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A systematic model-based analysis of a downer regenerator in fluid catalytic cracking processes

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ABSTRACT

Performance improvement of a catalyst regenerator for gasoline production in a fluid catalytic cracking (FCC) process is needed to achieve higher burning efficiency. This study performed a systematic model-based analysis of a downer-type regenerator to recover the activity of FCC catalyst by using a one-dimensional model of the regenerator coupled with its hydrodynamic characteristics and the kinetics of catalyst regeneration. The results of a sensitivity analysis showed that higher carbon content on spent catalyst causes a higher regeneration temperature. The ratio of the recycled-to-spent catalyst flow rate in range of 1.0–3.5 and temperatures of the spent catalyst in range of 703.15–803.15 K have insignificant effects on the overall performance of the regenerator. The suitable superficial gas velocity and the spent catalyst flow rate are in range of 4–7 m s^{-1} and 20–40 kg m^{-2} s^{-1}, respectively.

1. Introduction

A fluid catalytic cracking (FCC) is an important process in oil refinery industries. The purpose of this process is to crack low-value heavy hydrocarbons (e.g., gas oil) to valuable light products (e.g., gasoline). It is known that FCC and its ancillary units provide about 45% of the total gasoline production and the revenue about 40% of the total refinery's income (Ramachandran, Rangaiah, & Lakshminarayanan, 2007; Roman, Nagy, Cristea, & Agachi, 2009; Sadeghbeigi, 2000). Due to environmental awareness and requirement of high-quality products, a further improvement of FCC performance is still needed. In general, an FCC process is composed of two major units: a reactor and a regenerator. The strong interaction between these two units causes the complexity of the process. Cracking reactions of long-chain hydrocarbons are carried out in the FCC reactor. In the past, it was mostly operated in a riser mode in which hydrocarbon feedstock and catalyst were fed at the bottom of the reactor. Presently, a gas–solid concurrent down-flow reactor, which is also known as a downer, is found to be a promising reactor for the FCC process because it can overcome the drawback of a conventional up-flow reactor (or the riser) caused by the catalyst back-mixing (Chen, Li, & Kwauk, 2005; Qi, Zhang, & Zhu, 2008; Talman & Reh, 2001; Wu, Cheng, & Jin, 2008). In the downer, gas and solid catalyst move downward; this can avoid the back-mixing of catalyst and reduce hot spots that may occur in the riser reactor (Zhu, Yu, Jin, Grace, & Issangya, 1995). Many previous studies showed that the operation of the downer reactor nearly reaches the plug-flow condition (Cheng, Wu, Zhu, Wei, & Jin, 2008; Liu, Wei, Zheng, & Jin, 2006; Qi et al., 2008; Talman, Geier, & Reh, 1999; Wei & Zhu, 1996; Wu, Cheng, Ding, & Jin, 2010; Zhao, Ding, Wu, & Cheng, 2010).

In the FCC regenerator, coke deposited on catalyst's surface is eliminated by combustion reactions (Sadeghbeigi, 2000). The recent trend of using low-quality feedstock for the FCC process causes high carbon content on the spent catalyst surface. This leads to the rapid deactivation of catalyst and extreme regeneration operation with high temperatures, which will deactivate the catalyst permanently. Different types of the FCC regenerator have been proposed to improve its burning efficiency. An example of a regenerator design is a high-efficiency regenerator in which the bottom chamber of the regenerator is operated in the turbulent fluidized bed state, thereby resulting in a better gas–solid contact efficiency and smaller vessel. A regenerator with two-stage combustion is another design. The first stage combustion is used to burn most of the hydrogen-rich compounds and also the majority of the carbon deposited on the catalyst surface at low temperatures

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Nomenclature

a	recycled to spent catalyst flow rate ratio (G_{sr}/G_{ss})
C_C	carbon concentration on catalyst surface (kg (kg catalyst)$^{-1}$)
C_{Cs}	carbon content on spent catalyst (kg (kg catalyst)$^{-1}$)
C_H	hydrogen concentration on catalyst surface (kg (kg catalyst)$^{-1}$)
C_{O_2}	oxygen concentration (kmol m^{-3})
C_{pc}	specific heat capacity of catalyst (kJ (kg K)$^{-1}$)
C_{pg}	specific heat capacity of gas (kJ (kg K)$^{-1}$)
C_D	drag coefficient
C_{Ds}	standard drag coefficient
d_p	diameter of catalyst particle (m)
D	downer diameter (m)
f_g	friction coefficient between gas and wall
f_s	friction coefficient between solid and wall
F_{fg}	friction force between gas and wall (N)
F_{fs}	friction force between solid and wall (N)
F_D	drag force between gas and particle (N)
Fr	Froude number, $Fr = U_g/(g\,d_p)^{1/2}$
g	acceleration due to gravity (m s^{-2})
G_g	gas flow rate (based on cross-sectional area of downer) (kg m^{-2} s^{-1})
G_s	total solid flow rate (based on cross-sectional area of downer, $G_{ss} + G_{sr}$) (kg m^{-2} s^{-1})
G_{sr}	recycled catalyst flow rate (based on cross-sectional area of downer) (kg m^{-2} s^{-1})
G_{ss}	spent catalyst flow rate (based on cross-sectional area of downer) (kg m^{-2} s^{-1})
ΔH_C	enthalpy due to carbon combustion (kJ kg^{-1})
ΔH_H	enthalpy due to hydrogen combustion (kJ kg^{-1})
k_C	carbon combustion reaction constant ((kPa s)$^{-1}$)
k_H	hydrogen combustion reaction constant ((kPa s)$^{-1}$)
p_{O_2}	partial pressure of oxygen (kPa)
P	pressure (kPa)
r_C	carbon combustion rate (kg (kg catalyst s)$^{-1}$)
r_H	hydrogen combustion rate (kg (kg catalyst s)$^{-1}$)
R	ideal gas constant (R = 8.314 kJ (kmol K)$^{-1}$)
Re_g	Reynolds number defined by $Re_g = \rho_g U_g D/\mu_g$
Re_r	Reynolds number defined by $Re_r = d_p\rho_g\lvert\bar{V}_g - \bar{V}_s\rvert/\mu_g$
T	temperature (K)
T_a	air temperature at inlet (K)
T_g	regenerated catalyst temperature (K)
T_s	spent catalyst temperature (K)
U_g	superficial gas velocity (m s^{-1})
$\bar{V}_g$	cross-sectionally averaged gas velocity (m s^{-1})
$\bar{V}_s$	cross-sectionally averaged solid velocity (m s^{-1})
z	downer length (m)

Greek letters

α	mass ratio of hydrogen to carbon in coke
β	molar ratio of CO_2 to CO in the flue gas
$\bar{\varepsilon}_g$	cross-sectionally averaged voidage
$\bar{\varepsilon}_s$	cross-sectionally averaged solid holdup
ρ_g	gas density (kg m^{-3})
ρ_s	catalyst density (kg m^{-3})
μ_g	gas viscosity (Pa s)

Subscript

out	outlet condition of regenerator
0	initial condition

within a short time, whereas the second one is applied to combust the remaining carbon at high temperatures with a longer time. This prevents the exposure of catalyst to high temperature steam occurred from the burning of hydrogen-rich components that may cause the permanent deactivation of the catalyst (Avidan & Shinnar, 1990). The other new developed regenerator is referred to as a riser regenerator because it operates in the riser mode having the advantages of high heat and mass transfers and high solid–gas contact efficiency (Bai, Zhu, Jin, & Yu, 1997; Bai, Zhu, Jin, & Yu, 1998). However, some theoretical and experimental studies indicated that the operation of the riser in which gas and solid flowing against the direction of gravity suffers from the severe back-mixing and non-uniform flow structure causing the wide residence time distribution of the gas and solid phases (Jin, Zheng, & Wei, 2002; Werther & Hirschberg, 1997). Since the radial distributions of gas and solid in a downer is more uniform than that in a riser, the use of the downer as a regenerator would be a promising approach.

Model-based process analysis is the effective way to understand a process behavior and the obtained data can be employed for design and enhancement of the process. Singh, Gernaey, and Gani (2009) proposed the model-based, computer-aided system approach for design and analysis of the pharmaceutical process including the monitoring system and this case study was extensively studied by Gernaey and Gani (2010). Arenas, Cruz, and Gani (2006) used the same approach to design the copolymerization process.

In this study, the performance of a downer regenerator of FCC process is analyzed based on a systematic model-based approach. A one-dimensional model of the downer regenerator, which consists of mass and energy conservative equations, hydrodynamic characteristics and regeneration kinetics of FCC catalyst under steady state condition, is employed to perform a sensitivity analysis of the regenerator with respect to key operating parameters such as recycled and spent catalyst flow rates, superficial gas velocity, carbon content on spent catalyst, and spent catalyst temperature, on the catalyst regeneration performance.

2. Systematic model-based analysis

A systematic procedure for model-based analysis and design of processes starts with defining a process objective. This step is important because the designed process has to be satisfied with this process objective. Then, details of the process configuration are considered and a mathematical model is developed for analysis of the process behavior. After the model analysis is performed, a suitable model solution approach is selected for process simulation. A sensitivity analysis is then carried out to determine key process parameters, which are used for optimal design of the process.

2.1. Process objective

The objective of a FCC downer regenerator is to eliminate coke deposited on the surface of catalyst. Therefore, the required final product is the regenerated catalyst that has low carbon and hydrogen contents. However, a temperature of the regenerated catalyst should not be higher than the refractory limit of the catalyst.

2.2. Description of a downer regenerator

Fig. 1 shows an FCC process consisting of a riser reactor and a downer regenerator. The feedstock consisting of heavy hydrocarbons is preheated and then injected with steam at the bottom of the reactor through a distributor. The injected feedstock contacts the hot regenerated catalyst circulated from the regenerator, and then vaporizes. Feedstock vapor and catalyst move upward and cracking reactions occur at the same time, increasing the gas velocity due to a