MEDIÇÃO E ADSORÇÃO DE IONS DE METAIS PESADOS A PARTIR DE ÁGUA COM NANO-ADSORBENTES POROSOS POR MÉTODO DE ABSORÇÃO ATÔMICA

MEASUREMENT AND ADSORPTION OF HEAVY METALS ION FROM WATER USING POROUS NANO-ADSORBENTS BY ATOMIC ABSORPTION METHOD

اندازه گیری و جذب یون فلزات سنگین از آب با استفاده از نانوجاذب های متخلخل به روش جذب اتمی

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RESUMO

Este trabalho investigou a localização ideal de sistemas fotovoltaicos como uma das gerações distribuídas em micro-redes, no que diz respeito à potência ativa e reativa. As micro-redes fornecem a qualidade da energia de acordo com as necessidades dos clientes, os efeitos positivos das micro-redes no mercado de eletricidade e a redução de custos. Por outro lado, seus efeitos na redução da poluição do ar levaram muitos pesquisadores e especialistas a perceber a questão das micro-redes. Assim, considerando a capacidade de geração de energia ativa e reativa para sistemas fotovoltaicos em 24 horas, eles podem ser usados de forma mais eficiente. Os algoritmos apresentados em micro-grade de 33 barramentos foram aplicados no MATLAB, e os resultados analisados. Os resultados mostraram que a potência reativa gerada reduziria significativamente a potência ativa das perdas do sistema. Às 9h, considerando a capacidade do inversor fotovoltaico para gerar a energia ativa e reativa, o perfil de tensão do sistema melhorou mais efetivamente. Às 12 horas, existe a radiação máxima e a potência ativa gerada, e toda a capacidade do inversor é usada para gerar a energia ativa. A energia reativa fotovoltaica gerada levou à melhoria do perfil de tensão.

Palavras-chave: Íons de metais pesados, Método de Absorção atômica, química analítica, cinética de adsorção termodinâmica

ABSTRACT

This paper has investigated the optimal localization of photovoltaic systems as one of the distributed generations in micro-grids, with regard to active and reactive power. Micro-grids provide the power quality in accordance with customers' needs, positive effects of micro-grids on the electricity market and economic savings. On the other hand, their effects on reducing air pollution have caused many researchers and experts to notice the issue of micro-grids. So, considering the ability of active and reactive power generation for photovoltaic systems in 24 hours, they can be used more efficiently. The algorithms presented on 33 bus micro-grid are applied in MATLAB, and the results have been investigated. The results have shown that the generated reactive power would significantly reduce the active power of system losses. At 9 AM, considering the PV inverter capability for generating the active and reactive power, voltage profile of the system has improved more effectively. At 12 PM, there are existed the maximum radiation and active power generated, and the whole capacity of the inverter is used to generate the active power. The PV reactive power generated has led to the improvement of the voltage profile.

Keywords: Heavy Metals Ion, Atomic Absorption Method, Analytical chemistry, kinematic adsorption thermodynamics.

چارچوب‌های فلز-آلی متخلخل گونه نوظهوری از مواد متخلخل با مساحت سطح بالا و طراحی پذیری نامحدود هستند که می‌توانند به شکل موثری به عنوان جاذب آلاینده‌ها مورد استفاده قرار بگیرند. در این مطالعه، جذب فلزات سنگین به ویژه Hg(II) و Pb(II) توسط UiO-66-NH_2 که یکی از شناخته شده ترین و پایدارترین MOF هاست از محیط آبی مورد مطالعه قرار گرفت. روش جذب اتمی برای نظارت بر میزان جذب و مطالعه سینتیک و ترمودینامیک جذب استفاده شد. جذب سریع و انتخابی 35 میلی گرم بر گرم نسبت به جیوه و 30 میلی گرم بر گرم نسبت به سرب در زمان کوتاه کمتر از پانزده دقیقه برای این چارچوب بدست آمد. این ساختار چندین بار قابلیت استفاده مجدد دارد و می‌تواند بدون کاهش در میزان جذب حداقل برای 5 مرحله متوالی به عنوان جاذب مورد استفاده قرار بگیرد. نتایج برجسته این کار نشان می‌دهد که جاذب‌های NH_2 -functionalized Zr-MOFs جذب موثری (نزدیک به صد در صد) برای حذف یون جیوه و سرب در غلظت‌های اولیه کم (در حدود 20 میلی گرم بر لیتر) از خود نشان می‌دهند و غلظت آلاینده در آب را به کمتر از حدود استاندارد برای آب آشامیدنی می‌رسانند. مقدار جذب قابل توجه 30 میلی گرم بر گرم نسبت به Pb(II) و 35 میلی گرم بر گرم برای Hg(II) در شرایط بهینه (pH=6 و دمای 30 درجه سانتیگراد) و زمان کمتر از 15 دقیقه به دست می‌آید. سینتیک جذب مرتبه دوم با جذب شیمیایی سازگار است و نشانگر آن است که می‌دهد انتقال، مبادله و یا به اشتراک گذاری الکترون‌ها انجام شده است و فرایند جذب از طریق تشکیل پیوندهای شیمیایی رخ داده است. از سوی دیگر همخوانی نتایج تجربی با مدل ایزوترم لانگمویر در غلظت‌های مختلف نشان می‌دهد که فرایند جذب یکنواخت و همگن است. نتایج نشان می‌دهد که MOF های حاوی آمین می‌توانند گزینه خوبی برای جذب فلزات آلاینده از محیط‌های آبی باشند.

کلمات کلیدی:

فلزات سنگین، روش جذب اتمی، شیمی تحلیلی، سینماتیک ترمودینامیک جذب.

1. INTRODUCTION

The rapid growth of industry and agriculture, lifestyle changes and urbanization have increased water pollution [1-3]. Among the sources of water pollution, heavy metals are one of the most critical pollutants due to their lack of bio-degradation, water resistance and high toxicity [4]. Hg(II) is one of the most dangerous metal ions that enter the water through the mining industry, batteries, pharmaceuticals, metallurgy, etc. and damage the brain, kidneys and nervous systems. [5]. Also, Pb(II) is harmful to humans and animals, even at very low concentrations in water, because it remains in the food chain. To remove heavy metals from wastewater, various methods have been used such as chemical treatment, ion exchange, nanofiltration, reverse osmosis, low energy, membrane processes, and adsorption [10]. Among all these methods, adsorption is widely accepted due to low prices, high efficiency, design simplicity, and selectivity. Heavy metal ions can be removed by various types of materials such as activated carbon, clay, clay loamants, chitosans, or natural zeolites [14].

As an electron receiver, Hg(II) employs electron absorbent agent groups to form corduroy bonds [15]. Therefore, functional groups such as thiol, amine, sulfamine and the like can be used as an enhancement medium for increasing absorption capacity. The amine group may be able to create new structures, such as Imino, with Hg(II) , which can result in high, effective and selective amnesic adsorption to Hg(II) [16, 17]. Pb(II) is also an electron receptor and has an empty orbital, so it can interact with the electron-diffusion species and is effectively absorbed by these materials. To solve the problem of low capacity capability and low efficiency of absorption method, nanomaterials and especially metal-organic frames (MOFs) have been

used to absorb heavy metal ions from water as a new category of porous materials with high surface area [18]. They have a remarkable ability to repair environmental problems, with benefits as well as higher efficiency and faster absorption in water treatment. MOFs with free amine-containing ligands with acceptable water resistance can be a good alternative to heavy metal ion adsorption. [19]

Here, we use an atomic absorption method to study the absorption of ions by using an amine-polymerized porous metal-organic framework with high chemical and thermal stability (UiO) (UiO-66-NH_2) Heavy metals, including mercury and lead, have been investigated by this structure. Amine groups ($-\text{NH}_2$), which have a pair of electrons and act as open-lowis, can play a role in the formation of corded bands with heavy metal ions (Lewis acids) [20]. The ability of actin receptor for Lewis acids can be controlled by adjusting pH, which affects absorption [21]. The effects of adsorption time, temperature, pH, and initial concentration of ion on the adsorption of mercury and lead ions were investigated. Additionally, kinetic and thermodynamic studies of absorption, as well as the ability to retrieve the framework, have also been studied. The results show an acceptable absorption capacity of 35 mg.g^{-1} for mercury and 30 mg.g^{-1} for the lead in less than 15 minutes for this framework. Also, UiO-66-NH_2 can be easily retrieved and used as an absorbent for at least 5 cycles.

2. MATERIALS AND METHODS

Today's modern world is slowly in need of electrical energy with high quality and reliability. The increased need of availability and high reliability, requiring to use of the new energy resources like generators, old transmission, and distribution networks, all of them run the present challenges in order to increase the reliability, security, and quality of power. Therefore,

researchers and experts, in order to achieve more efficient ways to provide electrical power, have introduced new technologies such as microgrid networks. The presence of microgrids in distribution networks provides many advantages for customers. Microgrids have the ability to provide power quality in accordance with customers' needs. In such circumstances, it is clear that it is important to have an optimal strategy for the location of distributed generation units in microgrids, and not to consider it will waste time and financial resources. The reference [16] offers a removed sequential algorithm to the placement and determines the capacity of DGs, [1] carries out a new innovative approach based on cost-benefit analysis to determine the capacity and optimal placement of DG. The reference [2] offers the method of genetic algorithm optimization for the development of DG resources in distribution. Placement of distributed generations' resources that photovoltaic systems are one of them have been studied in many types of research [17-20]. The reference [21] presented rational and logical issues to construct the microgrids. The effects of DG on the reliability and efficiency with the presence of time-varying loads in [22] have been studied. The reference [23-24] investigated the reliability of a microgrid network with optimal placement of distributed generations in it. In all studies conducted in the past, the resources of distributed power generation (DG) are mentioned as a source of active power generation. But this paper tries to, by a new approach, addresses the optimal placement of photovoltaic systems which known as one the of the DG resources in microgrids, considering the reactive power generation in addition to the active power.

All raw materials were purchased from chemical manufacturing companies and used without further purification (Sigma Aldrich, Merck, and Acros). The IR spectrum (by KBr) was recorded with the Nicholote 100 spectrometer with a Fourier optical converter, ranging from 400 to 4000 cm^{-1} . Heat analysis (TGA) was carried out by loading the samples on an aluminum pan under an inert nitrogen atmosphere with a temperature gradient of 10 $^{\circ}\text{C}/\text{min}$ in the temperature range of 26-600 $^{\circ}\text{C}$. Crystallographic measurements of UiO-66- NH_2 were performed by a spectroscopic device with the Bruker APEX detector. The intensity of the data using

Graphite monochromated Mo-K α radiation ($\lambda = 0.71073 \text{ \AA}$) was collected. X-ray powder diffraction (XRD) was measured using a Philips X'pert diffractometer with a monochromator (Cu-

K α) ($\lambda = 1.54056 \text{ \AA}$). Simulation of XRD powder based on single crystal data using Mercury software the nitrogen absorption/desorption isotherm was measured at liquid nitrogen temperature (77 K) using the Micromeritics ASAP 2020 analyzer. A specific surface area was calculated by Brunauer-Emmett-Teller (BET).

2.1. Mechanochemical synthesis of UiO-66- NH_2

The solvothermal synthesis of this metal-organic framework has been reported in the literature [22]. In order to reduce the time and increase the efficiency of the methodology, we used the framework for the synthesis of the framework. For this purpose, 3.8 grams of ZrCl_4 salt and 2.17 grams of 2-aminomethacrylic acid were poured into a Chinese masonry and added a few drops of DMF solvent. The resulting mixture was washed slowly for 30 minutes and added two drops of solvent every minute. After thirty minutes, the yellow powder was obtained three times and washed with 10 ml of DMF each time to remove unreactive raw material. The precipitates were rinsed for 4 hours at 80 $^{\circ}\text{C}$ to dry completely. In order to remove the solvent enclosed in the cavities, the structure was vacuumed for 4 hours at 200 $^{\circ}\text{C}$ prior to any absorption. Efficiency is about 60%.

2.2. Adsorption process

The appropriate amount of $\text{Pb}(\text{NO}_3)_2 \cdot 4\text{H}_2\text{O}$ and $\text{Hg}(\text{NO}_3)_2 \cdot 4\text{H}_2\text{O}$ was dissolved in 250 ml of deionized water to allow mother liquor with concentrations (10,20,30,40,50,100,150) mg per liter of the desired ions. Absorption experiments were performed by adding 10 mg of adsorbent to 50 milliliters of Hg(II) and Pb(II) solutions in a 100-milliliter conical flask at a constant temperature of 400 rpm. The effect of the initial concentration of heavy metals ions, solution pH and contact time on the absorption capacity of UiO-66- NH_2 was investigated. PH was adjusted by adding partial amounts of 0.1 M NaOH and HNO_3 solutions in the range of 2-7. Time 2 hours and ambient temperature were selected to start studies. Then, the mixture was centrifuged at 12000 rpm for 4 minutes and sampled for atomic absorption spectrometry. Absorption capacity and removal efficiency (% adsorption) were obtained from Equations (1) and (2), respectively:

$$Q_t = \left(\frac{C_0 - C_t}{M} \right) V \quad (\text{Eq. 1})$$

$$R\% = \left(\frac{C_0 - C_e}{C_0} \right) \times 100 \quad (\text{Eq. 2})$$

Where C_0 and C_e are the concentration of primary and equilibrium metals (mg/L), m is the adsorbent mass (g) and V volume (L) of the sample.

To study the absorption kinetics, the absorption process was stopped at different times from 30 seconds to 120 minutes, and the sampling was done. Also, to study the isotherm of absorption, the initial concentration of 5 to 200 mg/L was poured into a conical tube with 10 mg of adsorbent and shifted to 298 K for 2 hours.

3. RESULTS AND DISCUSSIONS

3.1. Characterization of the Adsorbents

The XRD pattern is shown in Figure 1A shows that the crystalline structure of UiO-66-NH₂ is consistent with previously reported crystalline samples. The size of the crystallite size was calculated using the Scherrer's calculator and was obtained in the range of about 15 ± 2 nm. The FTIR spectrum of the synthesized framework is shown in Fig. 1B. In the form of index peaks in 3425, 3348, 2888, 1564 and 1378 cm⁻¹, respectively, anomic tensile vibration peaks of -NH, symmetric vibration -NH, tensile vibration C-H, and symmetric oscillation of O=C-OH are observed. The SEM image shows the surface morphology of the synthesized material in Figure 1C.

The nitrogen absorption isotherm is shown in Figure 2A, which represents a type-1 curve that confirms the microporous nature of the framework. This framework contains a specific BET surface area of 1330 m²/g. The distribution of the cavity size associated with the framework obtained from the Barrett-Joyner-Halenda (BJH) plot is shown in Fig. 2B.

The results show that MOF has a high microporous volume (V_p) of 484.84 cm³g⁻¹ and a narrow cavity distribution of 0.6nm and significant surface area.

3.2. Investigation of Hg(II) and Pb(II) adsorption

Since functional groups play an essential role in the selective absorption of heavy metals, it has been proven that amine carrier materials are desirable species for the adsorption of Hg(II) and Pb(II) [19], UiO-66-NH₂ were studied for the absorption of metal ions.

3.2.1 Effect of pH

In the process of adsorption of ions, solution pH is one of the most critical factors that affect not only the distribution of adsorbent load, and it may also affect the adsorbent species [23]. PH studies on the adsorption of Hg(II) and Pb(II) by UiO-66-NH₂ showed that pH significantly affects the absorption rate. Due to the low concentration of lead ions and mercury ions in the form of precipitate at pH values above 7, and due to the high stability of UiO-66-NH₂ in water and acidic media, pH changes in the range of 3-7 were studied, and the results in Figure 3A is shown. In this process, the initial concentration of the metal ion was 50 mg/L, the contact time was 10 minutes, and the temperature was 298 K. It is clearly seen that by increasing the pH from 2 to 7, the absorption capacity increases dramatically. These observations can be explained by the isoelectric point (IEP), which is obtained by plotting the curvature of the adsorbent zeta potential values at different pH values (Fig. 3B). The isoelectric point, which is determined using a standard method and shows electrophoretic mobility in a situation where the total load of the particle is zero [24], for this adsorbent is 3.8. When the pH > IEP, the MOF surface load will be negative.

In the case of UiO-66-NH₂ at low pH levels, the MOF surface is protonated, and an electrostatic barrier is formed to absorb Hg(II) onto the protonated NH group, so the adsorption of Hg(II) is limited. To make Also, high concentrations of H⁺ ions in the solution lead to a competition between Hg(II) and H⁺ to occupy the active absorption site [25]. The electrostatic impedance between Hg(II) and UiO-66 (NH₂) decreases with increasing pH and decreasing H⁺ in the solution, and more vacant centers are created to absorb Hg (II), which leads to increased absorption. At pH > 7, OH-ions are released into the environment, and the OH-combination with Hg(II) leads to the formation of a deposit that cannot be investigated through adsorption with solid adsorbent. Therefore, absorption in alkaline materials was not studied.

According to Figure 3, the maximum adsorption capacity for Hg(II) is shown in pH 7. It should also be noted that the pH of the solution of Hg(II) in the presence of UiO-66-NH₂ is 6.1 and due to the fact that this value is close to optimal pH, the adsorption processes were then carried out without changing the pH of the environment. Also, the process of adsorption of Pb(II) was

investigated by UiO-66-NH₂, which showed a low absorption capacity at optimal pH. According to the acid and open hard, and soft theory [26], Pb(II) is harder than Hg(II) acid and is, therefore, less absorbed by UiO-66-NH₂. The effect of pH on the adsorption of Pb(II) by UiO-66-NH₂ was also investigated. Regarding the distribution of Pb(II) species at different pHs of the solution, the adsorption rate of Pb(II) was investigated in the pH range of 3-8. Pb²⁺ is believed to dominate in the lower pH of the species, but when the pH is higher than 7.5, Pb (OH)⁺ is produced as the dominant species; further increasing the pH of the environment eventually leads to the formation of Pb (OH)². Regarding the presence of Pb²⁺ and Pb (OH)⁺ in solution in the pH range of 5.5-6.5 and increasing the absorption in this range, it seems that UiO-66-NH₂ does not differ between these two species. The reason for the absorption of these species is the negative charge level of the adsorbent. Figure 3 shows that the absorption capacity of UiO-66-NH₂ increases to 3 mg/g to 30 mg/g as compared with Pb (II). The highest absorption capacity at pH was 7, which is very close to the pH of Pb(II) solution in the presence of UiO-66 (NH₂); therefore, further studies were carried out without changing the pH.

3.2.2 The effect of the initial concentration of M (II)

The effect of changing the initial concentration of Hg(II) and Pb(II) to the absorption by UiO-66 (NH₂), (20, 30, 40, 50, 60, 70, 80, 90, 100 mg/L) without change the pH of the solution was checked for 2 hours at ambient temperature. As shown in Fig. 4, the adsorption capacity is clearly increased by increasing the concentration of M (II) due to the increase in the propulsion force due to the increase of the concentration gradient pressure [27]. Ultimately, due to the restriction of free adsorption sites, absorption is saturated. The maximum absorption capacity of UiO-66-NH₂ was 35 and 30 mg/g, respectively, relative to Hg(II) and Pb (II). When the initial concentration of M (II) is low, the absorption rate is reduced to 100%, which decreases with increasing concentrations. These observations are due to the net content of UiO-66-NH₂ binding sites.

3.2.3 Absorption kinetics

In order to investigate the mechanism governing the absorption process and determine whether absorption is controlled by a chemical or physical mechanism, the kinetic models of common adsorption, such as first-order pseudo-second-order, are used to study the experimental data obtained from the atomic absorption analysis. Because The correlation coefficient of the second-order pseudo-second-order model for Hg(II) and Pb(II) is close to 1 ($R^2 = 0.997$ and 0.9973) (Figure 5) and shows that the pseudo-second-order model compared to the quasi-first-order model ($R^2 = 0.9755$) is more consistent with experimental data. Therefore, the observed process is consistent with chemical absorption, which indicates that the transfer, exchange, or exchange of electrons has taken place and the process of absorption has occurred through the formation of chemical bonds.

3.2 Isotherm Absorption

The absorption process continues until adsorbent and absorbent reach a dynamic equilibrium. The equilibrium relationship is described by the absorption isotherm, which provides information on the interaction between the absorbent surface and the absorbing species [28, 29]. In order to describe the interaction between UiO-66-NH₂ and Hg(II) as well as Pb (II), the Langmuir isotherm model was studied in different concentrations. Langmuir model is often used to describe single-layer adsorption and assumes that all adsorption sites are the same. The relations between Langmuir's Isotherms are as follows:

$$\frac{C_e}{Q_e} = \frac{1}{K_L Q_m} + \frac{C_e}{Q_m} \quad (\text{Eq. 3})$$

$$R_L = \frac{1}{1 + K_L C_0} \quad (\text{Eq. 4})$$

Correlation Coefficient (R^2) for Langmuir Isotherm Model ($R^2 = 0.9980$) shows that the absorption process is uniform and homogeneous. Also, the R_L value between 0 and 1 for all concentrations shows that the absorption process is desirable. The values of Q_m and K_L are derived from the gradient and width of the C_e / Q_e curve in relation to C_e .

3.3 Thermodynamic Studies

The thermodynamic parameters were investigated at a temperature range of 288 to 323 K Kelvin. The equilibrium constant (K_0), Gibbs free energy (ΔG° , kJ mol⁻¹), enthalpy (ΔH° , kJ mol⁻¹) and entropy (ΔS° , kJ mol⁻¹K⁻¹) are calculated based on the following equations.

$$K_0 = \frac{Q_e}{C_e} \quad (\text{Eq. 5})$$

$$\Delta G^\circ = -RT \ln K_0 \quad (\text{Eq. 6})$$

$$\ln K_0 = \frac{\Delta S^\circ}{R} - \frac{\Delta H^\circ}{RT} \quad (\text{Eq. 7})$$

The thermodynamic parameters of Hg(II) and Pb(II) adsorption by UiO-66-NH₂ are presented in Table 1. The negative value of the free energy of Gibbs represents the self-absorption process.

3.4. UiO-66-NH₂ selective absorption study.

In comparison, UiO-66 (NH₂) shows good performance for removal of Hg(II) and Pb(II) with rapid adsorption. In addition, a selective absorption test was performed for various ions. The absorption of heavy metal cations such as Co²⁺, Cd²⁺ and Cu²⁺ by UiO-66-NH₂ was investigated. Atomic absorption spectroscopy showed that UiO-66-NH₂ effectively absorbed Hg(II) and Pb(II) (Fig. 6).

3.5. Reconstruction and reuse of the metal-organic framework

Reconstitution of an adsorbent is a critical issue for the selection of suitable adsorbents for water purification systems. To this end, a recovery experiment was conducted on the adsorbent to determine the potential impact of reducing the adsorbent function after several absorption steps. The desorption process was performed using 15 milliliters of a nitric acid solution with concentrations of 0.1, 0.25 and 0.50 moles, and the recovery rate was obtained at 40, 69 and 93 percent, respectively. Accordingly, absorption / desorption steps were performed using a 0.50 molar solution of nitric acid. The adsorption / desorption function is shown in Figure 7 after the three cycles obtained from the adsorbent.

The absorption capacity of absorbent material remains unchanged after five periods. These results indicate the cost-effectiveness of this absorbent.

4. CONCLUSION

The outstanding results of this work show that NH₂-functionalized Zr-MOFs adsorbents exhibit an effective absorption (close to 100%) to remove mercury ions and lead in low initial concentrations (about 20 mg/l), and The concentration of pollutants in water is below the standard limit for drinking water. Significant absorption rate is 30 mg/g and Pb(II) and 35 mg/g for Hg(II) in optimal conditions (pH = 6 and temperature 30 °C) and time is less than 15 minutes. The second-order adsorption kinetics are consistent with chemical absorption, indicating that the transfer, exchange, or exchange of electrons has taken place and the adsorption process has occurred through the formation of chemical bonds. On the other hand, matching the experimental results with Langmuir isotherm at different concentrations shows that the adsorption process is uniform and homogeneous. The results indicate that AMF-containing MOFs can be a good option for adsorption of polluting metals from aqueous media.

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Figure 1. a) Pattern XRD, b) IR spectrum, and c) SEM image of synthesized UiO-66-NH₂

Fig. 2. a) N₂ gas absorption isotherm and b) UiO-66-NH₂ pore size distribution

Figure 3 (a) The effect of pH of aqueous solution on the absorption of lead and mercury ions; and b) changes in the U.sub.20-66 (NH₂) zeol potential due to changes in the pH of the adsorption medium

Figure 4. The effect of changing the initial concentration of a) ions of Hg(II) and b) Pb(II) on the absorption capacity of UiO-66-NH₂

Figure 5. Second-order pseudo-second-order adsorption for a) Hg(II) and ion-ion absorption of Pb(II) by UiO-66-NH₂

Figure 6. Selective absorption graphs of Hg(II) and Pb(II) by UiO-66-NH₂.

Figure 7. Reuse function of UiO-66-NH₂ after several absorption / depletion periods of heavy metal ions.

Table 1. Thermodynamic parameters for adsorption of Hg(II) and Pb(II) by UiO-66-NH₂.

	T(K)	ΔG° (kJ mol ⁻¹)	ΔH° (kJ mol ⁻¹)	ΔS° (kJ mol ⁻¹ K ⁻¹)	R ²
Hg(II)					
	288	-3.634	2.769	11.458	0.9997
	303	-5.871			
	313	-6.324			
	323	-7.211			
Pb(II)					
	288	-4.184	1.542	7.261	0.9971
	303	-5.049			
	313	-5.617			
	323	-6.365			

Table 2: Parameters of metal ions [30].

M(II)	Ionic radius (Angstrom)	Pure hardness	Electronegativity
Hg ²⁺	1.12	7.7	2.00
Pb ²⁺	1.32	8.46	2.33
Cd ²⁺	1.03	10.3	1.69
Cu ²⁺	0.72	8.27	1.9
Co ²⁺	0.82	8.22	1.88