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Research of the Physical Properties of the Liquid Radioactive Waste Treatment Ion-Selective Sorbents

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Abstract. The prospects of ion-selective treatment for the liquid radioactive waste volume reducing are shown. The main problems of the hydrodynamics scale-up and ion-exchange equipment design are outlined. The short review of the methods of packed bed hydrodynamic processes modeling is presented. The experimental research technique of the required physical properties of the EKOSORB ion-selective sorbents for the hydrodynamic design and scale-up of the liquid radioactive waste treatment ion-exchange equipment is shown. The results of the liquid radioactive waste treatment ion-selective sorbents true and bulk density and porosity measurements are shown. The micro photos and data on the ion-selective sorbents particle's form, size, and structure are presented. The ion-selective sorbents layer pressure drops were calculated by the Ergun's equation.

INTRODUCTION

The nuclear power plants and radiochemical plants operating is accompanied by the formation of radioactive waste (RW) [1-4]. In this connection, the RW treatment is one of the important and essential tasks of the atomic industry. Most of the RW is a liquid radioactive waste (LRW) [1, 2]. The main target of LRW treatment is the final disposal of conditioned RW. One of the LRW treatment methods along with others is an ion-exchange and selective sorption treatment [5, 6]. The numerous researches [7-11] including our previous researches [12] have been devoted to the use of ion-selective sorbents for LRW treatment.

The industrial LRW ion-selective treatment is operated in various packed bed technological equipment. One of the most important problems of the packed bed equipment designing is the scale-up problem. Wherein, the reason for the mass transfer scale-up problems is the complicacy of packed bed hydrodynamics processes scale-up. In our previous research [13] we used the Ergun's equation-based methods and semi-empirical models for the packed bed hydrodynamics CFD-simulation and scale-up. To use those models and methods there is the need to know some physical properties of packed bed particles and layers. In this work the results of liquid radioactive waste treatment ion-selective sorbents physical properties research are presented.

There are several similar methods to describe the flow in the packed bed. Most of them use the Darcy-Forchheimer-like equations to describe the pressure drops in the packed bed as a sum of specific pressure drops due to friction and kinetic [14-17]. The most comfortable of those methods in terms of specifying CFD-simulation initial data in our opinion is Ergun's equation-based methods. Ergun's equation [18] describes pressure drops in the packed bed as the function of the fluid density and viscosity and the packed bed porosity and packed particles average size:

$$\frac{\Delta p}{L}=\frac{150\mu(1-\xi)^2}{d_p{}^2\xi^2}u_{eff}+\frac{1.75\rho(1-\xi)}{d_p\xi^3}u_{eff}{}^2. \quad (1)$$

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There Δp is the pressure drop, Pa; L is the packed bed layer height, m; μ is the fluid viscosity, Pa·s; ξ is the packed bed porosity; d_p is the packed bed particle size (diameter), m; u_{eff} is the fluid effective velocity, m/s; ρ is fluid density, kg/m^3.

The initial data for Ergun's equation can be determined by relatively simple experimental measurements. Due to low values of the flow velocities in a packed bad and high packed bed hydraulic resistance the results of Ergun's equation calculation usually take the form of dimensionless dependencies of the hydraulic resistance specific coefficient on the Reynolds number. Wherein Reynolds number usually is calculated from the packed bed particle average size and effective flow velocity through the packed bed.

Thus, for the next researches on the LRW sorption treatment equipment designing and scale-up, we needed to determine packed bed porosity and average particle size of the ion-selective sorbents.

EXPERIMENTAL MATERIALS, METHODS, AND EQUIPMENT

In our research, we studied the physical properties of the SPE EKOSORB ion-selective sorbents SMET, RACIR, NIKET, and MODIKS. The sorbent's bulk masses were measured by the digital analytical scales. The volume of each sample was 800 ml. The samples volumes were measured by the measuring cup with the 5 ml value of the division. The sorbent's particles surface structure, shape and average size were determined using micro-photo the digital camera.

For the ion-selective sorbents porosity measuring we used Boyle-Mariotte law-based method. Figure 1 shows the porosity measuring laboratory test-stand scheme. The test-stand consists of glass control vessel 1, glass measuring vessel 2, air compressor 3, air collector 4, ball valves V1, V2, V3, V4, manometer P with the 1 Pa instrumental precision, and thermometer T. The measuring and control vessels 1 and 2 have the full volume of 1000 ml. The air collector 4 have the full volume of 220 ml.

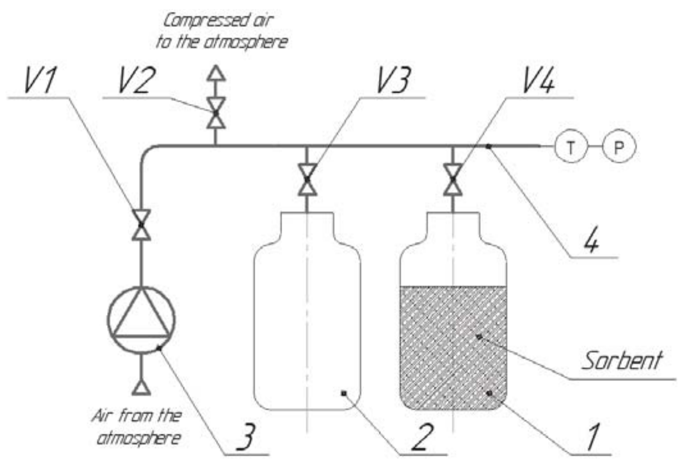


FIGURE 1. Porosity measuring laboratory test-stand scheme: 1 – measuring vessel, 2 – control vessel, 3 – air compressor, 4 – air collector, V1, V2, V3, V4 – ball valves, P – manometer, T – thermometer.

Before the measuring starts the measuring vessel 1 was filled with 800 ml of the sorbent. On the experiment start valves V2, V3, and V4 closes and air compressor 3 turns on. The atmospheric air enters the test stand and fills the air collector 4 and the control vessel 2 with increasing the air pressure in the air contour. When the air overpressure by the manometer P reaches the prescribeв value the air compressor 3 turns off and the valve V1 closes. The valve V4 opens and the air contour volume increases due to the measuring vessel 1 free space volume and the sorbent pores volume. The air overpressure in the air contour decreases with the air volume contour increasing.

The sorbet pores volume and sorbent porosity can be calculated by the air measured overpressure before and after valve V4 opening by Boyle-Mariotte law:

$$p_s V_s = p_e V_e, \tag{2}$$

$$V_s = V_{control} + V_{collector}, \tag{3}$$

$$V_e = V_s + V_{free} + V_{pores}, \tag{4}$$

$$V_{pores} = \left(\frac{p_s}{p_e} - 1\right) V_s - V_{free}, \tag{5}$$

$$V_{bulk} = V_{measuring} - V_{free}, \tag{6}$$

$$\xi = \frac{V_{pores}}{V_{bulk}}. \tag{7}$$

There p_s and p_e are the air overpressure before and after valve V4 opening respectively, Pa (kPa); V_s and V_e are the air contour volume before and after valve V4 opening respectively, ml; $V_{control}$, $V_{collector}$, V_{free}, V_{pores}, V_{bulk}, and $V_{measuring}$ are the volumes of the control vessel 1, air collector 4, free space in the measuring vessel 1, the sorbent pores, the bulk sorbent sample, ml; ξ is sorbent porosity. The sorbent true density can be calculated as:

$$\rho_{sorbent} = \frac{m_{bulk}}{V_{sorbent}}, \tag{8}$$

$$V_{sorbent} = V_{bulk} - V_{pores}. \tag{9}$$

There $\rho_{sorbent}$ is the sorbent true density, kg/m^3 (g/ml); m_{bulk} is the bulk sorbent sample mass, kg (g); $V_{sorbent}$ is the true sorbent volume, ml.

The measurements of all physical properties were repeated five times. The average measured values and the total measuring errors were calculated by Student method (t-test method) for the accepted error probability of no more than 10%.

RESULTS AND DISCUSSION

Table 1 shows the SPE EKOSROB ion-selective sorbents bulk and true densities, sorbent particles average sizes, and sorbents porosity measurement results. Table 2 shows the measuring errors estimations results by Student method. Table 3 shows the sorbents particles shape and surface characteristics. Figure 2 shows the micro-photos of sorbent particles.

Measuring results show that the sorbent samples bulk densities varies in the range of 740-1320 kg/m^3 and the sorbent samples true densities varies in the range of 1108-1681 kg/m^3. Thus, all samples except sample #4 have relatively low porosity. This fact may be explained by the irregular shape and the large size range of the sorbent particles. Because of those factors, there is the possibility of the dense placement of the particles in the packed bed especially for the particle's redistribution due to the layer motion, vibration, or the other mechanical actions with the sorbent layer.

According to Ergun's equation, due to a low porosity of the sorbents, the packed bed hydraulic resistance shall be relatively high. Thus, for the future researches and practical using it is need for the sorbents particle mechanical processing to decrease the particle shapes and sizes irregularity. Figure 3 shows the Ergun's equation estimated dependences of the sorbents packed beds hydraulic resistance specific coefficients on the Reynolds number calculated from the sorbent particle size and the effective fluid velocity through the packet bed.

TABLE 1. Physical properties of the SPE EKOSORB ion-selective sorbents.

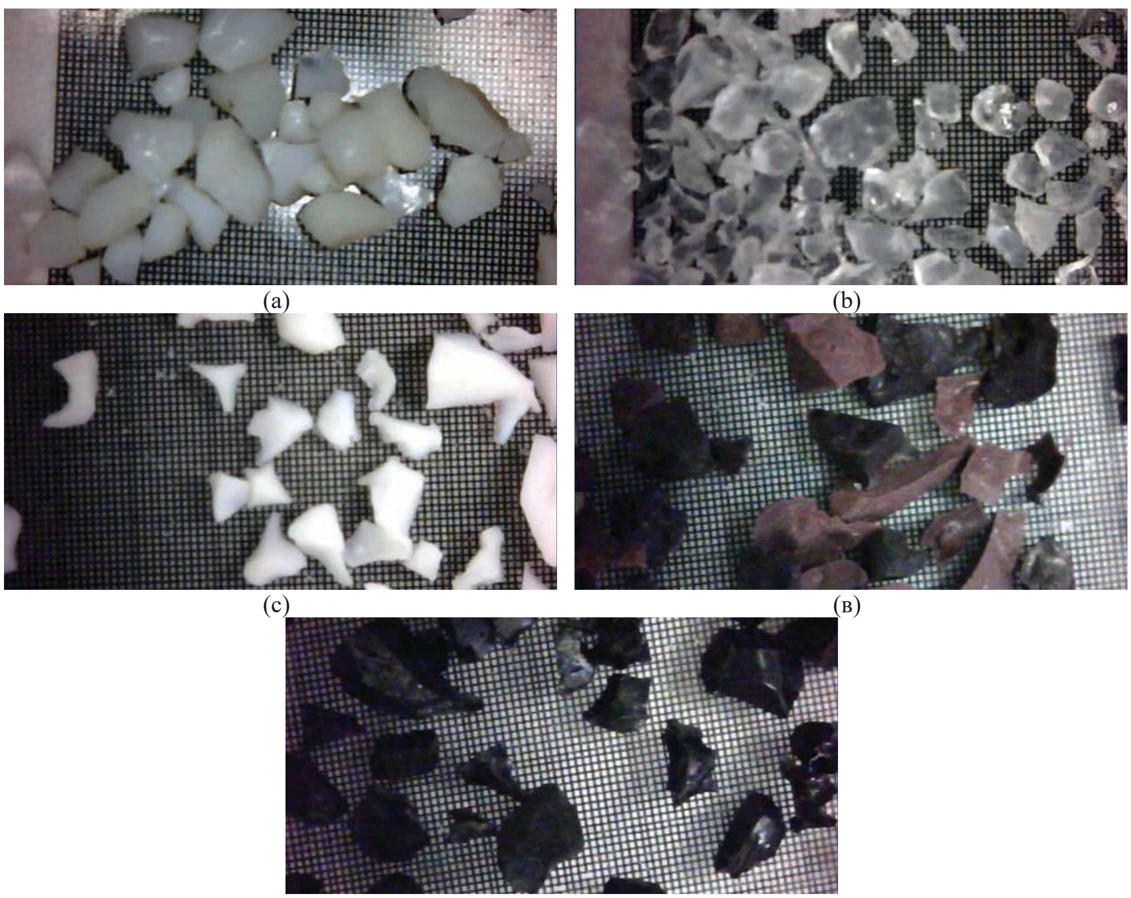
Parameter	**Ion-selective sorbent sample**				
	#1	**#2**	**#3**	**#4**	**#5**
Sorbent mark	SMET	RACIR	NIKET (1)	NIKET (2)	MODIKS
Bulk density, kg/m^3	1320	1092	1040	740	959
Porosity	0.214	0.187	0.061	0.404	0.234
True density, kg/m^3	1681	1343	1108	1241	1252
Particles average size, mm	0.9	0.8	1.7	1.1	1.4

TABLE 2. Measuring errors.

Physical property	Relative measuring error	
	Maximal	Average
Mass	8.2 %	6.0 %
Volume	5.6 %	5.1 %
Bulk density	13.1 %	11.1 %
Porosity	16.0 %	12.5 %

TABLE 3. Sorbents particles shape and surface characteristics.

Parameter	Ion-selective sorbent sample				
	#1	#2	#3	#4	#5
Particles shape	Irregular oval	Irregular polygon	Irregular	Irregular polygon	Irregular
Particles edges shape	Smooth	Smooth	Smooth	Sharp	Sharp
Particles color	White	Transparent	White	Brown	Black
Particles surface structure	Semi-gloss	Gloss	Matt	Matt	Gloss



(a) (b) (c) (в) (e)

FIGURE 2. Sorbent particles micro-photos, sale grid size is 0.1 mm: (a) sample #1 (SMET); (b) sample #2 (RACIR); (c) sample #3 (NIKET (1)); (d) sample #4 (NIKET (2)); (e) sample #5 (MODIKS);

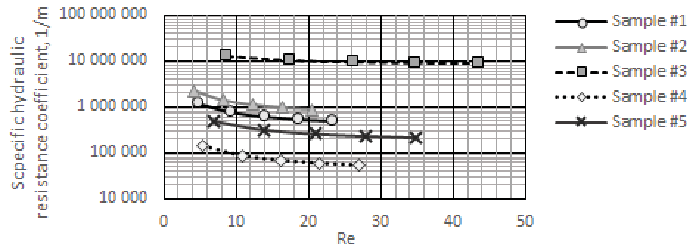


FIGURE 3. Estimated dependences of the sorbents packed beds hydraulic resistance on the Reynolds number.

CONCLUSIONS

It was shown that Ergun's equation may be used for the ion-selective sorption LRW treatment packed bed equipment designing and scale-up using CDF-simulation. The initial data for Ergun's equation are the ion-selective sorbent porosity and particle size and the fluid phase density and viscosity. The ion-selective sorbent porosity and particle size can be determined by relatively simple experimental measurements.

In our research, we determined the bulk and true densities and porosities and the particle sizes and shapes of the SPE EKOSROB ion-selective sorbents which show well effectively for the LRW treatment in earlier experimental researches. Measuring results show that the sorbent samples bulk and true densities varies in the ranges of 740-1320 kg/m^3 and of 1108-1681 kg/m^3, respectively. The estimated dependences of the sorbents packed beds hydraulic resistance on the Reynolds number were received.

The sorbents low porosity may be explained by the irregular shape and the large size range of the sorbent particles. Thus, for the sorbents layers hydraulic resistance decreasing it is need for the sorbent's particle mechanical processing.

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