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Gas flow behavior in industrial FCC disengager vessels with different coupling configurations between two-stage separators

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ABSTRACT

The gas flow behaviors and gas residence time distribution in industrial FCC disengager space are numerically studied with the combined consideration of the product gas, stripping gas and anti-coking steam. Although purge steam is used in the top dome in order to alleviate the coke formation in the refinery plants, its effectiveness is still obscure. In this study, the Reynolds stress model is applied to calculate the gas flow field and the scalar transport equations are used to obtain the gas residence time distribution. The species transport equations are used to get the local mass fractions of steam and oil vapors and further to verify the effectiveness of the anti-coking steam. In view of the wide use of "open" configuration, the optimizing position of the primary cyclone outlet is proposed for an industrial case in Qianguo refinery. Based on the results, suggestions are made for improved operation of the industrial units.

1. Introduction

As we know, fluid catalytic cracking (FCC) is a sequential reaction process in which many desirable products, such as gasoline, are intermediates [1]. Once the mixture of vapor products and catalyst leaves the riser reactor into the disengager, the cracking reactions must be terminated as sharply as possible; otherwise, desirable products will continue to crack, leading to excess productions of light gases and coke. Hence, the short residence time of product gas in the disengager is the objective we are always pursuing. In addition, with the use of heavier and heavier petroleum feedstocks, unwanted build-up of carbonaceous deposits in Chinese FCC disengager vessels has been a key process limitation to achieving the economical benefits of longer run length in refineries [2,3]. The reason of carbonaceous deposition and how to improve the current operations have been the hot topics in recent years [4–11]. To deeply understand these problems, the knowledge of gas flow behavior in FCC disengagers is very essential.

In a previous paper [12], the flow behavior and residence time distribution (RTD) of product gas and stripping gas in a bench-scale disengager was investigated. The results indicated that the coupling configuration between the two-stage cyclone separators affected the gas flow field and gas RTD. But for the commercial units, less information is available about the quantitative residence time. Currently, the anti-coking steam is usually used in the top dome of the disengager to alleviate the deposition. Theoretically, ample anti-coking steam can lower the partial pressure of oil vapors within the disengager, and sequentially decrease the dew point of heavy fractions so that they do not condense into the liquid droplets. Besides, anti-coking steam can also sweep out the dead zones and prevent the oil droplets from touching the dome wall as a gaseous shield, and therefore alleviate coke deposition to some extent. So far, the design of anti-coking steam system is still empirical and its effectiveness is unclear. Some refineries experienced the severe coking problems even with the ample anti-coking steam use.

Given the complexity of industrial units, this work aims to discuss the gas flow behaviors and RTD in the industrial disengager space with the combined consideration of the product gas, stripping gas and anti-coking steam. Case 1 investigates the gas flow behavior, gas RTD and the effectiveness of the anti-coking steam for two conventionally-used coupling configurations, "open" and "close-coupled". Case 2 focuses on an industrial disengager with "open" configuration in Qianguo refinery and aims to optimize the location of the primary cyclone outlet. The results will provide the guidance for the optimization of the disengager and help to further understand the coke formation processes simultaneously.

2. Mathematical models

In this work, the gas flow behavior is studied on the platform of commercial computational fluid dynamics (CFD) software, Fluent 6.1. Given the strong swirling turbulent flow field in the cyclones [13–17], the Reynolds stress model (RSM) is applied to simulate the steady gas flow field in the disengager space, which has been validated effective in predicting the flow field in the bench-scale FCC disengager unit [12]. The SIMPLEC algorithm is used for pressure–velocity coupling,

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QUICK difference scheme is used to discretize the convection terms, and a central differencing scheme is used to discretize the diffusion terms. A scalar transport equation [12] is coupled with the known flow field to obtain the gas RTD. The following species transport equation is used to simulate the local mass/volume fraction of oil vapors and steam in order to verify the effectiveness of anti-coking steam. The oil vapor density here is 3.6 kg/m^3 and the steam density is 0.86 kg/m^3 (at the conditions of 0.2 MPa and 230 °C).

$$\frac{\partial}{\partial t}(\rho Y_i) + \nabla\cdot(\rho v Y_i) = -\nabla\cdot\left(\left(\rho D_{i,m} + \frac{\mu_t}{Sc_t}\right)\nabla Y_i\right) + S_i \quad (1)$$

Here Y_i is mass fraction of species i; ρ is the density of mixture, kg/m^3; S_i is the rate of creation by addition from the dispersed phase plus any user-defined sources; $D_{i,m}$ is the diffusion coefficient for species i in the mixture, m^2/s; $Sc_t = \mu_t/\rho D_t$ is the turbulent Schmidt number and the value is 0.7; D_t is the turbulent diffusivity, m^2/s, and μ_t is the turbulent viscosity, Pa s.

3. Cases description

Both of Case 1 and Case 2 are of industrial disengager size. In order to clearly describe the effect of the two conventionally-used coupling configuration on the gas flow behavior, gas RTD and especially the effectiveness of the anti-coking steam, only a primary and a secondary cyclone is arranged in a 3.9 m i.d. disengager vessel for Case 1. The results in the literature [12] indicated the “open” coupling configuration is not a desirable one for the quick discharge of product gas. But it is still widely used in some older refineries. Hence, Case 2 focuses on a disengager with “open” configuration with an annual processing capacity 0.8 million tonnes in Qianguo refinery. For this configuration, the distance of the primary cyclone outlet to secondary cyclone inlet is undoubtedly a key parameter. In order to improve the current operations, Case 2 aims is to optimize the location of the primary cyclone outlet. For both cases, the inlet of the primary cyclone and some internals is neglected in order to obtain the structured grid for convenient convergence of the equations.

3.1. Case 1

3.1.1. Geometry

Fig. 1a shows the most conventionally-used coupling configuration between two-stage separators, “open” configuration. The mixture of vapor products and catalyst is discharged from the riser and enters the primary cyclone separator, and subsequently the un-separated catalyst particles and product gas go into an open disengager space. The diameter D_p of the primary cyclone is 1 m with two key design parameters, $K_A = 4.4$ ($K_A = \pi D_p^2/4ab$, the ratio of the cross section area of cyclone cylinder to its inlet area) and $\tilde{d}_r = 0.5$ ($\tilde{d}_r = d_r/D_p$, the ratio of the cyclone exit-tube diameter to the cyclone cylinder diameter). The diameter D_s of the secondary cyclone separator is 0.9 m with $K_A = 5.5$ and $\tilde{d}_r = 0.33$. The anti-coking steam sparger is located at the top of the disengager. Fig. 1b shows the “close-coupled” configuration used in many modern FCC units, which is also vividly described as “face to face” configuration. The outlet of the primary cyclone is “closely coupled” to the inlet of the secondary cyclone. There is a gap between the primary cyclone outlet duct and the secondary cyclone inlet duct to allow stripper vapor to enter the secondary cyclones. In this case, a 90° elbow is used to connect with the original outlet duct of the primary cyclone to achieve the close-coupled to the inlet of the secondary cyclone. The gap “L” is set at 200, 400 and 600 mm.

3.1.2. Boundary conditions

(1) Primary cyclone outlet: the gas flow field in the primary cyclone is separately simulated. The velocities in the primary cyclone outlet are input via a user-defined-function as the boundary conditions. The Reynolds stress $\overline{u_i' u_j'}$ and the turbulence dissipation rate ε can be computed via the equations:

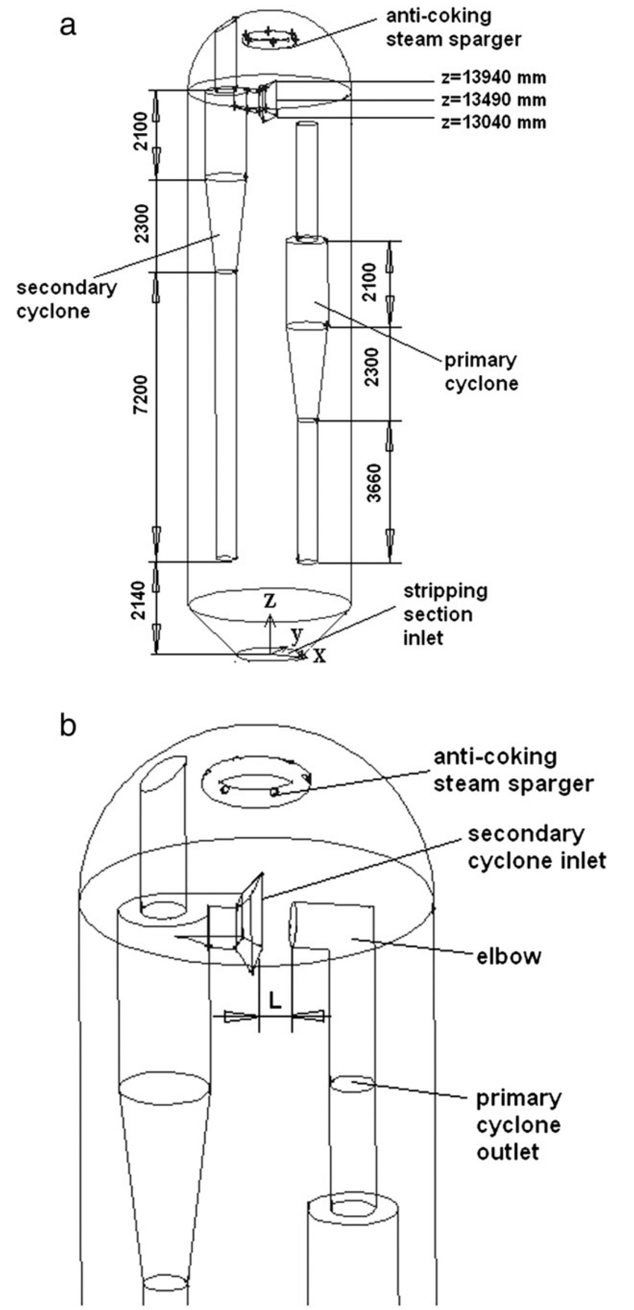

Fig. 1. A sketch of the disengager vessel with (a) “open” and (b) “close-coupled” configurations.

$$\overline{u_i' u_j'} = k = \frac{3}{2} I^2 v_{exit}^2 \quad (2)$$

$$\varepsilon = \frac{k^{3/2}}{0.3 D_h} \quad (3)$$

Where k stands for the turbulent kinetic energy, I for the turbulent intensity (I = 0.037), v_{exit} for the average velocity of the primary cyclone outlet, D_h for the hydraulic diameter of the primary cyclone outlet. The mass fractions of the gas in the primary cyclone outlet are 93% oil vapors and 7% steam.