EXPERIMENTAL ANALYSIS OF THE GAS-SOLID FLOW IN A RING-BAFFLED CFB RISER USING LASER DOPPLER ANEMOMETRY (LDA) AND PHASE-DOPPLER ANEMOMETRY (PDA)

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Abstract. *FCC risers are largely used in oil refineries to produce gasoline. FCC reactions yield is influenced by the catalyst particles distribution in the riser reactor. Due to the flow behavior, solid particles accumulate in the riser wall and bottom region. Internal ring baffles are an efficient alternative to improve to improve the solid particles distribution in circulating fluidized beds and FCC risers. Here the influence of an airfoil-shaped ring-type baffle on the solids distribution is investigated in a lab-scale CFB riser. Four ring baffles ith ring thickness of 10 mm were installed inside the CFB riser. The gas-solid flow was studied at four operational conditions. Gas velocity was measured based on Laser Doppler Anemometry technique (LDA) and titanium dioxide was used as tracer particle. Solid axial velocity and solid volume fraction in the cross section region was measured with Phase Doppler Anemometry (PDA). Glass beads were used to represent the catalyst solids phase. Results showed gas and solids acceleration in the rings region and solid volume fraction was redistributed by the rings. The ring installed immediately above the solids inlet redirect particles from the wall to the riser center. The best solid distribution was observed with the maximum gas velocity and the minimum solids flux.*

Keywords: *CFB riser. Airfoil-shaped ring baffles. LDA. PDA.*

1. INTRODUCTION

Fluid catalytic cracking (FCC) is one of the most important processes in the petroleum refining industry (Lopes et al. 2011). An FCC unit is basically composed of a riser reactor and a regenerator (Behjat, Hosseini, and Marvast 2011). The riser reactor is a long tube used to convert hydrocarbons with high molecular weight to products with lower molecular weight and high added value, like gasoline (Jiménez-García, Aguilar-López, and Maya-Yescas 2011; Chen and Luo 2014).

Circulating fluidized beds (CFB) are very useful in the literature to study the gas-solid flow in a riser reactor (Peng, Zhang, and Zhu 2012; Kim and Kim 2002). One of the most important problems identified in the gas-solid flow of CFB and FCC risers is the unequal solids distribution (Samuelsberg and Hjertager 1996; Deng et al. 2002). Due to the core-annulus profile formation, solid particles accumulates in the wall, resulting in a concentrated down-flow. Consequently, a diluted up-flow is formed in the center of the riser (Benyahia et al. 2000; Gao et al. 2012). If the solid particles are catalyst particles, this behavior implies in a lower conversion of the FCC reactions to the products of interest (Lopes et al. 2011).

An alternative to improve solids distribution in the axial and radial directions of a CFB riser is the insertion of internal ring baffles in the inlet region (Jin, Wei, and Wang 2003; Jiang et al. 1991a). Jiang et al. (1991b) analyzed ozone decomposition using FCC particles and concluded that internal ring baffles increase the solids fraction distribution in the radial direction. Zhu et al. (1997) studied the influence of the ring opening area on the solids fraction distribution and concluded that, for rings with 70% of opening area, a denser region is formed in the riser bottom. (Zhu, Salah, and Zhou 1997).

Samruamphianskun et al. (2012) studied the gas-solid flow in a ring-baffled riser varying four geometric properties: ring thickness, number of rings, opening area, the spacing between rings, and its uniformity. The ring opening area had the most important effect on the solids distribution. To determine the influence on the radial and axial solids distribution, Bu and Zhu (1999) investigated the influence of ring-type internals on the axial pressure distribution in a circulating fluidized bed with different opening areas. The opening area had more influence on the flow behavior.

Guío-Perez et al. (2014) studied a CFB riser with rings installed in the middle region and concluded that the effect of the rings is highly dependent on the operational conditions. The rings with smaller aperture area promoted solids redirection to the upper region at lower fluidization velocities. The ring above the solids inlet promotes segregation of particles according to their diameter.

In CFB risers, turbulent flow increases rings erosion and pressure drop. Therefore, short circuits may develop in the region immediately above the rings, due to the earlier transition of the laminar to the turbulent boundary layer. The airfoil-shaped ring-type baffles can improve solids distribution in CFB risers, avoiding short circuits and dead spots (Rossbach et al. 2015). Depending on the angle of attack and the maximum thickness, an airfoil can slows the laminar boundary layer detachment from its surface (Zhang et al. 2015).

The aim of this study is to propose an airfoil-shaped ring-type baffle, based on the literature, and to study the flow behavior in a ring-baffle riser under different operational conditions.

2. MATERIAL AND METHODS

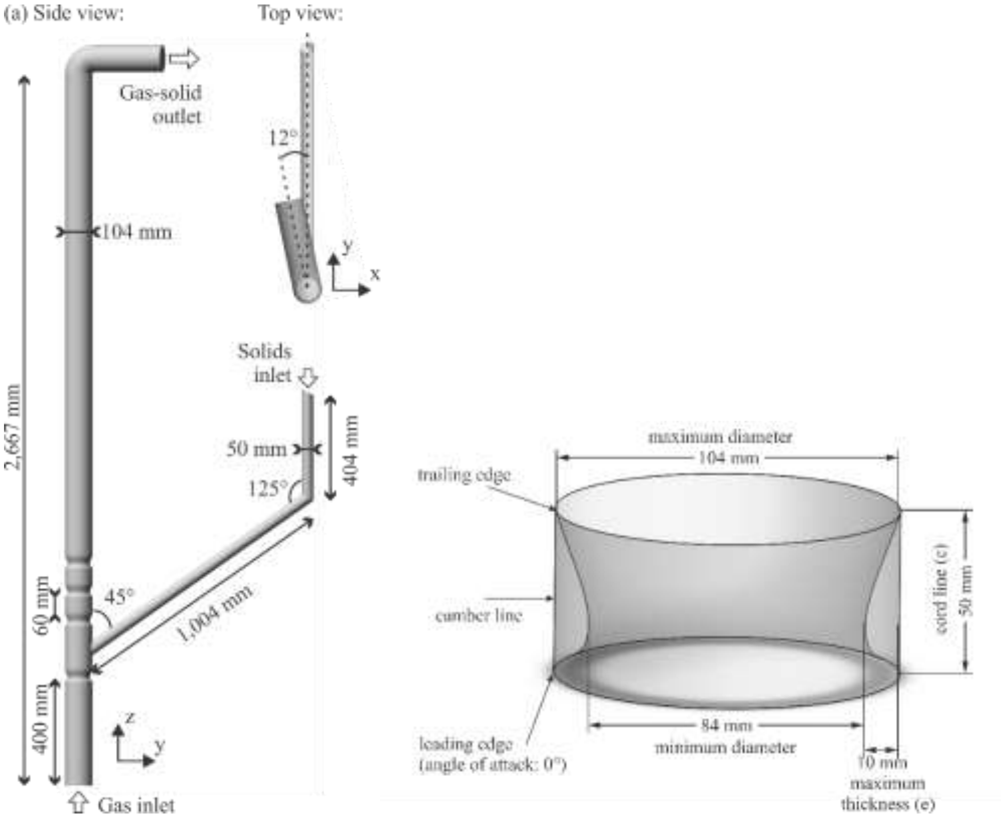
In this study, cold gas-solid flow was studied in a lab-scale circulating fluidized bed unit, without considering mass transfer, heat transfer, and chemical reactions. Figure 1 represents the experimental unit. Air is suctioned from the riser (1) bottom by an exhauster (7). Glass beads are injected in the solids inlet (2), with a mass flux controlled by the solids handler valve (3). Solids mass flux and gas velocity can be adjusted using the unit control and acquisition data system (6). Gas and solids pass through the cyclone (4). Solids are fed back, and the bag filter (5) collects the air contaminated with particles.

1 - Riser; 2 - Solids inlet; 3 - Solids handler;
4 - Cyclone; 5 - Bag filter;
6 - Control and aquisition data system; 7 - Exhauster

Figure 1. Lab scale circulating fluidized bed unit.

The ring-baffled riser geometry is shown in Figure 2-a. The rings position was determined in previous work. The ring below the solids inlet is located 400 mm above the gas inlet. For the other three rings, the spacing between rings is 60 mm. The adjustment of the rings geometry to an aerodynamic-shape may reduce the effect of drag force and erosion on the rings, and avoid solids back mixing and short circuits. The geometry of the airfoil-shaped ring-type baffle proposed is shown in Fig. 2-b. The maximum internal diameter of the baffle is 104 mm, and the minimum internal diameter is 84 mm. Some geometrical properties were defined in analogy with the airfoil geometrical properties. The ring height corresponds to the cord line (c) of an airfoil. The maximum thickness (e) is 10mm and the ratio between the maximum thickness and the cord line (e/c) of 20% is in according with the literature about airfoils. In the riser up-flow, gas and solids reach the leading edge with an angle of attack equal to 0° and get out by the trailing edge. The camber line is the external surface of the ring. Airfoil-shaped ring-type baffles can slows the laminar boundary detachment and the dead spots formation, avoiding back mixing. Under low Reynolds number, an airfoil with a small thickness and the minimum angle of attack can reduce pressure drop and flow instability in its surface. On this direction, Dongli et al. (Dongli et al. 2015) found the best results for an airfoil with angle of attack equal to 0°, under a Reynolds number equal to 300,000.

Two nonintrusive techniques were used to measure the gas-solid flow in this study. The axial component of the gas velocity was measured with Laser Doppler Anemometer (LDA). Phase Doppler Anemometer (PDA) was used to measure the axial component of the solid velocity, the solids concentration and the solids mean particle diameter. All these properties were measured at each of the points indicated in Fig. 3, at 0.81 m height (below the last ring) and 0.93 m height (above the last ring). The gas velocity measurement with LDA technique is based on the detection of tracking particles. When a particle pass through the intersection volume formed by two coherent laser beams, the diffused light intensity is changed. The laser frequency is the ratio between the particle velocity and the fringe spacing formed by the beams (Werther 1999; Albrecht et al. 2003). Titanium dioxide was used as tracking particle, with Stokes number between 1.55E-10 and 2.30E-10. Solid velocity measurement with PDA technique is based on the same principle of the LDA technique. The particle detection, however, is based on the interference caused by the passage of particles through the intersection of coherent light beams. Two detector receive the frequency signal with different phases. The phase shift between the two signals received is the particle diameter (Werther 1999; Albrecht et al. 2003). Glass beads of the Geldart B group, with Sauter superficial diameter of 71.9 µm, represent the solid phase.



(a) (b)

Figure 2. (a) Riser geometry and (b) airfoil-shaped ring-type baffle.

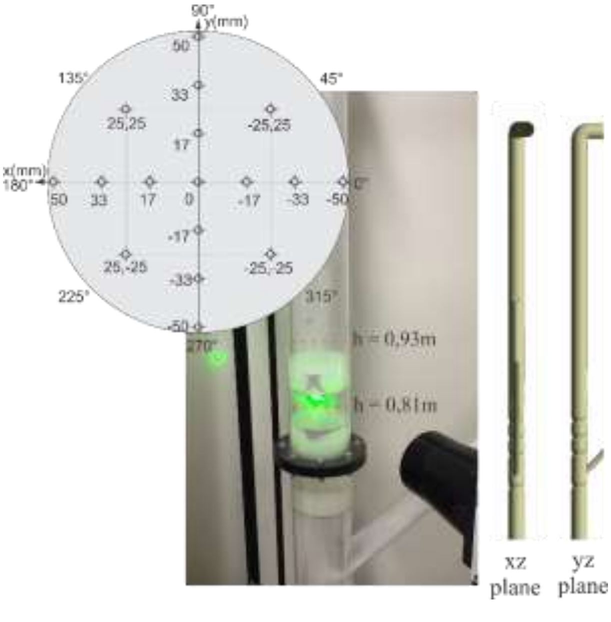


Figure 3. Points, axial positions and planes of measurements with PDA and LDA techniques.

Solid volume fraction was calculated for each experimental point shown in Figure 3, at 0.81 m and 0.93 m height. The particle volume is calculated with the Eq. (1).

$$V_p = \frac{4}{3}\pi D_p^3 \tag{1}$$

Solid volume fraction is the product between particle concentration and particle volume, according to Eq. (2).

$$f_s = C_p V_p \tag{2}$$

Gas velocity was measured under the superficial velocities of 5.6 m/s and 8.3 m/s. Solid velocity and mean particle diameter was measured at the same superficial velocities, with solid mass flux of 1.55 kg/m²s and 2.88 kg/m²s. For the gas-solid flow measurement, four operational conditions were studied, using the experimental planning shown in Table 1, where v_g is the gas velocity and G_s is the solids mass flux.

Table 1: Experimental planning.

Operational condition	v_g [m/s]	G_s [kg/m²s]	h [m]	f_s [-]
1	5.6	1.55	0.81 0.93	11.04E-4
2	5.6	2.88	0.81 0.93	20.64E-4
3	8.3	2.88	0.81 0.93	13.92E-4
4	8.3	1.55	0.81 0.93	7.68E-4

3. EXPERIMENTAL RESULTS AND DISCUSSION

Gas velocity was measured with the LDA technique in two planes: xz plane and yz plane, indicated in Figure 3. In the Figure 4, the velocity profiles obtained with the measured points are compared below (0.81 m) and above the ring (0.93 m). The mean gas velocity profiles in the xz plane (Fig.4-a) and in the yz plane (Fig. 4-b) points out the reduction in the gas velocity after passing through the ring. Table 2 shows the reduction in the mean velocity due to ring for each case.

Table 2: Mean reduction in the gas velocity after passing through the ring.

Plane	Superficial velocity	
	5.6 m/s	8.3 m/s
xz	24%	14%
yz	2%	14%

The reduction in the gas velocity is caused by the reduction-and-expansion effect caused by the gas passage through the ring. Gas velocity increases because of the free area reduction in the ring region, and decreases above the ring. Solid mean velocity profiles are shown in Figure 4-c, for the xz plane, and 4-d, for the yz plane. For the Condition 1, solid mean velocity is reduced. For the Conditions 2 and 4, the velocity reduction in negligible. For the Condition 3, a large velocity reduction is observed. In the plane xz, solid mean velocity profiles are symmetrical. In the plane yz, however, there is no symmetry. Solid particles are concentrated in the wall opposite to the solids inlet and reduces solid velocity in this wall. This behavior is more evident in the Condition 2, which is the most concentrated operational condition. After passing through the ring, solid velocity increases in the wall opposite to the solids inlet in all the operational conditions. The velocity increasing implies that solids concentration decreases in this position. Solid velocity profiles are more equilibrated after the ring in all the operational conditions, especially in the Condition 4. Therefore, the airfoil shaped ring baffle contributes to increase solids distribution in the CFB riser studied. Table 3 shows the mean reduction in the solids velocity for the operational conditions studied. In the Condition 2, the mean solid velocity increases in the xz planes and decreases a lot in the yz plane. In the Condition 3, solid velocity decreases in the two planes, but the reduction is not equilibrated between the xz and yz planes.

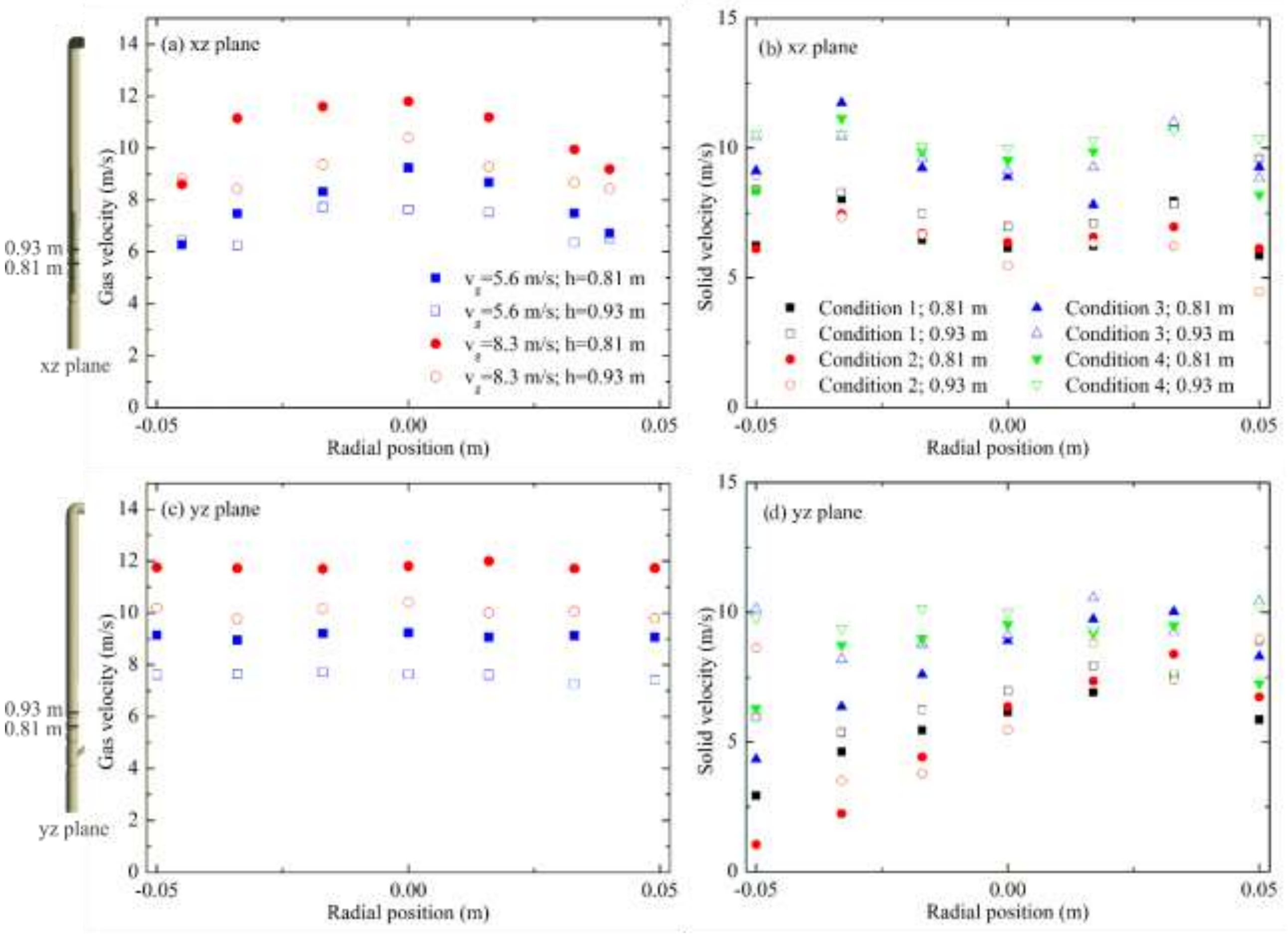


Figure 4: Gas and solid mean velocity profiles at xz and yz planes.

Table 3: Mean reduction in the solid velocity after passing through the ring.

Operational condition	Solid velocity reduction	
	Plane xz	Plane yz
1	18%	25%
2	-2%	29%
3	2%	20%
4	7%	12%

Figure 5 shows solid volume fraction contours generated with the points defined. In the Condition 1, solid particles are concentrated at the riser center below the ring, at 0.81 m height. After passing through the ring (0.93 m height), the particles are distributed in the radial direction, although a more concentrated region will remain in the center. In the Condition 2, solids are concentrated in the wall below the ring and are redistributed above the ring. In the Conditions 3 and 4, particles are concentrated in the center below the ring and are well distributed above the ring. A comparison of the solids dispersion coefficients below and above the ring is made in Table 4.

Table 4. Comparison of solids dispersion coefficient.

Operational condition	Height (m)		Reduction (%)
	0.81	0.93	
1	0.87	0.72	17
2	2.33	0.78	66
3	0.89	0.68	24
4	0.88	0.64	27

$$C_v = \frac{\sigma_{sd}}{\bar{x}} \tag{3}$$

The dispersion coefficient is defined by the Eq. (3), and is calculated for the 17 experimental points on each axial position. In terms of solids distribution, the best results were reached with Conditions 3 and 4, which have the lower solid dispersion coefficient. At Condition 2, solids dispersion coefficient is reduced in 66%, resulting in the better particle redistribution.

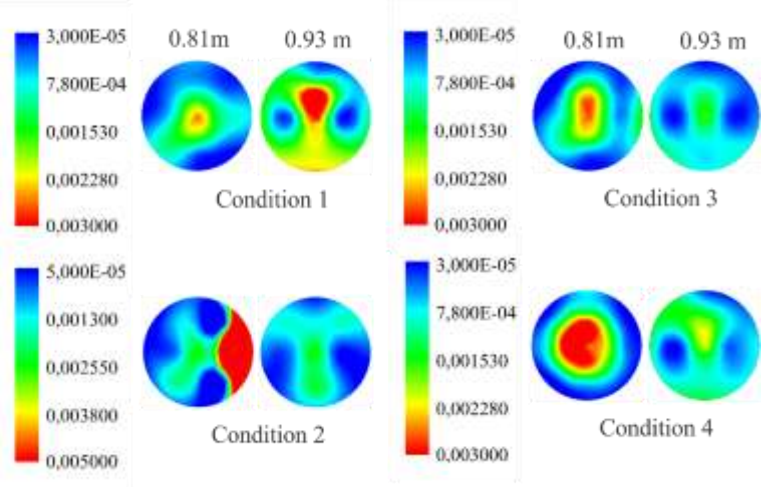


Figure 5: Solid volume fraction for the 4 operational conditions, at 0.81 m and 0.93 m height.

Figure 6 shows the gas-solid flow reorganization due to the rings. In the inlet region, the solid particles are concentrated in the opposite wall. After passing through the ring immediately above the solids inlet, the particles are redirected from the wall to the riser center. This behavior can be attributed to the airfoil shaped of the ring.

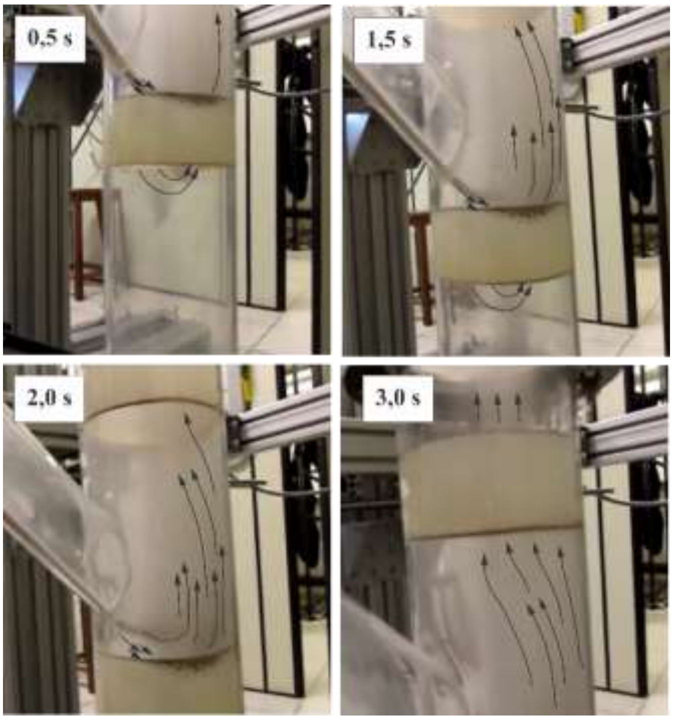


Figure 6: Gas-solid flow redirection in the CFB riser inlet due to the rings.

4. CONCLUSIONS

In this study, an airfoil-shaped ring-type baffle was proposed to redistribute solid particles in the cross section of a lab-scale CFB riser. LDA and PDA techniques were used to measure gas and solid velocity. Solid volume fraction was calculated using solid particle diameter and concentration obtained with PDA.

In the gas and solid velocity profiles, velocity reduction is observed above the ring. This behavior can be attributed to the reduction-and-expansion effect caused by the ring presence. The solid velocity increasing in the wall opposite to the solids inlet indicates the solids redistribution. The solid volume fraction contours shown clearly the particle redistribution. Solids dispersion coefficient decreases in all the cases, indicating better solids dispersion.

The analysis of the gas-solid flow and the solid volume fraction distribution in the ring-baffled riser shows that the airfoil-shaped ring-type baffles can improve solids distribution in the inlet region. This study is an important contribution to the FCC process and the researches about CFB risers.

5. ACKNOWLEDGMENTS

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