Chemical Engineering Journal 267 (2015) 124–131

Contents lists available at ScienceDirect

Chemical Engineering Journal

journal homepage: www.elsevier.com/locate/cej

Modeling the height of high-pressure ebullated beds based on superficial energy

Songshou Ye, Jinbao Zheng *, Jiexiang Wang, Juanjuan Li, Weikun Lai, Bing H. Chen *, Weiping Fang

College of Chemistry and Chemical Engineering, National Engineering Laboratory for Green Chemical Productions of Alcohols-Ethers-Esters, State Key Laboratory for Physical Chemistry of the Solid Surfaces, Xiamen University, Xiamen 361005, Fujian, PR China

HIGHLIGHTS

- Developed a model based on minimum energy for high-pressure ebullated beds.
- The parameters of the model obtained in this work are analyzed for various energy.
- The predictions of bed height are well in agreement with experiments.

ARTICLE INFO

Article history:
Received 15 July 2014
Received in revised form 13 December 2014
Accepted 5 January 2015
Available online 13 January 2015

Keywords:
Pressured ebullated bed
Bed height
Semi-empirical modeling
Minimum energy principle

ABSTRACT

Since the prediction of the height of fluidized beds, especially in high pressure multi-phase fluidized beds, depends mostly on empirical models in the reported literature, an attempt is preliminarily made in this work to develop a semi-empirical model for the behavior of bed expansion or contraction in high-pressure ebullated beds based on minimum energy principle. The model principally takes kinetic energy, potential energy, and energy balance resulted from interaction between different phases in the system into account. Reported experimental data are utilized to validate the model, and the obtained values of the model parameters basically reflect the contribution of kinetic energy, potential energy and surface interaction energy to the height of bed. A reasonably good agreement between the experimental data and the calculated height of ebullated bed is subsequently achieved, demonstrating that the model can be satisfactorily endowed with predictive capability within the reported experimental ranges.

1. Introduction

Ebullated bed reactors (EBRs) are the multiphase reactors widely used in diverse applications such as hydrocracking and hydrodesulfurization of residual feedstock, Fischer–Tropsch synthesis, and coal methanation [1,2]. As the petroleum refinery technology progressing, the residual material of refinery process is becoming heavier and thus getting worse in quality as the feedstock for hydrotreating. For such specific and challenge case, the conventional technologies are not suitable, and the EBRs have been outstandingly renewed the importance. Recently, EBRs are closely attracting to be used in H-Oil and LC-Fining processes for upgrading heavy oil, typically characterized by high temperature (400–450 °C) and high pressure (10–20 MPa) [3], because the EBR technology possesses many advantages such as very flexible in operation for such an application.

Yet, it has received scant attention of studying the hydrodynamics of high-pressure and high-temperature EBRs, because of its complexity [1]. Although EBR technology has been applied to hydrocracking heavy petroleum fractions in recent years, the information about the hydrodynamics, which is essential for the design and scale-up of these reactors, is secretly held by licensors. To the best of our knowledge, only few papers were published on high pressure/temperature hydrodynamics of EBR by the research group of Fan [4–6] and by Ruiz [7,8]. It was reported that the average bubble size decreased and the bubble size distribution became narrower with the increase of pressure, and thus higher gas velocities were required from the dispersed bubble regime to the coalesced bubble regime. However, much fewer studies were carried out in modeling the hydrodynamics of high-pressure EBRs, although a number of correlations with relevance to bed features were developed for ambient conditions [1]. Jiang et al. [5] modified the generalized wake model for bed expansion or contraction phenomena by taking the bubble size distribution effects into account. However, the assumption on the bubble rise velocity proposed in the model was valid only for low gas holdup.

* Corresponding authors. Tel.: +86 592 2186291; fax: +86 592 2184822.
E-mail addresses: jbzheng@xmu.edu.cn (J. Zheng), chenbh@xmu.edu.cn (B.H. Chen).

http://dx.doi.org/10.1016/j.cej.2015.01.018
1385-8947/

Nomenclature

Notation

A	cross-sectional area of bed (cm^2)
a	expansion ratio at minimum fluidization
A_b	the average surface area for bubbles (cm^2)
d_e	equivalent diameter of sphere having the same volume as the particle (cm)
d_p	diameter of the particle (cm)
E_{Sy}	the energy of system (J)
E_P	potential energy (J)
$E_P(ls)$	potential energy of pseudo liquid–solid mixture phase (J)
$E_P(g)$	potential energy of gas phase (J)
E_K	kinetic energy (J)
E_I	surface interaction energy between different phases (J)
ΔE_I	surface interaction energy per unit volume (J/cm^3)
Fr	Froude number, $Fr = u_g/gh_0$
$f_1(u_l), f_2(u_l)$	functions of liquid superficial velocity
G	superficial gas flow rate
g	gravitational acceleration (cm/s^2)
h_t, h_0	expanded and static bed heights (cm)
h_0^*	the pseudo height of bed for minimum fluidization (cm)
$k_1 \sim k_7$	semi-empirical equation parameters
m, m', m''	semi-empirical equation parameters
N_t	the number of bubbles in the bed
n	Richardson-Zaki index
P	pressure (MPa)
P_{max}	maximum pressure (MPa)
R_n	the radius of curvature at the nose of the bubble (cm)
u_g	superficial gas velocity (cm/s)
u_l	superficial gas velocity (cm/s)
u_b	the rise velocity of the bubbles (cm/s)
u_{br}	the rising velocity of the bubbles in stagnant liquid (cm/s)
u_{max}	maximum gas velocity (cm/s)
u_{lf}	pseudo-fluid velocity (cm/s)
u_{pt}	solid terminal velocity in the pseudo-fluid (cm/s)
V_g	the gas volume (cm^3)
V_{ls}	the volume of pseudo liquid–solid mixture phase (cm^3)

Abbreviations

ARD	average relative deviations
EBR(s)	ebullated bed reactor(s)
PLSM	pseudo liquid–solid mixture

Greek letters

α, α'	semi-empirical equation parameters
β, β'	semi-empirical equation parameters
γ, δ	semi-empirical equation parameters
ε_g^*	the overall gas holdup when there is no velocity for mixture phase
ρ_g	gas density (g/cm^3)
ρ_l	liquid density (g/cm^3)
ρ_s	solid density (g/cm^3)
ρ_{ls}	density of pseudo liquid–solid mixture phase (g/cm^3)
μ_l	liquid viscosity (Pa s)
$\Delta\sigma$	surface tension (N/m)

Subscripts

g	gas phase
l	liquid phase
ls	pseudo liquid–solid phase

Ruiz et al. [7] used the modified Richardson and Zaki equation, which set the bed porosity as the function of the velocity of the pseudo-fluid and single-particle terminal setting velocity in the pseudo-fluid, to predict the solid holdup in three-phase EBRs. But the Richardson–Zaki index was obtained from the porosity data of liquid–solid system in Ruiz's work. In the following, Ruiz et al. [8] also evaluated the hydrodynamics of high-pressure EBRs using five dimensionless groups based on the principles of dynamic similitude proposed by Safoniuk et al. [9]. The results indicated that these employed dimensionless groups were not enough to fully characterize the bed behaviors. Also, several empirical correlations were proposed for describing high-pressure hydrodynamics. For example, Morsi et al. [10] developed two empirical correlations to predict the effects of pressure and other factors such as gas velocity on the holdup of slurry bubble column reactors operating under typical Fischer–Tropsch conditions.

Since bed expansion behavior for EBR is a very important factor for reactor design, it is an industrial desire to develop sound mathematical models being capable of predicting bed height with acceptable accuracy. Therefore, the aim of this study is to develop a semi-empirical model enabling to describe the hydrodynamics thus the height of bed in high-pressure EBRs using reported experimental data. Since the point of view of energy or entropy have been successfully used to describing a system concerned with fluidized bed [11,12], a novel model was derived based on minimum superficial energy principle, mainly considering the kinetic energy, potential energy and energy balances resulted from interaction between phases.

2. Modeling

2.1. Model assumptions

It is known that the system of high-pressure fluidized bed is so complex that it is a better choice to model by simplification. Several assumptions were made here for the model derivation.

Assumption 1: Pseudo two-phase flow. Comparison to the density of the gas phase, the density of the liquid phase is closer to that of the solid particles. For simplification, the solid phase and the liquid phase are therefore considered as a 'pseudo-homogeneous mixture phase' (Fig. 1). As a result, the three-phase EBR system can be regarded as a pseudo two-phase system containing the gas phase and the pseudo solid–liquid mixture (PLSM) phase. Similar assumption was used in predicting the gas holdup in the three-phase internal loop airlift reactors by Hwang and Cheng [13]. Based on the assumption, the volume of gas phase and the PLSM phase can be expressed as following,

$$V_g = (h_t - h_0)A \quad (1)$$

$$V_{ls} = h_0 A \quad (2)$$

where V_g and V_{ls} represent the volumes of gas phase and PLSM phase, respectively; h_t and h_0 represent the heights of bed with aeration and without aeration, respectively, and A is the cross-sectional area of the fluidized bed.

Assuming the bed expansion is totally due to the formation of bubbles, the gas holdup can be written as following,