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Original Research

Analysis of flow dynamics and velocity in circulating fluidized beds: non-invasive measurements with gamma radiation

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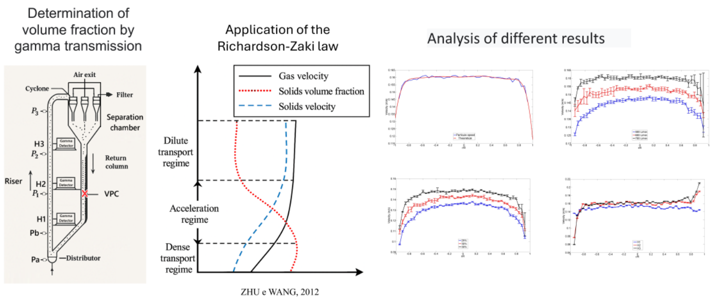

Abstract: This study introduces a non-invasive method for characterizing gas-solid flow in circulating fluidized bed (CFB) risers using gamma radiation transmission. By applying the Richardson-Zaki law and measuring radial gamma attenuation, the analysis quantifies FCC catalyst velocity profiles and solid holdup across varying flow conditions. Experiments explored the effects of superficial gas velocity (500–700 L/min), VPC valve openings (25–35%), and axial height on particle dynamics. Increasing the air flow rate raised catalyst velocity by up to 25%, while higher solid concentrations reduced velocity near the riser walls by approximately 22%. Velocity profiles exhibited parabolic shapes at lower positions and became uniform in the upper sections, confirming the establishment of fully developed core-annular flow. The method delivered results with high repeatability, showing less than 3% uncertainty across five repetitions. These findings provide a novel and precise tool for diagnosing flow regimes and optimizing riser performance in FCC and other multiphase process systems.

Keywords: Circulating fluidized beds, non-invasive measurement, gamma radiation, pneumatic transport systems, particle velocity profile, Richardson-Zaki law.

Introduction

Two-phase gas-solid circulating fluidized bed (CFB) systems with upward flow are widely employed across several fields, including chemistry and pharmaceuticals, due to their environmental and safety benefits [1-4]. Additionally, these systems enable precise control over fluid dynamics, including gas and solid injection rates, which is essential for process efficiency [5,6]. Understanding the specific operational conditions under various flow regimes, such as particle velocity and circulation rate, is equally important [5].

Consequently, substantial research has focused on investigating various flow structures that are relevant to these fields [4]. Over the past five decades, four distinct types of two-phase flows have been characterized: dilute ascending flow, core-annular flow, fast fluidization, and dense flow [7, 8]. Of these, core-annular flow has garnered significant attention, while the simpler dilute ascending flow regime has been studied comparatively less [1]. Thorough examination of these flow regimes deepens our understanding of CFB riser hydrodynamics, thus providing a reliable basis for interpreting phenomena accurately and enhancing the design, optimization, and operation of circulating fluidized bed reactors [2].

Typically, research assumes that particles in fluidized beds are spherical for simplification purposes, which is especially true in Computational Fluid Dynamics (CFD) studies [4]. Nevertheless, it is important to acknowledge that this assumption is an idealization. Effective heat and mass transfer in CFBs remains a pivotal criterion for their selection in industrial applications [9].

Various research groups have proposed different approaches to studying the hydrodynamics of fluidized beds, employing both invasive and non-invasive methods [4]. Non-invasive techniques tend to be more applicable in academic research, whereas invasive methods are commonly used in industrial settings [1]. Intrusive methods involve penetration into the flow, which can disrupt the system and potentially result in inaccuracies. Consequently, non-invasive methods are generally preferable. For instance, optical probes, although useful, often overestimate or underestimate measurements [1].

This study focuses on determining the velocity of fluid catalytic cracking (FCC) catalysts within a cold pilot unit (UPF). The investigation employs a non-invasive technique supported by gamma radiation transmission.

Experimental Section

Installation and equipment

The UPF operates as a model for studying FCC catalyst fluid dynamics. It stands within the Kornelius Keller laboratory at the Department of Nuclear Energy (DEN), which belongs to the Center for Technologies and Geosciences (CTG) at the Federal University of Pernambuco (UFPE). Built with transparent acrylic, the unit enables direct visual observation of the two-phase mixture.

The UPF consists of three main components. The first is the Riser, a transparent acrylic tube that measures 6.6 meters in height, with an external diameter of 0.102 meters and an internal diameter of 0.092 meters. The second component, the Return Column, has the same diameter but extends 3.14 meters in length. The third, the Separation Chamber, features a cylindrical section connected to a conical structure at its lower end, which links it to the return column. Figure 1 presents a schematic representation of the UPF.

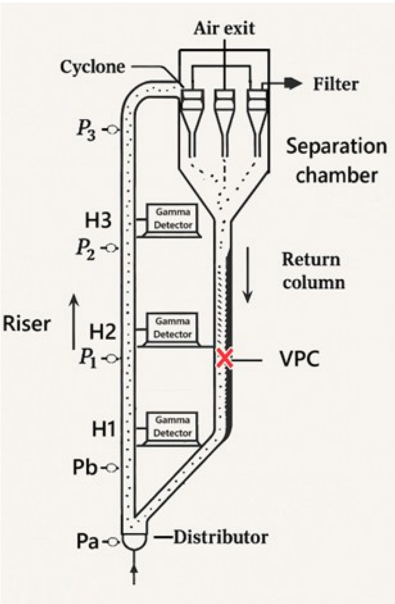

Figure 1. Representation of the UPF and its equipment.

A mechanical device called the Valve Pressure Control (VPC) integrates with the control interface to regulate the catalyst's entry into the riser.

To apply the gamma radiation transmission technique, three systems—each consisting of a source, detector, and multichannel analyzer—position themselves at different heights along the riser, forming test sections. These test sections move radially to obtain radial profiles of the two-phase mixture. The system uses an Americium-241 (Am-241) radioisotope as the radiation source, while a thallium-activated sodium iodide scintillator (NaI(Tl)) serves as the detector, capturing emitted gamma radiation.

The control interface allows adjustments to measurement parameters, including the number of gamma transmission points recorded and the duration allocated to each measurement. This setup ensures precise characterization and analysis of two-phase flow dynamics within the riser.

It is important to highlight that the unidirectional catalyst inlet affects the distribution of solids in nearby regions. Studies in [4, 9] have reported similar designs, where the unidirectional inlet alters the solids distribution profile.

Richardson-Zaki Law

The Richardson-Zaki law explains the behavior of homogeneous fluidized beds by establishing a relationship between velocity and volume fraction. Researchers commonly apply this law to liquid-fluidized bed systems, though exceptions occur when dealing with very dense particles [9]. However, its application also extends to gas-solid systems, where the maximum solids concentration imposes a limitation. Beyond this concentration, solid particles settle and form a cloud.

The maximum concentration corresponds to that of an incipient fluidized bed or to the conditions of minimum fluidization, where the void fraction equals 0.4 ($\varepsilon = \varepsilon_{mf}$) [10]. In this model, the surface velocity depends directly on particle characteristics and bed properties, including the terminal velocity of an isolated particle [10]. Equation 1 formally expresses the Richardson-Zaki law.

$$\varepsilon^n = \frac{u_p}{u_t} (\varepsilon_{mf} < \varepsilon < 1) \tag{1}$$

The linear relationship between the logarithm of the surface velocity and the logarithm of the volumetric fraction determines the exponent n, as shown in Equation 2.

$$\mathrm{n} = \frac{\log(\frac{u_{mf}}{u_t})}{\log \varepsilon_{mf}} \tag{2}$$

The term u_{mf} denotes the minimum fluidization velocity, while ε_{mf} refers to the gas volume fraction under minimum fluidization conditions.

Understanding terminal velocity plays a crucial role in analyzing the fluid dynamics of solid particles [11]. The terminal velocity of an isolated particle refers to the constant velocity it reaches in a stationary fluid, illustrating a specific application of Newton's third law. In this case, the terminal velocity matches the particle's settling velocity, $u_t = u_p$ [12].

$$u_t = \left(\frac{\mu_{ar}}{\rho_{ar} \cdot d_p}\right) . (3{,}23 + 0{,}23\, Ar_m) \tag{3}$$

The symbol ρ_{ar} represents the air density, and d_p denotes the particle diameter.

The modified Archimedes number represents the relationship between gravitational acceleration and particle drag force, with its value calculated using Equation 4.

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$$Ar_m = \frac{4}{3}\frac{g(\rho_p/\rho_g - 1)d_p^3}{v_g^2} \quad (4)$$

The symbol g denotes gravitational acceleration, ρ_p indicates particle density, ρ_g refers to gas density, and v_g represents the gas kinematic viscosity.

The Beer-Lambert equation undergoes adaptation to estimate the volumetric fraction of solids using gamma transmission, as shown in Equation 5.

$$\varepsilon = \pi r^2 \frac{1}{\frac{\mu}{\rho}\rho_p C}\ln\left(\frac{I_V}{I_F}\right) \quad (5)$$

The volumetric fraction calculation uses the mass attenuation coefficient (μ/ρ), the gamma source intensity with an empty riser (I_v), and the intensity under flow conditions (I_F). The term c represents the path length that the radiation travels through the riser.

Experimental design

Was investigated how variations in gas superficial velocity influence the FCC particle velocity profile by using flow rates of 500, 600, and 700 L/min, with the VPC valve kept at a 25% opening. The analysis shows that higher gas flow rates increase the velocity of FCC particles.

To examine the impact of solids feed rate on the velocity profile, a gas flow rate of 700 L/min was used with valve openings set at 25%, 30%, and 35%.

To investigate how height affects solid velocity in the riser, a flow rate of 700 L/min and a VPC valve opening of 25% were used. Gamma attenuation was measured at the heights labeled H1, H2, and H3 in Figure 1.

Each test was repeated five times, and I used these repetitions to calculate the expanded standard uncertainty at a 98% confidence level. The error bars in the graphs represent this uncertainty.

Results and Discussion

Previous studies [1, 2, 4, 5, 7, 9, 12-14] reported similar velocity distribution profiles, confirming consistency with the patterns identified in this work.

Figure 2 presents the radial velocity profile of FCC particles obtained under controlled operating conditions: a superficial gas flow rate of 700 L/min, a Valve Pressure Control (VPC) opening of 25%. These parameters were chosen to evaluate their combined impact on flow hydrodynamics within the riser.

The experimental velocity distribution closely follows the theoretical profile, as shown by the strong agreement between the measured (blue line) and predicted (red line) values. The velocity profile remains relatively flat across the central region (−0.6 < r/R < 0.6), indicating a well-developed core flow, while a sharp decline in velocity occurs near the riser walls due to boundary layer effects and increased wall-particle interactions.

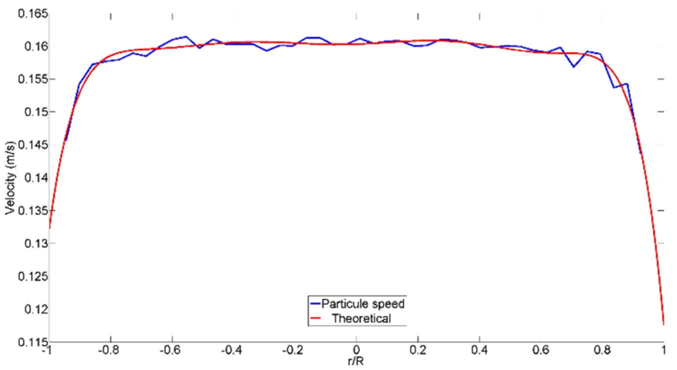

Figure 2. Particle velocity profile with compressed air flow of 700 L/min and VPC valve opening of 54%.

This behavior mirrors the profiles described in previous studies [1, 6, 8], where fully developed riser flow typically exhibits minimal velocity gradients at the core and steep drops near the boundaries. The excellent correlation between experimental and theoretical data confirms the reliability of the measurement approach and validates the assumptions made in the theoretical model under these operating conditions.

These findings reinforce the understanding of gas-solid flow dynamics in circulating fluidized bed systems and provide a strong foundation for further model validation and performance optimization.

Figure 3 presents the radial velocity profiles of FCC particles in the riser for three different superficial gas velocities: 500, 600, and 700 L/min. The profiles exhibit a typical parabolic distribution, with higher velocities near the centerline and decreasing values toward the riser walls, indicating the influence of wall effects and the presence of a core-annular flow structure.

An increase in gas flow rate leads to a clear upward shift in the velocity curves, demonstrating that higher superficial gas velocities promote faster particle movement. This behavior results from the enhanced momentum transfer from the gas phase to the solid particles, increasing drag forces and driving the particles upward more efficiently.

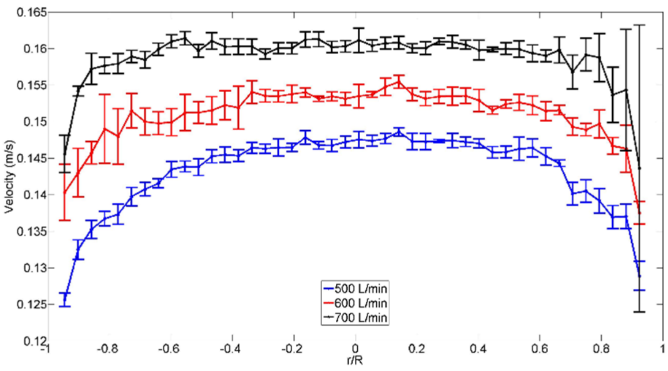

Figure 3. Particle velocity profile with compressed air flow rates of 500, 600, and 700 L/min and VPC valve opening of 25%.

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The error bars in the figure represent the expanded standard uncertainty at a 98% confidence level, calculated from five repeated measurements for each condition. The relatively narrow uncertainty ranges across the profiles confirm the consistency and repeatability of the experimental data.

These findings reinforce the critical role of gas velocity in controlling the hydrodynamics of FCC particles in riser reactors. They also align with previous studies, such as those reported in [6], which observed similar trends of increasing particle velocity with higher gas flow rates. Understanding this relationship is fundamental for the design and optimization of FCC units, as it directly affects catalyst residence time, mixing behavior, and overall reactor performance.

Figure 4 presents the radial profiles of FCC particle velocity in the riser for three different VPC valve openings: 25%, 30%, and 35%, with a fixed superficial gas velocity. The profiles show a clear downward shift and flattening trend as the valve opening increases. This behavior reflects the increase in solids concentration within the riser, which in turn reduces the particle velocity across the entire radial section.

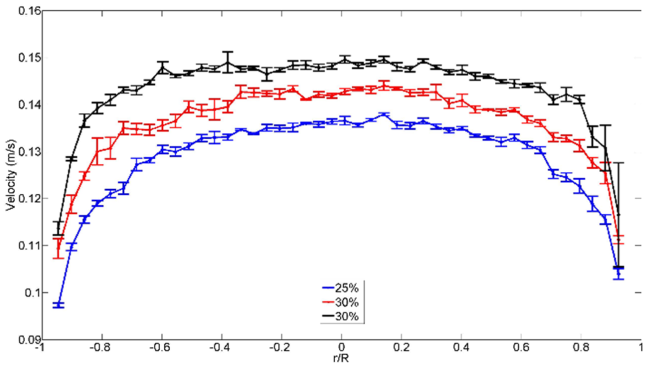

Figure 4. Particle velocity profile with compressed air flow rate of 700 L/min and VPC valve openings of 25, 30 e 35%.

The curves maintain a parabolic shape, with maximum velocities near the centerline and lower velocities near the wall region, highlighting the influence of core-annular flow and wall drag effects. As the solids flux rises due to a wider valve opening, the increased particle-particle interactions and energy dissipation contribute to the observed velocity reduction.

The error bars indicate the expanded standard uncertainty at a 98% confidence level, calculated from five repetitions for each experimental condition. These small deviations confirm the consistency and reliability of the measurements.

This reduction in particle velocity with increasing solids concentration aligns with theoretical expectations and supports previous observations reported in [6]. The results emphasize the impact of solid loading on hydrodynamic behavior in riser flows, which plays a critical role in optimizing transport processes and residence time distribution in FCC systems.

Figure 5 displays the radial velocity profiles of FCC particles at three axial positions along the riser: H1, H2, and H3. All measurements were conducted under identical operating conditions, with a constant gas flow rate and solids feed rate. The profiles reveal a clear trend: as height increases from H1 to H3, particle velocity rises and eventually stabilizes.

At the lowest measurement point (H1), located in the dense transport regime, the profile exhibits lower velocities and more radial variation, influenced by intense particle-particle interactions and limited gas-solid momentum transfer. Moving upward to H2 and H3, the profiles flatten and shift upward, indicating reduced energy dissipation and more uniform particle motion.

At H2 and especially at H3, the velocity profile becomes nearly uniform across the riser radius, suggesting that the flow enters a fully developed regime. In this region, particle velocity stabilizes, and the influence of local fluctuations diminishes. The measurements indicate that, beyond a certain riser height, particle movement reaches a dynamic equilibrium under the tested conditions.

The observed trends are consistent with riser hydrodynamics theory and support the concept that gas-solid flow behavior evolves along the height of the riser, transitioning from acceleration and heterogeneous distribution near the base to a more homogeneous and stabilized flow in the upper regions.

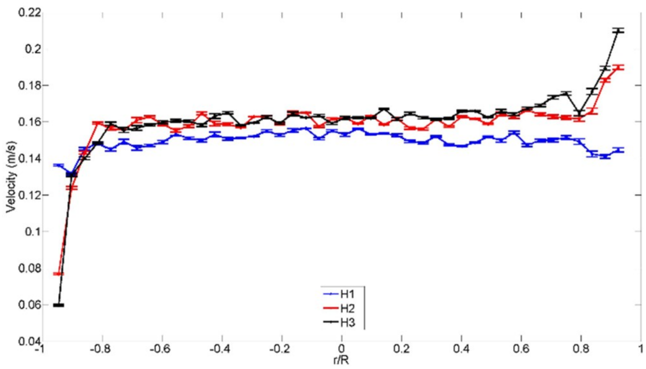

Figure 5. Particle velocity profile with compressed air flow rates of 700 L/min, VPC valve openings of 25 at three different heights

Conclusions

This study successfully applied a non-invasive gamma radiation transmission technique to characterize the hydrodynamics of a circulating fluidized bed riser under various operating conditions. By combining experimental measurements with the Richardson-Zaki law, the analysis captured detailed velocity profiles and solid concentration behavior along the riser height.

The results revealed that increasing the gas superficial velocity enhances particle acceleration, while higher solids feed rates reduce catalyst velocity due to intensified particle interactions. Measurements at different axial positions confirm that particle velocity stabilizes in the upper regions of the riser, indicating the formation of a fully developed flow regime.

The strong agreement between experimental data and theoretical predictions validated the accuracy of the measurement technique and the reliability of the applied models. These findings provide valuable insights for the optimization of gas-solid flow systems and support more efficient design and operation of FCC units and other industrial processes that rely on fluidized bed technology.

Future work will explore advanced detection systems and alternative isotopes to improve resolution in dense regions and broaden the applicability of the method to more complex flow regimes.

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Authors Contribution

M. Brito: Conceptualization, Methodology, Software, Formal analysis, Investigation, Writing – original draft; E. S. Barbosa: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Data curation, Supervision, Project administration; C. C. Dantas: Supervision, Project administration; A. C. D. Antonino: Supervision.

Conflicts of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

[1] B. GOPALAN; F. SHAFFER. Higher order statistical analysis of Eulerian particle velocity data in CFB risers as measured with high speed particle imaging. POWDER TECHNOLOGY, v. 242, p. 13-26, 2013. DOI: http://dx.doi.org/10.1016/j.powtec.2013.01.046.

[2] H. ZHANG; J. DEGRÈVE, J. BAEYENS, R. DEWIL. The voidage in a CFB riser as function of solids flux and gas velocity. PROCEDIA ENGINEERING, v. 102, p. 1112-1122, 2015. DOI: 10.1016/j.proeng.2015.01.234.

[3] Z. YAN; S. CHEN; Z. WANG; C. LI; Y. FAN; C. LU. Distributions of solids holdup and particle velocity in the FCC riser with downward pointed feed injection scheme. POWDER TECHNOLOGY, v. 304, p. 63-72, 2016. DOI: http://dx.doi.org/10.1016/j.powtec.2016.03.048.

[4] J. G. RAMÍREZ; Z. LIU; M. W. BALTUSSEN; K. A. BUIST; J. A. M. KUIPERS. CFD-DEM simulation of clustering behavior in a riser - effect of the collision model. POWDER TECHNOLOGY. v. 453, p. 1-13, 2025. DOI: https://doi.org/10.1016/j.powtec.2025.120610.

[5] Y. TANG; C. LIU; S. KUANG; Q. LIU; Z. CHEN; H. SONG, B. SU, J. YU, L. ZHANG, B. DAI. CFD modeling investigation of oxy-fuel combustion application in an industrial-scale FCC regenerator. JOURNAL OF THE ENERGY INSTITUTE, v. 117, p. 1-13, 2024. DOI: https://doi.org/10.1016/j.joei.2024.101796.

[6] Y. ZHAO; M. LV; X. SHI; X. LAN; j. GAO; W. JING. Optimizing droplet vaporization in the emulsified feeding technique of FCC: Impacts of operating conditions and reactor structures. CHEMICAL ENGINEERING SCIENCE. v. 306, p. 1-11, 2025. DOI: https://doi.org/10.1016/j.ces.2025.121278.

[7] S. F. GHAZVINI; E. N. IVASHKINA; V. A. CHUZLOV. New characterization models for macroscopic chemical-hydrodynamic behavior of catalytic cracking riser-reactor with interactive patterns of severe operating conditions using CFD calculations. JOURNAL OF THE TAIWAN INSTITUTE OF CHEMICAL ENGINEERS. v. 165, p. 1-14, 2024. DOI: https://doi.org/10.1016/j.powtec.2024.105767.

[8] N. Y. KIM; D. H. LEE; H. JANG; J. CHOI; J. B. JOO; D. KIM; Y. WON; H. RYU. Determination of the axial solid holdup profile by locating the splash zone in the riser. ADVANCED POWDER TECHNOLOGY. v. 36, p. 1-13, 2025.

[9] Y. DU; X. CHEN; S. LI; A. S. BERROUK; W. REN; C. YANG. Revisiting a large-scale FCC riser reactor with a particle-scale model. CHEMICAL ENGINEERING SCIENCE. v. 249, p. 1-16, 2022. DOI: https://doi.org/10.1016/j.ces.2021.117300.

[10] O. J. I. Kramer; P. J. Moel; E. T. Baars; W. H. Van Vugt; J. T. Padding; J. P. Van Der Hoek. Improvement of the Richardson-Zaki liquid-solid fluidization model on the basis of hydraulics. Powder Technology, vol. 343, pp. 465 – 478, 2019. DOI: doi.org/10.1016/j.powtec.2018.11.018.

[11] M. A. Cremasco. Operações unitárias em sistemas particulados e fluidomecâmicos, São Paulo: Edgard Blucher, 2012.

[12] D. WANG; C. YAN; C. LU, R. LI, B. ZHAO, S. ZHANG Constraint strength and axial/radial particle velocity profiles for anintegrated riser outlet. PARTICUOLOGY, v. 21, p. 179-186, 2015. DOI: http://dx.doi.org/10.1016/j.partic.2014.08.009.

[13] F. LIU; C. LI; X. ZENG; J. CHEN; J. GUAN; L. YANG. Study on the flow and collision characteristics of catalyst particles in FCC reactor. POWDER TECHNOLOGY . v. 438, p. 1-13, 2024.

[14] H. CHEN; Y. DING; S. GU; C. GENG; W. SHENG. Experiential investigation of cluster velocity and slip velocity in the CFB riser. POWDER TECHNOLOGY. v. 370, p. 1-8, 2020. DOI: https://doi.org/10.1016/j.powtec.2020.05.034.