Powder Technology 298 (2016) 21–29

Contents lists available at ScienceDirect

Powder Technology

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

The model prediction of solid phase hydrodynamics in FCC riser feed injection zones

Shuaishuai Zhou, Zihan Yan, Mengxi Liu *, Yiping Fan, Chunxi Lu *

State Key Laboratory of Heavy Oil, China University of Petroleum, Beijing 102249, PR China

ARTICLE INFO

Article history:
Received 16 February 2016
Received in revised form 7 April 2016
Accepted 25 April 2016
Available online 13 May 2016

Key words:
Riser feed injection zone
Particle concentration
Particle velocity
Model prediction

ABSTRACT

The research regarding particle concentration and particle velocity in Fluid Catalytic Cracking (FCC) riser feed injection zones is of great importance for FCC riser reactor design. In this study, the result of experiment data showed that the particle phase energy density was almost kept constant along radial direction in riser feed injection zone. Based on that, a basic model was proposed to predict particle concentration and particle velocity in an FCC riser feed injection zone. The average prediction deviations of the basic model were 12.00% and 5.71% for the particle concentration and particle velocity, respectively, under the experimental operating conditions. The basic model was simplified for conciseness purposes in the radial position $r/R = 0$–0.7. The average deviations after simplification were 11.64% and 11.41% for the particle concentration and particle velocity, respectively, in the radial position $r/R = 0$–0.7, under experimental operating conditions.

1. Introduction

Fluid catalytic cracking (FCC) is one of the main processes of heavy oil refining, and produces >75% of the gasoline, 35% of the diesel, and 35% of the propane in China. The riser is the key unit of the FCC process. The gas-solid flow dynamics inside the riser influence the recovery of the desired products by changing the contact between the gases and solids. The particle concentration profile along the riser's axial direction is an "S" shape, and a typical "core-annulus" structure will appear along the radial direction [1–5]. Wang et al. [6] divided the riser reactor into four zones: the pre-lift zone, feed mixing zone (feed injection zone), fully developed zone, and quenching zone. Wang also pointed out that the feed mixing zone should realize a uniform contact between the oil droplets and the catalyst, and also ensure that the mixture can be quickly turned into a plug flow in order to obtain an optimal yield of the desired products. He et al. [7] proposed a "two zone model", which mainly focused on the reaction performance in the feed injection and fully developed zones. The "two zone model" predicted that 65% of the reaction process was carried out in 10% of the riser's height, around the feed injection zone. The research results of Wang et al. and He et al. indicated that the performance of the feed injection zone had a great influence on the production yield. The research regarding the FCC riser feed injection zone has focused on the axial position of feed injection, feed unit structure, and gas-solid hydrodynamics. Cao et al. [8] divided the pre-lift zone into three subzones, based on the solid holdup variations along the axial direction. These included the moderate change subzone in the bottom, violent change subzone in the middle, and stable subzone in the top. Based on the experimental results, Cao suggested that feedstock nozzles should be located at the violent change subzone. The studies regarding the feedstock nozzle structure, feedstock nozzle radial location, and feedstock nozzle inclination, have been aimed at improving the gas solid contact within the feed injection zone [9–14]. Mauleon et al. [10] pointed out that the downward inclined feedstock nozzles can speed the feedstock atomization, as well as decrease coke formation, when compared with the traditional upward inclined feedstock nozzles. Mauleon also determined that the nozzle jet from the downward inclined feedstock nozzle favored the contact between the catalyst and feedstock, which resulted in a decrease in the required residence time. Fan et al. [15] conducted investigations of the hydrodynamics in the FCC riser feed injection zone using upward inclined feedstock nozzles. A model was proposed by Fan et al. to predict the particle concentration within the FCC riser feed injection zone. Yan et al. [16] investigated the performance of downward inclined feedstock nozzles with the same experiment apparatus utilized in the research done by Fan. The experimental results showed that the downward inclined feedstock nozzles provided a more efficient contact between the feedstock and the catalyst, which agreed with Mauleon's research results. Yan also claimed that the nozzle should be mounted with an angle of 30 to 45° from the negative of the riser's axial direction. Based on the two-fluid model (TFM), and energy-minimization multi-scale (EMMS) drag coefficient, Chen et al. [17] simulated the gas-solid hydrodynamics in the FCC riser feedstock injection zone using a Computational Fluid Dynamics (CFD) method. The results showed that the increase of the feed spray velocity facilitated the feed diffusion, and also reduced the transition region. However, the excessively high jet velocity may intensify the back-

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* Corresponding authors.
E-mail addresses: mengxiliu@sina.com (M. Liu), lcx725@sina.com (C. Lu).

http://dx.doi.org/10.1016/j.powtec.2016.04.046
0032-5910/

mixing near the wall, which would intensify the attrition or breakage of the catalysts. Theologos et al. [18] studied the gas-solid flow dynamics, heat transfer, and reaction performance inside a FCC riser using a 3-dimension CFD method. The results of this research showed that increasing the number of feedstock nozzles at the bottom of the reactor improved selectivity to the primary products, which resulted from the uniform contact between the catalyst and the feed oil, higher solid concentration, and lower reaction temperature. Li et al. [19] simulated the turbulent gas-solid flow and catalytic reactions in a FCC riser using a 3-D heterogeneous reactor model, in which 14-lump reaction kinetic equations were used. The simulation results were similar to those of Chen. The nozzle jet velocity played an important role in determining the two-phase flow structure in the feedstock injection zone, and a nozzle angle larger than 30° was preferable for improved gas-solid flow structure. Due to the complex dynamics in the FCC riser feed injection zone, few attempts have been made for the hydrodynamic predictions in this region [15]. In the present study, model for particle concentration and particle velocity prediction in a FCC riser feed injection zone were proposed.

2. Experiment apparatus

Experiment was carried out in a riser with an internal diameter D of 186 mm, and height of 14 m. The feedstock nozzles were located at 4.5 m above the gas distributor of the riser's reactor. Other details of the experiment's apparatus were given in the research conducted by Yan [16]. The experimental data used in the present study were registered in the feed injection zone, with nozzles mounted downward at an angle of 30° relative to the riser's axis [16]. The axial positions of the measurement points are given in Table 1, where h is the height of the measured point relative to the gas distributor, and ± 3D (internal diameter), ± 2D, $\pm$D, and 0D are the labels of the cross sections corresponding to the measured axial positions.

3. Modeling

The solid phase energy density and gas phase energy density were defined by Eq. (1) and Eq. (2), respectively.

$$E_p(h, r/R) = \frac{1}{2}\rho_p \varepsilon_s v_p^2 + \rho_p \varepsilon_s g h \tag{1}$$

$$E_g(h, r/R) = p + (1-\varepsilon_s)\rho_g g h + \frac{1}{2}(1-\varepsilon_s)\rho_g {v_g}^2 \tag{2}$$

The main components in the solid phase energy density were the kinetic energy density (the first item on the right hand side of Eq. (1)), and the potential energy density (the second item on the right hand side of Eq. (1)). The solid phase pressure was small compared to solid phase energy density and was omitted in present work. The main components in the gas phase energy density were the kinetic energy density (the third item on the right hand side of Eq. (2)), and the potential energy density (the second item on the right hand side of Eq. (2)), as well as the pressure (the first item on the right hand side of Eq. (2)).

Table 1
Axial position of measurement cross-section.

Cross section	Height h/m
−3D	3.825
−2D	4.125
−D	4.315
0D	4.500
D	4.685
2D	4.875
3D	5.175

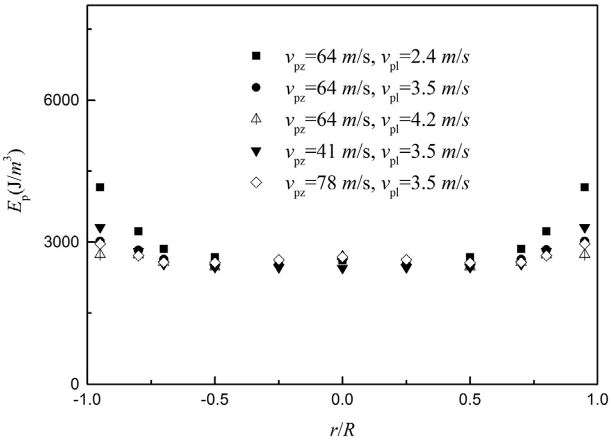

Fig. 1. Solid phase energy density radial distribution of 3D cross-section under different operating conditions.

The gas solid mixture could be treated as many small cells, and each cell satisfied Eq. (1) and Eq. (2). Then, the gas can travel freely in the cross-section through the voids between the particles. Since the gas radial diffusion coefficient is ignorable compared with the axial diffusion coefficient [20,21], in this study, the energy density consumption due to gas radial diffusion was omitted. In that case, the Bernoulli principle could be used. By comparing Eq. (2) with Eq. (3) (Bernoulli's principle), the conclusion that the gas phase energy density was a constant along the radial direction was obtained.

$$p + \rho g h + \frac{1}{2}\rho v^2 = C \tag{3}$$

Since the solid phase energy was supplied by gas, the solid phase energy density was also constant along the radial direction. Fig. 1 illustrated the experimental value of the solid phase energy density (calculated based on Yan's research), which proved that the solid phase energy density was constant along the radial direction. Fig. 2 shows the solid phase energy density calculated from the experimental data of Fan et al. [22], Van Bruegel et al. [23], and Bader et al. [24] (the cross-sections located 4.0 m to 4.5 m above the gas distributor). Fig. 2 shows that the solid phase energy density was a constant within the radial position r/R = 0–0.7, and slightly increased within the radial position r/R = 0.7–1. Two factors should be taken into consideration in order to explain this difference. Firstly, the particle-particle interaction did become intense in the radial position near the riser wall, which resulted in energy density consumption, and more energy density was required. Secondly, the

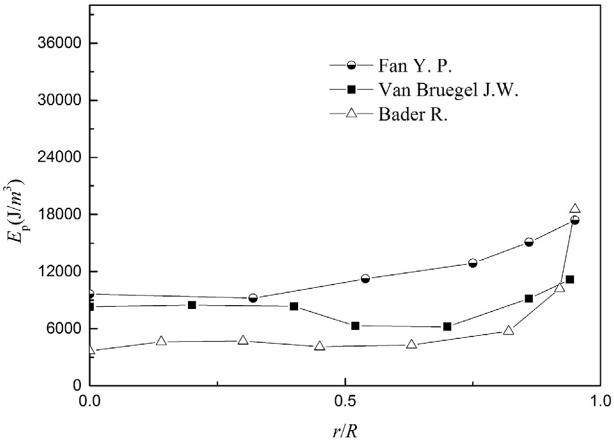

Fig. 2. Solid phase energy density radial distribution calculated from previous works.