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Effect of baffles on performance of fluid catalytic cracking riser

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ABSTRACT

Increasing demand of automobile fuel and a need to process heavier crude oil makes it imperative to find improvements to the design of existing fluid catalytic cracking (FCC) units. Several modifications to the design of the riser section of FCC units have been suggested in previous studies including: improved feed nozzle designs, multiple nozzle configurations, internal baffles, and novel two-stage-riser systems. In this study, we investigate the effects of baffles on the performance of FCC risers using computational fluid dynamics simulations. In this study, predictions from a basis model (without baffles) are compared with those from four different configurations including: (i) 5-cm baffles at 5-m spacing, (ii) 7.5-cm baffles at 5-m spacing, (iii) 10-cm baffles with 5-m spacing, (iv) 10-cm baffles at 2.5-m spacing, and (v) 10-cm baffles at 1-m spacing. The baffles force the catalyst away from walls toward the center of the riser, enhancing the radial dispersion of the catalyst and the heat transfer inside the riser. The use of longer baffles and smaller spacings further increases the dispersion, yielding more homogeneous radial profiles. The changes in the radial dispersion result in variations in the conversion, yields, and pressure drops. The baffles increase conversion of vacuum gas oil (VGO) and the yield of gasoline. However, the simulations showed that longer baffles and a larger number of baffles did not always give a higher yield or higher conversion. Among the simulated configurations, the 5-cm baffles at 5-m spacing gave the highest conversion of VGO, whereas the 10-cm baffles at 1-m spacing resulted in the highest yield of the gasoline. Thus, rational optimization of baffle configurations is required to achieve optimal performance.

1 Introduction

The fluid catalytic cracking (FCC) unit in petroleum refineries converts heavy residues to valuable light products such as gasoline and diesel. Around 350 FCC units operate worldwide, accounting for 50% of gasoline production (Sadeghbeigi, 2012). While demand for gasoline is growing, the need to process heavier crude oil fractions is also increasing (Sadeghbeigi, 2012). Heavier feedstocks feature decreased yields of lighter products and increased yields of unwanted coke. Higher coke production causes faster deactivation of the FCC catalyst. These practical challenges can be tackled by changing the design and operational parameters of FCC units. Several design changes have been suggested in previous studies, including: improved feed nozzles for faster vaporization (Chen, 2006); the use of multiple nozzles for higher feed distributions (Li, Fan, Lu, & Luo, 2013; Theologos, Nikou, Lygeros, & Markatos, 1997); internal baffles to improve the radial distribution of catalyst (Johnson & Davydov, 2014, Chen, 2006; Dries, 2003); and novel cyclone configurations as riser terminal devices (Chen, 2006; Chen et al., 2007). This study focuses on identifying possible improvements in FCC units from the use of internal baffles in the riser section.

The FCC riser section is a long vertical pipe, where all cracking reactions take place. In the riser, regenerated catalyst is fast-fluidized by a gaseous mixture of steam and hydrocarbons. The hydrocarbon feedstock to the FCC riser is residue from the vacuum distillation unit, known as vacuum gas oil (VGO). VGO enters the riser through atomizing feed nozzles, which are generally located above inlets for the catalyst and steam. Upon entering, droplets of VGO vaporize as they come into contact with hot catalyst and steam. After vaporization, cracking of the hydrocarbon takes place as the catalyst and the gaseous mixture of hydrocarbon and steam travel upward. The hydrodynamics of the upward reactive flow of the three phases (catalyst, gas, and droplets) dictate the product

Abbreviations: CFD, computational fluid dynamics; E–E, Eulerian–Eulerian; FCC, fluid catalytic cracking; KTGF, kinetic theory of granular flow; QUICK, quadratic upstream interpolation for convective kinetics; SIMPLE, semi-implicit method for pressure-linked equations; VGO, vacuum gas oil.

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Nomenclature

A	Surface area, m^2
A_C	Constants in catalyst deactivation function
B_C	Constants in catalyst deactivation function
C	Concentration, kg/m^3
C_{j0}	Initial concentration, kg/m^3
$C_{i,s}$	Concentration of vaporizing component at droplet surface, $kmol/m^3$
$C_{i,g}$	Concentration of vaporizing component at bulk of gas phase, $kmol/m^3$
C_D	Drag coefficient, $kg/(m^3\,s)$
d_d	Droplet size, m
E	Activation energy, J/kmol
F	Force, $(kg\,m)/s^2$
F_{cat}	Mass flow rate of catalyst, kg/m^3
F_{Dd}	Drag on droplet, $(kg\,m)/s^2$
Fr_R	Constant in frictional pressure equation
$F_{VGO-gas}$	Mass flow rate of vaporized VGO, kg/m^3
$F_{VGO-liquid}$	Mass flow rate of liquid VGO, kg/m^3
g	Gravity, m/s^2
h	Specific enthalpy, J/kg
h	Heat transfer coefficient, $J/(m^2\,K\,s)$
k	Mass transfer coefficient, m/s
k	Number of reactions
kr_{ij}	Rate constant
Kr_i^0	Frequency factor
M	Molecular weight, kg/kmol
Nu	Nusselt number
P	Pressure, Pa
q	Heat flux, $J/(m^3\,s)$
ΔQ	Heat exchange, $J/(m^3\,s)$
R	Reaction rate, $kg/(m^3\,s)$
r_j	Net rate of production of j^{th} species, $kg/(m^3\,s)$
r_{ij}	Rate of production of j^{th} species in i^{th} reaction, $kg/(m^3\,s)$
R	Universal gas constant, J/(kmol K)
Re	Reynolds number
S	Source term
S_{gh}	Energy source term in the gas phase from the endothermic heat of reaction
T	Temperature, K
t	Time, s
u	Velocity, m/s
y	Mass fraction

Greek letters

ε	Volume fraction
ρ	Density, kg/m^3
λ	Heat of vaporization, J/kg
φ	Catalyst deactivation function
β	Drag coefficient, $kg/(m^3\,s)$
$\bar{\bar{\tau}}$	Stress, $kg/(m\,s^2)$

Subscripts

g	Gas phase
s	Solid (catalyst) phase
d	Droplet phase
gs	Gas phase to solid phase
gd	Gas phase to droplet phase
dg	Droplet phase to gas phase
j	Lump or species
r	Reaction
cat	Catalyst

conversion and yields. Experimental data from cold-flow studies of FCC catalyst–air flow in risers show heterogeneous flow patterns with a wide radial distribution of the catalyst volume fraction (Miller & Gidaspow, 1992; Li & Kwauk, 1994; Knowlton, Geldart, Masten, & King, 1995; Nieuwland, Meijer, Kuipers, & Van Swaaij, 1996; Bhusarapu, Al-Dahhan, & Duduković, 2006). The heterogeneous radial distribution is known as the core–annulus radial flow profile, which is characterized by a higher solid concentration near the wall and lower values at the center. The core–annulus flow pattern results in poor mixing between the phases, and also reduces heat and mass transfer between the phases. Enhancement of mixing between the phases can be achieved with the use of internal baffles in the FCC riser (Jiang, Bi, Jean, & Fan, 1991; Zhu, Salah, & Zhou, 1997; Chen, 2006; Wang, Lu, & Li, 2008; Samruamphianskun, Piumsomboon, & Chalermsinsuwan, 2012).

Design alternatives for the FCC riser can be investigated experimentally or through computational modeling and simulations. Experiments on the FCC riser are not only expensive but often impractical owing to the severe operating conditions. Thus, computational modeling is a more feasible approach to investigating alternate riser designs. Several computational models are available for the FCC riser, which can be divided into two broad categories, namely, phenomenological and computational fluid dynamics (CFD) models. The phenomenological models are differential equations for mass and heat balances over an elemental reactor volume, which are solved to predict conversion, yield, and temperature along the height of the riser. The CFD models couple flow and reaction kinetic models, which enables determination of the effects of hydrodynamic parameters on the cracking process. Hence, CFD models have been used to investigate design alternatives and operating flow conditions in FCC risers. Several different CFD models should be found in the literature (Table 1) with varying degree of complexity. (Behjat, Shahhosseini, & Marvast, 2011; Chang et al., 2012; Chang & Zhou, 2003; Das Sharma, Pugsley, & Delatour, 2006; Gan, Zhao, Berrouk, Yang, & Shan, 2011; Gao, Xu, Lin, Yang, & Guo, 1999, 2001; Lan, Xu, Wang, Wu, & Gao, 2009; Lopes, Rosa, Mori, Nunhez, & Martignoni, 2011; Nayak, Joshi, & Ranade, 2005; Theologos & Markatos, 1993; Theologos et al., 1997; Wu, Cheng, Ding, & Jin, 2010; Zhu, Jun, Patel, Wang, & Ho, 2011). Table 1 shows that the majority of previous CFD models have used the Eulerian–Eulerian gas–solid flow model to capture the reactive flow of the gas and catalyst phases, assuming that vaporization of the VGO droplets is instantaneous. However, Gupta and Subba Rao (2001), Nayak et al. (2005), and Behjat et al. (2011) have shown that droplet vaporization phenomenon can affect the hydrodynamics, yields, and conversion of risers. Table 1 also shows that CFD models have been previously used to investigate the effects of feed nozzle configuration (Li et al., 2013; Theologos et al., 1997), feed atomization (Gupta & Subba Rao, 2001; Nayak et al., 2005), and various operating conditions on the performance of FCC risers. Moreover, innovative two-stage riser systems (Gan et al., 2011) and rotating fluidized beds (Trujillo & De Wilde, 2010) have also been investigated. Despite several reports, no previous studies have examined the effect of baffles on FCC riser performance.

In this study, a computational modeling and simulation approach is used to investigate the effects of baffles on the hydrodynamic behavior and performance of an FCC riser. A CFD model that captures flows of gas, catalyst, and droplet phases is developed. The gas and catalyst phases are represented as Eulerian phases; while the droplets are represented by the Lagrangian approach. Interactions among the three phases, such as momentum, heat, mass, and species transfer are accounted for in the model. The model is initially validated with the use of two sets of plant data (Ali & Rohani, 1997; Derouin, Nevicato, Forissier, Wild, & Bernard, 1997). The validated model is systematically used to investigate the impact of different sizes (0, 5, 7.5, and 10 cm) of baffles and baffle spacings (5,