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Constraint strength and axial/radial particle velocity profiles for an integrated riser outlet

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ABSTRACT

To study axial/radial profiles of particle velocity in the affected region of an integrated riser outlet, a cold model was developed for the integrated riser reactor combining the gas–solid distributor with the fluidized bed. Constraints, related to the gas–solid distributor and the upper fluidized bed, imposed on the particle flow in the riser outlet region, were investigated experimentally. The experimental results showed that with increasing superficial gas velocity, these constraints have strong influences on particle flow behavior, the particle circulation flux in the riser, and the height of the static bed material of the upper fluidized bed. When the constraints have greater prominence, the axial profile of the cross-sectionally averaged particle velocity in the outlet region initially increases and then decreases, the rate of decrease being proportional to the constraint strength. Along the radial direction of the outlet section, the region where the local particle velocity profile tends to decrease appears near the dimensionless radius $r/R = 0.30$ initially and then, with increasing constraint strength, gradually extends to the whole section from the inner wall. Based on the experimental data, an empirical model describing the constraint strength was established. The average relative error of the model is within 7.69%.

Introduction

Circulating fluidized bed riser reactors have been widely used in energy, chemical engineering, and other fields. The outlet structure of these risers varies in type depending on the technical requirements. T-, L-, C-, and V-type outlet structures have been widely involved in prior research and applications on riser reactors. Briefly, these outlet structures can be classified as either abrupt (such as the T-type) or smooth (such as the L- and C-type). Many scholars have studied shape effects of outlet structures on gas–solid flow behavior in the riser. For instance, the smooth outlet structures were studied for their effects on solids distributions, both axially and radially, in a riser. The curves calculated for the axial distributions in a CFD simulation were exponential for the L-type outlet and C-shaped for T-type outlet (Wu, Jiang, Xu, & Xiao, 2010). Similarly, the L- and T-type outlet structures were studied with respect to particle velocity distributions along both axial and radial directions in the riser under low density operating conditions. The results showed that the T-type outlet was found to cause more significant reflux than the L-type outlet. Moreover, a reduction in outlet section area of the T-type structure resulted in a longer reflux length in the side-wall area (Van engelandt, Heynderickx, De Wilde, & Marin, 2011). L- and T-type outlet structures in a square cross-sectional riser were also studied in regard to mass flow rate distributions. The results showed that the reflux ratio (the ratio of the downflow flux of solids in the riser to the external circulation flux) was higher in T-type outlet structures than the L-type (Lackermeier & Werther, 2002; Van der Meer, Thorpe, & Davidson, 2000). The three outlet structures (C-, L-, and T-type) were studied in regard to the residence time distribution of particles. Under the same experimental operations, enhancing reflux within the outlet increased the mean residence times of particles (Harris, Davidson, & Thorpe, 2003). The heat transfer coefficient in the upper segment of a riser of the L- and T-type outlet structures was also studied. The heat transfer coefficient was found to be enhanced in the outlet area or the whole area for the T-type outlet (Gnanapragasam & Reddy, 2008; Gupta & Reddy, 2005; Zhang, Yang, Wu, Zhang, & Lu, 2013). Further, high-density circulating fluidized beds of outlet structures (C-, L-, and T-type)

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Nomenclature

D_r	riser diameter (m)
d_p	particle diameter (μm)
Fr	Froude number ($Fr = U_{g,r}/\sqrt{gd_p}$)
$G_{s,r}$	solids circulation flux (kg/(m^2 s))
g	acceleration of gravity (m/s^2)
H_b	static bed height in the upper fluidized bed (m)
h	axial position in the integrated riser (m)
K	constraint index
$k_{\text{slip},e}$	cross-sectionally averaged slip coefficient in the outlet area
$k_{\text{slip},i}$	cross-sectionally averaged slip coefficient at the entrance of outlet area
L	region where the cross-sectionally averaged particle velocity begins to decrease at the outlet area along the axial direction (m)
ΔP_D	pressure drop of gas–solid distributor (Pa)
R	radius of the integrated riser (m)
r	radial position of the integrated riser (m)
$U_{g,D}$	gas velocity through holes in of gas–solid distributor (m/s)
$U_{g,r}$	superficial gas velocity of the integrated riser (m/s)
U_t	particle terminal velocity [$U_t = 1.74\sqrt{gd_P(\rho_P - \rho_g)/\rho_g}$] (m/s)
$V_{p,r}$	local particle velocity in the integrated riser (m/s)
$\bar{V}_{p,r}$	cross-sectionally averaged particle velocity in the integrated riser (m/s)
$\bar{V}_{p,r,e}$	cross-sectionally averaged particle velocity in the area of integrated riser outlet (m/s)
$\bar{V}_{p,r,i}$	cross-sectionally averaged particle velocity at the entrance of the integrated riser outlet area (m/s)
$\varepsilon_{s,r}$, $\bar{\varepsilon}_{s,r}$	local and average solids holdup of the integrated riser
ε'	particle terminal holdup [$\varepsilon_s' = G_{s,r}/\rho_p(U_{g,r} - U_t)$]
ρ_g, ρ_p	gas and particle densities (kg/m^3)

have been studied. The C-type riser outlet was found to readily cause an operation pattern of high density circulation within the bed compared with the L- and T-type outlets (Kim, Tachino, & Tsutsumi, 2008). Three-dimensional distributions of particle velocity and holdup of solids in the C-type outlet area were studied under high solids flux operations. The results showed that the C-type outlet had a certain constraint strength for gas–solid flow under high solids flux conditions (Yan, Pärssinen, & Zhu, 2003). Based on the above research findings, the outlet structure of the riser has an important influence on gas–solid flow behavior. Changing the geometric structure of the outlet imposes different constraints, and hence influences flow behavior. The outlet structures are classified into three constraint patterns, specifically, strong (such as the T-type), medium (such as the L-shape), and weak (such as the C-type). Furthermore, the difference in the axial voidage distributions was noted under different constraint strength (Cheng, Wei, Yang, & Jin, 1998).

The above-mentioned riser outlet structures are usually used in the traditional circulating fluidized beds. However, for some special reaction processes, for example, the catalytic cracking and catalyst regeneration in petroleum refining (Huang, Mao, Xu, & Hou, 2006; Lu et al., 2007), and titanium tetrachloride production in the metallurgical industry (Xu & Yuan, 2004), which are characterized by their unique reaction kinetics for the partition transformation or their partition control pattern, traditional riser reactors cannot meet process requirements. Considering this fact, a type of coupled reactor essentially composed of a lower riser segment below an upper fluidized bed segment is proposed in this work. A gas–solid distributor is linked between the outlet of the riser and the bottom inlet of the fluidized bed. Our coupled reactor is used to reduce the content of olefins in fluidized catalytic cracking (FCC) gasoline, and was developed and built by China University of Petroleum (Beijing) as *olefin reduction technology in FCC naphtha upgrading* (Luo, Zhang, Zhang, & Song, 2006; Yang, Tian, & Gao, 2007). In the coupled reactor, the main function of the fluidized bed reactor is to prolong the reaction time so as to further improve the reduction of the olefin content. The main functions of the riser reactor are: (a) to achieve mixing and heat transfer, and to promote the reaction between the high-temperature catalyst and low-temperature oil-gas, while reducing the gas–solid mixing temperature in the fluidized bed reactor and equalizing temperatures in the bed to increase the selectivity of olefin reduction; (b) to meet the pressure balance of the whole loop system to ensure the normal circulation of catalysts between the regenerator and the auxiliary reactor; and (c) to make the operation more flexible through using a single riser or different bed material heights of the upper fluidized bed to adjust the reaction time, so as to meet different requirements of olefin reduction. While the gas–solid distributor can be used as a channel by which the gas–solid mixtures enter the fluidized bed layer, it also enables these mixtures to distribute uniformly into the fluidized bed.

Compared with the riser in a conventional T-, L-, or C-type outlet structure (Gnanapragasam & Reddy, 2008; Gupta & Reddy, 2005; Harris et al., 2003; Kim et al., 2008; Lackermeier & Werther, 2002; Van der Meer et al., 2000; Van engelandt et al., 2011; Wu et al., 2010; Yan et al., 2003; Zhang et al., 2013), the gas–solid flow behavior in our integrated riser is more complicated. Its behavior is not only determined by the superficial gas velocity and the solids circulation flux but also by geometric constraints imposed by the gas–solid distributor at the riser outlet and the upper fluidized bed in the outlet area. To distinguish from the conventional riser reactor, a cold model prototype of the integrated riser reactor was built in the early stage of this work. In a previous study, the particle flow behavior in the integrated riser was studied experimentally. A preliminary analysis was made of the geometric constraints imposed by the shape of gas–solid distributor (Wang & Lu, 2008; Wang, Lu, & Yan, 2009). However, the evolving characteristics of the local particle velocity along the axial direction in the riser outlet area and geometric constraints from the gas–solid distributor needed to be systematically investigated. Moreover, for the different outlet structures, most researchers only described the strength of these constraints qualitatively. The lack of a quantitative assessment hinders the industrial application and design improvements of integrated riser reactors.

In this paper, to study the axial/radial evolving characteristics of particle velocity in the outlet area under different experimental conditions, a cold model of the integrated riser reactor in the form of a "riser-gas–solid distributor-fluidized bed" aligned vertically was established. Furthermore, the influence of the constraint strength on gas–solid flow behavior in the area of the integrated riser outlet under different operating conditions was also analyzed and quantified by defining a constraint index.

Experimental

Experimental apparatus

The experimental unit of the integrated reactor used in this study (Fig. 1) is mainly composed of a lower riser segment situated

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