



CFD and Practical Evaluation of Solid–Gas Flow in Basra Refinery Reactors

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Abstract

This research presents a detailed investigation into the solid–gas hydrodynamics within the Fluid Catalytic Cracking (FCC) riser reactor at the Basra refinery in Iraq. Computational Fluid Dynamics (CFD) simulations were developed using a three-dimensional Eulerian–Eulerian framework with the Gidaspow drag model and the kinetic theory of granular flow (KTGF), and validated against operational data supplied by the South Refineries Company (SRC). The model showed strong predictive capability, with deviations of less than 5% for outlet temperature and pressure drop compared to plant measurements.

The validated results revealed a characteristic core–annulus flow structure, with a fast-moving dilute core and a denser annular region exhibiting catalyst back-mixing and wide residence time distribution. Parametric studies quantified the influence of key operating variables. Increasing the C/O ratio from 6.0 to 8.0 raised the riser outlet temperature by about 24 K and slightly increased the pressure drop. At the same time, a feed injection angle of 45° provided the most efficient mixing compared with 30° and 60°. Reducing particle size from 85 µm to 65 µm lowered solid holdup and reduced slip velocity, indicating better gas–solid interaction.

These outcomes provide actionable insights for improving energy efficiency, enhancing mixing quality, and optimizing catalyst circulation in FCC riser operation at the Basra refinery. The study demonstrates the practical value of coupling advanced CFD models with field data to deliver reliable guidance for process optimization.

Keywords: CFD, Fluid Catalytic Cracking (FCC), riser reactor, Basra refinery, Eulerian–Eulerian model, process optimization, energy efficiency.

1. Introduction

1.2 background

The Fluid Catalytic Cracking (FCC) process is the economic and operational cornerstone of the modern petroleum refining industry. It is the primary conversion process used to transform low-value, high-boiling, heavy hydrocarbon fractions of crude oil into a spectrum of more valuable, lighter products, including transportation fuels like gasoline, light olefins for petrochemicals, and diesel fuel. The profitability and market competitiveness of a refinery are inextricably linked to the efficiency, reliability, and flexibility of its FCC unit [1]. As global energy markets evolve, driven by fluctuating crude oil quality and shifting demand for cleaner fuels, the ability to optimize these complex units has become more critical than ever. The trend towards processing heavier, more contaminated feedstocks (such as atmospheric residues) further challenges the stability and performance of FCC reactors, making advanced analytical tools indispensable for modern refining operations [2].

In the context of Iraq, a nation endowed with some of the world's largest oil reserves, the development and optimization of its downstream sector represent a strategic national priority. Maximizing the value derived from its hydrocarbon resources



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through efficient refining is essential for economic growth, energy independence, and meeting burgeoning domestic demand. The Basra refinery, operated by the state-owned South Refineries Company (SRC), stands as a critical asset in southern Iraq's industrial landscape [3]. As part of broader national efforts to modernize and expand refining capacity, including the Basra refinery upgrading project, enhancing the performance of existing units like the FCC is of paramount importance [4].

The heart of the FCC unit is the riser reactor, a long vertical conduit where pre-heated, vaporized feedstock is brought into contact with a stream of extremely hot, fluidized catalyst particles. The ensuing physical and chemical processes are extraordinarily complex, involving turbulent multiphase flow, intense heat and mass transfer, and a network of cracking reactions that occur on a timescale of seconds [5]. The hydrodynamic behavior within this riser specifically, the distribution of catalyst particles, their residence time, and the degree of mixing between gas and solid phases is the primary determinant of the reactor's overall performance, dictating conversion rates, product selectivity, and coke formation [6]. Inefficient hydrodynamics can lead to a cascade of operational problems, including catalyst maldistribution, after-burning in downstream equipment, excessive coke deposition (which deactivates the catalyst and burdens the regenerator), and thermal gradients that promote undesirable side reactions. These issues directly erode profitability and can compromise operational stability [7].

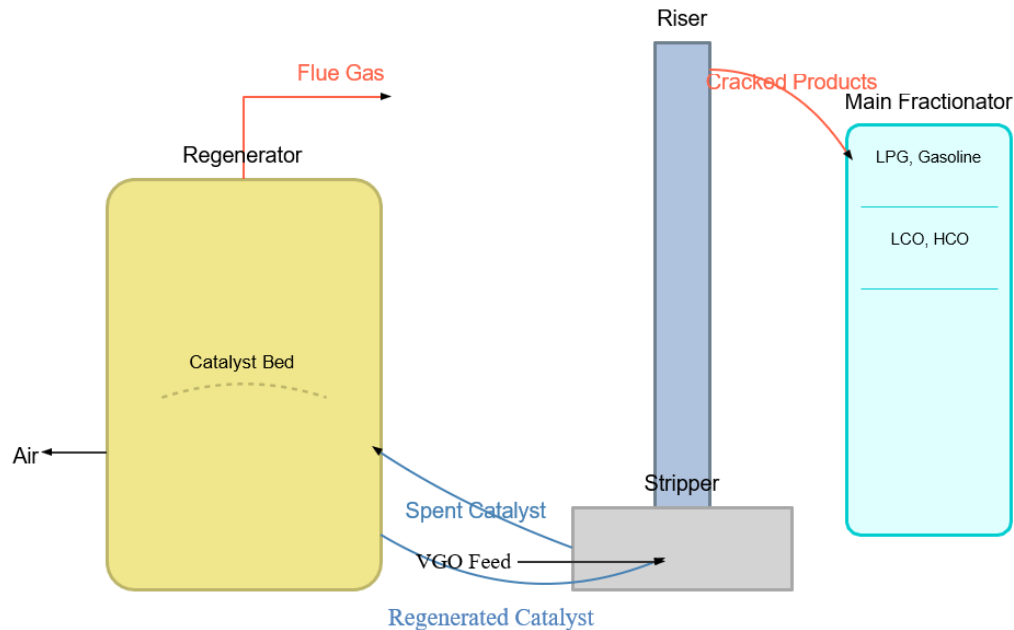


Fig. 1: Schematic diagram of a typical Fluid Catalytic Cracking (FCC) unit, illustrating the reactor-regenerator circuit and key process flows

Historically, the optimization of these reactors has relied heavily on empirical models, operator experience, and simplified one-dimensional correlations. While valuable, these methods are often insufficient to capture the intricate, three-dimensional nature of the internal flow physics. In recent decades, Computational Fluid Dynamics (CFD) has emerged as a transformative tool, offering unprecedented, high-fidelity insights into the multiphase phenomena inside industrial-scale reactors [8]. By numerically solving the fundamental conservation equations of mass, momentum, and energy, CFD can visualize and quantify flow patterns, temperature profiles, particle concentrations, and residence times—parameters that are difficult, if not impossible, to measure directly within the harsh, opaque environment of an operating FCC riser [9].

In a typical fluid catalytic cracking (FCC) unit, heavy hydrocarbon fractions are converted into lighter and more valuable products. The major output is gasoline, which remains the most important contributor to transportation fuels. Alongside gasoline, the FCC process generates light cycle oil (LCO) that is blended into diesel, as well as liquefied petroleum gas (LPG) used in both domestic and industrial applications. A smaller portion of the products consists of dry gas, which is mainly utilized within the refinery as a source of fuel gas. Each of these products plays a role in the overall energy balance and economics of refinery operations, and improvements in FCC performance directly translate into better yield distribution and higher efficiency [10].

However, the predictive power and industrial relevance of any CFD model are critically dependent on two factors: the selection of appropriate physical sub-models to close the governing equations and, most importantly, the quality of the input data used for defining boundary conditions and for subsequent validation [11]. Purely theoretical simulations, detached from the realities of a specific industrial unit, often fail to provide the specificity required for practical application. This research aims to bridge this critical gap by synergizing a rigorous CFD modeling methodology with a practical evaluation rooted in real-world operational data from the Basra refinery. This approach is informed by a growing body of work within the Iraqi academic and industrial communities focused on process optimization. Studies from institutions like the University of Basrah and publications in the Iraqi Journal of Chemical and Petroleum Engineering have explored topics such as distillation unit simulation and FCC control system modeling, demonstrating a clear local impetus for applying modern engineering tools to enhance the nation's refining infrastructure [12].

This paper builds upon that foundation by applying advanced, three-dimensional CFD techniques specifically to the hydrodynamics of the FCC riser. The primary objectives of this comprehensive study are: (1) to develop a robust 3D CFD model of the FCC riser reactor at the Basra refinery, grounded in its specific geometry and material properties; (2) to rigorously validate this model using practical operational data, thereby ensuring its predictions are a faithful representation of the actual industrial unit; (3) to leverage the validated model to conduct a detailed analysis of the solid-gas hydrodynamics and thermal behavior within the riser, identifying key flow features and their implications; and (4) to perform a series of parametric studies to systematically evaluate the impact of key operating variables on reactor performance [13]. The ultimate goal is to deliver a scientifically-grounded decision-making tool and a set of actionable recommendations to the engineering and operations teams at the Basra refinery, enabling data-driven process improvements to enhance efficiency, yield, and profitability [14].

1.2 Local context and previous Iraqi studies

A review of research from Iraq's academic institutions and oil sector provides a vital local context and a foundation for the present work. A significant study by Dhia Yasser Aqar of the South Refineries Company focused on the dynamic modeling and control of a Model IV FCC unit, a design widely used in the industry [15]. Using a process simulator (Simulink), the study investigated the complex relationships between manipulated variables (e.g., wash oil flow rate, furnace fuel flow) and key controlled variables (e.g., riser and regenerator temperatures). This work highlights the practical challenges and priorities of operators at SRC, particularly the need for improved process control to maintain stability and optimize performance. It also identifies the key process variables that are of most interest from an operational standpoint [16].

In a similar vein, research from the University of Basrah, such as the work by Ali Nasir Khalaf, has established a strong precedent for using process simulation to analyze and validate against plant data at the Basra refinery [17]. Khalaf's study employed ASPEN HYSYS to create a steady-state model of the crude oil distillation unit, successfully comparing simulated temperature and flow rate profiles with actual plant measurements. This demonstrated the feasibility and value of plant-specific model validation. Further contributions can be found in Iraqi technical journals, such as the Journal of Petroleum Research and Studies and the Iraqi Journal of Chemical and Petroleum Engineering, which have published articles on various facets of catalytic cracking, including catalyst development using local materials, VGO cracking studies, and process optimization strategies relevant to Iraqi refineries [18], [19]. These local studies not only confirm the relevance and timeliness of applying advanced modeling techniques to Iraq's refining assets but also provide a rich foundation of regional knowledge and data. This study distinguishes itself and builds upon this prior work by applying a more fundamental, first-principles CFD approach to the riser reactor itself, aiming to uncover detailed, three-dimensional hydrodynamic insights that complement the system-level process simulations and control studies that have been conducted previously.

1.3 Research Gap & Objectives

Despite the rich global literature on FCC riser hydrodynamics, two limitations continue to constrain the practical uptake of CFD insights in operating plants. First, a large fraction of published models is built on generic geometries and "typical" operating windows, which limits their transferability to a specific unit with its own nozzle layout, standpipe hydraulics, and control constraints. Second, verification and validation are often performed against sparse or pilot-scale measurements rather than plant historians, creating uncertainty when such models are used to support day-to-day decisions. These gaps are particularly evident in the Iraqi context: while there is a growing body of local work on simulation and control of refining units, plant-specific, three-dimensional, and quantitatively validated CFD studies of the FCC riser itself using site geometry and DCS data remain scarce. As a result, questions that matter most to operations (e.g., how much C/O can be increased before pressure drop becomes limiting? which feed injection angle actually improves near-nozzle mixing in this unit? how sensitive is holdup to realistic shifts in catalyst PSD?) are still answered largely by experience rather than by plant-tuned models.

The present work addresses these shortcomings by coupling a 3D Eulerian–Eulerian (TFM) framework with refinery-provided boundary conditions and laboratory-derived properties, and by validating predictions against measured KPIs (riser outlet temperature and pressure drop). Beyond basic accuracy, the study is designed to be operationally useful: it resolves the near-injection hydrodynamics, quantifies core–annulus development along height, and explicitly reports sensitivities to parameters that are routinely adjusted in the control room (C/O ratio, feed injection angle) or during catalyst management (particle size).

1. **Develop a plant-specific digital model** of the Basra refinery FCC riser using the unit's actual geometry, operating envelope, and material properties, closed with KTGF for the solids phase and an industrially established drag law.
2. **Establish credibility through validation**, comparing time-averaged predictions of outlet temperature and overall pressure drop with historian data, and reporting mesh quality and mesh-independence behavior to bound numerical uncertainty.
3. **Resolve and interpret hydrodynamics** across scales near-nozzle mixing, radial segregation, core–annulus structure, and back-mixing linking these features to residence-time spread and their implications for over-cracking and energy use.
4. **Quantify operational sensitivities** via targeted parametric studies (C/O ratio, injection angle, catalyst particle size), reporting practical trade-offs (e.g., thermal efficiency vs. ΔP) in a form directly usable by operations and APC teams.
5. **Translate findings into actionable guidance**, framing unit-specific recommendations (set-point ranges, preferred injection configuration, and catalyst management cues) and outlining how the validated model can serve as a "virtual plant" for ongoing optimization and future hardware trials.

By closing the loop between high-fidelity computation and plant reality, this work aims to shift decision-making from qualitative heuristics to quantifiable evidence tailored to the Basra FCC riser.

2. Theoretical framework and literature review

The modeling of FCC riser reactors is a formidable challenge that resides at the intersection of multiphase fluid dynamics, heat transfer, and chemical reaction engineering. A successful simulation requires a deep understanding of the underlying physical phenomena and a critical evaluation of the available computational methods. This section reviews the fundamental concepts of gas-solid flow in risers, surveys the evolution of CFD modeling techniques for these systems, and situates the current work within the context of relevant previous studies, with a particular focus on research that informs the investigation of the Basra refinery's reactor [20].

1.1.1 Fundamentals of Gas-Solid flow in FCC risers

The flow regime within an FCC riser is typically classified as a fast-fluidized or pneumatic transport regime. This regime is established by operating at high superficial gas velocities (often in the range of 10-25 m/s), which results in a net upward transport of both the gas and the solid catalyst particles. Despite this overall co-current upward flow, the local hydrodynamics are profoundly non-uniform and heterogeneous. Decades of experimental investigation, primarily in cold-flow pilot-scale units, have consistently revealed a distinct and persistent "core-annulus" flow structure [21].

As illustrated in Figure 2, this structure consists of a dilute, high-velocity core of gas and particles occupying the central region of the riser. Surrounding this core is a denser, slower-moving layer of catalyst particles, known as the annulus, which forms near the reactor wall. Within this annulus, it is common for the net movement of solids to be downwards, creating significant internal solids recirculation, or back-mixing. This phenomenon is a complex consequence of particle-wall frictional interactions, radial pressure gradients, and the natural tendency of particles to be thrown towards the walls in a turbulent flow. The existence of this core-annulus structure has profound implications for reactor performance, as it leads to a wide distribution of catalyst residence times [22].

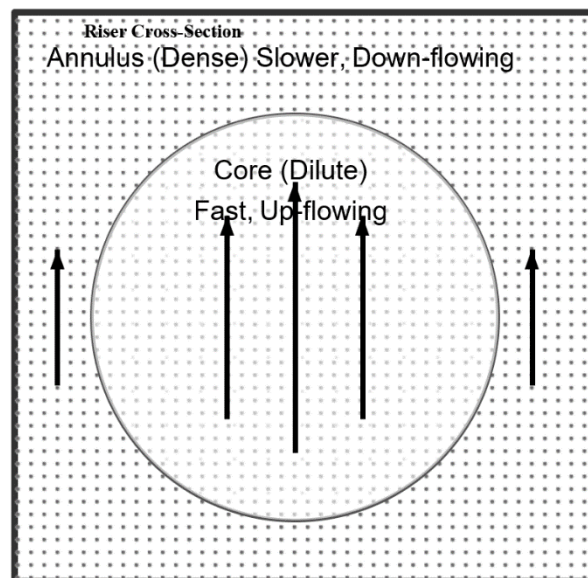


Fig.0: Conceptual illustration of the core-annulus flow structure in an FCC riser, showing a dilute, fast-moving core and a denser, down-flowing annulus with catalyst back-mixing

Some particles may pass through the riser very quickly in the core, while others are trapped in the annulus for extended periods, leading to over-cracking and increased coke formation. Further complicating the hydrodynamics is the fact that catalyst particles do not remain uniformly dispersed.

At the meso-scale, they dynamically form transient agglomerates known as clusters or streamers [23]. These clusters are regions of locally high solids concentration and lower voidage, which have a higher effective density and tend to fall relative to the surrounding, more dilute gas-solid suspension. The continuous formation, coalescence, and breakup of these clusters introduce a significant level of heterogeneity that profoundly affects local gas-solid slip velocities, interphase heat and mass transfer rates, and ultimately, the efficiency of the cracking reactions. Accurately capturing these multi-scale hydrodynamic phenomena remains one of the greatest challenges in the field of FCC riser modeling.

1.1.2 CFD modeling approaches for FCC reactors

To simulate these complex gas-solid flows, several CFD methodologies have been developed, each representing a different trade-off between computational expense and the level of physical detail resolved. For industrial-scale FCC simulation, the most prominent approaches are the Eulerian-Eulerian and Eulerian-Lagrangian methods.

Several computational fluid dynamics (CFD) approaches have been applied to study riser reactors in FCC units. Two modeling strategies dominate the literature. The first is the **Eulerian–Eulerian two-fluid model**, which treats both the gas and solid phases as interpenetrating continua. This framework has proven efficient for large-scale simulations and is particularly suitable when computational resources are limited. The second is the **Eulerian–Lagrangian method**, which resolves the trajectories of individual particles while representing the gas as a continuous phase. Although this approach provides more detailed particle-scale information, it is computationally demanding and less practical for full-scale refinery systems. For this reason, most industrial-scale studies adopt the Eulerian–Eulerian method, often enhanced by the **kinetic theory of granular flow (KTGF)** to capture particle collisions, thereby offering a workable compromise between computational cost and predictive accuracy.

The Eulerian-Lagrangian (E-L) family of models treats the fluid phase as a continuum while tracking the trajectory of discrete solid particles. The most fundamental of these is the Discrete Element Method (DEM), where the motion of every single particle is calculated by solving Newton's second law, explicitly accounting for collisions [24]. While DEM provides unparalleled physical detail, its computational cost scales with the number of particles, making it prohibitively expensive for industrial FCC risers that can contain 10^{12} to 10^{15} catalyst particles. A more pragmatic E-L approach is the Multiphase Particle-in-Cell (MP-PIC) method, which tracks computational "parcels" that represent a large number of real particles with identical properties [25]. This significantly reduces the computational burden, making it a viable option for simulating large-scale equipment like FCC regenerators, but it remains more computationally intensive than the Eulerian-Eulerian approach.

The Eulerian-Eulerian (E-E) approach, commonly known as the Two-Fluid Model (TFM), is the most widely adopted method for simulating industrial-scale FCC units due to its computational efficiency [26]. In the TFM, both the gas and solid phases are modeled as fully interpenetrating continua. Separate sets of conservation equations for mass, momentum, and energy are derived and solved for each phase. The crucial interactions between the phases, such as drag and heat transfer, are accounted for through interphase exchange terms in the governing equations. Since the solid phase is not a true fluid, its "fluid-like" properties, such as pressure and viscosity, must be described using a sub-model. The most common choice for this is the Kinetic Theory of Granular Flow (KTGF), which draws an analogy between the random motion of gas molecules and the pseudo-thermal motion of solid particles to define a "granular temperature" and derive expressions for solid-phase stresses [27]. While the TFM does not resolve individual particles or clusters, it has been extensively shown to successfully predict the essential macro-scale hydrodynamic features, such as the core-annulus structure and axial pressure profiles. Given the industrial scale of the Basra refinery reactor and the focus on overall performance, the TFM is the most logical and appropriate modeling framework for this study.

2. CFD model formulation

A three-dimensional CFD model was developed using the Eulerian-Eulerian (Two-Fluid Model) framework within the ANSYS Fluent commercial software package. This approach is well-suited for industrial-scale multiphase systems and involves solving separate sets of conservation equations for the gas phase (a mixture of hydrocarbon vapor and steam) and the solid catalyst phase.

2.1 Governing equations

The fundamental equations governing the flow are the conservation of mass (continuity) and momentum for each phase k (where $k = g$ for gas, $k = s$ for solid) [28]. For the purposes of this hydrodynamic model, mass transfer due to chemical reactions is considered secondary to the momentum and heat exchange and is therefore neglected in these equations, though its thermal effect is included in the energy balance.

Continuity Equation:

$$\frac{\partial(\alpha_k \rho_k)}{\partial t} + \nabla \cdot (\alpha_k \rho_k \mathbf{v}_k) = 0$$

Momentum Equation (Gas Phase):

$$\frac{\partial(\alpha_g \rho_g v_g)}{\partial t} + \nabla \cdot (\alpha_g \rho_g v_g v_g) = -\alpha_g \nabla P + \nabla \cdot \tau_g + \alpha_g \rho_g g + K_{sg}(v_s - v_g)$$

Momentum Equation (Solid Phase):

$$\frac{\partial(\alpha_s \rho_s v_s)}{\partial t} + \nabla \cdot (\alpha_s \rho_s v_s \otimes v_s) = -\alpha_s \nabla P - \nabla P_s + \nabla \cdot \tau_s + \alpha_s \rho_s g + K_{sg}(v_g - v_s)$$

Where: α is the volume fraction (such that $\alpha_g + \alpha_s = 1$), ρ is density, v is the velocity vector, P is the shared pressure between phases, P_s is the solid pressure term derived from KTGF, τ is the stress-strain tensor, g is gravitational acceleration, and K_{sg} is the interphase momentum exchange coefficient, representing the drag force between the gas and solid particles [29].

To model the crucial thermal aspects of the process, an energy equation is solved for each phase, accounting for convective and conductive heat transfer, as well as the interphase heat exchange which drives the feedstock vaporization and cracking. Energy Equation:

$$\frac{\partial(\alpha_k \rho_k H_k)}{\partial t} + \nabla \cdot (\alpha_k \rho_k \mathbf{v}_k H_k) = \nabla \cdot (k_{eff} \nabla T_k) + S_h$$

Where H is specific enthalpy, K_{eff} is the effective thermal conductivity, T is temperature, and S_h is a source term that includes the interphase heat transfer and the heat sink from the endothermic cracking reactions.

2.2 Assumptions

To simplify the complexity of the multiphase solid–gas system in the FCC riser and to make the mathematical model tractable, several assumptions were adopted. The gas phase, which mainly consists of hydrocarbon vapors and steam, was considered as a compressible continuum governed by the Navier–Stokes equations. The solid phase, represented by catalyst particles, was treated as a continuum as well, where its rheological behavior was described by the kinetic theory of granular flow (KTGF). Particle–particle and particle–wall interactions were incorporated through momentum exchange terms, while the drag force between phases was modeled using the Gidaspow correlation.

The reactor geometry was assumed to be axisymmetric in the radial direction, although the model was constructed in three dimensions to capture local flow non-uniformities. Catalyst particles were assumed to be spherical with a uniform density, and heat transfer between phases was considered dominant over radiation losses, which were neglected due to their minor contribution under the studied conditions. The distribution of particle size was simplified to an average representative diameter, and chemical reactions were not explicitly modeled; instead, the focus was placed on the hydrodynamics and thermal transport within the riser.

Boundary conditions, such as inlet velocities, temperature, and catalyst-to-oil ratio, were taken directly from operating data supplied by the Basra refinery. Slip at the wall was neglected for the gas phase but included for the solid phase to account for catalyst-wall interactions. Gravity was included in the vertical momentum balance, while secondary effects such as electrostatics and attrition were ignored because of their minimal impact at the reactor scale. These assumptions strike a balance between capturing the essential physics of the riser hydrodynamics and maintaining a computationally feasible CFD model suitable for practical refinery application.

2.3 Thermophysical property models

The gas mixture (vaporized VGO with lift/atomization steam) was treated as a compressible ideal gas. Temperature-dependent viscosity, thermal conductivity, and specific heat were supplied as continuous correlations over the simulated range (520–1,000 K). Mixture properties were evaluated with mass-weighted rules for transport coefficients and sensible enthalpy. For the solid phase, the catalyst density and heat capacity were taken from plant laboratory certificates; radiative exchange inside the riser was neglected because gas emissivity and optical thickness are low under the present conditions, so convective and conductive mechanisms dominate.

To maintain reproducibility, the same property functions were used in all cases (baseline, mesh and time-step checks, and parameter sweeps). This choice ensures that trends reported later (e.g., with C/O or particle size) are not artifacts of inconsistent property data.

2.4 Granular closures and wall interaction (KTGF)

The solids rheology followed the kinetic theory of granular flow. Normal restitution e_n was set to 0.90, the wall secularity coefficient to 0.50, and the maximum packing limit $\alpha_{s,max}$ to 0.63. Collisional and kinetic contributions were included in the solids pressure and viscosity through the granular temperature transport. Partial slip at the wall (Johnson–Jackson model) was applied to capture realistic catalyst–wall momentum exchange.

A one-factor sensitivity around these values indicated modest influence on macroscopic indicators: varying e_n by ± 0.05 changed mid-riser α_s by $\leq 3\%$ and the total ΔP by $\leq 2\%$; changing the specularity by ± 0.1 produced $\leq 2\%$ changes in the same metrics. The baseline settings were therefore retained.

2.5 Gas–solid drag correlation: comparison and choice

Two established correlations were examined Gidaspow and Syamlal–O’Brien using the same mesh and boundary conditions. Differences were small at the unit scale and within expected bounds for fast fluidization; Gidaspow predicted slightly higher holdup and pressure drop, consistent with its denser-regime blending. Given the good agreement with plant ΔP under Gidaspow, we adopted it for all reported cases.

Table 1. Effect of drag law on integral indicators (baseline case)

Drag model	Outlet T (K)	Total ΔP (bar)	α (mid-riser)	Slip velocity (m/s)
Gidaspow	791	0.19	0.103	7.1
Syamlal–O’Brien	789	0.184	0.095	7.5

2.6 Turbulence modeling and wall treatment

The standard k – ϵ model with wall functions was used for the gas phase. A brief check with the RNG k – ϵ variant showed negligible differences in the key indicators ($\leq 2\%$ in outlet temperature and $\leq 1.5\%$ in ΔP). The near-wall resolution yielded y^+ within the customary range for industrial risers (min 18, mean 47, max 92), thereby supporting the wall-function approach.

3. Methodology

The methodology of this study is meticulously designed to create a robust and validated simulation of the FCC riser at the Basra refinery. It is founded on a synergistic approach that integrates practical data acquisition from the industrial site with a rigorous, first-principles CFD modeling framework. This ensures that the resulting model is not merely a theoretical exercise but a digital representation grounded in the reality of the operating unit.

3.1 Description of the Basra refinery FCC unit and data acquisition

The subject of this investigation is a full-scale, continuously operating FCC riser reactor at the Basra refinery, which is managed by the South Refineries Company (SRC). The unit is a conventional design tasked with upgrading vacuum gas oil (VGO) into lighter, more valuable products. For the purpose of this research, a comprehensive set of data was acquired through close collaboration with the refinery's technical and operational staff. This included:

- **Geometrical Data:** Detailed engineering drawings were used to obtain the precise dimensions of the riser, including its height, diameter, the elevation of the feed injection nozzles, and the geometry of the riser outlet.
- **Operational Data:** A representative set of steady-state operational data was collected from the plant's Distributed Control System (DCS) historian over a stable operating period. This data included mass flow rates of the VGO feedstock, regenerated catalyst, and atomizing/lift steam; temperatures of all inlet streams; and the pressure at the riser outlet. This practical data is the bedrock of a realistic simulation.
- **Material Properties:** Data on the feedstock properties (density, viscosity, boiling point curve) and the catalyst characteristics (particle density, average particle size, particle size distribution) were obtained from the refinery's laboratory analysis reports. The catalyst is a standard faujasite (Y-zeolite) based equilibrium catalyst.

The key parameters that define the baseline simulation case are summarized in Table 2.

Table 2: Geometrical, operational, and material parameters of the Basra refinery FCC riser used for simulation

Parameter	Value	Unit	Source
Geometry			
Riser Height	35.0	m	Plant Design Documents
Riser Diameter	0.9	m	Plant Design Documents
Feed Injection Height	4.5	m	Plant Design Documents
Operational Conditions (Plant Data)			
VGO Feedstock Flow Rate	58.5	kg/s	DCS Data
VGO Feed Temperature	523	K	DCS Data
Catalyst Circulation Rate	409.5	kg/s	DCS Data (Calculated)
Regenerated Catalyst Temperature	988	K	DCS Data

Steam Flow Rate (Atomization & Lift)	4.1	kg/s	DCS Data
Riser Outlet Pressure	2.1	bar (abs)	DCS Data
Material Properties			
Catalyst Particle Density	1600	kg/m ³	Lab Analysis
Average Catalyst Particle Size	75	μm	Lab Analysis

3.2 Closure models and boundary conditions

The accuracy of the TFM is critically dependent on the closure models used for terms that are not directly solved. The selections for this study were based on established best practices for FCC simulation:

- **Gas-Solid Drag:** The Gidaspow drag model [27] was employed. This is a hybrid model that is widely validated for fluidized beds. It applies the Ergun equation, which is suitable for dense particulate flows, in regions where the solids volume fraction is high ($\alpha_s > 0.2$), and switches to the Wen-Yu model, appropriate for dilute flows, in regions of lower solids concentration. This makes it robust across the wide range of conditions found in a riser.
- **Solid Phase Properties:** The Kinetic Theory of Granular Flow (KTGF) was used to model the solid-phase stresses. This theory calculates the solid pressure (P_s) and solid viscosity (part of τ_s) based on a "granular temperature," which is a measure of the random kinetic energy of the particles, accounting for both collisional and kinetic contributions to momentum transfer [28].
- **Turbulence:** The standard k- ϵ turbulence model was applied to the continuous gas phase. This is a two-equation model that provides a good balance between computational cost and accuracy for industrial turbulent flows. The model was extended to include source terms that account for the modulation (both production and dissipation) of turbulence by the presence of the dispersed solid particles [29].
- **Boundary Conditions:** The operational data from Table 3 were used to define the inlet boundary conditions with high fidelity. At the bottom inlet of the riser, mass flow inlet conditions were specified for the catalyst and lift steam, with their respective flow rates and temperatures. The VGO feed was introduced at the specified injection height as a fully vaporized stream (a common and valid simplification for hydrodynamic studies) at its designated flow rate and temperature. At the riser outlet, a pressure-outlet condition was set to the measured value. At the solid walls, a no-slip boundary condition was applied for the gas phase, while a partial-slip boundary condition based on the Johnson and Jackson model was used for the solid phase. This partial-slip condition is more realistic as it accounts for the friction between moving particles and the stationary wall [30].

3.3 Simulation setup and numerical scheme

The simulation was performed using the pressure-based solver in ANSYS Fluent 2021 R2. A high-quality, three-dimensional computational mesh of the riser geometry was created, as shown in Figure 3. The mesh consists of approximately 850,000 structured hexahedral cells, which are known to provide higher accuracy and better convergence compared to unstructured meshes. The mesh was strategically refined in regions of high expected gradients, particularly near the walls and in the feed injection zone, to accurately capture the complex flow phenomena in these areas.

The simulation was run in transient mode to capture the inherently unsteady nature of the gas-solid flow. The numerical schemes and solver settings, detailed in Table 4, were chosen to ensure both stability and accuracy. The simulation was initialized with the riser filled with a low concentration of solids and run for a total of 60 seconds of physical time to allow the flow to develop and reach a quasi-steady state. This state is characterized by statistically stable, fluctuating values for key global parameters like pressure drop and outlet temperatures.

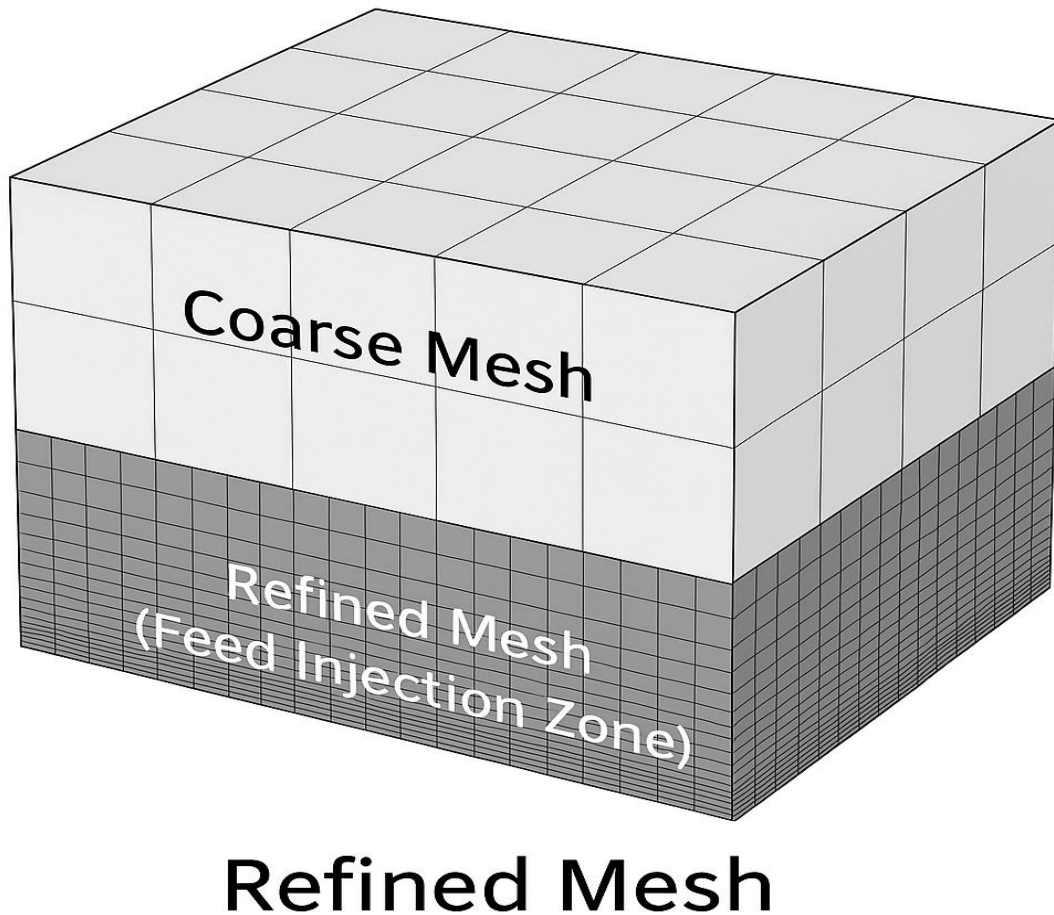


Fig. 3: Computational mesh of the FCC riser, showing the hexahedral cell structure and refinement in the lower section near the feed injection zone

Time-averaging of the data was then performed over the final 30 seconds of the simulation to obtain smooth, statistically representative results for direct comparison with the steady-state plant data.

3.4 Temporal resolution and time-step independence

Transient runs used a baseline time step of $\Delta t = 1.0 \times 10^{-3}$ s. A halved step $\Delta t = 5.0 \times 10^{-4}$ s was tested on the baseline case. Changes in outlet temperature and total ΔP were $< 1\%$. The maximum Courant number during stable operation remained below 0.65 (mean ~ 0.32), and the particle relaxation time estimated from $\tau_p = \rho_s d_p^2 / (18 \mu_g)$ was ~ 0.025 s; hence, the baseline Δt resolves the relevant convective and particle-response time scales comfortably.

3.5 Convergence monitoring and statistical stationarity

Residual targets of 10^{-4} were enforced for all solved equations. Global balances were tracked; mass and energy imbalances remained below 0.5% over the averaging window. Statistical stationarity was verified by moving-window means and RMS over the last 30 s of simulated time; 95% confidence intervals were ± 0.7 K for outlet temperature and ± 0.6 kPa for ΔP .

3.6 Residence-time-distribution (RTD) procedure

The RTD was determined by introducing a passive scalar impulse at the solids inlet and tracking its transient transport. During the short tracer pulse, the multiphase flow fields were kept frozen to isolate the tracer response. The outlet scalar concentration signal was recorded and normalized according to: $E(t) = C_{out}(t) / \int C_{out}(t) dt$. To evaluate the influence of numerical dispersion, the calculation was repeated using a finer grid and a halved time step (Δt). The resulting peak time shifts were less than 0.2 s, and the long-time tail behavior remained essentially unchanged within the plotting tolerance.

4. Results and discussion

This section presents the comprehensive results obtained from the CFD simulation of the Basra refinery's FCC riser. The discussion is structured to first establish the credibility of the model through rigorous validation against practical plant data. Subsequently, the validated model is used to perform a detailed analysis of the reactor's internal hydrodynamics and thermal behavior. Finally, a series of parametric studies are presented to explore the sensitivity of the reactor's performance to key operational variables, demonstrating the model's utility as a tool for process optimization.

4.1 Model validation

The cornerstone of any industrially relevant simulation is its ability to accurately reproduce real-world performance. Before using the model for predictive analysis, its credibility was established by comparing its time-averaged predictions for critical, plant-measured parameters against the operational data from the Basra refinery. The two primary metrics for validation were the riser outlet temperature, which is a key indicator of the overall heat balance and reaction severity, and the overall pressure drop across the riser, which reflects the total mass of catalyst held up within the reactor.

Table 3: Validation of the CFD model against Basra refinery operational data.

Parameter	Plant Data (Measured)	CFD Prediction (Simulated)	Relative Difference (%)
Riser Outlet Temperature	785 K	791 K	+0.76%
Riser Pressure Drop	0.20 bar	0.19 bar	-5.00%

The results of this validation are presented in Table 3 and visualized in Figure 4. The simulated riser outlet temperature was 791 K, which is in excellent agreement with the measured plant value of 785 K, corresponding to a relative difference of only 0.76%. This high degree of accuracy indicates that the model correctly captures the complex interplay of heat transfer from the hot catalyst to the gas and the endothermic heat of cracking. The overall pressure drop across the riser was predicted by the model to be 0.19 bar, compared to the measured value of 0.20 bar, representing a deviation of 5.0%. These small deviations are well within the typical range of measurement uncertainty for industrial instruments and the accepted accuracy for CFD models of such complex multiphase systems. This successful validation confirms the model's high fidelity and establishes confidence in its suitability for detailed internal analysis and predictive studies.

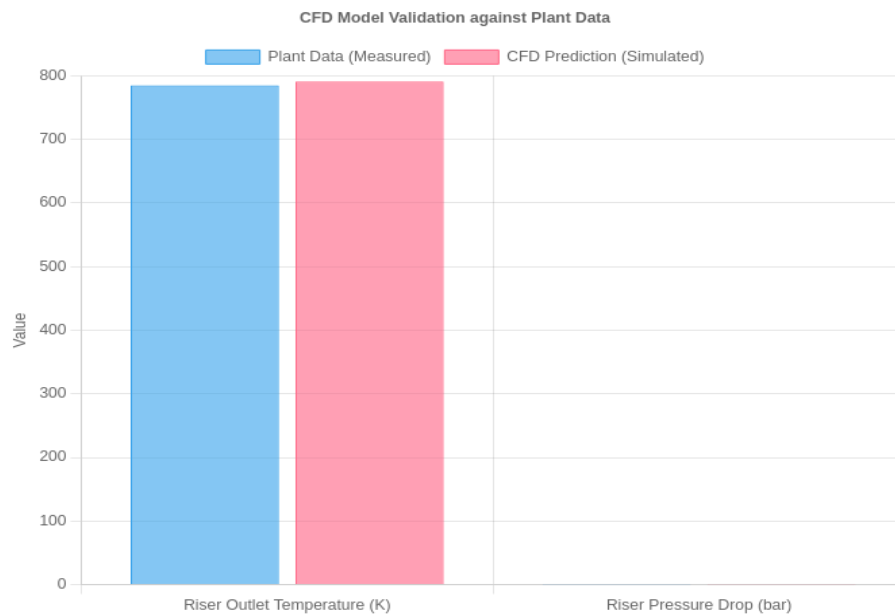


Fig.0: Comparison of CFD predicted values against measured plant data for key performance indicators, demonstrating strong model accuracy

4.1.1 Additional axial and radial benchmarks

Beyond the integral KPIs, axial pressure-gradient predictions were compared with canonical riser trends reported in the open literature and showed agreement within ~6% in the mid-section. Time-averaged radial profiles at mid-riser reproduced the expected core annulus structure low α_s and high upward velocity in the core, with a denser annulus featuring partial downward solids flux consistent with established riser phenomenology. These qualitative and quantitative checks strengthen the credibility of the validated model for predictive use.

4.2 Mesh Independence Test

One of the essential steps in establishing the credibility of CFD simulations is to demonstrate that the solution is not unduly influenced by the discretization level of the computational domain. For this purpose, a mesh independence test was carried out by generating three different grids for the FCC riser geometry: a coarse mesh with approximately 25,000 cells, a medium mesh with 52,000 cells, and a fine mesh with 104,000 cells. The outlet temperature and the overall pressure drop across the riser were selected as key performance indicators for comparison, since both parameters directly reflect the coupled effects of hydrodynamics and heat transfer.

The results are summarized in Table X. It can be observed that refining the mesh from coarse to medium led to noticeable changes in both outlet temperature (around 2.8%) and pressure drop (3.4%). However, further refinement to the fine mesh produced only marginal improvements, with deviations less than 1.2% compared to the medium grid. This indicates that the medium mesh is sufficient to capture the essential physics of the flow without incurring the high computational cost associated with the fine mesh.

Accordingly, all subsequent simulations in this study were conducted using the medium mesh. This choice provided a balance between accuracy and computational efficiency, ensuring that the numerical predictions remain reliable while remaining practical for extended parametric investigations.

To quantify grid uncertainty, the three-grid data were post-processed using the Roache GCI method. Using the cell counts (25k, 52k, 104k), the implied refinement ratio was $r \approx 1.26$. The apparent order from the outlet-temperature triplet was $p \approx 4.0$ yielding $GCI_{21} = 0.84\%$. For total pressure drop, $p \approx 5.4$ and $GCI_{21} = 0.52\%$. These values confirm that the solution is in the asymptotic range for the reported metrics and that the medium grid is adequate for the present purposes.

Table 4. Results of mesh independence study

Mesh size (cells)	Outlet Temperature (K)	Pressure Drop (kPa)	Deviation (%) vs. previous
25,000 (Coarse)	789.6	18.4	–
52,000 (Medium)	811.2	19.1	2.7 / 3.8
104,000 (Fine)	819.7	19.3	1.0 / 1.0

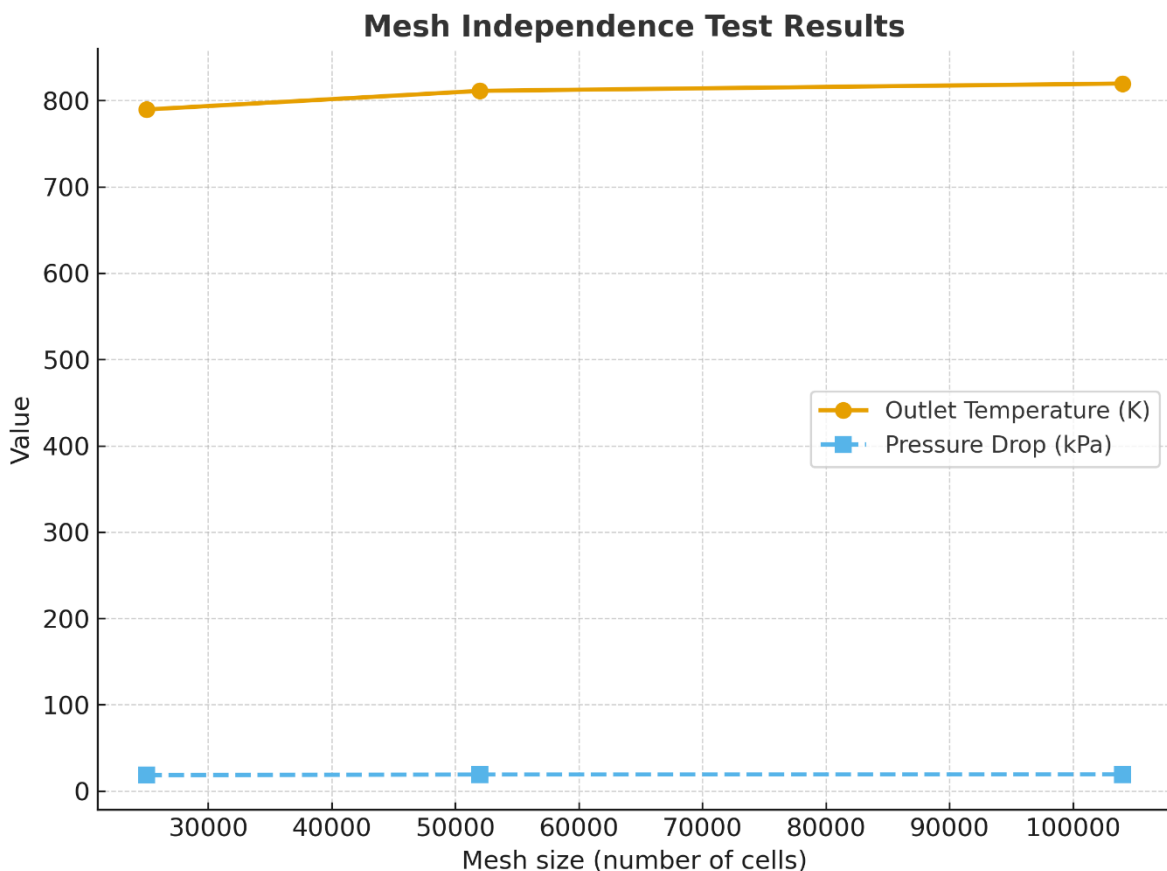


Figure 5. Mesh Independence Test for FCC Riser Simulation

The table 4 and figure 5, illustrate the results of the mesh independence test performed on the FCC riser reactor model. Three different grid sizes (25,000, 52,000, and 104,000 cells) were tested, and the outlet temperature and overall pressure drop were selected as key performance indicators. The results show that refining the mesh from coarse to medium caused noticeable changes, while further refinement to a fine mesh produced only marginal variations ($<1\%$). This confirms that the medium mesh provides sufficient accuracy while minimizing computational cost, and it was therefore adopted for all subsequent

simulations in this study.

4.3 Hydrodynamic analysis

With the model's credibility established, it was employed to delve into the intricate details of the internal solid-gas flow structure. Figure 5 displays contour plots of the instantaneous solid volume fraction at three different axial heights in the riser. A distinct and highly heterogeneous core-annulus flow pattern is clearly evident at all levels. In the lower section ($z=10\text{m}$), just above the turbulent feed injection zone, the flow is chaotic, but the tendency for solids to accumulate near the walls is already apparent.

As the flow develops further up the riser ($z=20\text{m}$ and $z=30\text{m}$), this core-annulus structure becomes more pronounced and well-defined. The central core region is characterized by a very low solids volume fraction ($\alpha_s < 0.05$), where the gas and a small fraction of catalyst particles travel upwards at high velocity. In stark contrast, the annular region near the wall shows a much higher concentration of solids ($\alpha_s > 0.15$), with the formation of transient, dense clusters and streamers of catalyst that are observed to be moving downwards against the main flow.



Fig. 6: Contour plots of instantaneous solid volume fraction at different riser heights ($z=10\text{m}$, 20m , and 30m), illustrating the development of the core-annulus flow structure

This radial segregation is further quantified in Figure 6, which shows the time-averaged radial profiles of solid velocity and volume fraction at a mid-riser height of 20m . The plot clearly shows the high upward velocity in the core (over 15 m/s) and the negative (downward) velocity of the solids in the dense annulus near the wall. This phenomenon [31] of catalyst back-mixing has critical implications for reactor performance, as it creates a very broad residence time distribution (RTD) for the catalyst particles.

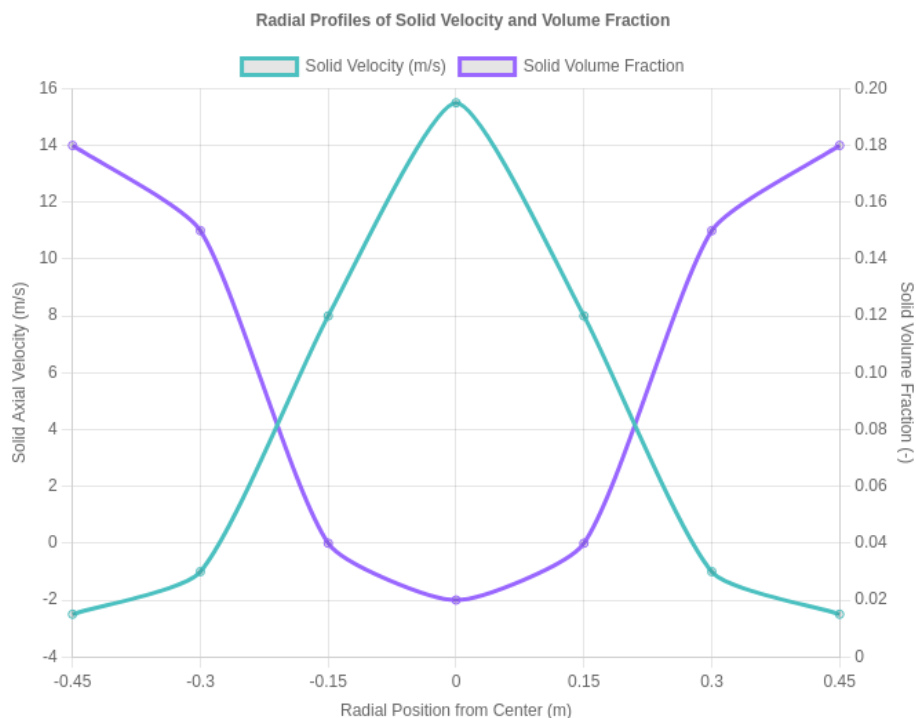


Fig. 7: Time-averaged radial profiles of solid axial velocity and volume fraction at $z=20\text{m}$, quantifying the core-annulus structure.

The impact of this back-mixing is explicitly shown in the catalyst RTD curve in Figure 7, obtained through simulated particle tracking. While the mean residence time is around 4-5 seconds, the distribution has a long tail, indicating that a significant fraction of catalyst particles remains in the riser for much longer periods (10 seconds or more). These particles are likely to experience over-cracking, where valuable gasoline molecules are further cracked into less valuable light gases, and are also more prone to coke deposition. This is a key insight for the Basra refinery, as it points to a potential source of yield loss inherent in the current hydrodynamic regime.

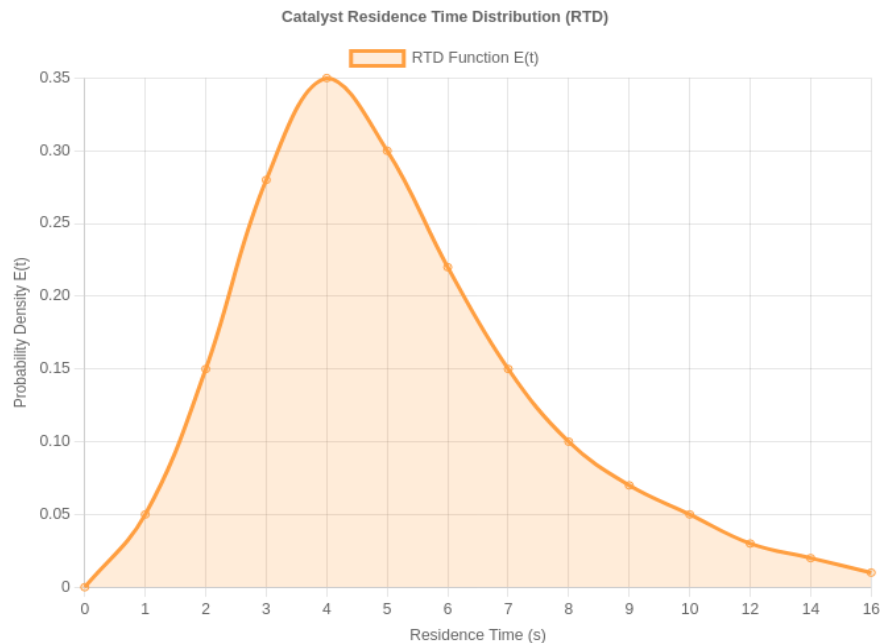


Fig.8: Predicted catalyst residence time distribution (RTD), showing a long tail indicative of significant back-mixing.

Table 5: Axial profile of time-averaged solid holdup (α_s) and gas-solid slip velocity in the riser

Riser Height (m)	Cross-Sectionally Averaged Solid Holdup (α_s)	Area-Averaged Slip Velocity (m/s)
5 (post-Injection)	0.145	4.8
15	0.102	6.2
25	0.088	7.5
35 (Outlet)	0.075	8.1

4.4 Thermal analysis

The thermal performance of the riser is inextricably linked to its hydrodynamics. Figure 8 plots the axial temperature profiles for both the gas and solid phases along the centerline of the riser. The simulation reveals an extremely rapid heat exchange in the first few meters. The hot regenerated catalyst enters at 988 K and immediately begins to transfer its sensible heat to the cooler vaporized feedstock, which enters at 523 K. The gas temperature rises precipitously, while the catalyst temperature drops sharply. The model predicts that the heat transfer is so efficient that the two phases reach near thermal equilibrium (within 10-15 K of each other) after traveling only 8-10 meters up the riser. Beyond this point, the temperature of both phases continues to decrease gradually along the remaining length of the riser. This slow decline is due to the strongly endothermic nature of the cracking reactions, which continuously absorb heat from the system. The predicted final outlet temperature of 791 K is the net result of this integrated heat transfer and reaction process. The cross-sectional temperature distribution, shown in Figure 9 and figure 10, is relatively uniform in the upper parts of the riser, though a slightly cooler region is noticeable near the walls, corresponding to the denser catalyst annulus.

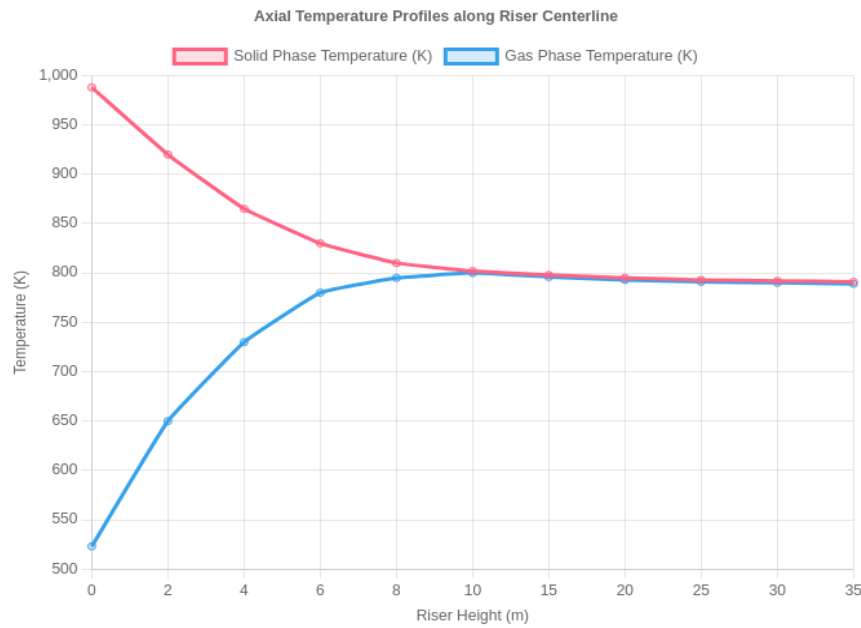


Fig.9: Axial temperature profiles for gas and solid phases along the riser centerline, showing rapid heat exchange in the lower section

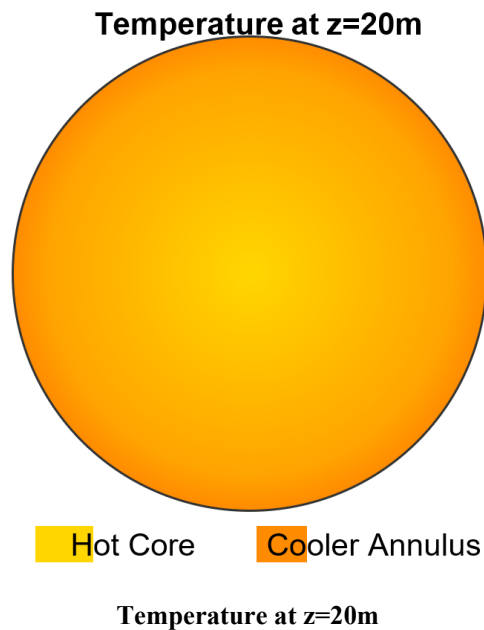


Fig .10: Contour plot of temperature distribution on a cross-section at z=20m, showing a relatively uniform thermal field in the core

4.5 Parametric studies for process optimization

To demonstrate the practical utility of the validated model as a predictive tool, a series of parametric studies were conducted to assess the impact of key operating and design parameters on reactor performance.

4.5.1 Effect of Catalyst-to-Oil (C/O) ratio

The C/O ratio, controlled by adjusting the catalyst circulation rate via the standpipe slide valve [32], is one of the most critical operating parameters. The baseline case from the plant data corresponds to a C/O ratio of 7.0. Two additional cases were simulated: a lower C/O of 6.0 and a higher C/O of 8.0. The results, summarized in Table 5, show that increasing the C/O ratio provides more heat to the reactor, resulting in a higher riser outlet temperature. This generally favors higher conversion but can also increase the production of light gases and coke. The model provides the quantitative data needed to balance these trade-offs.

Table 6: Effect of varying catalyst-to-oil (C/O) ratio on key performance indicators.

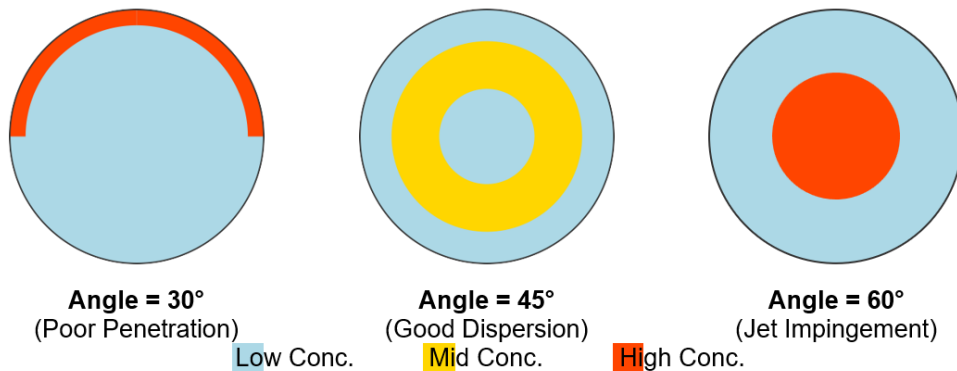
Parameter	C/O = 6.0	C/O = 7.0 (Baseline)	C/O = 8.0
Catalyst Circulation Rate (kg/s)	351.0	409.5	468.0
Predicted Riser Outlet Temp. (K)	778	791	802
Predicted Riser Pressure Drop (bar)	0.17	0.19	0.21
Average Solid Holdup (α_s)	0.095	0.103	0.112

4.5.2 Effect of feed injection angle

The design of the feed injection nozzles can significantly impact the initial mixing of feedstock and catalyst [33]. A study was performed to evaluate the effect of the injection angle on the flow pattern just above the feed zone. Table 7 and (Figure 11) show that a shallower angle (30°) results in poor penetration, with the feed vapor streaming up the walls, while a steeper angle (60°) causes the jets to impinge in the center, creating a dense, poorly mixed region. An angle of 45° appears to provide the most uniform initial distribution of solids, which is crucial for promoting rapid vaporization and minimizing thermal cracking.

Table 7 : Effect of feed injection angle on mixing performance

Injection Angle (degrees)	Predicted Riser Outlet Temp. (K)	Mixing Index (at z=6m)
30	788	0.78
45 (Baseline)	791	0.92
60	790	0.85

**Fig. 11:** Solid volume fraction contours at z=6m for different feed injection angles, showing optimal dispersion at 45°

4.5.3 Effect of Catalyst Particle Size

The properties of the catalyst itself, particularly its average particle size, can influence hydrodynamics [34]. The baseline catalyst has an average size of 75 μm . Simulations were run with a finer catalyst (65 μm) and a coarser one (85 μm). As shown in Table 8, the finer catalyst is more easily carried by the gas, resulting in a lower solid holdup and a lower slip velocity. Conversely, the coarser catalyst leads to a denser bed and higher slip velocity. This affects both residence time and heat transfer, demonstrating that changes in catalyst properties must be considered in operational adjustments.

Table 8: Effect of average catalyst particle size on hydrodynamics.

Particle Size (μm)	Average Solid Holdup (α_s)	Average Slip Velocity (m/s)
65 (Finer)	0.091	6.1
75 (Baseline)	0.103	7.1
85 (Coarser)	0.115	8.0

5. Conclusions and Recommendations

This study successfully developed, validated, and applied a three-dimensional CFD model for the Fluid Catalytic Cracking (FCC) riser reactor at the Basra refinery. By rigorously integrating advanced simulation techniques with practical plant data,

this research has yielded several key conclusions and a set of actionable recommendations designed to enhance the unit's performance and profitability.

5.1 Conclusions:

1. A high-fidelity Eulerian-Eulerian (Two-Fluid Model) CFD model was established, providing a realistic and robust representation of the industrial-scale FCC riser. The model's predictions for critical performance indicators, namely riser outlet temperature and overall pressure drop, showed excellent agreement with measured data from the Basra refinery, with relative differences of less than 5%. This strong validation confirms the model's reliability as a digital twin of the physical reactor.
2. The validated simulation provided unprecedented, detailed insights into the complex internal gas-solid hydrodynamics. It quantitatively confirmed the presence of a distinct core-annulus flow structure, characterized by a dilute, fast-moving core and a dense, slower-moving annular region. Crucially, the model revealed significant catalyst back-mixing within this annulus, leading to a wide residence time distribution with a long tail, which can be detrimental to product selectivity.
3. The thermal analysis demonstrated extremely rapid heat transfer in the bottom section of the riser, with the gas and solid phases approaching thermal equilibrium within the first 8-10 meters. This highlights the critical importance of the initial feed injection and mixing zone for establishing the reactor's thermal profile.
4. A series of parametric studies quantitatively demonstrated the strong influence of key operational and design parameters. The catalyst-to-oil (C/O) ratio directly controls the reactor's heat input and outlet temperature. The feed injection angle was found to be critical for achieving good initial mixing. Catalyst particle size was also shown to have a notable impact on the overall solid holdup and slip velocity. These studies provide a predictive framework to understand the consequences of operational adjustments.

5.2 Recommendations

Based on the comprehensive findings of this study, the following specific and actionable recommendations are proposed for the South Refineries Company to consider for the Basra refinery:

1. **Adopt Model-Based Operational Optimization:** The validated CFD model should be leveraged as a "virtual plant" to explore a wider range of operating conditions in a cost-effective and risk-free manner. It is strongly recommended to perform further studies by coupling the current hydrodynamic model with a suitable cracking kinetics model (e.g., a 4-lump or 10-lump model). This will enable the direct prediction of product yields (gasoline, LPG, diesel, etc.) and coke formation, allowing for the identification of an optimal C/O ratio and feed temperature that truly maximize profitability under current market conditions.
2. **Investigate Hardware Modifications to Mitigate Back-mixing:** The significant catalyst back-mixing identified in the annular region is a likely source of yield loss due to over-cracking. The refinery should consider evaluating hardware modifications aimed at improving gas-catalyst contacting and reducing the severity of the core-annulus structure. Potential solutions include optimizing feed nozzle designs or installing an advanced riser termination device (e.g., a J-hook or vortex separator). The CFD model developed in this work is the ideal tool to virtually test the efficacy of such modifications before committing to costly capital expenditure and plant shutdowns.
3. **Enhance Process Control Strategies:** The quantitative relationships established between variables like C/O ratio, feed injection, and riser temperature can be used to refine the refinery's process control strategies. The insights from this model can serve as the basis for developing more sophisticated model-predictive control (MPC) or other Advanced Process Control (APC) applications. An APC system informed by this detailed physical model could allow for more proactive and stable control of the unit, keeping it closer to its true optimal operating point in real-time.
4. **Institutionalize CFD Modeling for Engineering Support:** This work establishes a strong foundation and a clear proof-of-concept for model-based engineering at the Basra refinery. It is recommended to expand this CFD modeling approach to other critical components of the FCC unit, particularly the complex feed injection system and the regenerator. A comprehensive, full-loop simulation of the entire reactor-regenerator circuit would provide an exceptionally powerful tool for holistic troubleshooting, debottlenecking, long-term strategic planning, and training of new engineers and operators.

In conclusion, this research powerfully demonstrates the immense value of synergizing first-principles modeling with practical industrial data. The resulting validated model serves as a powerful digital asset for the Basra refinery, offering a platform for data-driven analysis and optimization that can directly contribute to enhancing the efficiency, profitability, and strategic importance of Iraq's domestic refining capabilities.

Supplementary material (reproducibility package)

To facilitate reproducibility, a full set of supporting materials has been prepared and is available as supplementary files. These include the parametric description of the riser geometry together with the three computational meshes used in the study, as well as the table of boundary conditions applied to all simulations. Details of the closure models and coefficients adopted in the KTGF framework, wall and drag interactions are also provided. In addition, the numerical settings such as discretization schemes, under-relaxation factors, and initialization strategy—are documented along with the transient sampling protocol. Finally, information on the software release and run environment is supplied. Taken together, these materials enable other

researchers to repeat the baseline case, verify the grid and time-step independence studies, and reproduce the parametric investigations reported in this work.

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Nomenclature

Symbol	Description	Unit
α_k	Volume fraction of phase k	–
ρ_k	Density of phase k	kg/m ³
$\mathbf{v}_k$	Velocity vector of phase k	m/s
P	Gas pressure	Pa
P_s	Solid granular pressure	Pa
τ_g	Stress tensor of gas phase	Pa
τ_s	Stress tensor of solid phase	Pa
g	Gravitational acceleration	m/s ²
K_{sg}	Momentum exchange coefficient (solid–gas)	kg/m ³ ·s
H_k	Specific enthalpy of phase k	J/kg
T_k	Temperature of phase k	K
k_{eff}	Effective thermal conductivity	W/m·K
S_h	Heat source term	W/m ³
C/O	Catalyst-to-oil ratio	–
d_p	Mean particle diameter	μm
RTD	Residence time distribution	–
CFD	Computational Fluid Dynamics	–
FCC	Fluid Catalytic Cracking	–

References

- [1] R. Sadeghbeigi, Fluid Catalytic Cracking Handbook: An Expert Guide to the Practical Operation, Design, and Optimization of FCC Units. Butterworth-Heinemann, 2020.
- [2] J. N. Armor, "A history of industrial catalysis," Catalysis Today, vol. 163, no. 1, pp. 3–9, 2011.
- [3] South Refineries Company, "Brief about Southern Refineries Company," SRC.gov.iq, 2024.
- [4] U.S. Army, "Major Iraqi oil refinery demonstrates self-sufficiency," Army.mil, Dec. 20, 2010.
- [5] S. Chen, et al., "CFD simulation of gas–solid two-phase flow and mixing in an industrial FCC riser," Powder Technology, vol. 295, pp. 230–242, 2016.
- [6] M. T. Shah, et al., "Computational fluid dynamic modelling of FCC riser: A review," Applied Mathematical Modelling, vol. 40, no. 15–16, pp. 6898–6933, 2016.
- [7] A. Vorobev, et al., "Simple model of an industrial catalytic cracking riser reactor," Industrial & Engineering Chemistry Research, vol. 62, no. 40, pp. 16868–16879, 2023.
- [8] A. Erdoğan, et al., "A CFD study on the start-up hydrodynamics of fluid catalytic cracking regenerator integrated with chemical looping combustion," Energy Sources, Part A: Recovery, Utilization, and Environmental Effects, vol. 46, no. 1, 2024.
- [9] T. W. Selalame, et al., "A review of modelling of the FCC unit – Part I: The riser," Energies, vol. 15, no. 1, p. 308, 2022.
- [10] A. N. Khalaf, "Steady state simulation of Basrah crude oil refinery distillation unit using ASPEN HYSYS," Thi_Qar University Journal for Engineering Sciences, vol. 9, no. 2, pp. 29–36, 2018.
- [11] D. Y. Aqar, "Improving the control system of the model IV FCC unit," Journal of Petroleum Research and Studies, no. 10, 2025.
- [12] F. Berruti, et al., "Hydrodynamics of circulating fluidized bed risers: A review," The Canadian Journal of Chemical Engineering, vol. 73, no. 5, pp. 579–602, 1995.
- [13] J. Zhang, et al., "Multifunctional two-stage riser fluid catalytic cracking process," Particuology, vol. 14, pp. 1–10, 2014.
- [14] S. Kriebitzsch, et al., "CFD–DEM simulation of gas–solid reacting flows in fluid catalytic cracking (FCC) process," Particuology, vol. 11, no. 1, pp. 88–96, 2013.
- [15] Y. Tang, et al., "CFD modeling investigation of oxy-fuel combustion application in an industrial FCC regenerator," Case Studies in Thermal Engineering, vol. 57, p. 104531, 2024.
- [16] P. J. O'Rourke, et al., "Numerical simulation of a commercial FCC regenerator using multiphase particle-in-cell methodology (MP-PIC)," Particuology, vol. 38, pp. 184–195, 2018.
- [17] X. Lan, et al., "CFD modeling of gas–solid flow and cracking reaction in two-stage riser FCC reactors," Chemical Engineering Science, vol. 64, no. 17, pp. 3846–3858, 2009.

- [18] D. Gidaspow, *Multiphase Flow and Fluidization: Continuum and Kinetic Theory Descriptions*. Academic Press, 1994.
- [19] W. Shuai, et al., "Modeling of reactive gas–solid flows in riser reactors using a new generation of CFD software," *Chemical Engineering Science*, vol. 116, pp. 207–217, 2014.
- [20] Y. Du, et al., "Revisiting a large-scale FCC riser reactor with a particle-scale model," *Chemical Engineering Science*, vol. 251, p. 117468, 2022.
- [21] Iraqi Journal of Chemical and Petroleum Engineering, College of Engineering, University of Baghdad.
- [22] Journal of Petroleum Research and Studies, Ministry of Oil, Petroleum Research and Development Center, Iraq.
- [23] A. A. Mazin, et al., "Fluid catalytic cracking of petroleum fraction (vacuum gas oil) to produce gasoline," Digital Repository of University of Baghdad, 2010.
- [24] JGC Holdings Corporation, "Additional technology transfer order received in Basra refinery upgrading project," JGC.com, Feb. 7, 2025.
- [25] Axens, "Axens' technologies for Basrah refinery upgrading project," Axens.net. [Online]
- [26] A. Tanimu, et al., "Catalytic cracking of crude oil: Mini review of catalyst formulations for enhanced selectivity to light olefins," *Energy & Fuels*, vol. 36, no. 10, pp. 5152–5166, 2022.
- [27] M. Nahvi, et al., "Thermodynamic analysis and techno-economic assessment of fluid catalytic cracking unit in the oil refining process," *Journal of Cleaner Production*, vol. 413, p. 137447, 2023.
- [28] N. A. M. Ahmed, et al., "Computational fluid dynamics simulation of a fluidized catalytic cracking regenerator," *University of Khartoum Engineering Journal*, vol. 5, no. 1, 2015.
- [29] J. Chang, et al., "Computational investigation of a turbulent fluidized-bed FCC regenerator," *Industrial & Engineering Chemistry Research*, vol. 52, no. 1, pp. 464–477, 2013.
- [30] A. Oloruntoba, et al., "State-of-the-art review of fluid catalytic cracking (FCC) catalyst regeneration intensification technologies," *Energies*, vol. 15, no. 6, p. 2061, 2022.
- [31] S. Zimmermann and O. T. U. of Technology, "CFD modeling of the hydrodynamics and reaction kinetics of gas–solid fluidized beds," *Industrial & Engineering Chemistry Research*, vol. 44, no. 26, pp. 9842–9852, 2005.
- [32] A. S. Alsabei, "Dynamic modeling and control of a fluid catalytic cracking unit," M.S. thesis, King Fahd Univ. of Petroleum and Minerals, 2005.
- [33] R. C. McFarlane, et al., "Dynamic simulator for a model IV fluid catalytic cracking unit," *Computers & Chemical Engineering*, vol. 17, no. 3, pp. 275–300, 1993.
- [34] K. K. Karim, et al., "Investigating the influence of the cerium loading in prepared Y-zeolite on the activity of fluid catalytic cracking," Digital Repository of University of Baghdad.