influence of process parameters on the deposit thickness

Studies on the formation of the cake layer on the membrane during filtration of the radiolabeled bentonite suspension depending on process parameters were performed. As a result of these experiments the changes in the specific radioactivity of bentonite layer formed on the membrane surface during the progress of filtration were recorded using a radiometer These changes were correlated with the increase in the thickness of this deposit. An exemplary plot of the relative radioactivity (*A*) versus time (*t*) is presented in Fig. 2.

Next, on the basis of these results and using the developed calibration curve, the bentonite layer thickness in situ during radiotracer experiments was determined. The increase in the thickness (δ) of the bentonite deposited on the membrane surface during filtration in dependence of the concentration (*c*) of the feed solution (Fig. 3), feed velocity (*u*) (Fig. 4), and operating pressure difference (Δ*p*) (Fig. 5) was analyzed.

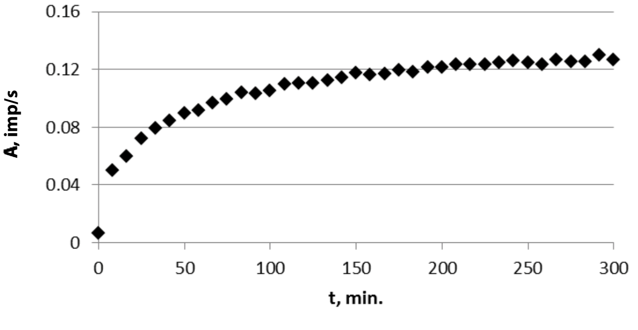

Fig. 2. The change in the relative radioactivity of the deposit layer accumulated on the membrane surface during filtration of the bentonite suspension; *c* = 0.5 g/L, Δ*p* = 0.15 MPa, *u* = 0.0075 m/s.

The performed studies showed that the thickest deposit was formed when the suspension with the highest concentration was filtered (Fig. 3). In this case, the rate of the deposit formation was fast during the whole experiment and the steady state was achieved only at the end of the experiment (300 min). For the suspension of low concentration of bentonite (0.5 g/L) the steady state was achieved relatively quickly and the thickness of the bentonite layer on the membrane surface was only 0.06 mm. In case of more concentrated suspension (5 g/L), the thickness of the layer was equal to 0.2 mm.

It was also proved that the increase in cross-flow velocity of the filtered suspension caused a decrease in the thickness of the deposit layer on the membrane surface (Fig. 4). In case of high cross-flow velocity (0.021 m/s), high rate of deposit formation at the beginning of filtration process as well as fast achievement of steady state (plateau) was observed. On the contrary, the high and increasing rate of deposit formation during the whole experiment was observed in case of low cross-flow velocity (0.0075 m/s).

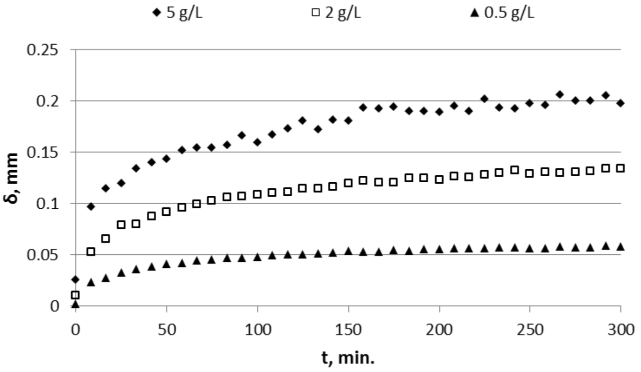

Fig. 3. The change in the deposit thickness accumulated on the membrane surface during filtration of the bentonite suspension of different concentration; Δ*p* = 0.15 MPa, *u* = 0.0075 m/s.

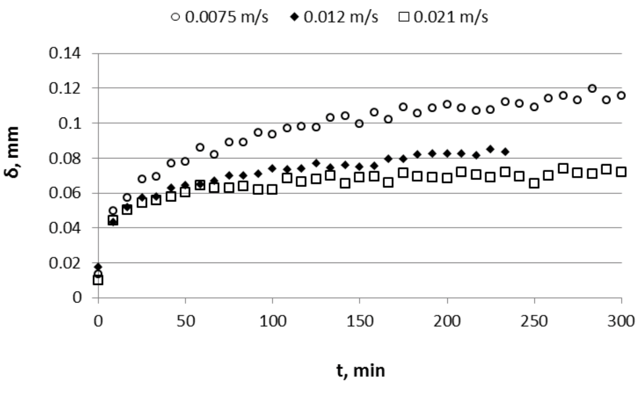

Fig. 4. The change in the deposit thickness accumulated on the membrane surface during filtration of the bentonite suspension at different cross-flow velocities; Δ*p* = 0.3 MPa, *c* = 2 g/L.

When the influence of operating pressure difference was considered, it was found that the higher the pressure, the thinner layer deposited on the membrane surface. This effect occurred for both concentrations of the bentonite suspension applied: 2 g/L (Fig. 5(a)) and 5 g/L (Fig. 5(b)), but in case of the higher concentration of the feed solution the difference in deposit thickness in steady state was slightly larger (ca. 0.08 mm) than in case of solution of the lower concentration (ca. 0.02 mm).

3.2. Kinetic model of deposit formation on the membrane surface

In order to quantitatively describe a rate of the deposit formation on the membrane surface, two kinetic models: a pseudo-first-order and a pseudo-second-order, were considered. The pseudo-first-order model can be expressed as follows:

$$\log\left(\delta_{e,\exp}-\delta_t\right)=\log\delta_{e,\mathrm{cal}}-\frac{k_1 t}{2.303} \qquad (3)$$

where $\delta_{e,\exp}$ – thickness of the deposit at steady state, determined experimentally (mm); δ_t – thickness of the deposit accumulated on the membrane surface at time t (mm); and $\delta_{e,\mathrm{cal}}$ – calculated deposit thickness, mm; k_1 – kinetic constant in the model (min^{-1}).

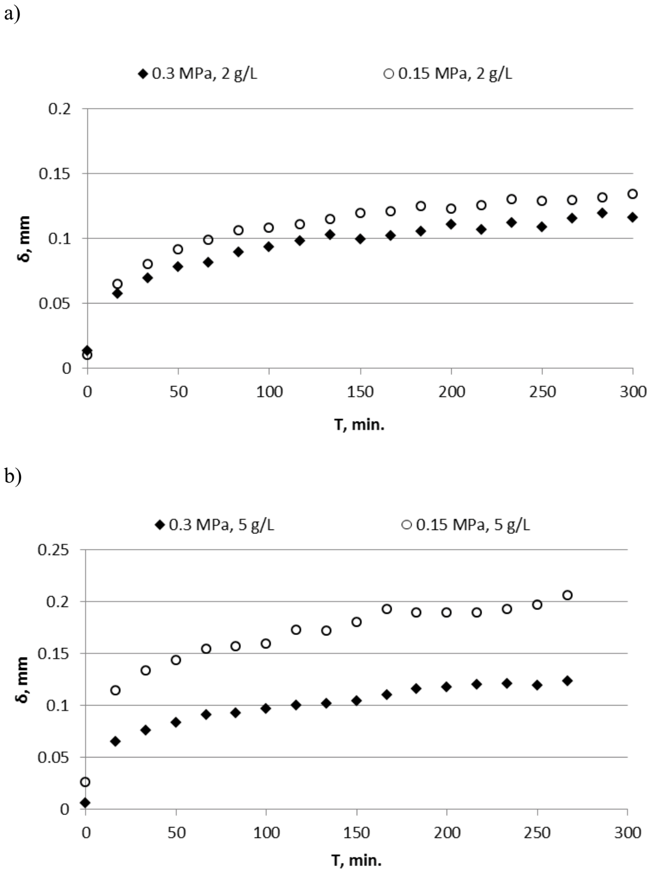

Fig. 5. The change in the deposit thickness accumulated on the membrane surface during filtration of the bentonite suspension at different operating pressures; $u = 0.0075$ m/s; (a) concentration of the bentonite suspension $c = 2$ g/L and (b) $c = 5$g/L.

The pseudo-second-order kinetic model can be expressed as follows:

$$\frac{t}{\delta_t}=\frac{1}{h}+\frac{1}{\delta_{e,\mathrm{cal}}}t \qquad (4)$$

where h is the initial rate of the deposit accumulation on the membrane surface, at $t = 0$ and it can be calculated from the following equation:

$$h = k_2 \times \delta_{e,\exp}^2 \qquad (5)$$

k_2 – kinetic constant in the model (mm min)$^{-1}$.

The change in the deposit thickness during filtration of bentonite suspension as well as linear relations for two proposed kinetic models are presented in Figs. 6(a)–(c). The results were achieved at selected process conditions: $\Delta p = 0.3$ MPa, $c = 2$ g/L, $u = 0.021$ m/s.

On the basis of experimental results, the kinetic constants (k_1 and k_2) as well as other model parameters ($\delta_{e,\mathrm{cal}}$, R^2) of the process were calculated and they are listed in Table 1.

The results of the experiments showed that the rate of the deposit formation on the membrane surface during the filtration of the bentonite suspension could be approximated by the pseudo-second-order kinetic model. In all process conditions, the values of the layer thickness ($\delta_{e,\mathrm{cal}}$) estimated from a pseudo-second-order model were more comparable with the values of the layer thickness determined experimentally ($\delta_{e,\exp}$) than those determined from the pseudo-first-order kinetic model. This compatibility with experimental data was expressed by high determination coefficients ($R_2^2 = 0.9974 \div 0.9988$), while for the pseudo-first-order kinetic model, correlation coefficients ranged from 0.8780 to 0.9825. For kinetic model, which better described process of deposit formation, values of the calculated deposit thickness ($\delta_{e,\mathrm{cal}}$) were slightly higher than ones determined experimentally ($\delta_{e,\exp}$) in each of the tested process conditions.

As it was found, in case of the better model, the kinetic constant (k_2) decreased as the concentration of the suspension filtered through the membrane increased. It means that filtration of more concentrated suspensions leads to the slower achievement of steady state in comparison with the filtration of less concentrated medium. As far as the influence of the cross-flow velocity is considered, the kinetic constant increases with the increase in the velocity of the liquid above the membrane surface. The increase in the cross-flow velocity promotes faster achievement of steady state of the deposit formation on the membrane.

3.3. Calculation of permeability and resistance of the deposit formed on the membrane surface

Based on the experiments conducted using ^{140}La as a radiotracer, it was also possible to determine a permeability (K) of the bentonite layer formed on the membrane surface as a result of filtration.

Pressure-driven convective flow model, which is the basis of the pore flow model, is most commonly used to describe flow in porous medium. The basic equation covering this type of transport is Darcy's law [1], which links the permeate

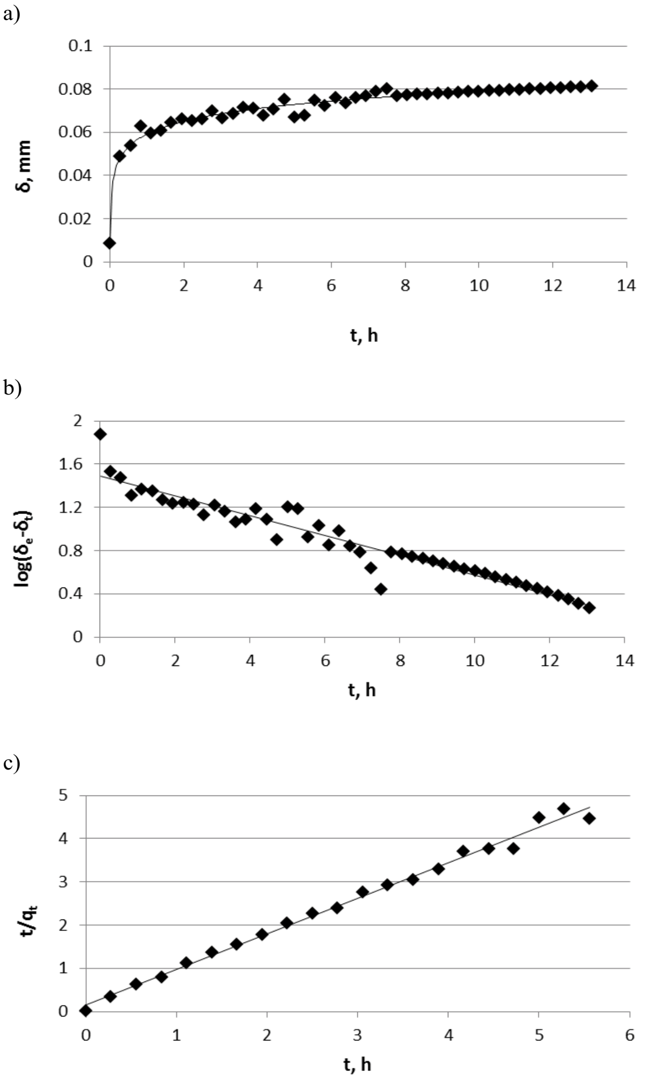

Fig. 6. The kinetic curves of the deposit formation on the membrane surface during filtration of the bentonite suspension, Δp = 0.3 MPa, c = 2 g/L, u = 0.021 m/s; (a) variation of the deposit thickness, (b) linear relation for the pseudo-first-order kinetic model, and (c) linear relation for the pseudo-second-order kinetic model.

flux (J) to the operating pressure difference (Δp) according to Eq. (6) as follows:

$$J = \frac{\Delta p}{\mu \times R_{\text{tot}}} \tag{6}$$

where Δp – the operating pressure difference (MPa); $R_{\text{tot.}}$ – the total hydraulic resistance (m^{-1}); and μ – the viscosity of the permeate (Pa s).

The total resistance is the sum of two contributions, one caused by the membrane and second caused by the cake layer. A permeate flux through the cake layer (J_δ), in case of microporous membranes of resistances negligible when compared with the cake layer resistance, can be described by Eq. (7) as follows:

$$J_\delta = \frac{\Delta p}{\mu \times R_\delta} \tag{7}$$

where R_δ is the cake layer resistance.

A permeate flux through the bentonite layer can be also described by the relationship analogical to the equation of filtration through the sediments as follows:

$$J_\delta = \frac{\Delta p \times K}{\mu \times \delta} \tag{8}$$

where K is the cake permeability (m^2) and δ is the thickness of the cake layer (mm).

This equation can be used, when the flow of the filtrate through the deposit is laminar, as then the permeability equation is valid.

Knowing the permeate flux, the viscosity of the liquid and previously determined (using radiometric method) thickness of the layer, a cake permeability (K) can be calculated, using Eq. (8).

Then, from comparison of Eqs. (7) and (8), a cake layer resistance R_δ can be calculated according to Eq. (9).

$$R_\delta = \frac{\delta}{K} \tag{9}$$

The calculated values of the layer permeability (K) and the resistance of this layer (R_δ) are listed in Table 2.

Table 1
The comparison of parameters of kinetic models of the deposit formation on the membrane surface obtained for different process conditions

Experimental conditions				Pseudo-first-order kinetic model			Pseudo-second-order kinetic model		
c (g/L)	u (m/s)	Δp (MPa)	$\delta_{e,\text{exp}}$ (μm)	$\delta_{e,\text{cal}}$ (μm)	k_1 (min^{-1})	R_1^2	$\delta_{e,\text{cal}}$ (μm)	k_2 (mm·min)$^{-1}$	R_2^2
2.0	0.0075	0.30	217	79	0.0039	0.9786	222	0.00014	0.9988
2.0	0.0120	0.30	100	43	0.0037	0.9825	102	0.00023	0.9982
2.0	0.0210	0.30	83	28	0.0032	0.9353	83	0.00035	0.9979
0.5	0.0075	0.15	69	33	0.0035	0.9765	70	0.00028	0.9974
2.0	0.0075	0.15	157	104	0.0053	0.8780	164	0.00012	0.9976
5.0	0.0075	0.15	231	112	0.0044	0.9652	238	0.00010	0.9981

R_1^2, R_2^2 – determination coefficients for the pseudo-first-order and pseudo-second-order kinetic model, respectively.

Table 2
A list of K values and R_δ values calculated on the basis of experimental results

N	c (g/L)	u (m/s)	Δp (MPa)	$K \times 10^{18}$ (m^2)	$R_\delta \times 10^{13}$ (m^{-1})
1	2	0.0075	0.30	6.2	3.30
2	2	0.012	0.30	3.7	2.20
3	2	0.021	0.30	5.1	2.10
4	0.5	0.0075	0.15	6.1	1.02
5	2	0.0075	0.15	12.0	2.57
6	5	0.0075	0.15	7.9	4.00

Summarizing this part and the data collected in Table 2, it can be concluded that the permeability (K) of the bentonite layer slightly differed depending on the feed concentration and the flow velocity, however the relation was not unambiguous. Results of the calculations also revealed that the second parameter under consideration – a resistance of the cake layer (R_δ) decreased with the increasing flow velocity (u) and the operating pressure difference (Δp), while the increasing concentration of the feed solution caused a decrease of the value of the deposit resistance (R_δ). This parameter, according to Eq. (8), is strongly related to the thickness of the layer, the higher the thickness of the layer – the higher the value of its resistance.

4. Conclusions

The application of the radiometric method using radiotracers for the membrane fouling investigation was presented. The influence of process parameters: flow velocity, pressure and feed concentration on the rate of membrane blocking was tested and two kinetic models: pseudo-first-order and pseudo-second-order, were considered in order to quantitatively describe a rate of the deposit formation on the membrane surface. Results of the studies showed that by application of radiotracers it was possible to assess the thickness of the cake layer deposited on the membrane during the filtration process. Obtained results also revealed that the applied method allowed to estimate the kinetics of formation of the deposit on the membrane surface. It was proven that the kinetics of the growth of the layer on the membrane could be described by the pseudo-second-order kinetic model.

Additionally, it was demonstrated that based on the experiments conducted using radiotracers it was possible to determine a permeability of the bentonite layer formed on the membrane surface as a result of filtration as well as its resistance.

Overall, the obtained results revealed the great potential of the radiometric method, which could be applied for the identification of the cake layer formation as well as for quantification of this phenomenon through measures of the thickness of deposit formed on a membrane surface. Information regarding the progress of the membrane blocking in this method was obtained in situ during experiments, which allowed for the prompt response toward process conditions regulation. Therefore, the method described in the paper can be successfully applied for controlling the performance of the membrane processes. This novel method can be considered as an alternative or the supplementary to other known techniques of fouling phenomena investigation.

Symbols

A_m — Specific radioactivity of the bentonite accumulated on the membrane, imp/s
A_t — Total activity of the radiolabeled bentonite used in the experiment, imp/s
c — Concentration of the bentonite suspension, g/L
δ — Thickness of the cake layer, mm
$\delta_{e,\exp}$ — Thickness of the deposit at steady state, determined experimentally, mm
δ_t — Thickness of the deposit accumulated on the membrane surface at time t, mm
$\delta_{e,\mathrm{cal}}$ — Calculated deposit thickness, mm
h — Initial rate of the deposit accumulation on the membrane surface at $t = 0$, mm/min
J — A permeate flux, m^3/m^2 s
J_δ — A permeate flux through the cake layer, m^3/m^2 s
K — Cake permeability, m^2
k_1 — Kinetic constant in the model, min^{-1}
k_2 — Kinetic constant in the model, (mm·min)$^{-1}$
m — Mass of the radiolabeled bentonite, kg
μ — Viscosity of the liquid, Pa·s
Δp — Operating pressure difference, Pa
R_δ — A cake layer resistance, m^{-1}
R_1, R_2 — Correlation coefficients for the pseudo-first-order and pseudo-second-order kinetic model, respectively
r_m — Radius of the membrane, m
ρ — Density of the bentonite, kg/m^3
u — Feed velocity, m/s

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References

[1] A.G. Fane, T.H. Chong, P. Le-Clech, Fouling in Membrane Processes, E. Drioli, L. Giorno, Eds., Membrane Operations – Innovative Separations and Transformation, Wiley-VCH Verlag GmbH & Co. KGaA, Weinheim, 2009, pp. 121–138.

[2] R. Field, Fundamentals of Fouling, K.-V. Peinemann, S. Pereira Nunes, Eds., Membranes for Water Treatment, Vol. 4, Wiley-VCH Verlag GmbH & Co. KGaA, Weinheim, 2010, pp. 1–23.

[3] F. Arndt, U. Roth, H. Nirschl, S. Schutz, G. Guthausen, New insights into sodium alginate fouling of ceramic hollow fiber membranes by NMR imaging, AIChE J., 62 (2016) 2459–2467.

[4] L. Benavente, C. Coetsier, A. Venault, Y. Chang, C. Causserand, P. Bacchin, P. Aimar, FTIR mapping as a simple and powerful approach to study membrane coating and fouling, J. Membr. Sci., 520 (2016) 477–489.

[5] J.S. Ho, J.H. Low, L.N. Sim, R.D. Webster, S.A. Rice, A.G. Fane, H.G.L. Coster, In-situ monitoring of biofouling on reverse osmosis membranes: detection and mechanistic study using electrical impedance spectroscopy, J. Membr. Sci., 518 (2016) 229–242.

[6] K.-L. Tung, H.-R. Damodar, R.-A. Damodar, T.-T. Wu, Y.-L. Li, N.-J. Lin, C.-J. Chuang, S.-J. You, K.-J. Hwang, Online monitoring of particle fouling in a submerged membrane filtration system using a photointerrupt sensor array, J. Membr. Sci., 407–408 (2012) 58–70.

[7] X. Liu, W. Li, T.H. Chong, A.G. Fane, Effects of spacer orientations on the cake formation during membrane fouling: quantitative analysis based on 3D OCT imaging, Water Res., 110 (2017) 1–14.

[8] O. Thygesen, M.A.B. Hedegaard, A. Zarebska, C. Beleites, C. Krafft, Membrane fouling from ammonia recovery analyzed by ATR-FTIR imaging, Vib. Spectrosc., 72 (2014) 119–123.

[9] M. Bass, V. Freger, Facile evaluation of coating thickness on membranes using ATR-FTIR, J. Membr. Sci., 492 (2015) 348–354.

[10] K.-L. Tung, S. Wang, W.-M. Lu, C.-H. Pan, In situ measurement of cake thickness distribution by a photointerrupt sensor, J. Membr. Sci., 190 (2001) 57–67.

[11] M. Hamachi, M. Mietton-Peuchot, Experimental investigations of cake characteristics in crossflow microfiltration, Chem. Eng. Sci., 54 (1999) 4023–4030.

[12] V.Y. Lister, C. Lucas, P.W. Gordon, Y.M.J. Chew, D.I. Wilson, Pressure mode fluid dynamic gauging for studying cake build-up in cross-flow microfiltration, J. Membr. Sci., 366 (2011) 304–313.

[13] K. Akerman, Techniczne zastosowanie metody atomów znaczonych, WNT, Warsaw, 1970.

[14] Radiotracer Applications in Industry — A Guidebook, Technical reports series no. 423, International Atomic Energy Agency, Vienna, 2004.

[15] C. Agarwal, A.K. Pandey, S. Chaudhury, V.T. Aher, A.K. Patra, P.U. Sastry, A. Goswami, Ionic transport in polyelectrolyte-filled cation-exchange membranes, J. Membr. Sci., 446 (2013) 125–131.

[16] P. Jagasia, P.K. Mohapatra, D.R. Raut, P.S. Dhami, V.C. Adya, A. Sengupta, P.M. Gandhi, P.K. Wattal, Pertraction of radio-cesium from acidic feeds across supported liquid membranes containing calix-crown-6 ligands in a fluorinated diluent, J. Membr. Sci., 487 (2015) 127–134.

[17] R.M. Mc Donogh, H. Bauser, N. Stroh, U. Grauschopf, Experimental in situ measurement of concentration polarisation during ultra- and micro-filtration of bovine serum albumin and Dextran Blue solutions, J. Membr. Sci., 104 (1995) 51–63.

[18] A. Miskiewicz, G. Zakrzewska-Trznadel, Investigation of hydrodynamic behaviour of membranes using radiotracer techniques, EPJ Web Conf., 50 (2013) 01005-p1-p7.

[19] A. Miskiewicz, G. Zakrzewska-Trznadel, A. Dobrowolski, A. Jaworska-Sobczak, Using tracer methods and experimental design approach for examination of hydrodynamic conditions in membrane separation modules, Appl. Radiat. Isot., 70 (2012) 837–847.

[20] H. Ito, Compaction properties of granular bentonites, Appl. Clay Sci., 31 (2006) 47–55.