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Experimental investigation and modeling of copper ion adsorption in packed and expanded bed

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ABSTRACT

Expanded bed adsorption (EBA) is well demonstrated integration technology for capturing bio-products from un-clarified feedstock. Liquid mixing and axial dispersion plays a crucial role in the performance of an expanded bed. In this study, a high density ion exchange resin (INDION225H) is explored for using in expanded bed adsorption. Liquid mixing and axial dispersion in the packed and expanded bed has been examined using RTD studies. Breakthrough experiments on adsorption of copper ions were performed in a packed and an expanded bed. The study provides an insight into dispersion in the packed and expanded bed, which would be useful in commercial operations like water and waste water treatment.

Adsorption breakthrough experiments were further simulated using an axially dispersed plug flow model. Simulation results are in good agreement with the experimental outcome. Plug flow behavior was observed up to a velocity of 0.00135m/s, which corresponds to a bed expansion of 18%. Results endorse that proper choice of adsorbent and superficial velocity can allow for carrying out bigger scale adsorptive separations like waste water treatment in expanded bed, with a minimum impact on the bed efficiency. A new non dimensional number has also been proposed for the performance analysis of expanded bed.

1. Introduction

Expanded bed adsorption is an established technology in bio-industry, which can handle feed stocks with suspended impurities [1,2]. Specially designed adsorbents and process conditions are required to form a stable fluidized or expanded bed, combining the hydrodynamic properties of fluidized bed retaining the plug flow characteristics of the packed bed. It allows small particulates in the feed solution to pass through the external void in the bed with simultaneous adsorption of desired component. Therefore, a solid-liquid separation step gets eliminated from the process, reducing overall operational time, expenses and capital investment [3,4]. Several studies are reported, where accumulation of activated carbon (passed from earlier stage) in the packed bed reduces column performance. Accumulated carbon then becomes the base/platform for algal growth in the column. Thereby it increases pressure drop, and subsequently reduced throughput. On the other hand, expanded bed allows entry of such matter, which can easily pass through the bed without hampering ion exchanger performance. Hence, use of expanded bed operation does not require filtration of the feed for removal of suspended particle. Hence use of expanded bed in place of packed bed can intensify processes in de-mineralization plants, capturing of trace metals from water etc. After a successful demonstration of expanded beds in bio-industry, widening its horizons on further bigger scales like waste water treatment processes will be a great challenge. In the recent years, boom in industrialization supplemented with generation of waste and its adverse impact on the health of living being and the environment. One of these are waste water containing trace metals and its removal adds to operational costs of the industry [5]. Efficient processes are needed for isolating trace metals from the waste water in order to reduce cost of operation.

For separation of trace metals from water and waste water, various methods are reported. These are broadly categorized as precipitation, membrane separation, electrodialysis, ion exchange and adsorption. Trace metal concentration in the waste water and the process economics are the important attributes for the selection of the separation process. However, ion exchange and adsorption are preferred method for dilute feed. In most of the processes bio-adsorbents and ion exchange resins are reported as

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Nomenclature

Latin (Uppercase)
B_o Bodenstein number
C Feed concentration (g/mL)
D Axial dispersion coefficient (m^2/s)
H Height of the expanded bed (m)
N Number of theoretical plates
W Peak width at half peak height of the RTD curve (m)

Latin (lowercase)
k_{ldf} Lumped intra-pellet diffusion kinetic coefficient (s^{-1})
q Average adsorbed phase concentration (g/g)
q^* Hypothetical adsorbed phase concentration at adsorption equilibrium (g/g)
q_s Monolayer saturation adsorption capacity (g/g)
t Residence time (s)
u Superficial velocity (m/s)

Greek
ε Bed porosity
ρ Adsorbent density (kg/m^3)

adsorbents, because bio-adsorbents are cheap and ion exchange resins are easy to regenerate.

The key desired characteristics of the adsorbent for expanded bed are, high density (it allows operation at higher velocity, so smaller adsorber vessels are needed for carrying out desired level of separation), a broad particle size distribution (forms stable fluidized bed) and high porosity (reduced mass transfer resistances and resulting in enhanced dynamic adsorption capacity) [6,7]. Many researchers have reported the impact of these parameters on the performance of expanded beds, with different adsorbents and columns [6,7]. It is important to note that, axial distribution of adsorbents and bed voidage results in complex liquid mixing, which varies along the column height. It impacts the overall mass transfer and adsorption kinetics of the target solute, which ultimately influences mass transfer zones in column and hence the adsorption efficiency. Therefore, better understanding of induced process parameters like liquid mixing and axial dispersion in expanded beds, compared to packed bed is necessary. It is a fundamental building block for evaluating complex adsorption performance and improving efficiency of expanded beds.

Measures of performance in packed bed like axial dispersion coefficients, the number of theoretical plates (or the number of equilibrium stages), and the height equivalent to theoretical plate are being used to assess its performance in expanded beds [8]. However, these are the results of liquid mixing and axial dispersion inside the column, which is a function of adsorbent characteristics (geometry, density, porosity, sphericity, and particle size distribution), liquid viscosity and velocity. These studies have been reported by many researchers [9,10]. Also an empirical correlation is proposed by considering these parameters, for the variation of the local effective axial dispersion coefficient along with column height [11,12]. To understand better the insight of expanded bed, researchers have distributed the expanded bed in different zones and each zone is analysed for liquid mixing and axial dispersion. Yun et al. [11,12], reported that local axial dispersion and liquid mixing are decreased gradually from bottom to the top of the column. A 3-zone model was reported for investigating protein adsorption in an expanded bed; as a function of particle size, bed voidage and local axial dispersion coefficient in different zones [13]. Many independent studies on packed and expanded bed are reported. However, reports on back to back performance of high density ion exchange system in packed vs. expanded bed is rare in prior literature. The adsorbent matrix widely studied in bio-separation is having specific gravity in the range of 1.15–1.20, with mean particle size of 100-250 μm. These adsorbents are studied for 1.5–3.0 fold expansion, in expanded bed adsorption. In this work, performance of high density ion exchange resin have been investigated for packed and expanded bed operations. Such resins are being used commercially for ion exchange process. It is important to note that, this relative understanding of packed and expanded bed should be useful for considering transition of an adsorption process from packed to expanded bed.

In the present work, residence time distribution (RTD) and dynamic adsorption breakthrough experiments were performed in a packed and an expanded bed. A high density ion exchange resin INDION225H was used as adsorbent for performance evaluation in a glass column with 2.54 cm ID. Experiments to study RTD were performed by giving pulse of acetone at the inlet. The results are analyzed, and a new non dimensional number, D_{ax}/(u.HETP), has been proposed to identify deviation of expanded bed from plug flow. Copper is used as a model solute for adsorption performance studies. Dynamic adsorption breakthrough experiments were modeled using the axially dispersed plug flow model. Linear driving force (LDF) model was assumed to describe the rate of adsorption. Finite difference explicit method has been used to discretize the model equations. Mathematical model was further simulated using MATLAB. Also an empirical model is developed for describing the complex relationship of hydrodynamics and kinetics of adsorption in packed and expanded beds. With the analysis of its performance, a suitable range of liquid velocities for expanded bed operation is also suggested.

2. Experimental

2.1. Materials

The ion exchange resin, INDION225H used in this study, was supplied by M/s Ion Exchange, Mumbai, India. Its properties are provided in following Table 1. Commercial grade copper sulphate was used as a source of model solute, procured from M/s Sisco Research Laboratory, Mumbai, India. Analytical grade acetone was supplied by M/s Labort Chemicals, Surat, India. A medicinal syringe was used for pulse injection of acetone.

2.2. Experimental set-up

Experimental set-up for the packed and expanded bed is shown in Fig. 1. It consists of a 2.54 cm diameter glass column of 50 cm height, fabricated from local vendor. The liquid distributor of column is a metal (SS) perforated plate, having 14 holes of 1 mm diameter. It is covered with a metal wire screen of 100 mesh (i.e. 150 μm openings). Fluid distributor was fixed to the metal (SS) adaptors. Active column height (Bed height and free liquid height)

Table 1
Properties of INDION 225H Ion Exchange Resin.

Matrix	Styrene divinyl benzene copolymer
Functional groups	Sulphonic acid
Physical form	Golden yellow to brown beads
Ionic form	H form
Density	1.485 g/mL
Uniformity coefficient	1.7 maximum
Particle Size Range	0.3–1.0 mm
Mean Particle Size	0.6 mm