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Numerical Analysis of Particle Uneven Distribution at Riser and Deposit Phenomenon at Cyclone in RFCC Reactor

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One of the main problems associated with reactors in commercial Residue Fluidized Catalytic Cracking (RFCC) process in refinery plant is that each of six outlets of the riser has different particle mass flow rates. This phenomenon causes particle uneven distribution and catalyst loss. High conversion of cracking reaction requires uniform catalyst distribution in the riser. The riser termination device (RTD) is installed to reduce product gas residence time and achieve rapid separation between catalysts and product gas. RTD is made up of six close-coupled cyclone sets at the top of riser. Also, particle deposit formation in the cyclone duct has caused shutdown problems as well as a decrease of the cyclone efficiency. This study analyzes flow pattern of catalyst particles in the riser and the cyclone. Moreover, particle mass flow rates are investigated at each outlet by the number of feed injector. The cracking reaction is taken into account in the simulation scheme and its conversion is evaluated in the riser by employing multiphase-particle in cell (MP-PIC) method, one of computational particle fluid dynamics (CPFD) methodologies. It applies both a stochastic particle model and Lagrangian method for particle phase, and Eulerian method for fluid phase, respectively. Mass flow rates at the outlets of riser are different from each outlet from 107.8 kg/s to 144.1 kg/s, which means solid loading ratio for certain cyclones increased. The solid loading ratio affects the cyclone separation efficiency. As a result, particle uneven distribution flow was identified. Standard deviations of particle mass flow rate at the 4-injector riser case and 6-injector riser case represent respectively 11.3 and 8.8. So, this article suggests that particle uneven distribution will be alleviated by using 6-injector riser than 4-injector riser.

1. Introduction

The fluid catalytic cracking (FCC) process is the primary conversion unit in refinery industry. FCC has some strength such as its continuous particle handling ability and its good heat and mass transfer characteristics. This process converts and cracks heavy hydrocarbons to more valuable light hydrocarbons using catalyst. Residue Fluid Catalytic Cracking (RFCC) process is typical heavy oil upgrading (HOU) process and composed of riser and stripper and regenerator. The RFCC process makes a profit by producing valuable low-molecular-weight-hydrocarbons such as LPG, naphtha, gasoline and etc. from the atmospheric residue (AR), which consists of high-molecular-weight-hydrocarbons. The residue cracking reactions are occurred with catalysts in the riser. After the cracking reactions the product gases and catalysts flow in to the reactor cyclones which are used to separate catalyst from product gas.

Serious problems that affect the safety of operation occur in the reactor. This serious problem was reported that a deposit formed at the duct and dipleg of the reactor cyclone, which cause malfunction of the cyclone. When the deposit is formed at the duct of the reactor cyclone, it has negative effects on the separation efficiency. The deposit occurs on the inner surface and clogged the catalyst flow area, causing significant catalyst carryover to the main fractionators with product gas. This resulted in extreme loss of catalyst inventory, and the process had to be shutdown.

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One of the problems associated with abnormal flow pattern is uneven distribution phenomenon that each six outlets of the riser have different particle mass flow rate. Uneven distribution of particle from the riser to the cyclone accelerated the deposit formation in the cyclone dipleg. When particle loading ratio is decreased at a certain cyclone by the uneven distribution phenomenon, deposit formation rate is increased by increasing of contacting chance between particle and wall.

In general, the mechanism of deposit formation has been reported that the wet catalysts with condensed hydrocarbons are attached to the wall according to flow in the low-speed zone (Gao et al., 2004). So, Analysis of gas-solid flow pattern in the cyclone and riser is needed to understand and solve the deposit formation phenomenon. In the previous CFD-DEM model for the simulation was developed to describe the multiphase flow in the gas cyclone (Chu et al., 2011). This model is validated by its successful capturing the flow pattern in the cyclone. For the analysis of a multiphase flow of FCC particles in the riser, CFD model of the standard kinetic theory was developed by Gidaspow (1994) and modified by Yang et al. (2004) using the energy minimization multi-scale approach. And the kinetic theory based CFD model which can compute the turbulence properties, the Reynolds stresses, the kinetic energy spectra and the dispersion coefficients of gas–solid flow in the turbulent fluidization regime was developed by Jiradilok et al. (2006).

In this paper, the dynamic behavior of the fluid and the particle phase in the cyclone are analyzed and case studies as various size are carried out by using CPFD methodology. And the dynamic behavior of the fluid and the particle phase in the riser are analyzed and uneven distribution phenomenon is confirmed by estimating of mass flow rate at the outlets of riser.

2. Cyclone simulation for the duct deposit problem

2.1 Simulation conditions

Simulation of the reactor cyclone is carried out by the actual operating data. The simulation conditions of product gas and RFCC catalyst are listed in Table 1. All calculations were run for the fully developed three-dimensional mesh.

Table 1: Properties of product gas and RFCC catalyst

	Product gas	
Molecular weight	Density	Viscosity
67 g/mol	2.85 kg/m^3	0.019 cP
	RFCC catalyst	
Molecular weight	Density	Mass flow rate
78 g/mol	1964 kg/m^3	1.25 kg/s

Table 2: RFCC catalyst particle size distribution

Size (μm)	Cumulative weight fraction
30.0	0.23
37.5	0.35
45.0	0.64
52.5	0.95
62.5	1

2.2 Particles and fluid flow pattern analysis in the cyclone

In this chapter, particle flow patterns and fluid flow patterns were analysed at overall and the duct respectively. Figure 1 shows the particles flow pattern of overall the cyclone up to 10 seconds. This result shows that macroscopically steady state of flow feature is reached at 3.52 seconds and is validated by the similarity of the overall flow feature of the cold model of the cyclone. And the particles flow along their way and go around the way four times and decrease their velocity magnitude at the dust hopper, as shown in Figure 1.

Figure 2 can be seen the (a) velocity magnitude of fluid and (b) pressure at cross section of the duct. The low speed zone which means less than 8m/s of fluid velocity magnitude is observed into 34mm size at duct 90◦ in

Figure 2 (a). When the escaped particles from their own way flow into the low speed zone, the deposit is formed. After the deposit formation, the deposit will grow backwardly on the previous formed one.

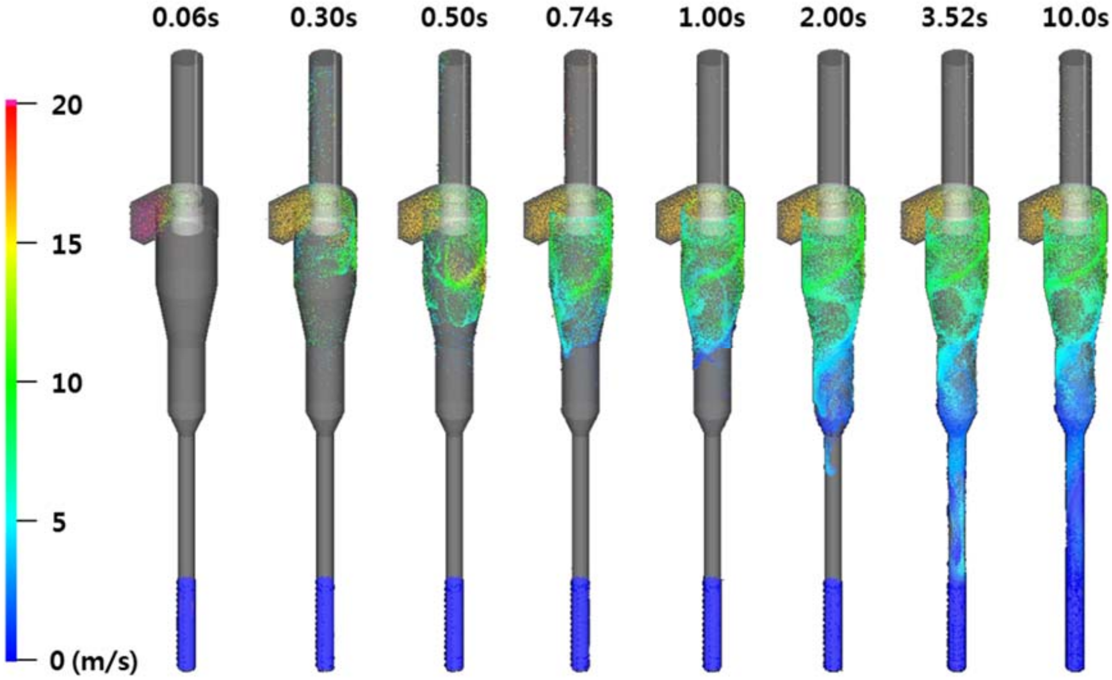

Figure 1: The dynamic flow to 10 seconds of particles in the cyclone: velocity magnitude of particles.

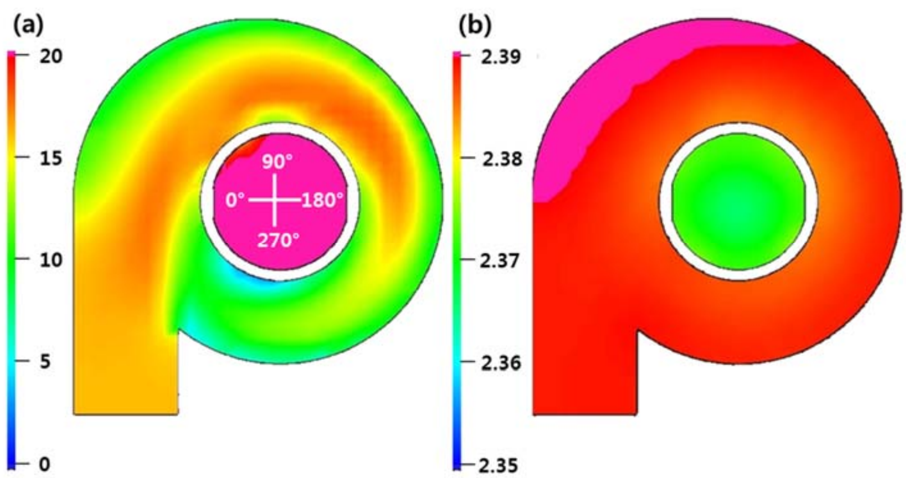

Figure 2: The flow pattern at the cyclone duct: (a)velocity magnitude of fluid, and (b) pressure.

2.3 Case studies of flow pattern as the deposit size and shape

The deposit formation started at duct 90°, so the expected deposit formation region was assumed to be the wall at this geometric position. In this study, Case studies are carried out as the duct depending on the various sizes and shapes. Yaodong et al. (2000) announced that the deposit formed as 90° to 220° from actual the deposit shape in Figure 3 (a). Figure 3 (b)-(g) shows geometries of the cyclone ducts of difference thickness of the expected deposit region from 30mm to 180mm. Figure 4 shows velocity magnitude of fluid at 10seconds of duct depending on the thickness. As the deposit gets larger, overall velocity decreases under the influence of pressure increase. Tendency of the obstacle of deposit growth by scouring phenomena at 90mm is seen in Figure 4 (d). As the result the deposit shape is expected to be shaped like merged (b) and (d) from Figure 4.

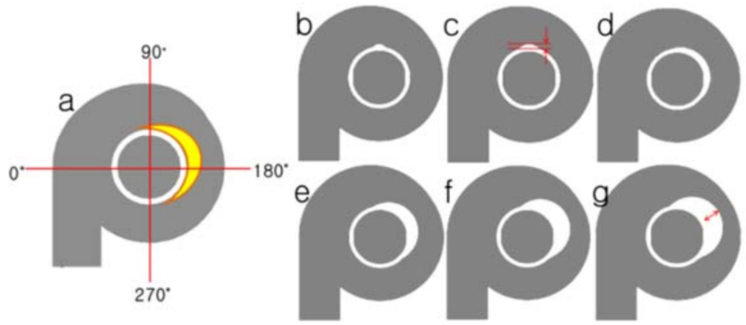

Figure 3: (a) Actual the deposit shape and Geometry of duct depending on the maximum thickness is: (b)34mm, (c)55mm, (d)30mm, (e)90mm, (f)150mm, and (g)180mm

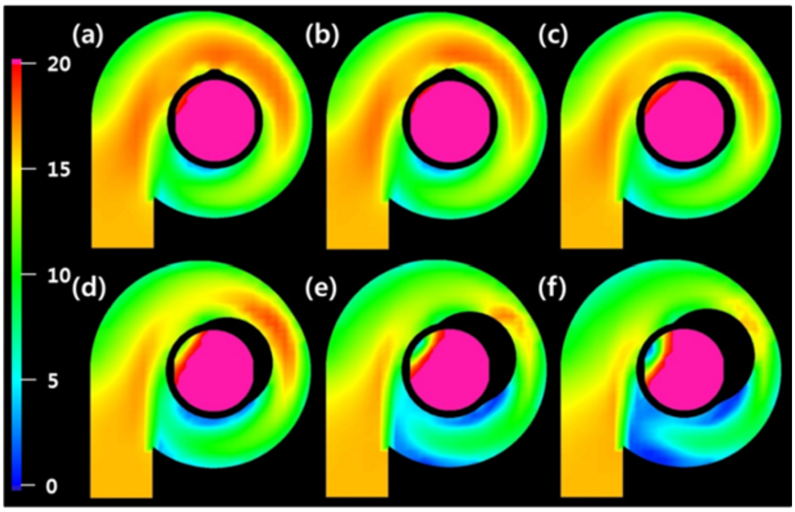

Figure 4 Velocity magnitude of fluid at 10seconds of duct depending on the thickness is: (a)34mm, (b)55mm, (c)30mm, (d)90mm, (e)150mm, and (f)180mm.

3. Riser simulation for uneven distribution phenomenon

3.1 Simulation conditions

The actual operating data are used for simulation of the gas-solid flow analysis. Figure 5 shows the simulation boundary condition and the geometry of the riser. Diameter of riser is 1.7m and overall height is 60m. The 4 injectors are located 25 m height. Mass flow rates of RFCC catalyst; residue and steam present 752.5 kg/s, 91.2 kg/s and 1.79 kg/s, respectively. All calculations were run for the fully developed three-dimensional mesh.

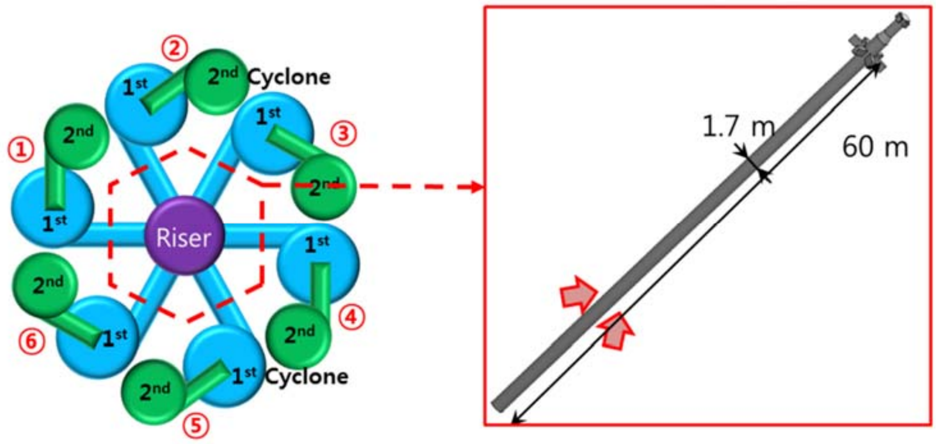

Figure 5: The simulation boundary condition and the geometry of the riser

3.2 Riser flow pattern of the particles

In this study, simulation results of the fluid and particles flow pattern are represented at overall riser which has 4 injectors. Figure 6 displays fluid velocity magnitude and particle volume fraction in the riser up to 20 seconds. Figure 6 (a) shows that the fluid velocity increases at the injection part of the riser over than 20 m/s however velocity decreases at the top part of the riser outlet. Figure 6 (b) shows that macroscopically steady state is reached at 3 seconds and the top part of the riser is denser than the bottom part. It can be seen that there is a deviation in particle volume fractions from outlet to outlet. This deviation of particle volume fraction causes uneven distribution phenomenon.

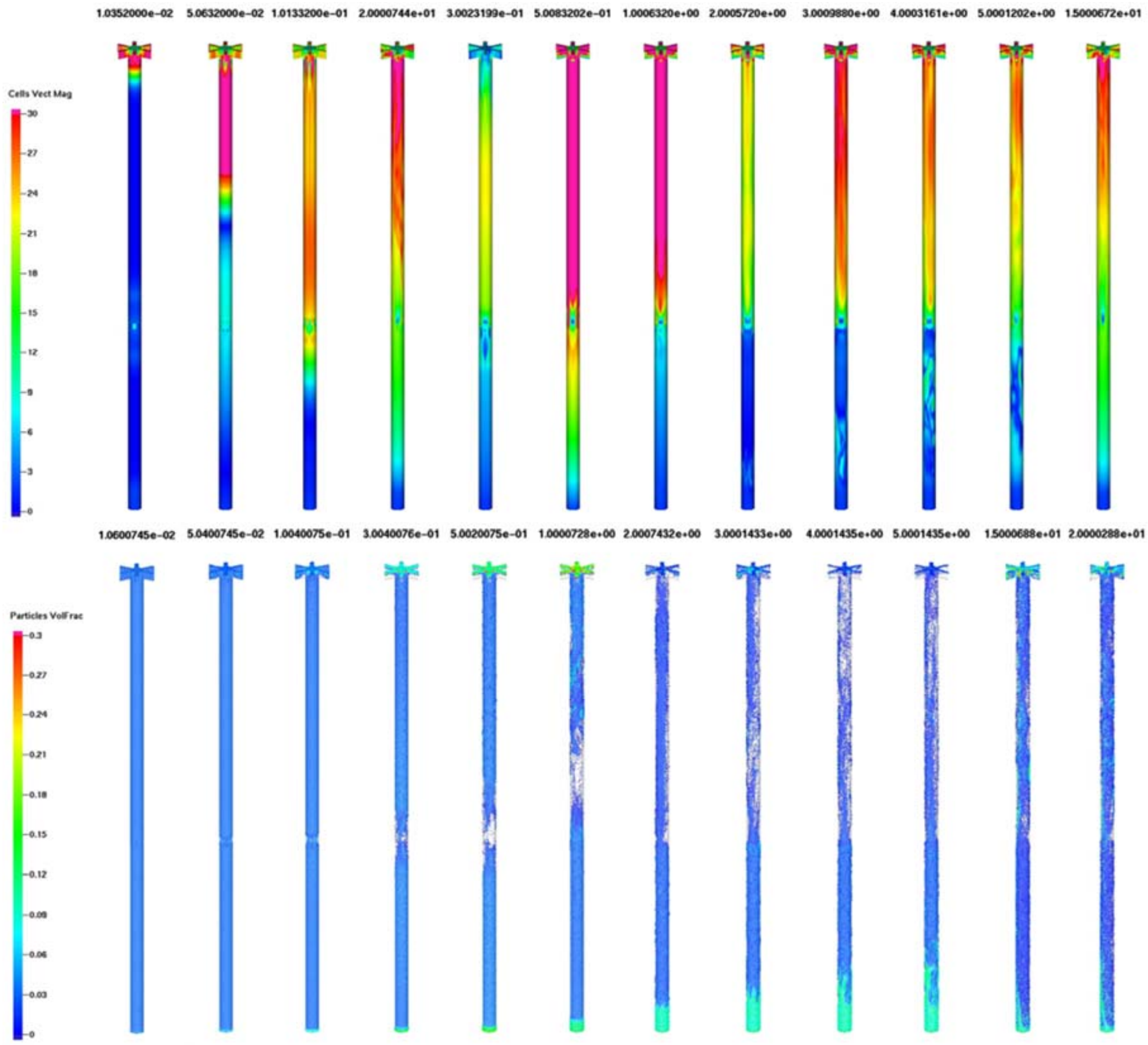

Figure 6: The flow pattern in the riser (a) fluid velocity magnitude and (b) particle volume fraction

3.3 Uneven distribution of particle to the riser outlet

The particle mass flow rates of each individual riser outlet are shown in Figure 7 which has 4 injectors. It can be seen that the particle mass flow rates are different depending on the location of outlet from 107 kg/s to 142 kg/s. The outlet ①, ②and ③ have relatively lower mass flow rate than the mean value (dashed line), whereas the outlet ④, ⑤ and ⑥ have higher mass flow rate than average. Figure 8 shows the particle mass flow rates of 6-injector riser. There is a deviation in mass flow rates from outlet to outlet. It can be seen that the outlet ①, ⑤and ⑥ have relatively lower mass flow rate than the mean value (dashed line), whereas the outlet ②, ③and ④ have higher mass flow rate than average. Standard deviations of particle mass flow rate at the 4-injector riser case and 6-injector riser case represent respectively 11.3 and 8.8.

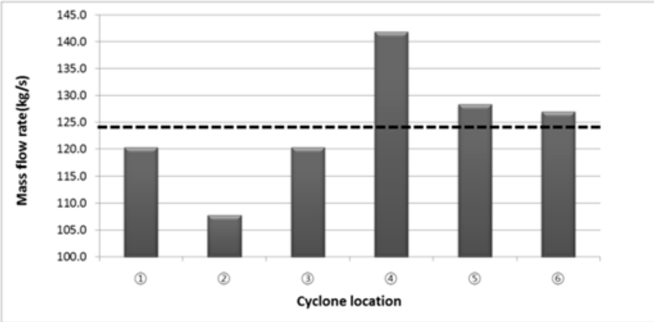

Figure 7: Mass flow rate of particle vs. the riser outlet location (4-injector riser)

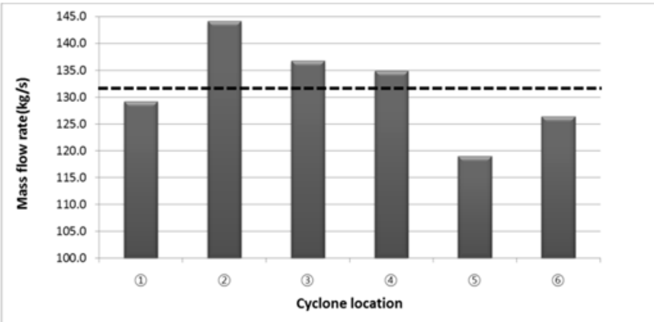

Figure 8: Mass flow rate of particle vs. the riser outlet location (6-injector riser)

4. Conclusions

This study analysed the flow pattern of particles and fluid using CPFD simulation with the actual process data. The result is verified by similarity of the overall flow features between simulation result and the cold model, and separation efficiency, 98.9%. We forecasted shape and size of the deposit formation on cyclone duct.

The problem of uneven distribution from the riser to the cyclone was revealed through difference of the amount of deposit each cyclone diplegs. Fluid and particle velocities increased about 20 m/s at the injection part of riser. Mass flow rates at the outlets of riser are different from each outlet from 107 kg/s to 144 kg/s, which means solid loading ratio for certain cyclones increased. As a result, particle uneven distribution flow was identified. And this article found that particle uneven distribution will be alleviated by using 6-injector riser than 4-injector riser by case study.

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