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Application of activated carbon fibre (ACF) for lead removal in aqueous solution

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ABSTRACT

In this study, the adsorption of lead from aqueous solution by activated carbon fibre (ACF) was investigated. Several series of experiments were conducted to examine the effect of operating conditions such as the equilibrium time, the flow rate, and the initial concentration that are known to affect the adsorption rate. Average removal efficiency was almost 98% for the initial lead concentration of less than 10 mg/L. Breakthrough point in ACF unit reached at 4.5 h of operational time with the flow rate of 40 mL/min and initial lead concentration of 10 mg/L. Adsorption capacity of the filter was found to be 0.5 mg/mg of ACF. The removal efficiency has decreased by the factor of 0.53 after one hour of operating time. Among the several regression curves tested, three dimensional non-linear regressions gave over 90% of fitting while for other linear regression curves it was in the range of 60–70% depending upon the various operating parameters. Non-linear models described the relationships of permeate lead concentration (C) with initial concentration (C_0) and operation time (t), giving a good generalization of the kinetics of lead in ACF for the laboratory tested ranges.

Keywords: Activated carbon fibre; Adsorption; Lead; Regression curve; Aqueous solution

1. Introduction

Water contamination by heavy metals in ecosystem is a major environmental problem encountered in many industrial areas. Lead is one of the most toxic heavy metals and it is harmful to living species. It can enter the human body through inhalation, ingestion or skin contact and cause adverse effects on virtually every system in the body [1,2]. Long term exposure to lead can cause kidney damage, high blood pressure, affect the liver, reproductive system and the central and peripheral nervous system [3–5]. Moreover exposure to lead in childhood may cause neurological disorders. Process industries such as acid battery manufacturing, metal plating and finishing, ammunition, tetraethyl lead manufacturing, cable covering, plumbing, chemical industries, ceramic and glass industries produce lead contaminated wastewater [6,7]. Lead is also used as corrosion inhibitor for the water carrying pipes [7]. Increased concentration of lead in water is mainly due to inappropriate wastewater disposal practices and also due to its bioaccumulation potential [8]. Irrigation of agricultural land with wastewater containing lead can pollute the agricultural production [9] and affect humans through the food chain. Effluent standard set by USEPA for lead is 5 mg/L although the surface water standard in natural water courses for the protection of aquatic life is 25 mg/L. Standard maximum level of lead contamination in drinking water varies from country

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to country. In USA it was 0.015 mg/L but the maximum contaminant level goal (MCLG) is zero for no expected health risk to water users [9].

There is a number of technologies such as chemical precipitation, coagulation, ion exchange, ultrafiltration, reverse osmosis (RO) and electro dialysis that may be used for the treatment of water and wastewater containing lead [10–12]. Each of the methods mentioned above has its advantages and disadvantages. For example, precipitated heavy metal limits the possibility of anaerobic digestion for sludge stabilization when chemical precipitation is used as a treatment method [13,14]. The use of RO and ion exchange is quite effective but both of the methods require additional pretreatment and have higher operating cost [15,16]. Amongst the above mentioned processes adsorption appears to be an attractive alternative for the treatment of wastewater containing heavy metals at low concentration [17,18]. Activated carbon fibre (ACF) is a suitable system for the removal of toxic cations from different streams of water and wastewater. Due to its high microporous structure, it has high surface area and higher adsorption rate than granular activated carbon (GAC) [19]. Results of preliminary laboratory-scale experiments show high removal of lead from wastewater achieved by means of ACF [20]. Other researchers had studied adsorption of lead on siderite [21], GAC [22] and plant leaves [23]. So far no research results on ACF for lead removal were found. For the extensive use of ACF in the removal of toxic substances and lead, it is necessary to know the optimal operational parameters. In this study, several series of experiments were conducted to investigate the performance of ACF for lead removal and to study the kinetics of lead in ACF. To optimize the system, initial concentration, flow rate and operational time were varied. Mathematical modeling was conducted using Statistical Package for Social Scientists (SPSS) to simulate the experimental results.

2. Methodology

In this study, feed solution was prepared by mixing stoichiometric amounts (varies depending on the initial lead concentration) of lead acetate with distilled water. After the solution was mixed thoroughly, it was fed to ACF apparatus and the experiment was conducted for 6 h. Samples were collected every half an hour interval. All the experiments were carried out at the ambient laboratory temperature of average 26°C. Experimental module consisted of a feed tank, a cartridge filter followed by two sets of ACF and effluent tank. The function of cartridge filter in the system was to prolong the life span of ACFs. The ACFs used were 25.4 cm (10 inch) of length, 6.8 cm and 2.8 cm of outside and inside diameters respectively, and 2 cm of thickness. Total mass of ACF used per filter was 120 mg (ACF, Korea). Schematic diagram of the experimental apparatus and details of ACF units used in the experiment are shown in Fig. 1 and Fig. 2 respectively.

Initial concentration, flow rate and operation time were the variable parameters. The samples were analyzed by an atomic absorption spectrophotometer for the measurement of lead containing effluent. Statistical Package for Social Scientists (SPSS) and curve fitting software were used for the stimulation of the adsorption and regression models.

3. Results and discussion

3.1. Effect of operational time

A series of experiment was conducted to investigate the effect of operational time on lead removal from waste-

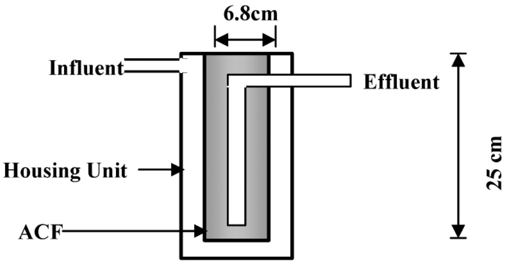


Fig. 2. Detailed apparatus of activated carbon fibre filter (Model FMC – 250 A; Mfg: KOREA ACF).

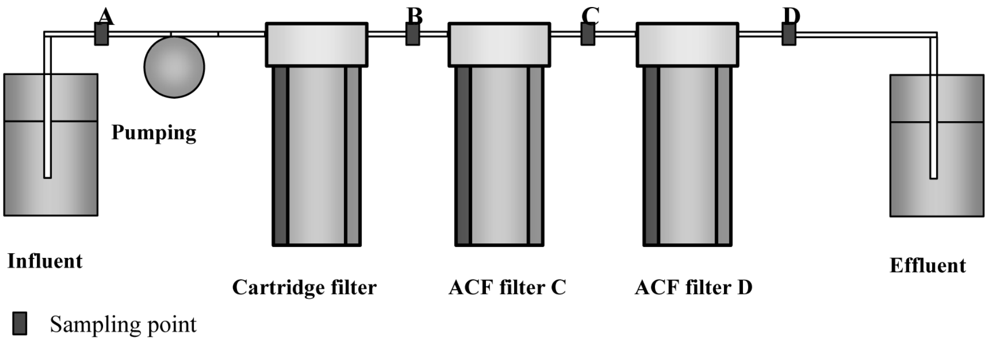


Fig. 1. ACF set-up for lead removal from wastewater.

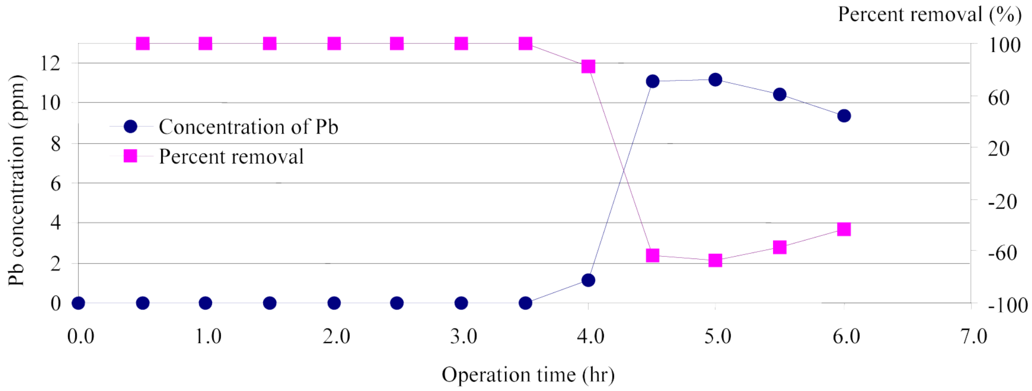


Fig. 3. Effect of operation time on lead removal.

water. Overall lead removal efficiency was almost 98% at the second ACF filter unit. Lead removal efficiency of the first ACF filter is as shown in Fig. 3. During the six hours of operational time, a breakthrough reached at the time of 4.25 h. After the breakthrough lead removal decreased steadily. Previous research on lead removal by adsorption on siderite [21] has shown the similar results. Breakthrough point reached after 90 min of operational time in a set-up containing 10 g/L of siderite and 50 mg/L of lead. Adsorption capacity of activated carbon is an important factor to identify the efficiency of lead removal. Based on the experimental results, adsorption capacity of lead was found to be 0.5 mg/mg of the ACF.

3.2. *Effect of initial concentration*

Another series of experiment was conducted to investigate the effect of initial lead concentration on its removal from ACF. It was found that lead removal efficiency decreased with the increase of initial concentration in the feed solution. Lead removal efficiency was almost 100% up to 10 mg/L while it dropped steadily with the increase of initial concentration. As shown in Fig. 4 a sharp decrease in the removal efficiency started at the initial concentration of 25 mg/L. The reason for this decrease at higher initial concentration is the limited adsorption space of ACF available to the pollutant. Similar result was obtained by another researcher who examined the adsorption on plant leaves [23]. In his experiment for concentration ranging from 500 µg/L to 1500 µg/L, the removal decreased with the increase of lead concentration in the solution. Similar research carried out by others has shown that the removal efficiency of siderite decreased from 100% to 52.2% when initial concentration of lead increased from 25 mg/L to 200 mg/L [21]. The change of concentration gradient affects to the saturation rate and breakthrough time [22]. In the ACF process, percentage of lead removal for the first filter was higher than the second one while overall removal efficiency for two ACFs in series was higher than the single one.

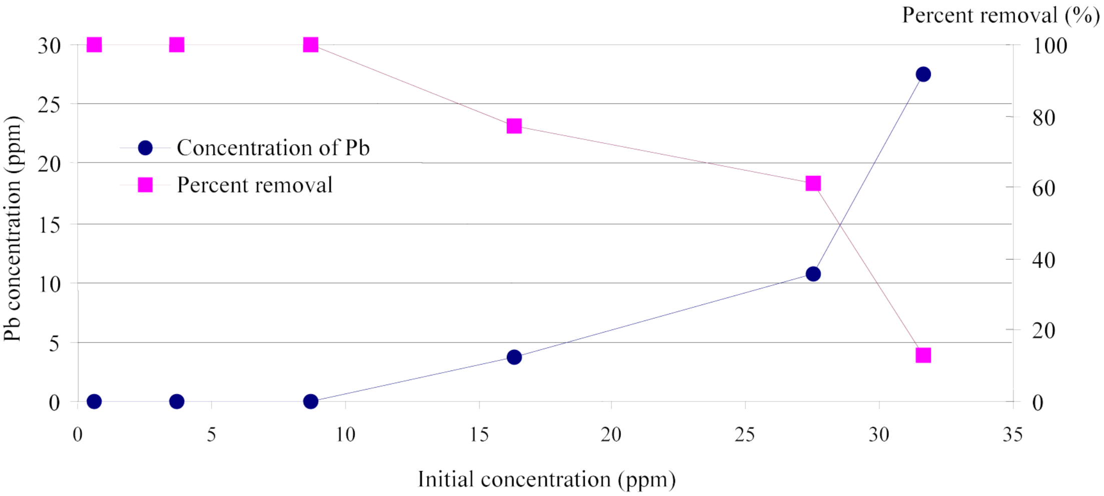


Fig. 4. Effect of initial concentration of lead on its removal.

3.3. Effect of flow rate

The last series of experiment was conducted to investigate the effect of flow rate on lead removal. The effectiveness of adsorption is dependent on contact time which is a function of flow rate. Lead removal decreases with the increase of flow rate in continuous adsorption process. Lead removal efficiency of the first filter is shown in Fig. 5. The obtained removal efficiency was 100% at the flow rate of 40 mL/min or less for the initial lead concentration of 10 mg/L, but it decreased with the increase of flow rate. Initial flow rate of 40 mL/min can be therefore assigned as the optimum for the efficient removal of lead from the ACF process. In the previous works it was observed that with the increase of contact time the adsorption yield increases up to its breakthrough point after which it remains constant [21].

3.4. Mathematical modeling for lead removal in ACFs

In order to investigate the kinetics of lead in aqueous solution by ACF, mathematical models were prepared with the usage of Statistical Package for Social Scientists (SPSS). The following three models were tested to determine the statistically significant co-relations between different parameters and variables analyzed in the laboratory experiments.

3.4.1. Linear two–dimensional regression models

Experimental results were tested with linear two-dimensional regression models. Empirical mathematical relationships between the lead effluent concentration and time, initial concentration and flow rate in linear two-dimensional regression models are represented by the following Eq. (1), Eq. (2) and Eq. (3) respectively.

$$C = -3.66 + 2.14 \times t \tag{1}$$

$$C = -4.73 + 0.72 \times C_0 \tag{2}$$

$$C = -6.82 + 0.2 \times Q \tag{3}$$

where C = effluent concentration of lead; t = operational time; C_0 = initial concentration of lead; Q = flow rate.

From the analysis, R-square value was found to be 0.64, 0.75 and 0.63 respectively for the variation of t, C_0, and Q. As shown in Fig. 6, the relationship is non-linear for all those three conditions. Linear model might be conveniently used for short time, low initial concentration and lower flowrate only, beyond which it is non-linear.

3.4.2. Non-linear two-dimensional models

The experimental results were tested with non-linear two dimensional models for the variables of operational time, initial concentration of lead, and flow rates. Figs. 7, 8 and 9 show the non-linear relationships between effluent lead concentrations and those variables. Eq. (4) gives the relationship of effluent concentration with time. The R-square value for this curve was 1.0.

$$C = \frac{\left[0.000713 - \left(0.0016 \times t^{2}\right) + \left(0.000665 \times t^{4}\right) - \left(9 \times 10^{-5} \times t^{6}\right) + (3.8 \times 10^{-6} \times t^{8})\right]}{\left[1 - \left(0.15564 \times t^{2}\right) + \left(0.009128 \times t^{4}\right) - \left(0.00024 \times t^{6}\right) + \left(2.67 \times 10^{-5} \times t^{8}\right)\right]} \tag{4}$$

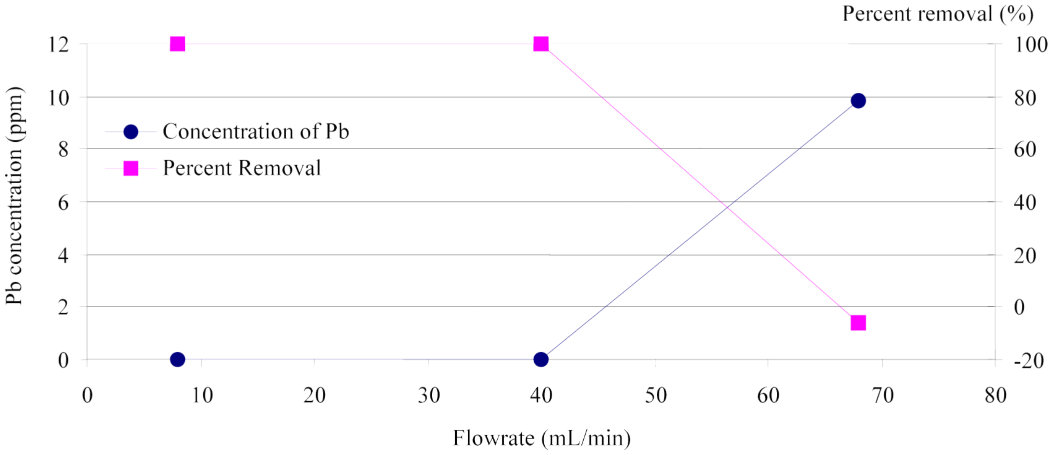
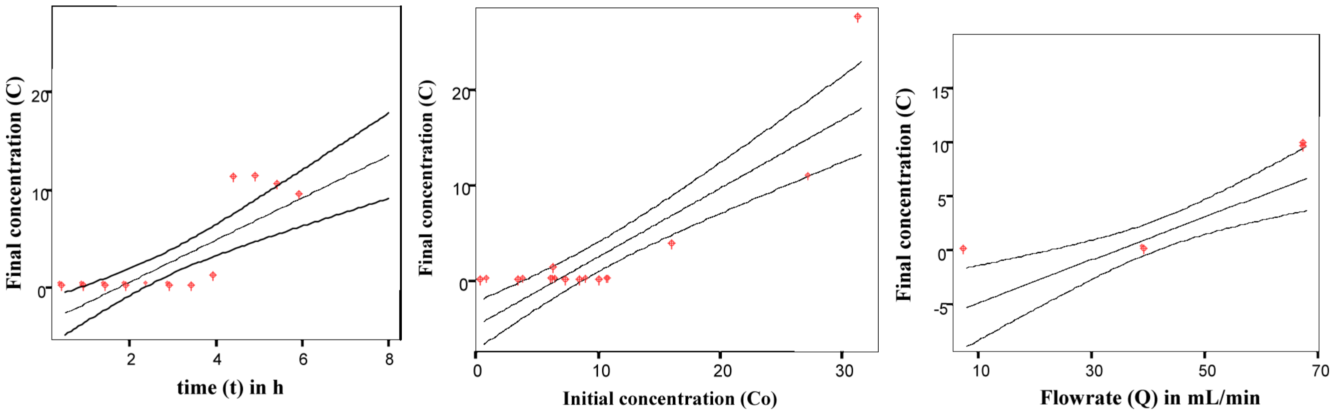


Fig. 5. Effect of flow rate on lead removal.



a. Effect of time b. Effect of initial concentration c. Effect of flow rate

Fig. 6. Linear two-dimensional regression models.

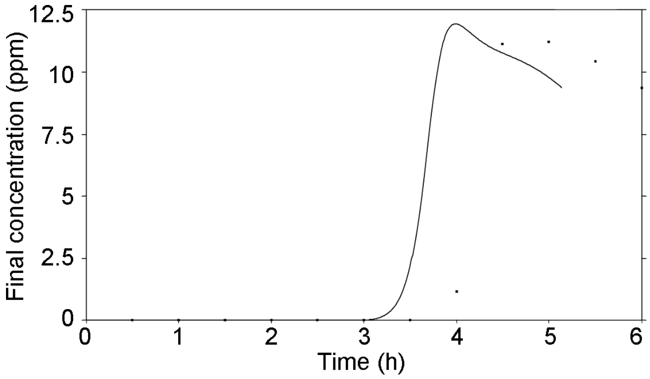


Fig. 7. Variation of effluent concentration of lead with time.

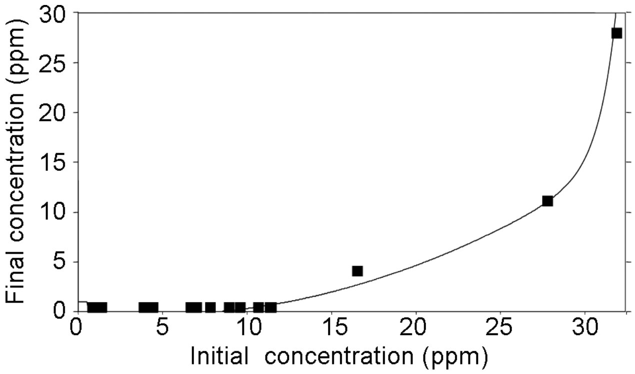


Fig. 8. Variation of final concentration of lead with its initial concentration.

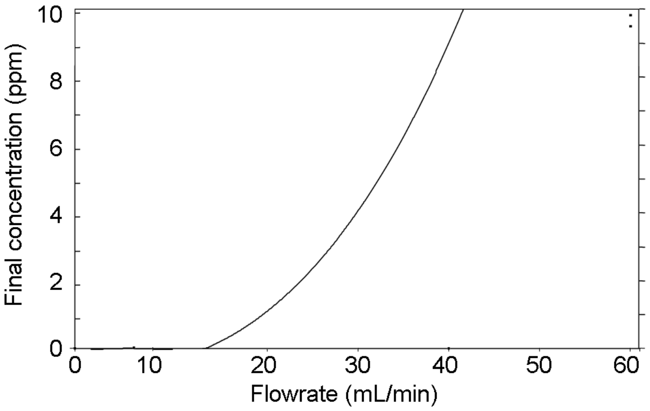


Fig. 9. Variation in effluent concentration of lead with flow rate.

Similarly, the results were tested for the effluent concentration using non-linear two dimensional models. Eq. (5) shows the tested model result.

$$C = -0.27909 - (0.41016 \times C_0) + (0.024181 \times C_0^2) + (2.29 \times 10^{-13} \times e^{C_0}) + (0.74401 \times C_0^{0.5}) \quad (5)$$

The relationship between C and C_0 is shown in Fig. 8. Tested results have shown that Eq. (5) gives *R*-square value of 0.99 and best fits the curve.

Eq. (6) represents the relationships between effluent concentration and flow rate in the tested model. Tested model result gave the *R*-square value of 0.9997. Thus, the equation is best fit for the laboratory test. It can be used to forecast effluent concentration of lead for tested variation of flowrate.

$$C = -0.27909 - \left(0.41016 \times C_0\right) + \left(0.024181 \times C_0^2\right) + \left(2.29 \times 10^{-13} \times e^{C_0}\right) + \left(0.74401 \times C_0^{0.5}\right) \quad (6)$$

For the tested range of parameters, the non-linear two dimensional model fits the results with the highest accuracy.

3.4.3. Linear regression model

The model was tested with 95% confidence interval of variable effluent concentration (C) with the variables of initial concentration (C_0), flow rate (Q), total amount of lead removed in mg (X), and removal efficiency in percentage (E). For the independent variables such as C_0, X and E, the R-square value was found to be 0.905, while it was only 0.663 and 0.618 for the variables C_0, X, t and C_0, Q, t respectively. It shows that the model is suitable for the determination of effluent concentration with dependent C_0, X and E. It can also be used with other set of independent variable with less accuracy. Linear regression model was simple and easy to use compared to non-linear model. From the tested model the following Eq. (7), Eq. (8) and Eq. (9) were developed for the above mentioned three variables.

$$C = -5.891 + (0.783 \times C_0) + (2.723 \times t) - (0.158 \times X) \tag{7}$$

$$C = -11.628 + (0.418 \times C_0) + (1.399 \times t) - (0.18 \times Q) \tag{8}$$

$$C = -5.22 + (0.392 \times C_0) + (1.608 \times t) \tag{9}$$

3.4.4. Non-linear three-dimensional model

Fig. 10 shows the tested model results for three dimensional non-linear model generated to describe effluent concentration of lead in relation to C0 and t. This model is suitable for the generalization of the findings in the laboratory analysis. It was found as highly accurate for the tested range. The R-square value for this model was found to be 0.901 and the equation is represented by Eq. (10).

$$C = -0.10262 + GAUSS\,t\left(28.54279, 6.292934, 1.23915\right) \times LOGNORM\,C_0\left(1, 41.85738, 1.416938\right) \tag{10}$$

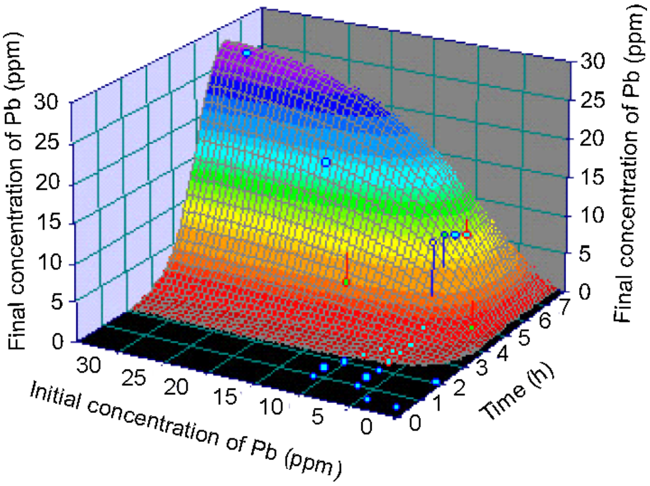


Fig. 10. Variation of effluent concentration of lead with C_0 and t.

4. Conclusion

Operational time, flow rate and initial concentration of lead in feed solution affect the removal efficiency of lead from waste stream in ACF adsorption process. The removal increased with the decrease of the concentration and flow rate. Flow rate of 40 mL/min was found to be the optimum for the efficient removal of lead at the initial lead concentration of 10 mg/L. At these conditions the lead removal reached 100% from the second ACF whereas it varied with operational time for the first filter. In the given condition, break though time was found to be 4.5 h. The maximum capacity of ACF in the process of lead removal was found to be 0.5 mg Pb/mg ACF. With the increment of operational time by one hour, the removal efficiency of the filter decreased by the factor of 0.53. In mathematical modeling of the process the non linear models have shown higher accuracy than the two dimensional linear models. They are however complicated, uncertain in generalization and difficult to use. From the various tested results of models, it is clear that non linear models best describe the relationship of C with C_0 and t. For the kinetics of lead, three dimensional non –linear models give higher accuracy and the R-square value was found to be 0.90.

Acknowledgments

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