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Kinetic modeling and isotherm study for naphthalene adsorption on boehmite nanopowder

R. Abu-Elella[a], M.E. Ossman[a,b,*], M. Abd-Elfatah[a], A. Elgendi[a]

[a]*Petrochemical Engineering Department, Pharos University, Alexandria, Egypt*
Tel. +20 100 139 2281; email: mona.ossman@pua.edu.eg
[b]*Informatic Research Institute (IRI), City for Scientific Research and Technology Applications (CSAT), Borg Elarab, Alexandria, Egypt*

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ABSTRACT

Boehmite was synthesized and characterized in order to study the adsorption behavior and possibility to remove naphthalene as one of the polycyclic aromatic hydrocarbons (PAHs) from industrial waste water. The removal of naphthalene was investigated in terms of various parameters namely: pH, operating time, initial concentration of naphthalene and weight of adsorbent using batch technique. The data showed that the adsorption of naphthalene onto boehmite is not affected by changes in the pH. Adsorption data of naphthalene on the boehmite nanopowder were analyzed according to Freundlich, Langmuir adsorption and Redlich–Peterson models. The data were found to be best described by the Freundlich model. The kinetics of the adsorption was found to be fitted with a pseudo second order model. The negative values for free energy indicated that the spontaneous nature of the adsorption with a high performance of naphthalene for boehmite and also negative values of the enthalpies indicated that the process is exothermic. The study presented revealed that boehmite can be a promising adsorbent for the removal of PAHs such as naphthalene.

Keywords: Naphthalene; Nanomaterial; Adsorption; Boehmite; PAH

1. Introduction

Polycyclic aromatic hydrocarbons (PAHs) are an important family of environmental pollutants which are capable of reacting with DNA to promote mutagenic and carcinogenic response [1]. They are mainly emitted from combustion processes including engine exhaust, industrial processes, natural gas, domestic heating systems, barbecue, smoke, incomplete combustion of fossil fuels, volcanic eruptions and forest fires [2].The high stability and lipid solubility of PAHs lead to their accumulation in organism. Most PAHs are hydrophobic with high boiling and melting points and electrochemical stability. Therefore, they can exist and be accumulated in soils or water for a long time. Human beings are on the top of food chain, and therefore are the most greatly damaged. The US Environmental Protection Agency (EPA) has included 16 PAHs in the list of priority pollutants [3], the World Health Organization (WHO) has recommended a limit for PAH in drinking water [4], and the European Environmental Agency (EEA) has included these compounds in its list of priority pollutants to be monitored in

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*Corresponding author.

industrial effluents [5]. Despite this they have been identified in a variety of waters and wastewaters [6,7]. Due to the refractoriness and difficulty of biological degradation of PAHs, it is found that PAHs have accumulated in the air, water bodies, soil, and food. Therefore, immediate attention to the effective treatment of PAHs is needed. Various methods have been reported in literature to treat PAHs such as biological degradation [8–11], scrubber absorption [12,13], high-energy electron beam irradiation [14], ozonation [15], and catalytic oxidation [16]. There are only a few technologies that are economically feasible for the removal of trace organic contaminants from aqueous solution. Owing to the high concentrating ability of typical adsorbents, adsorption is proved to be one of the most attractive and effective techniques to remove organic contaminants from aqueous streams in water/wastewater treatment [17]. One of the most important PAHs is naphthalene ($C_{10}H_8$); it is a natural constituent of coal tar and commonly used as a wood preservative, moth repellent and raw material to produce methyl anthranilate, phthalate esters, chloronaphthalene and synthetic resins, etc. Compared with other PAHs species, naphthalene, the simplest PAH, has less toxicity and is easily found in the environment. Therefore, the adsorption of naphthalene as the target compound of study can provide useful information not only for the treatment of naphthalene but also for dealing with complicated PAHs [18]. In recent years, the use of inorganic materials in the adsorption process as adsorbent for treating wastewater has come to the forefront [19–21]. Inorganic materials have proved to be useful and of common use due to their low costs and high effectiveness [22]. Although activated carbon is the most commonly used sorbent, it still has some limitations in application, such as flammability, difficulty of regenerating adsorbed high-boiling-point organics, etc. In contrast to the activated carbon, zeolite can be used in more specific situations with the advantages of the framework's open structure, rich ion-exchange chemistry, etc. [18], but without the disadvantages of activated carbon. Therefore, zeolites were used as adsorbents to concentrate organics from streams [23].

A universal absorbent has not been found yet, neither a perfect adsorbent for any given purpose has been developed. Recently, nanotechnology has introduced different types of nanomaterials to water industry that can have promising outcomes. Nano sorbents such as CNTs (carbon nanotubes), polymeric materials (e.g. dendrimers) and boehmite (AlOOH), which is widely used in ceramic materials, can be used in water applications [24]. However, the nano-size form of this alumina is anticipated to be more catalytically active than its presently more commonly used forms and if indeed sorption is the key mechanism, then the substantial increase in surface area of the nano form would increase capacities very significantly. There is therefore scope for development of such nano-boehmite materials for sorption of pollutants. Boehmite was thought to exist under two distinct forms, well-crystallized boehmite and pseudo boehmite, with significantly different morphologies, porosity and surface areas but it was found that pseudo boehmite is simply micro- or rather nano-crystallized boehmite [25]. Thus, boehmite was selected as a model adsorbent because it possesses well-defined properties and has been extensively utilized as a representative aluminum oxyhydroxide phase (α-AlOOH) [26].

The aim of this work is to study the possibility of using boehmite nano-powder as an adsorbent for removal of naphthalene from waste water, and study the variables that are affecting the removal process such as; initial concentration, pH, and weight of the adsorbent. Additionally the kinetic and thermodynamic properties were determined to interpret and elucidate how the adsorption mechanism of naphthalene ions works.

2. Experimental

2.1. Materials and method

2.1.1. Preparation of adsorbent (boehmite)

Aluminum nitrate {$Al(NO_3)_3 \cdot 9H_2O$, 99.5%} (Aldrich), sodium carbonate {Na_2CO_3, 98%} (Junsei) and deionized water were used as starting chemicals. Initially, aluminum nitrate (0.041 M) solution is made by dissolving 15.614 g in 400 mL of deionized water. Similarly (0.075 M) a solution of sodium carbonate is prepared by dissolving 7.95 g in 400 mL of deionized water.

Two hundred milliliters of deionized water is taken in a 2 L capacity round-bottom flask and stirred well using a magnetic stirrer. Then sodium carbonate and aluminum nitrate solutions are added to 200 mL of deionized water (from separate burettes) drop by drop to precipitate Al cations in the form of hydroxides. The temperature was maintained at 70°C during the precipitation/digestion experiment. The pH after precipitation was found to be in the range of 7.5–8.5. The precipitates were further digested at 70°C for 3 h. The digested precipitates were filtered and re-dispersed again in 2 L of hot deionized water, filtered and finally washed with ethanol first followed by acetone to avoid contamination of Na ions; and air dried at room temperature. The air-dried precipitates were calcined in a programmable furnace at 550°C/5 h in air with a heating rate of 28°C/min to produce nano-sized γ-Al_2O_3 powder.

2.1.2. Preparation of adsorbate (naphthalene)

Due to the low water solubility of naphthalene ($33\,mg\,L^{-1}$ max), the water methanol solution was used as the aqueous solution. It is noted that methanol is a good solvent to enhance the adsorption of non polar naphthalene from the hydrophobic environment, forming the naphthalene-containing solutions. A certain amount of naphthalene (0.15 g) was dissolved in 45 mL of 1-methanol, and subsequently diluted with 4500 mL of distilled water, to prepare a stock solution of naphthalene having a concentration of $30\,mg\,L^{-1}$. It was stored in airtight glass bottles in the dark at room temperature.

2.2. Batch experiment

2.2.1. Effect of contact time

The time of contact of the adsorbent and the adsorbate is of great importance in adsorption since the contact time depends on the nature of the system used. Adsorption experiments for naphthalene on boehmite were carried out as follows: to each of the 0.2 g boehmite samples, 200 mL of solution was added. The samples were stirred using an IKA RT5 model magnetic stirrer operated at 400 rpm at room temperature for periods ranging from 5 min to 2 h, and then centrifuged and 5 mL portions of the liquid phases were measured.

2.2.2. Effect of pH

The pH of the aqueous solution is a significant controlling factor in the adsorption mechanism, in order to optimize the pH for maximum removal efficiency. Batch experiments at room temperature were carried out by taking in contact 200 mL of naphthalene solution with 0.2 g of boehmite for 1 h of stirring time (period needed to reach the complete adsorption equilibrium between the two phases), at several pH values (2–11), adjusting continuously the solution's pH with HNO_3 and NaOH solutions and the percentage uptake of the synthesized boehmite was obtained.

2.2.3. Effect of amount of adsorbent

Under optimum conditions of stirring time and pH, the effect of adsorbent dosage on the adsorption of naphthalene was studied by stirring 200 mL of naphthalene solution with 0.04–0.2 g of adsorbent for 1 h at room temperature and at a constant pH of 7.5

2.2.4. Adsorption experiments

Adsorption experiments were carried out in batch mode by mixing 0.2 g of boehmite and 200 mL of naphthalene solution in close vials, continuously stirring at different time intervals to attain equilibrium distribution in the studied system on a water bath at a fixed temperature. After stirring the solutions were centrifuged and the percentage of naphthalene adsorbed by the boehmite was determined from the difference between the initial C_i and the final C_f concentrations of naphthalene in aqueous solution, before and after contact. The initial and equilibrium concentrations of the aqueous solutions were measured using a UV spectrometer at a wavelength of 275.5 nm. The amount of solute adsorbed per unit gram of the adsorbent q_e (mg/g), was evaluated from the equation:

$$q_e = \frac{(C_i - C_f)V}{M} \tag{1}$$

where V is the volume of the solution, C_i is the initial concentration of the adsorbate solution, C_f is the concentration of the solute in the bulk phase at equilibrium and M is the mass of the adsorbent. All experiments were carried out at room temperature except in the temperature dependence study where the temperature was varied from 298 to 343 K.

2.2.5. Effect of initial concentration

In adsorption processes, concentration of naphthalene also plays an important role. For this investigation, naphthalene adsorption on boehmite was studied with a constant amount of 0.2 g of boehmite and varying naphthalene concentrations (10–33 ppm) in aqueous phase at a pH of 7.5, room temperature and 1 h of contact time. Experimental data obtained from this study were evaluated with Freundlich, Langmuir and Redlich–Peterson isotherms models.

2.2.6. Effect of temperature

Temperature dependence on the adsorption process is associated with several thermodynamic parameters. The effect of temperature on the naphthalene removal was investigated by performing batch experiments at 298–343 K, an initial naphthalene concentration of 30 ppm, contact time of 1 h and an initial pH of 7.5 on boehmite.

2.3. Characterization of boehmite

2.3.1. Morphology analysis

In order to know the structure of boehmite, Scanning Electron Microscopy (SEM) was employed to visualize sample morphology. In the present work, the boehmite prepared was analyzed by this technique using SEM "JEOL JSM 6360LA", to study the surface morphology of boehmite.

2.3.2. XRD X-ray diffraction

The crystal structure was investigated by X-ray diffraction (XRD). Data were collected on a Shimadzu XRD-7000, using filtered Cu*K* radiation and a graphite secondary-beam monochromatic. Diffraction intensities were measured by scanning from 5 to 90° (2θ) with a step size of 0.02° (2θ).

2.3.3. Determination of the point of zero charge

The point of zero charge (PZC) of boehmite was determined by the mass titration procedure developed by Noh and Schwarz [27]. Different masses of the boehmite ranging from 0.05 to 3 g and 10 mL of a 0.1 N NaCl solution were added to 25 mL plastic bottles. The bottle was capped and was stirred continuously with a Teflon-coated stirring bar for 48 h. After this time, the final pH of the solution was measured. The final pH was graphed against the mass of the boehmite and the final pH approached an asymptotic value with the increase in the mass of boehmite. This asymptotic value of the final pH was the PZC.

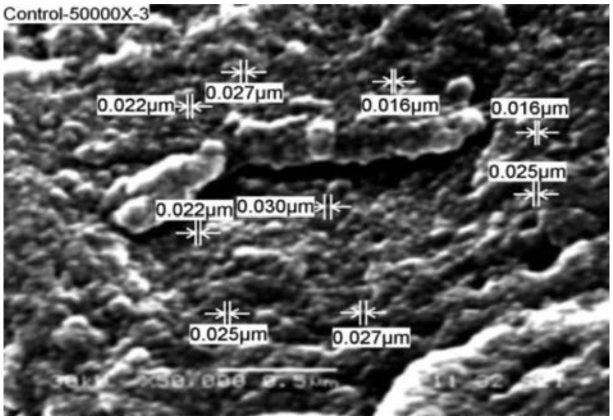

Fig. 1. The SEM scans of boehmite nano powder before adsorption.

3. Results and discussion

3.1. Characterization of boehmite

Fig. 1 shows the porous morphology of the adsorbent with pores of different sizes. The prepared nanostructured alumina was obtained by the line fitting method with Origin program. The size of these nanocrystallities ranged from 11 to 30 nm.

The X-ray diffraction pattern of the synthesized boehmite sample is shown in Fig. 2. According to this synthesis, the boehmite sample showed a typical boehmite-type pattern when compared with the Shimadzu XRD-7000 card in the conventional way. The presence of sharp and intense lines at low values of 2θ angles and less intense and fairly asymmetric lines at higher angular values show a moderate broadening of the lines due to the crystallite size (100–300 Å). The specific surface area of boehmite was 234 m^2/g and the total pore volume was 0.19 mL/g.

3.2. Effect of contact time

In order to establish equilibration time for maximum uptake and to know the kinetics of adsorption process, the adsorption of naphthalene (as a one of the PAHs) on boehmite nano powder adsorbent was studied as a function of contact time. Fig. 3 shows that the rate of uptake of the PAHs is rapid in the beginning and 50% adsorption is completed within 10 min. and the time required for equilibrium adsorption is 20 min.

3.3. Effect of pH

The removal of a pollutant from an aqueous medium by adsorption was examined. Fig. 4 shows that the adsorption capacity of naphthalene does not vary measurably within pH 2–11. As can be seen from Fig. 4, the maximum naphthalene removal was observed at around a neutral pH value. It was observed that the adsorption procedure is slightly dependent on the pH of the solution, which affects the surface charge of the adsorbent and the degree of ionization of the adsorbate. The pH of waste water or

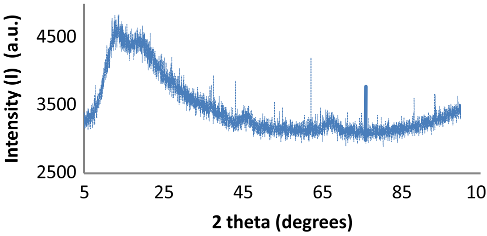

Fig. 2. X-ray diffraction (XRD) pattern of the synthesised boehmite sample.

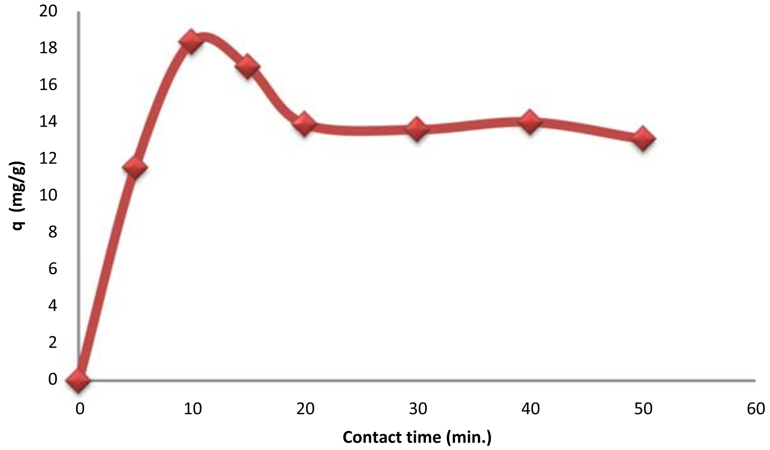

Fig. 3. Effect of contact time for the adsorption of naphthalene, conc. 30 ppm, adsorbent weight 1 g/l, at 25℃, pH 7.

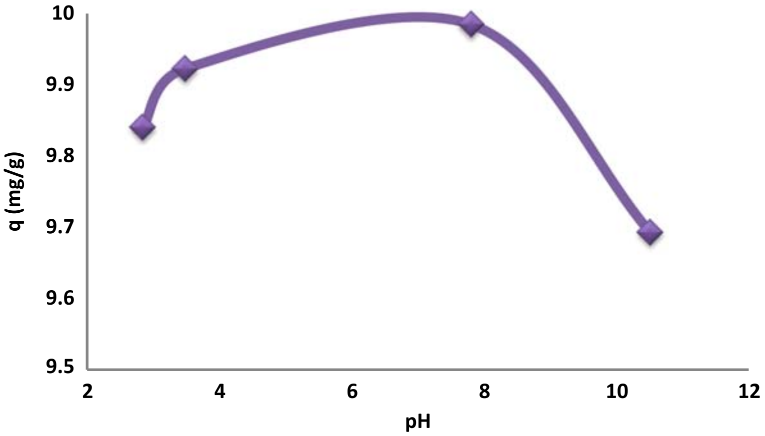

Fig. 4. Effect of pH for the adsorption of naphthalene onto boehmite nano powder for concentration 30 ppm, weight of adsorbent is 1 g/L at 25℃.

the medium controls the electrostatic interactions between the adsorbent and the adsorbate. The surface nature of the adsorbent depends not only on the surface functional groups but also on the point of zero charge (pH_{PZC}) of the adsorbent [27]. At a lower pH (acidic pH), the total or external surface charges on the adsorbent are positive. Thus, lower adsorption of naphthalene took place at lower pH value. The lowest naphthalene adsorption was observed at pH 3. Cationic adsorption is favored at $pH > pH_{PZC}$ and anionic adsorption is favored at pH < pHPZC [29]. A pHzpc (point of zero charge) of 8.6 has been previously reported for boehmite [28], additionally the pHzpc of boehmite was determined and was found to be 8.4. Then, only anionic species could be adsorbed on this material below of their zero point charge (zpc) value. When the pH value was increased, the surface of the boehmite was more negatively charged, therefore, the adsorption of naphthalene with positive charge reached the maximum at a pH value of 7.5. The maximum adsorption capacity occurred at pH 7.5 and above this value, it decreased. A similar observation has been reported [30,31].

3.4. Effect of adsorbent dosage on naphthalene uptake

The results of the experiments with varying adsorbent dosages are presented in Fig. 5. It was found that with an increase in the adsorbent dosage from 0.2 to 1.0 g/L, the adsorption capacity of boehmite decreases from 150 mg/g to 60 mg/g. Also the number of possible binding sites increased the adsorption capacity of boehmite for naphthalene decreased and that various reasons have been suggested to explain the decreased adsorption capacity at increasing adsorbent concentrations including availability of solute, electrostatic interactions and interference between binding sites [32].

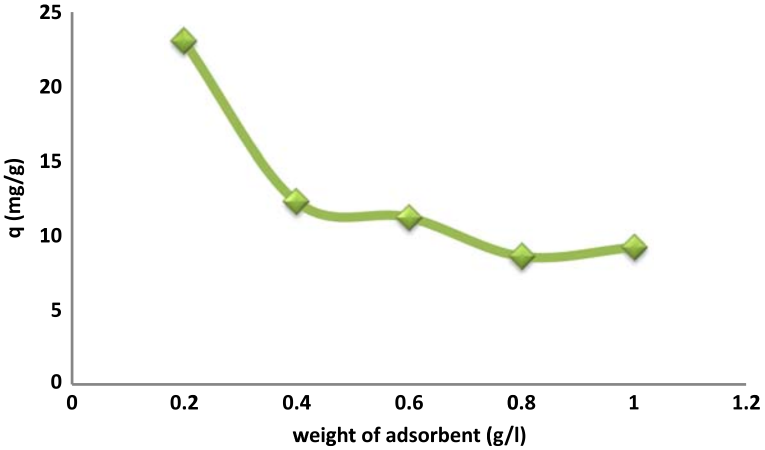

Fig. 5. Effect of adsorbent dosage for the adsorption of naphthalene onto boehmite nano powder for a concentration of 30 ppm, pH 7 and at 25˚C.

3.5. Modeling of adsorption isotherm

In order to describe the naphthalene adsorption behavior on boehmite, isotherms data obtained were fitted to the Freundlich and Langmuir adsorption models. The Freundlich behavior was tested by the following equation:

$$\log q_e = \log Kf + \frac{1}{n}\log C_e \tag{2}$$

where q_e is the amount of naphthalene adsorbed at equilibrium (mg/g), C_e is the equilibrium concentration of naphthalene in solution (ppm) and Kf as well as $1/n$ are the Freundlich constants, Kf and $1/n$ are related to adsorption capacity and intensity of adsorption, respectively. The values of n and Kf can be calculated from the slope and intercept of the plot of log q_e vs. log C_e derived from Eq. (2). The magnitude of the exponent $1/n$ gives an indication of the favorability of adsorption.

The adsorption data were also tested using Langmuir isotherm equation in the linearized form:

$$\frac{C_e}{q_e} = \frac{1}{q\max\ b} + \frac{1}{q\max} C_e \tag{3}$$

where C_e is the equilibrium concentration of the naphthalene in solution (ppm), q_e is the amount of naphthalene adsorbed at equilibrium (mg/g), and b and $q$max are Langmuir constants, related to the binding constant and the maximum adsorption capacity, respectively.

A plot of specific sorption (C_e/q_e) vs. C_e gives a straight line of slope (1/$q$max) and intercepts (1/$q$max b). Langmuir equation is probably the most widely applied model for isotherm adsorption, it considers that the adsorption energy of each molecule is the same, independent of the surface of the material, the adsorption takes place only on some sites and there are no interactions between the molecules.

The adsorption data were also tested using The Redlich–Peterson isotherm, this isotherm contains three constants, A, B and g, and involves the features of both the Langmuir and the Freundlich isotherm models. It can be described by the following non-linear Eq. (4):

$$q_e = \frac{AC_e}{1 + BC_e^g} \tag{4}$$

where g must fluctuate between 0 and 1 and it can characterize the isotherm as if $g = 1$, the Langmuir will be the preferable isotherm, while if $g = 0$, the Freundlich will be the preferable isotherm. The three isotherm constants A, B and g, can be evaluated from Eq. (4) using nonlinear regression analysis in SPSS program Version10.0, which is applicable to computer operation and was developed to calculate the isotherm constants through maximization of the coefficient of determination, and the results are included in Table 1. The coefficient R^2 for Redlich–Peterson isotherm was lower than for the Langmuir and Freundlich isotherm models for the data obtained from adsorption of naphthalene onto boehmite.

A comparison of correlation coefficients for the isotherms is listed in Table 1. The correlation coefficient, R^2, for the Freundlich isotherm is greater than that for the Langmuir isotherm and Redlich–Peterson isotherm. It is clear that the Freundlich isotherm has best fitted for the adsorption of naphthalene onto boehmite. Freundlich plots have high linearity (>0.980) also indicating the process to have conformed to the empirical Freundlich pattern of adsorption on

Table 1
Langmuir and Freundlish isotherm constants for adsorption of naphthalene onto boehmite

Isotherm model	Boehmite
Langmuir	
Q_0 (mg g^{-1})	200
b (L mg^{-1})	3.8×10^{-3}
No. of parameter estimated	2
Data point available	4
R^2	0.78
Freundlich	
$1/n$	0.702
Kf (mg g^{-1})	2.1727
No. of parameter estimated	2
Data point available	4
R^2	0.98
Redlich–Peterson	
A (L g^{-1})	12.0
B (L mg^{-1})^g	1.52
g	0.398
No. of parameter estimated	3
Data point available	4
R^2	0.745

non-specific, energetically non-uniform, heterogeneous surface in terms of functional groups.

The behavior observed in this study may be attributed to the fact that nonpolar naphthalene molecules initially adsorb onto the hydrophobic basal surface of the boehmite and spread out until monolayer coverage is reached, then multilayer adsorption begins to occur by means of interaction of the previously adsorbed naphthalene molecules with the molecules to be adsorbed. From this, it would seem that hydrophobic bonding forces initially drive the adsorption of the naphthalene onto boehmite. Relatively higher fractional values of $1/n$ $(0 < 1/n < 1)$ indicate a fair validity of classical Freundlish isotherm over the entire concentration of naphthalene.

3.6. Kinetics of adsorption

The adsorption kinetics is important as it controls the process efficiency. In this study, six kinetic models, including first order, pseudo-first-order, second order, pseudo-second order, Elovich and intraparticle diffusion models, were used to investigate the adsorption process of naphthalene on boehmite. The pseudo-first-order rate expression of Lagergren may be written as follows [33]:

$$\log(q_e - q_t) = \log q_e - \frac{k_1}{2.303} t \tag{5}$$

where q_e and q_t are the amounts of naphthalene adsorbed onto boehmite at equilibrium and at time t, respectively (mg/g), and k_1 is the rate constant (min^{-1}).

The pseudo-second-order kinetic model may be expressed by the following relationships [30]:

$$\frac{t}{q_t} = \frac{1}{k_2 q_e^2} + \frac{1}{q_e} t \tag{6}$$

where k_2 is the rate constant (g/m mol min).

Kinetic parameters along with correlation coefficients of the kinetic models are shown in Table 2.

As can be seen from Table 2, higher correlation coefficients (R^2) of pseudo-second-order equation and the reasonable calculated q_e values close to the experimental data indicated that the pseudo-second-order kinetic model might be suitable to describe the kinetics adsorption process of naphthalene onto boehmite.

The adsorbate transport from the solution phase to internal active sites occurs in several steps, the rate of internal mass transfer is in most cases the rate-determining step in adsorption processes. Kinetic data were used further to check the possibility of intraparticle diffusion by using the Weber and Morris equation [34]. Its linear form is

$$q_t = kd\, t^{0.5} + c \tag{7}$$

where kd is the intra-particle diffusion rate (m mol/g min$^{0.5}$) and c is a constant.

If the plot of q_t vs. $t^{0.5}$ gives a straight line, then the adsorption process is controlled by intra-particle diffusion only. However, if the data exhibit multi-linear plots, then two or more stages influence the adsorption process. Fig. 6 is the plot of q_t vs. $t^{0.5}$, which indicated that the plot of q_t vs. $t^{0.5}$ was multi-linear. The multilinear of plot of q_t vs. $t^{0.5}$ was due to the extensive pore size distribution of studied adsorbents including micro-, meso- and macropore. The first one could be attributed to adsorption of naphthalene over the shell and macropore of boehmite, and hence it is the fastest adsorption stage. The second one was ascribed to the intra-particle diffusion through mesopores. The third stage may be regarded as the diffusion through micro pores, and, of course, this stage is followed forthwith by the establishment of equilibrium.

3.7. Thermodynamic study of adsorption

The standard free energy change (ΔG^0) is the fundamental criterion of spontaneity of a process and

Table 2
Kinetic parameters for the adsorption of naphthalene onto boehmite

First order kinetics	
k_1 (min)	0.0015
q_1 (mg/g)	49.66
R_1^2	0.7292
Pseudo first order kinetics	
k_1 (min)	0.002
q_1 (mg/g)	2.986
R_1^2	0.025
Second order kinetics	
k_2 (g/mg min)	0.00003
Q_2 (mg/g)	49.75124
R_2^2	0.7418
Pseudo second order kinetics	
k_2 (g/mg min)	0.0008
q_2 (mg/g)	45.87156
R_2^2	0.9993
Elovich	
α (mg g^{-1} min^{-1})	626.9022
β (g mg^{-1})	0.01336
R_2^{2E}	0.876
Intraparticle diffusion	
Kp (mg g^{-1} min$^{-1/2}$)	14.7
C	186.3
R^2	0.818

can be determined using the equilibrium constant as shown below:

$$\Delta G^\circ = -RT \ln K \tag{8}$$

where R is the universal gas constant (8.314 J mol^{-1} K^{-1}), T is the absolute temperature (K) and K is the equilibrium constant. Similarly, the standard enthalpy change ΔH^0 from 25 to 70℃ was computed from the following equation,

$$\ln K = \frac{\Delta S^0}{R} - \frac{\Delta H^0}{RT} \tag{9}$$

In order to evaluate the thermodynamic parameters for the adsorption of naphthalene onto boehmite, the adsorption studies were carried out at different temperatures (25, 40, and 70℃). Since Freundlich adsorption isotherm is the best fit value of Kf was used in places of K in the calculations of all thermodynamic parameters.

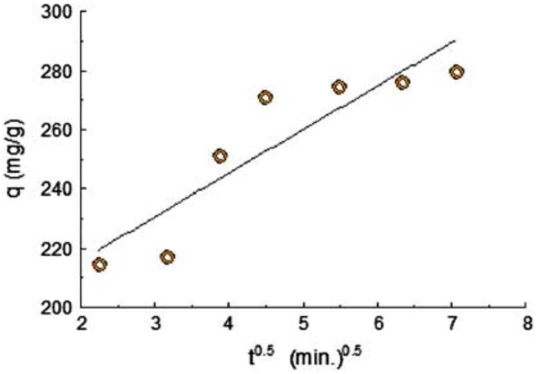

Fig. 6. Intraparticle diffusion plots for the adsorption of naphthalene onto boehmite.

A plot of $\ln K$ vs. $1/T$ should be a straight line as shown in Fig. 7. ΔH^0 and ΔS^0 values were obtained from the slope and intercept of this plot, respectively. The standard free energy change (ΔG^0), standard enthalpy change (ΔH^0), and standard entropy change (ΔS^0) were obtained from Eqs. (8) and (9)89 and the values associated with the adsorption of naphthalene onto boehmite are listed in Table 3. Negative values of ΔG^0 indicate the feasibility of the process and the spontaneous nature of adsorption with the high performance of naphthalene for boehmite.

An negative value of ΔH^0 indicates the exothermic nature of the process, while a negative value of ΔS^0 reflects the decrease in the randomness at the solid/liquid interface during the adsorption process.

4. Conclusion

The results of this investigation show that boehmite which was prepared with high specific surface area (SSA) has a suitable adsorption capacity for the removal of naphthalene from aqueous solutions. The equilibrium adsorption is practically achieved in 20 min. The experimental results were analyzed by using Langmuir, Freundlich and Redlich–Peterson isotherm models and the correlation coefficients for Freundlich fitted better than Langmuir and Redlich–Peterson equations. The kinetic study of naphthalene adsorption on boehmite was performed based on pseudo-first-order, pseudo second-order, Elovich and intraparticle diffusion equations. The data indicate that the adsorption kinetics follow the pseudo second-order rate with intraparticle diffusion as one of the rate determining steps.

The negative values for free energy and the enthalpies indicated that the adsorption of naphthalene on boehmite is spontaneous and exothermic. The present study

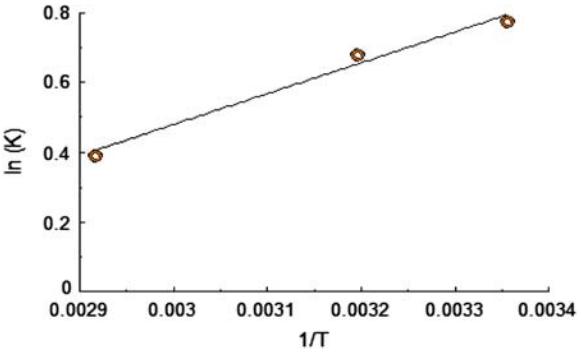

Fig. 7. Plot of $\ln K$ vs. $1/T$ for naphthalene adsorption onto boehmite.

Table 3
Values of thermodynamic parameters for naphthalene adsorption onto boehmite

Temp. (℃)	ΔG (KJ/mol)	ΔH (KJ/mol)	ΔS (KJ/mol K)	R^2
25	−1.61717	−7.4077	−0.0182	0.981
40	−1.3441			
70	−1.1651			

concludes that boehmite can be a promising adsorbent for the removal of PAHs, naphthalene in particular.

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