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Modelling and numerical simulation of liquid–solid circulating fluidized bed system for protein purification

Pei Wen Lau[a], *Ranjeet Utikar*[a,*], *Vishnu Pareek*[a], *Stuart Johnson*[b], *Sandeep Kale*[c], *Arvind Lali*[c]

[a] *Department of Chemical Engineering, Curtin University, Perth, Western Australia, Australia*
[b] *School of Public Health, Curtin Health Innovation Research Institute, Curtin University, Perth, Western Australia, Australia*
[c] *DBT-ICT-Centre of Energy Biosciences, Institute of Chemical Technology (ICT), Mumbai, India*

ABSTRACT

A novel liquid–solid circulating fluidized bed (LSCFB) was modelled for protein recovery from the feed broth. A typical LSCFB system consists of downer and riser, integrating two different operations simultaneously. A general purpose, extensible, and dynamic model was written based on the tanks-in-series framework. The model allowed adjusting the degree of backmixing in each phase for both columns. The model was validated with previously published data on extraction of bovine serum albumin (BSA) as model protein. Detailed dynamic analysis was performed on the protein recovery operation. The interaction between the riser and downer were captured. Parametric studies on protein recovery in LSCFB system were carried out using the validated model to better understand the system behaviour. Simulation results have shown that both production rate and overall recovery increased with solids circulation rate, superficial liquid velocity in the downer and riser, and feed solution concentration. The model was flexible and could use various forms of ion exchange kinetics and could simulate different hydrodynamic behaviours. It was useful to gain insight into protein recovery processes. The general nature of the model made it useful to study other protein recovery operations for plant and animal proteins. It could also be useful for further multi-objective optimization studies to optimize the LSCFB system.

Keywords: Adsorption; Liquid–solid circulating fluidized bed (LSCFB); Dynamic modelling; Dynamic simulation; Protein recovery; Tanks-in-series

1. Introduction

Liquid–solid circulating fluidized bed (LSCFB) systems are rapidly being applied in biochemical separation technology (Nakhla et al., 2007; Patel et al., 2006). Typical LSCFB system consist of two parts viz. a downer and a riser, integrating principal reactions or adsorption processes with continuous circulation of solid particles between these two. Typically, the downer is used for reaction or adsorption process to provide a longer residence time. Whereas, the riser, with its higher liquid velocity and excellent plug flow characteristics, is used for fast desorption or regeneration of adsorbents. Lan et al. (2000, 2002a) introduced the concept of LSCFB for adsorption processes. They studied the effect of operating conditions on the hydrodynamics of LSCFB and developed LSCFB systems for the continuous recovery of bovine serum albumin (BSA) and whey proteins from unclarified broths using Diaion HPA25® anion ion exchangers. Patel et al. (2006) developed an LSCFB system with anoxic and aerobic beds for simultaneous removal of carbon, nitrogen and phosphorus from municipal wastewater. While these studies have demonstrated that such LSCFB adsorption have potential applications, these systems are still poorly understood. Other than all the benefits of fluidization, including low and stable pressure drops across the fluidized beds, this technology has attracted attention for its enhanced mass and heat transfer, reduced backmixing, and

* *Corresponding author at*: Department of Chemical Engineering, Faculty of Science and Engineering, School of Chemical and Petroleum Engineering, Curtin University, Perth, Western Australia 6102, Australia. Tel.: +61 8 9266 9837; fax: +61 8 9266 2681.
E-mail address: r.utikar@curtin.edu.au (R. Utikar).
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Nomenclature

a	specific surface area of the adsorbent (m^2/m^3)
C	protein concentration in liquid phase (kg/m^3)
D	diameter (m)
D_m	molecular dispersion coefficient (m^2/s)
g	gravitational constant (m/s^2)
G_s	solids circulation rate ($kg/m^2/s$)
H	height (m)
h_l	height of liquid phase subtank (m)
h_s	height of solid phase tank (m)
K_d	dissociation constant (kg/m^3)
k_f	film mass transfer coefficient (m/s)
K_L	lumped mass transfer rate coefficient (m/s)
k_r	desorption rate constant (s^{-1})
L	length (m)
n	bed expansion index
q	protein concentration in solid phase (kg/m^3)
P	protein production rate (kg/h)
R	fraction protein recovered
S	amount of adsorbent (kg)
t	time (s)
U	superficial liquid velocity (m/s)
V_p	total volume of minor LSCFB sections (m^3)

Greek symbols

ε	bed voidage
ε_s	solids holdup
ε_p	voidage in minor LSCFB sections
μ	viscosity of liquid (kg/m/s)
ρ	density (kg/m^3)
Δt	time step (s)
Ψ	constant factor defined in Eq. (16B)

Subscripts

a	apparent
c	liquid–solid separator
$c1$	liquid–solid separator upper section
$c2$	liquid–solid separator lower section
d	downer
e	exiting
eq	equilibrium
fe	solids feed pipe
i	liquid phase subtank
j	solid phase tank
l	liquid phase
m	maximum
M	number of solid phase tanks
N	number of liquid phase subtanks per solid tank
o	initial/entering
p	adsorbent
r	riser
$r1$	riser distribution region
$r2$	riser top dilute region
re	solids return pipe
s	solid phase
t	terminal
w	wet

Superscript

eff	effective

easy handling of particles of mixed sizes and densities lead to a much more effective processing (Zhu et al., 2000). Besides, the riser-downer configuration of LSCFB system makes it possible to have continuous processes with adsorption and desorption conducted simultaneously, further enhancing the efficiency and equipment size reduction (Atta et al., 2009; Lan et al., 2002a). Overall, LSCFB systems have advantages of economy; however their success is strongly dependent on better understanding of the LSCFB dynamics.

In this paper, the application of LSCFB system for continuous protein recovery was studied. A general purpose, extensible, and dynamic mathematical model based on the tanks-in-series approach was established. The model allows for adjustment of the backmixing degree in each phase (solid and liquid) for both riser and downer and therefore providing flexibility to match the residence time distribution of industrial systems. The model predictions were validated using the available experimental data on the BSA recovery onto Diaion HPA25® using the LSCFB system (Lan et al., 2002b). The validated model was then used to study the effects of various parameters on LSCFB performance.

2. Protein recovery using LSCFB

A schematic diagram of the LSCFB system is shown in Fig. 1 (Mazumder et al., 2009). The LSCFB was configured by two interconnected fluidized beds, namely a downer and a riser. Other important components of LSCFB involved a liquid–solid separator, a measurement device of solid circulation rate, a solid return pipe, a top washing section, an inclined solid feed pipe, and a bottom washing section. In this study, the downer was of 120 mm diameter, and 2.5 m height, while the riser was 3 m in height and 38 mm in diameter. The cross-sectional area ratio of riser to that of the downer were 10.

Lan et al. (2000, 2002b) investigated continuous recovery of BSA to polymeric adsorbents Diaion HPA25®. The synthetic adsorbent particles which had an average size of 0.32 mm diameter were applied into the system. The continuous protein adsorption was conducted with downer as the adsorption vessel; whereas, the riser was used for regeneration of adsorbents. The downer operates in conventional fluidization regime, and in this study the liquid velocity was kept below the particle terminal settling velocity but enough to fluidize the particles. In the downer, the liquid and solid phases were kept in counter-current contact. The feed stream was injected through a distributor into the bottom of the downer, and the solid particles moved down counter-currently to the rising feed stream. The particles then travelled from downer to the bottom of riser through solids feed pipe. The riser was a fast fluidization vessel wherein the primary and auxiliary liquid streams were injected into the bottom of the riser. The function of auxiliary liquid stream through the liquid distributor was to stir up particles at the bottom of the riser whereas the primary liquid stream was introduced into the riser to transport the particles. The riser operated at a total liquid velocity higher than the particle terminal settling velocity. The two phases moved co-currently to the top of the riser and then separated within the liquid–solid separator. The particles were then transferred from the riser to the top of the downer via the solids return pipe.

As discussed previously, in a continuous protein recovery process, both downer and riser contained two liquid solutions of different properties, i.e. the feed solution contained 2 g/L