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Numerical simulation of counter-current flow field in the downcomer of a liquid–solid circulating fluidized bed

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ABSTRACT

A comprehensive study on the hydrodynamics in the downcomer of a liquid–solid circulating fluidized bed (LSCFB) is crucial in the control and optimization of the extraction process using an ion exchange LSCFB. A computational fluid dynamics model is proposed in this study to simulate the counter-current two-phase flow in the downcomer of the LSCFB. The model is based on the Eulerian–Eulerian approach incorporating the kinetic theory of granular flow. The predicted results agree well with our earlier experimental data. Furthermore, it is shown that the bed expansion of the particles in the downcomer is directly affected by the superficial liquid velocity in downcomer and solids circulation rate. The model also predicts the residence time of solid particles in the downcomer using a pulse technique. It is demonstrated that the increase in the superficial liquid velocity decreases the solids dispersion in the downcomer of the LSCFB.

Introduction

The extraction of functional solids materials from the industrial broth has received high attentions during the recent years due to concerns on limitations of the natural resources (Lan, 2001). The continuous ion exchange process using the conventional fluidized is one of the major extraction equipment which has been used extensively (Byers et al., 1997; Gordon, Tsujimura, & Cooney, 1990; Higgins, 1969; Himsley, 1981). Although the conventional fluidized beds have some benefits such as low and stable bed pressure drop and the direct application of unclarified broth feeds, the continuous transportation of a large number of particles between vessels becomes a challenging issue (Gaikwad, Kale, & Lali, 2008). Because of the unique features of the liquid–solid circulating fluidized bed (LSCFB) including the continuous operation in vessels, high throughout due to high liquid velocity in the riser, high efficient liquid–solid contact, integrated reactor, and smaller processing volumes, Zhu, Karamanev, Bassi, and Zheng (2000) proposed an LSCFB system as a potential candidate for the continuous extraction process. A typical LSCFB is comprised of a riser, a downcomer, a liquid–solid separator, and other auxiliary components. Also, the liquid–solid flow pattern is co-current in the riser and counter-current in the downcomer.

To take advantage of the exceptional characteristics of LSCFBs, Lan, Zhu, Bassi, & Margaritis (2002) and Lan et al. (2000) reported an LSCFB ion-exchange system for the continuous extraction of proteins. In addition to modeling the riser, they also developed a semi-empirical correlation to predict the solids holdup in the downcomer. The correlation was derived from Richardson and Zaki equation (Richardson & Zaki, 1954; Kwauk, 1992). Further, they studied the effects of operating conditions on the overall efficiency of the protein extraction process. Feng, Jing, Wu, Chen, and Song (2003) carried out the cesium separation using a continuous ion exchange circulating fluidized bed.

Control and optimization of the extraction process using an ion exchange LSCFB require a comprehensive study on the hydrodynamics in the riser and downcomer. In the last decade, computational fluid dynamics (CFD) techniques have received more attentions in simulating the transport phenomena in liquid–solid fluidized bed reactors; however, there are only a few studies in the literature on the behavior of the two-phase flow in a downcomer. In addition, because of the counter-current contact of the two phases, the flow field in the downcomer is more complex. As far as we know, there has been no CFD study on the liquid–solid counter-current flow in the literature.

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Nomenclature

Notation

C_D	drag coefficient, –
d_p	mean particle diameter, m
D	riser diameter, m
e	restitution coefficient for interparticle collisions, –
e_w	restitution coefficient for particle-wall collisions, –
g	acceleration due to gravity, m/s^2
g_0	radial distribution function, –
G_s	solids circulation rate, $kg/(m^2\,s)$
K_{sl}	interphase momentum exchange coefficient, $kg/(m^3\,s)$
k_{Θ_s}	granular conductivity, $kg/(m^3\,s)$
n	bed expansion index
p_s	solids pressure, Pa
P	fluid pressure, Pa
r	radial location, m
Re	Reynolds number, –
t	time, s
U_t	particle terminal velocity, m/s
U	superficial liquid velocity, m/s
v	velocity, m/s
x	axial location, m

Greek letters

α_s	local solids volume fraction, –
$\bar{\alpha}_s$	mean solids volume fraction at certain cross-section, –
α_{sd}	solids volume fraction in the dense zone of the downcomer
Φ_{ls}	interphase energy exchange, $kg/(m\,s^3)$
γ_Θ	Collisional energy dissipation rate, $kg/(m\,s^3)$
λ	solids bulk viscosity, (kg m)/s
μ	viscosity, (kg m)/s
υ	kinematic viscosity, m^2/s
Θ	granular temperature, m^2/s^2
ρ	density, kg/m^3
τ	shear stress, $kg\,m/s^2$

Subscripts

l	liquid phase
s	solid phase
f	fluid
a	auxiliary
d	downcomer

Din, Chughtai, Inayat, Khan, and Qazi (2010) developed a CFD model to simulate a liquid–liquid counter-current flow in the pulsed sieve plate extraction column. The model was based on Eulerian–Eulerian approach with the standard multiphase k–ε turbulence model. A pulse generation model was incorporated to simulate the effect of pulses in the system. By comparison with the experimental data, the CFD results show 27.83% error.

The purpose of this study is to develop a sophisticated CFD model to simulate the liquid–solid flow field in an LSCFB downcomer. This model is based on Eulerian–Eulerian approach incorporating the kinetic theory of granular flow. The proposed model is used to examine the effect of the operating condition on the hydrodynamic characteristics and to obtain the residence time distribution (RTD) of solid particles using a pulse technique.

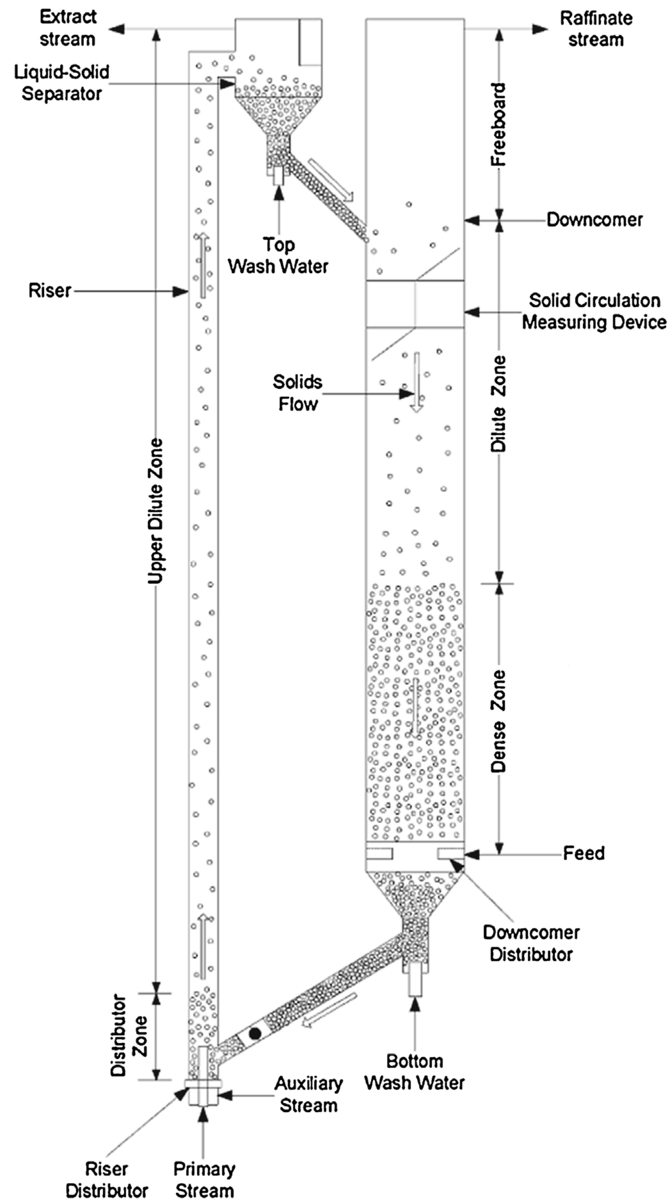

Fig. 1. Schematic diagram of the LSCFB ion-exchange system (Lan et al., 2000).

Configuration of the LSCFB ion-exchange system

The LSCFB ion exchange system used in this study was developed by Lan et al. (2000), where an experimental study on hydrodynamics and kinetics of the protein extraction process in this LSCFB ion exchange system was conducted. In that study, a lab scale system was designed and manufactured. The schematic diagram of the LSCFB ion exchange system used by Lan et al. (2000) is shown in Fig. 1. It is comprised of a riser, a downcomer, a liquid–solid separator, a top solids-return pipe, a bottom solids-return pipe, a top washing section, a bottom washing section, a riser distributor, and a downcomer distributor. The riser is 3.0 m in height and 0.038 m in diameter, and the downcomer is 2.5 m in height and 0.120 m in diameter.

In the downcomer, Bovine serum albumin (BSA) solution was used as a liquid feed and Diaion HPA25 (Mitsubishi Chemical Corporation, Japan) particles were used as solid ion-exchange particles (d_p = 0.32 mm, ρ = 1.08 g/mL, and U_t = 4.5 mm/s).