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Numerical gas-solid flow analysis of ring-baffled risers

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ABSTRACT

In order to improve the gas-solid flow in a lab-scale circulating fluidized bed (CFB) riser, airfoil-shaped ring-type internals were used in a CFD-based design of experiments. The best geometrical properties and arrangement of the ring baffles in the riser were defined with a design of experiments. Four variables were studied: ring thickness, number of rings, spacing between rings and the insertion of a bottom ring. A catalyst-to-gas ratio of 0.181 kg/kg was used, with a gas velocity of 5.6 m/s. Numerical simulations were performed with the k-epsilon turbulence model and the Gidaspow drag model. KTGF was used to describe the solids properties. The solids distribution was evaluated through dispersion coefficient analysis. Four structures for the particle concentration were identified: U-shaped, A-shaped, O-shaped and I-shaped. The best result, with a 45% decrease in the solids dispersion coefficient in comparison with the case without rings, was found in the case with 10 mm ring thickness and four rings. Analysis of the best case showed that the rings promote winding flow, observed in the direction of gas and solid velocity vectors.

1. Introduction

Fluid catalytic cracking (FCC) is an important process in the petroleum refining industry. Through this process, heavy vacuum gas oil is converted into lighter fractions such as gasoline. An FCC unit is basically composed of a riser reactor, where chemical reactions take place, and a regenerator, responsible for the removal of coke deposited on the catalyst particles. The gas oil feed is vaporized and mixed with the catalyst particles in the bottom riser region. The contact between the gas and solid phases occurs in the same way as in a circulating fluidized bed (CFB).

Because of the core-annulus profile formation [1], catalyst particles accumulate near the riser wall. Thus, a dense region is formed in contrast to a dilute region in the center, a phenomenon known as turbophoresis [2]. Consequently, overcracking occurs in the dense region and undercracking occurs in the dilute region [3]. Many authors have demonstrated that solid particles are concentrated in the wall region of the riser, while the center region is diluted [4,5]. The complex and turbulent flow in the riser inlet region induces back-mixing and short circuits [3,6,7]. To reduce the solids concentration in the dense region near the wall, Peng et al. [8] studied the use of air jets from the riser circumference numerically. Under appropriate jet velocities, the solids concentration near the wall can be significantly reduced and the flow structure becomes more uniform.

The use of internal ring baffles in the riser inlet region improves the solids distribution and helps to increase the mass, heat and momentum transfer [7]. Thus, the conversion of the gas oil into products improves due to better contact between the phases [3,7]. Jiang et al. [9] analyzed ozone decomposition experimentally, using FCC particles and concluded that internal ring baffles improve the chemical reactions involved in the conversion at average and high velocities, by increasing the solids fraction distribution in the radial direction. Zhu et al. [10] studied the influence of the ring opening area on the solids fraction distribution experimentally, using three ring baffles with 70%, 90% and 95% of opening area, installed in different axial positions. For rings with 70% of opening area, a denser region is formed in the riser bottom. Also, the insertion of ring baffles induces the formation of an S-shaped velocity profile in the axial direction [10]. Samruamphianskun et al. [11] studied the gas-solid flow in a ring baffled riser numerically, varying four geometric properties of the square-shaped rings: ring thickness, number of rings, opening area, and the spacing between rings and its uniformity. The ring opening area and the spacing between rings had the most important effect on the solids distribution.

Bu and Zhu [12] investigated the influence of ring-type internals on the axial pressure distribution in a circulating fluidized bed experimentally, in order to determine its influence on the radial and axial solids distribution. Four ring opening areas between 70% and 95% were studied and their effect under different operational conditions was tested. The opening area showed a strong influence on the flow behavior. The optimum opening area is related to the operational conditions applied and, in this case, a 90% opening produced the most homogeneous gas-solid flow.

Guío-Perez et al. [13] investigated the increase in the total pressure drop as a result of ring-type internals installed in a circulating fluidized bed experimentally. Previously designed wedge-shaped rings were

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installed in the middle zone of the downer fuel reactor, while the air riser reactor did not have rings. The aspects studied were the aperture ratio, equivalent to the ring thickness, the number of rings, the fluidization velocity and the particle circulation rate. The authors observed that the reactor can be divided into two distinct zones, according to the effect of the rings. In the region below the solids inlet, the gas and solids are in counter-current flow and the presence of rings makes the solids distribution more homogeneous. The effect of the rings in the riser is strongly dependent on the fluidization velocity. Regarding the aperture area, the authors concluded that a smaller aperture area promotes solids redirection to the upper regions at lower fluidization velocities. However, it reduces the operational conditions interval. The ring above the solids inlet promotes segregation of the particles according to their diameter.

The homogeneity of the solids dispersion in the gas-solid flow can be measured by different techniques. The most common parameters used are the standard deviation and the solids dispersion coefficient. The standard deviation of the solids volume fraction can be related to the time-mean local concentration. However, this parameter can be used only to compare cases with the same number of experimental points [14,15]. On the other hand, the dispersion coefficient is reliable for cases with different numbers of experimental points, because it weights the standard deviation according to the average values. Dispersion coefficients in circulating fluidized beds differ by five or more orders of magnitude and can be computed from the Reynolds stress in a turbulent gas-solid flow [16]. Du and Wei [17] used the solids dispersion coefficient to study the increase in the particle density and concentration near the walls experimentally. The authors observed that the solids dispersion coefficient decreases with increasing particle density and concentration and increases with an increase in the particle sphericity and superficial gas velocity. Another way to measure the solids dispersion coefficient in CFD simulations is by using the classical definition, which is the ratio between the standard deviation and the averaged solid volume fraction.

The aim of this study was to explore the effect of the airfoil-shaped ring baffle configuration parameters on the solids distribution in a lab scale CFB riser, in terms of the ring thickness, the spacing between rings, the number of rings and the insertion of a bottom ring. CFD simulations were performed based on a design of experiments to study the influence of these parameters on the solids distribution, using the solids dispersion coefficient along the cross-section and the pressure drop as response variables of the system. The main contribution of this study is to propose an airfoil shape for the ring baffles used in CFB risers. The aerodynamic shape of these rings can help to redistribute solid particles in a CFB riser with a lower pressure drop, avoiding back-mixing and short-circuits and reducing ring erosion.

Table 1
Eulerian-Eulerian gas-solid model.

Mass conservation equations
Gas phase: $\frac{\partial}{\partial t}(f_g\rho_g) + \nabla \cdot (f_g\rho_g \mathrm{v}_g) = 0$ (1)
Solids phase: $\frac{\partial}{\partial t}(f_s\rho_s) + \nabla \cdot (f_s\rho_s \mathrm{v}_s) = 0$ (2)

Momentum conservation equations
Gas phase: $\frac{\partial}{\partial t}(f_g\rho_g \mathrm{v}_g) + \nabla \cdot (f_g\rho_g \mathrm{v}_g \mathrm{v}_g) = \nabla \cdot \tau_g + f_g\rho_g \mathrm{g} - f_g\nabla p + \mathrm{F}_{gs}$ (3)
Solid phase: $\frac{\partial}{\partial t}(f_s\rho_s \mathrm{v}_s) + \nabla \cdot (f_s\rho_s \mathrm{v}_s \mathrm{v}_s) = \nabla \cdot \tau_s + f_s\rho_s \mathrm{g} - f_s\nabla p - \nabla p_s + \mathrm{F}_{sg}$ (4)

Stress tensor
Gas phase: $\tau_g = f_g\mu_g[\nabla \mathrm{v}_g + (\nabla \mathrm{v}_g)^T] - \frac{2}{3} f_g\mu_g(\nabla \cdot \mathrm{v}_g)\mathrm{I} + f_g\tau_t$ (5)
Solids phase: $\tau_s = f_s\mu_s[\nabla \mathrm{v}_s + (\nabla \mathrm{v}_s)^T] - \frac{2}{3} f_s\mu_s(\nabla \cdot \mathrm{v}_s)\mathrm{I}$ (6)

Drag model
Gas phase: $\mathrm{F}_{gs} = \beta(\mathrm{v}_s - \mathrm{v}_g)$ (7)
Solids phase: $\mathrm{F}_{sg} = \beta(\mathrm{v}_g - \mathrm{v}_s)$ (8)

Gidaspow model
With $f_s > 0.2$: $\beta = 150\frac{f_s^2\mu_g}{f_g d_s^2} + \frac{7}{4}\frac{|v_s - v_g| f_s\rho_g}{d_s}$ (9)
With $f_s < 0.2$: $\beta = \frac{3}{4} C_D \frac{|v_s - v_g| f_s\rho_g}{d_s} f_s^{-2.65}$ (10)
With $Re > 1000$: $C_D = 0.44$ (11)
With $Re < 1000$: $C_D = \frac{24}{Re}(1 + 0.15Re^{0.687})$ (12)

KTGF model
Dynamic viscosity: $\mu_s = \mu_{s,col} + \mu_{s,kin} + \mu_{s,fr}$ (13)
Collisional viscosity: $\mu_{s,col} = \frac{4}{5} f_s\rho_s d_s g_0(1 + e_{ss})\sqrt{\frac{\Theta}{\pi}}$ (14)
Kinetic viscosity: $\mu_{s,kin} = \frac{10\rho_s d_s\sqrt{\pi\Theta}}{96 f_s(1+e_{ss})g_0}[1 + \frac{4}{5} g_0 f_s(1 + e_{ss})]$ (15)
Frictional viscosity: $\mu_{s,fr} = \frac{p_s \ ,\sin\varphi}{2\sqrt{I_{2D}}}$ (16)
Solids pressure: $p_s = f_s\rho_s\Theta + 2\rho_s(1 + e_{ss}) f_s^2 g_0\Theta$ (17)
Radial distribution function: $g_0 = [1 - (\frac{f_s}{f_{s,máx}})^{\frac{1}{3}}]^{-1}$ (18)
Bulk viscosity: $\lambda_s = \frac{4}{3} f_s\rho_s d_s g_0(1 + e_{ss})\sqrt{\frac{\Theta}{\pi}}$ (19)
Granular temperature:
$\frac{3}{2}[\frac{\partial}{\partial t}(\rho_s f_s\Theta_s) + \nabla \cdot (\rho_s f_s \mathrm{v}_s\Theta_s)] = (-P_s\mathrm{I} + \tau_s) : \nabla \mathrm{v}_s + \nabla \cdot (\mu_s\nabla\Theta_s) - \gamma_{\Theta_s} + \phi_{gs}$ (20)
Collisional energy dissipation: $\gamma_{\Theta_s} = \frac{12(1-e_{ss}^2)g_0}{d_s\sqrt{\pi}}\rho_s f_s^2\Theta_s^{3/2}$ (21)
Kinetic energy transfer between gas and solids phase due to velocity fluctuations:
$\phi_{gs} = -3k_{gs}\Theta_s$ (22)
Parameters of the KTGF model: $e_{ss} = 0.9$; $f_{s,\max} = 0.63$

k-ε model
Turbulent kinetic energy:
$\frac{\partial}{\partial t}(f_g\rho_g k_g) + \nabla \cdot (f_g\rho_g \mathrm{v}_g k_g) = \nabla \cdot (f_g\frac{\mu_{t,g}}{\sigma_k}\nabla k_g) + f_g G_{k,g} - f_g\rho_g\varepsilon_g$ (23)
Turbulent energy dissipation:
$\frac{\partial}{\partial t}(f_g\rho_g\varepsilon_g) + \nabla \cdot (f_g\rho_g \mathrm{v}_g\varepsilon_g) = \nabla \cdot (f_g\frac{\mu_{t,g}}{\sigma_\varepsilon}\nabla\varepsilon_g) + f_g\frac{\varepsilon_g}{k_g}(C_{1\varepsilon}G_{k,g} - C_{2\varepsilon}\rho_g\varepsilon_g)$ (24)
Gas viscosity: $\mu_g = \mu_{l,g} + \mu_{t,g}$ (25)
Shear viscosity: $\mu_{t,g} = \rho_g C_\mu\frac{k_g^2}{\varepsilon_g}$ (26)
Production of turbulent kinetic energy: $G_{k,g} = \mu_{t,g}S^2$ (27)
Modulus of the mean rate-of-strain tensor: $S = \sqrt{2\mathrm{S} : \mathrm{S}}$ (28)
Parameters of the k-ε model:
$C_{1\varepsilon} = 1.44$; $C_{2\varepsilon} = 1.92$; $C_{3\varepsilon} = 1.2$; $C_\mu = 0.09$
$\sigma_k = 1.0$; $\sigma_\varepsilon = 1.2$

2. Mathematical modeling

In this study, a transient Eulerian-Eulerian approach was used to describe the 3-D gas-solid flow [5,18]. The k-epsilon turbulence model was applied to describe the gas turbulence [19,20] and the kinetic theory of granular flow (KTGF) was used for the solid phase properties, such as solids viscosity and solids pressure, among others [21,22]. A two-fluid model is adopted [23], with the gas and solid phases related according to the Gidaspow drag model [24,25]. The mathematical modeling used is shown in Table 1.

3. Methodology

The numerical simulations were performed in the lab-scale CFB riser schematized in Fig. 1-a. The riser of 2.78 m height has an internal diameter of 0.104 m. The solids inlet has an inclination of 55° and is positioned at a height of 0.525 m. The gas feed is positioned in the bottom region. The inclination of the gas and solids outlet is 12° relative to the solids inlet. To improve the solids distribution in the CFB riser, an airfoil-shaped ring-type internal was proposed. The ring shape is based on a NACA airfoil [26], whose design slows the laminar boundary layer detachment and the vortex formation. In the gas-solid flow, this feature can avoid solids back-mixing and short circuits in the region of the rings. The design of the rings is schematized in Fig. 1-b, where the measurements are specified for the rings with a thickness of 10 mm and 15 mm. The airfoil curve is obtained by combining a triangle and a circle, using the coordinates, the lengths and the circle center and its radius specified in Fig. 1-b. For the sake of clarity, ring dimensions hereafter will be presented in millimeters (mm).

The design of experiments shown in Table 2 was proposed to study the influence of the geometrical properties on the solids distribution. Four properties were chosen: ring thickness (A), spacing between rings (B), number of rings (C) and the insertion of a bottom ring below the solids inlet (D). The spacing between rings (B) is valid only for the rings above the solids inlet. The gas phase is represented by air