Mass Transfer Study of Water Hardness Removal by Ion Exchange in Batch Conical Air Spouting bed

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Abstract

In this paper, the function of a batch conical spouting bed for water hardness removal by using of ion exchange resin has been investigated. The effect of different parameters such as different initial total hardness and superficial air velocity has been studied. The experiments result showed that with the increase of air superficial velocity volumetric mass transfer coefficient has been increased.
Dimensional analysis of the present mass transfer data led to the following correlations:
for total hardness: $J_D = 0.17(Re * Fr)^{-0.25}$
The importance of this mass transfer correlation in the design and operation of air spouting beds used for conducting ion exchange reaction was highlighted.

Keywords: Conical spouting bed, Resin, Ion exchange, Hardness water, Mass transfer

Introduction

Water is essential substance to human that life cannot exist without. Soap does not lather in some waters or when such waters are boiled a shell will be remained in the container. These waters are called hard water. The divalent cations—calcium, magnesium, strontium, ferrous iron, and manganous manganese—cause hardness in water. A primary source of calcium and magnesium in water is the dissolution of limestone and calcium silicate. The total hardness of water mainly results from divalent cations calcium and magnesium expressed as equivalent calcium carbonate [1]. One of the methods for removing water hardness is the ionic exchange using polymeric strong acid cation resins (SAC) in sodium form. The sodium chloride solution (0.5 to 3.0 M) as a regeneration agent is use to regenerate this type of resin. regeneration this kind of resin is simple and inexpensive [2].Ion exchange mechanisms are as follows:(1) movement of the ions from the bulk solution to the film or boundary layer surrounding the exchange solid, (2) diffusion of the ions through the film to the solid surface, (3) diffusion of the ions inward through the pores of the solid to the exchange sites, (4) exchange of the ions by reaction, (5) diffusion of the exchanged ions outward through the pores to the solid surface, (6) diffusion of the exchanged ions through the boundary layer, and (7) movement of the exchanged ions into the bulk solution [3]. The spouted bed technology is a special type of fluidization. Usually used when the particles are coarse and uniform in size. Air is entered vertically through a centrally located small opening at the down of bed. Thus two distinct regions are formed: a dilute phase central core with upward-moving solid particles called spout and a dense phase annular region. Annular region between spout and bed wall contains a packed bed of solid particles slowly move downward and inward. The surrounding annular region called the annulus. The conical spouted beds have been used for drying, catalytic polymerization, coal gasification, and waste pyrolysis [4,5]. The pressure drop of spouted bed is normally lower than that for a fluidized bed [6].

In the present work, effect of different parameters such as different initial total hardness and air superficial velocity on fuction of a batch conical spouted bed in the water total hardness removal have been investigated.

Experimental

Fig.1 shows the schematic diagram of experimental apparatus used in the present work.The spouted bed was made of galvanized iron sheet. The diameter at the bottom was 3cm and at the top was 20cm.The spouted bed had a height 50cm.The cone angle was 18°.Ion exchange resins were kept by aluminum wire mesh as an air distributor that was placed at the bottom of the vessel. Air at different flow rate was passed through aluminum wire mesh to the spouted bed. Air flow rate was controlled by a ball valve and measured by a rotameter.

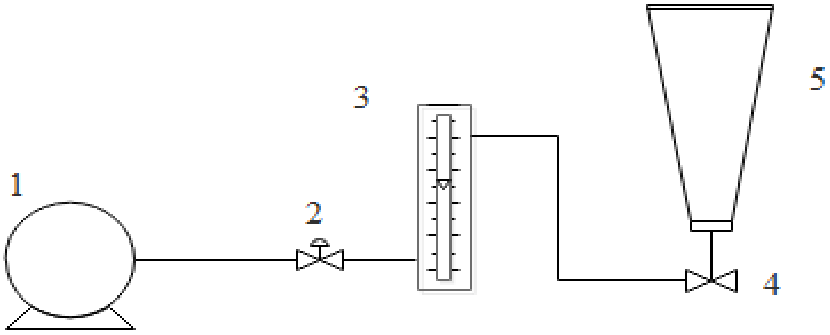

Fig.1. schematic diagram of experimental apparatus. (1) Central air pump;(2) ball vale;(3) rotameter;(4) non return valve;(5) spouted bed

Fresh strong acid cation resin in sodium form C100E(Purolite company) was used.Before doing the experiments it has been in the distilled water. Tabel 1.shows the properties of the used ion exchange resin.Two litrs of hardness water with different initial concentrations were prepared for every experiment. Edta titrimetric method was used for analyzing the remainig hardness amount [7]. All experiments were done at 25 °C.

The diffusion coefficient in electrolyte solution have been calculate from Nernst-Haskell equation [8]:

$$D^0_{AB} = \frac{RT[(1/n_+) + (1/n_-)]}{F^2[(1/\lambda^0_+) + (1/\lambda^0_-)]}$$

were
D^0_{AB} = diffusivity at infinite dilute solution, based on molecular concentration,cm^2/s
R=gas canstant,8.314 J/mol.K ,T=temperature,K
λ^0_+ , λ^0_- =limiting(zero concentration)ionic conductances,$(A/cm^2)(V/cm)(g\text{-equiv}/cm^3)$
n_+ ,n_-=valences of cation and anion,respectively
F= Faraday's costant= 96500 C/g-equiv

Results and discussion

The mass transfer behavior of the batch spouted bed is based on the following differential material balance with respect to the ion to be removed:

$$-m_s \frac{dC}{dt} = kAC^2$$

This upon integration yields:

At t=0, $C=C_0$ And at t=t, $C=C_t$

$$m_s \frac{C_0 - C}{C_0 * C} = kAt$$

Where
C_0= initial concentrations of hardness; C= concentration of hardness at time t; m_s = the solution mass, t= time, k= mass transfer coefficient, A= the surface area of resin which has been calculated from the equation [9]:

$$A = \frac{6m}{\bar{d}_s \rho_s}$$

Where
m= resin mass; d is average resin particle diameter; ρ_s is resin density.
The mass transfer coefficient k was calculated from the slope kA/m_s of the plot $\frac{C_0-C}{C_0*C}$ vs. time.
The volumetric mass transfer coefficient is related to the superficial air velocity according to the following equation:

$K\alpha V_g^{\ 0.27}$

The experiments result showed that with the increase of air superficial velocity volumetric mass transfer coefficient has been increased. With the increase of air velocity the flow pattern within the bed changed from stable spouting to jet spouting. Thus mass transfer coefficient was increased.The reason of the increase of K during stable spouting regime is increase of particle—circulation rate and particle cross rate at the bottom. Where particle circulation rate represent the total mass flow of particle at a given longitudinal position in the spout, and particle cross flow expresses the solid flow from the annular zone into the spout zone through the interface. Thus a strong mixing can be obtained by increasing air velocity, which results

in good mass transfer rate. The reason of the increase of K during jet spouting regime is because upraising air stream induces radial as well as axial momentum which causes decrease in the thickness of diffusion boundary layer surrounding each particle. The effect of superficial velocity was studied containing two regimes stable and jet spouting consequently the coefficient n expresses an average value of both regimes[4].
For gas spouting the mass transfer coefficient associat to the other variables by the dimensionless equation:

$$J_D = a(Re * Fr)^{\alpha}$$

Where
J_D= the mass transfer factor $(K/AV_g)*(\mu/\rho D)^{0.66}$
Re =the Reynolds number $(\rho\, d_b\, V_g/\mu)$
Fr = the Froude number $(V_g{}^2/g\, d_b)$. a and α are constant.

As a result the dimensionless correlation obtained:

$$J_D = 0.17(Re * Fr)^{-0.25}$$

Conclusions

The function of a batch conical spouting bed for water hardness removal by using of ion exchange resin has been investigated. The effect of different parameters such as different initial total hardness and superficial air velocity has been studied. The experiments result showed that with the increase of air superficial velocity volumetric mass transfer coefficient has been increased.The present mass transfer data have been associated in terms of J_D, Re and Fr.

table1. Properties of Purolite C100E resin.

Polymer Structure	Gel polystyrene crosslinked with divinylbenzene
Appearance	Spherical Beads
Functional Group	Sulfonic Acid
Ionic Form	Na^+ form
Total Capacity	1.9 eq/L (41.5 Kgr/ft³) (Na^+ form)
Moisture Retention	46 - 50 % (Na+ form)
Particle Size Range	300 - 1200 µm
Reversible Swelling, $Na^+ \rightarrow H^+$ (max.)	10 %
Reversible Swelling, $Ca^{2+} \rightarrow Na^+$ (max.)	8%
Particle Size Range	300 - 1200 µm
Specific Gravity	1.27
Uniformity Coefficient (max.)	1.7

Nomenclature Symbols

Symbol	Description	Unit
A	Surface area of resin	cm^2
a	Constant	-
C	Concentration of total hardness at time(t)	ppm
C_0	Initial concentration of total hardness	ppm
D	Diffusion coefficient	cm^2/s
d_b	Bubble diameter	cm
g	Acceleration gravity time	cm/s^2
k	mass transfer coefficient	cm/s
K	Volumetric mass transfer coefficient	cm^3/s
t	Time	s
Vg	Superficial air velocity	cm /s
m_s	Mass of solution	ppm
T	temperature	K
R	gas canstant	J/mol.K
F	Faraday's costant	C/g-equiv
n_+	valences of cation	-
n_-	valences of anion	-

Greek symbols

Symbol	Description	Unit
α	constant	-
ρ	Solution Density	gm/cm^3
μ	Solution viscosity	gm /cm.s
λ^{0}_{+}	ionic conductances	$(A/cm^2)(V/cm)(g\text{-}equiv/cm^3)$
λ^{0}_{-}	ionic conductances	$(A/cm^2)(V/cm)(g\text{-}equiv/cm^3)$

Dimensionless group

Symbol	Description
Fr	Froude number
J_D	J-factor for mass transfer
Re	Reynolds number
Sc	Schmidt number

References

[1] Boyd, CE., Water quality an introduction, 2nd ed., Springer,(2015).

[2] Bandrabur, B., Tataru-Farmus, R. E., Lazar, L., Bulgariu, L., Gutt, G.," Use of strong acid resin purolite C100E for removing permanent hardness of water –factors affecting cationic exchange capacity", Scientific Study & Research. Chemistry & Chemical Engineering, Biotechnology, Food Industry., 13 , 295-304 (2012).

[3] Davis, M. L., Water and wastewater engineering: Design principles and practice , McGraw-Hill Education, (2010).

[4] Darwish, A. S., Zewail, T. M., Yousef, N. S. and El Tawail, Y. A.," Investigation of the performance of a batch air spouting bed in conducting ion exchange reactions involving heavy metal removal", Journal of the Taiwan Institute of Chemical Engineers., 47, 171-176 (2015).

[5] Epstein, N., Grace, J. R., Spouted and spout-fluid beds: fundamentals and applications , Cambridge University Press, (2010).

[6] Coulson, J. M., Richardson, J. F., Backhurst, J. R. and Marker, J. H., Coulson & Richardson's Chemical Engineering, 5th ed., Butterworth-Heinemann London, (2002).

[7] Rice, E W., Baird, R. B., Eaton, A. D. and Clesceri, L. S., Standard methods for the examination of water and wastewater, 23rd ed., American Public Health Association Washington, DC, (2017).

[8] Benitez, J., Principles and modern applications of mass transfer operation, 3rd ed., John Wiley & Sons, (2016).

[9] Zewail, T. M.," The Role of Mass transfer in the removal of heavy metal ions by ion exchange using batch gas sparged vessel", Chemical and biochemical engineering quarterly., 24, 437-443 (2010).