



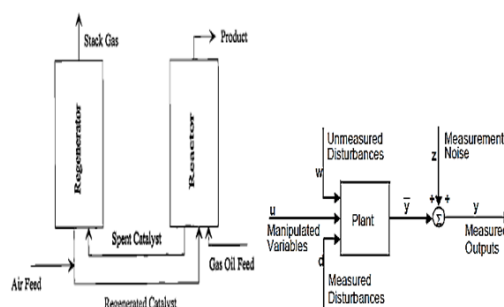
## SIMULATION OF A FLUID CATALYTIC CRACKING UNIT BY USING A LINEAR ALGEBRAIC CONTROLLER

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This research investigates and analyzes experimental data related to the reactor-regenerator system of the Fluid Catalytic Cracking Unit (FCCU). Over the past five decades, various mathematical models have been developed to represent FCC systems. However, achieving accurate alignment between these models and real-world operations remains challenging, especially as equipment continuously evolves to meet refining demands. The FCCU comprises a riser reactor, catalyst stripper, and regenerator. Among these, the riser reactor is crucial due to its complex flow dynamics and the presence of numerous hydrocarbons undergoing simultaneous reactions. This study introduces a novel kinetic approach, modeling the cracking of a single pseudo-component into two products in one reaction step. Each lump is treated as a pure compound with defined physical and chemical properties. A regenerator model from literature is coupled with the riser model for complete FCC simulation under steady-state. Additionally, advanced control strategies, including decouplers, and Model Predictive Control (MPC), are applied to improve temperature regulation and process stability.



### INTRODUCTION

The petroleum industry is foundational to modern civilization, primarily due to its contributions to efficient and high-speed transportation. For over six decades, catalytic cracking has remained a vital process in petroleum refining, evolving significantly in both operation and control. Among these processes, the Fluid Catalytic Cracking Unit (FCCU) plays a critical role in transforming heavy hydrocarbons into high-octane gasoline and light olefins. Traditional modeling of FCCU relies on lumping strategies – either based on boiling range or molecular structure

– each with specific advantages and limitations. These models assume feed and product streams consist of predefined component groups (lumps), though they often lack detailed chemical reaction data.

Recent models focus on single-event kinetics and continuous reaction mixtures, yet their application is restricted by analytical and computational complexities. FCC units are now preferred over thermal cracking due to their efficiency and superior product quality. In FCCUs, the cracking process produces coke that deactivates catalysts; regeneration restores catalyst activity by burning off coke, releasing heat for the endothermic

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cracking reactions. Advanced FCC units are heat-balanced systems designed to reuse this heat. Today, with over 400 units operating globally, FCCUs are central to refinery operations, and recent advances are driving development of better control strategies to address the system's non-linear dynamics and complex interactions.

### Process Description

Fluidized Catalytic Cracking (FCC) is a vital conversion process used in modern oil refineries to upgrade heavier hydrocarbons into lighter, high-value products such as gasoline. As a primary source of gasoline production, FCC involves complex chemical and physical phenomena and presents notable challenges for multivariable process control. The proper selection of

manipulated inputs and measured outputs is critical due to the strong interactions among process variables.

The FCC system consists of multiple subsystems: the feed and preheat section, the riser reactor, regenerator, catalyst circulation pathways, wet gas compressor, and air supply units. Of these, the riser reactor and regenerator are the core components. Inside the reactor, gas oil feedstock is vaporized and cracked in the presence of high-temperature catalyst, converting it into gasoline, coke, and light hydrocarbons. The catalyst, now deactivated by coke deposits, is sent to the regenerator where the coke is burned off using air, restoring the catalyst's activity. The heat released during coke combustion provides the thermal energy needed for the endothermic cracking reactions in the riser, making FCC a self-sustaining, heat-balanced process.

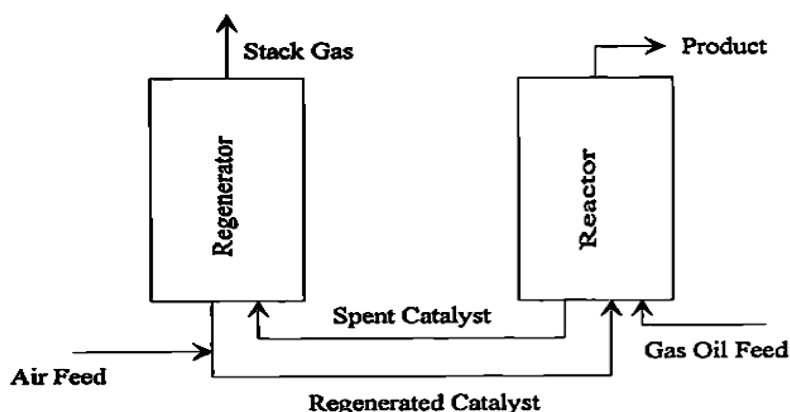


Fig. 1 – Outline Representation of FCC Unit.

### Reactor

The unit typically operates in a “side-by-side” configuration. Feedstock preheated to 315–430 °C is mixed with recycled slurry oil and introduced into the riser, where it contacts the hot catalyst. This mixture travels upward to the reactor at around 535 °C and 1.72 barg. The spent catalyst is separated from the cracked vapors and passes through a stripping section before being sent to the regenerator operating at approximately 715 °C and 2.41 barg.

Key controlled variables in the process include riser outlet temperature and regenerator temperature, while the manipulated variables typically involve the flow rates of regenerated catalyst, spent catalyst, and combustion air. Efficient regulation of these parameters ensures high product quality and stable FCC operation.

Until the mid-1960s, FCC units were typically designed with a dense-phase fluidized bed within the

reactor vessel, where it was believed that most of the cracking reactions occurred. The system was modelled accordingly, focusing on the reactor section as the main site of reaction. However, later studies showed that the majority of the catalytic cracking actually takes place in the riser, where both catalyst activity and temperature are at their peak. Initially, little attention was given to riser control, but with the introduction of highly active zeolite catalysts, more reactions began occurring within the riser itself. As a result, the reactor's role shifted to primarily separating catalyst from the cracked product vapours. To enhance riser performance, feed is injected via spray nozzles, and catalyst velocity is increased to optimize reaction conditions.

The reactor-regenerator section is considered the central component of the FCC process. Most modern reactors feature a riser that enables short contact time between the feed and the catalyst. Almost all cracking reactions now occur in this riser

before the mixture reaches the reactor separator. However, minor thermal and non-selective reactions may still take place in the reactor vessel. The preheated feed enters the riser near the bottom, where it immediately contacts the hot regenerated catalyst. The catalyst-to-oil ratio is typically maintained between 4:1 and 9:1 by weight. The heat from the catalyst vaporizes the feed and provides the energy needed for endothermic cracking reactions.

As vaporization and cracking proceed, the resulting expansion of vapours lifts the catalyst upward. The mixture then flows into the reactor separator, where catalyst and hydrocarbons are divided. The hydrocarbons move on to the fractionator for separation. The riser, generally about 2 meters in diameter and 30–35 meters long, behaves like a plug flow reactor but with some flow irregularities due to vapor drag.

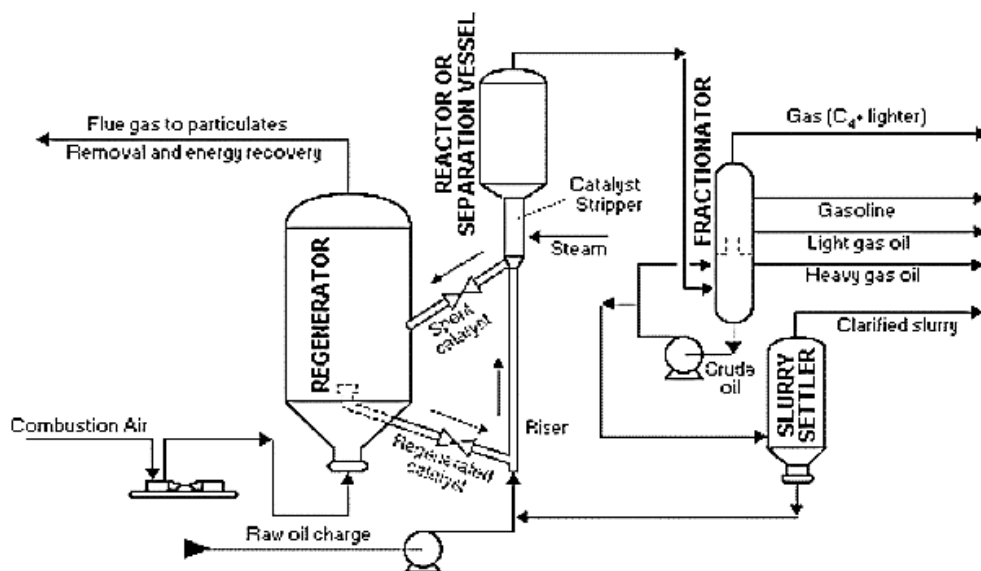


Fig. 2 – Instrumentation of FCC Unit.

### Regenerator

The catalyst reaches the reactor through the catalyst stripper. The regenerator plays a dual role – restoring catalyst activity and supplying the necessary heat for the cracking reactions in the reactor. Spent catalyst from the stripper is directed to the regenerator via a standpipe, and a slide valve installed in this pipe helps regulate the catalyst bed level within the stripper.

The regenerator's key functions are to burn off the coke deposited on the spent catalyst and to reheat the catalyst for reuse in cracking. The amount of coke on the spent catalyst typically ranges from 0.2% to 0.8% by weight, depending on the quality of the feedstock. Coke mainly consists of carbon and hydrogen, along with trace elements such as sulphur and nitrogen. Poorer feedstocks tend to deposit more coke on the catalyst surface.

To support the combustion process, a high-capacity air blower supplies sufficient air to fluidize the catalyst bed within the regenerator. This air enters through a distributor at the base of the regenerator, ensuring thorough mixing of air and

catalyst. As the coke is burned off, the exothermic reaction increases the catalyst temperature, and this thermal energy is transferred to the reactor during operation. Flue gases produced during regeneration are directed through cyclone separators, which recover any entrained catalyst particles.

The regenerator is typically designed to oxidize coke into either carbon monoxide or carbon dioxide. In older systems, partial combustion to carbon monoxide was favored to reduce air demand and lower capital costs. However, modern designs aim for complete combustion to carbon dioxide, which, while costlier, ensures more effective catalyst regeneration and enhances cracking efficiency.

### Flue Gas System

The flue gas recovery system harnesses the thermal energy from combustion gases. In some units, carbon monoxide is fully oxidized in a waste heat boiler to generate steam or drive turbines. In others, heat exchangers are used to convert boiler feedwater into high-pressure steam.

### Development of Model

A steady-state model is applied to describe the riser dynamics. This work utilizes a practical control strategy proposed by Joseph A. Bromley and Thomas J. Ward (1981).<sup>2</sup> The feedstock used is gas oil, which undergoes catalytic cracking to yield products such as gasoline and light gases. The model assumes that both reactor and regenerator pressures are regulated and remain constant.

The material balance for catalyst holdup in the reactor section is:

$$\frac{dH_{RA}}{dt} = [R_{RC} - R_{SC}]$$

With the corresponding regenerator balance:

$$\frac{dH_{RG}}{dt} = -\frac{dH_{RA}}{dt}$$

The mass balance for the spent catalyst concentration is:

$$\frac{dC_{SC}}{dt} = \frac{1}{H_{RA}} [R_{RC}C_{RC} - R_{RC}C_{SC} + 100R_{CF}]$$

where feed cracking rate is:

$$R_{CF} = R_{CC} + F_{CF}R_{TF} + 0$$

The balance for catalytic carbon concentration is:

$$\frac{dT_{RA}}{dt} = \frac{R_{RC}}{H_{RA}} (T_{RG} - T_{RA}) + \frac{1}{S_C H_{RA}} [-S_F D_{TF} R_{TF} (T_{RA} - T_{TF}) - \Delta H_{FV} D_{TF} R_{TF}] - \frac{\Delta H_{CR} R_{OC}}{S_C H_{RA}}$$

where:

$$R_{OC} = D_{TF} R_{TF} C_{TF}$$

### Regenerator Model

For effective FCC operation, temperature control in both reactor and regenerator is crucial to maintain product quality and prevent thermal

$$\frac{dT_{RG}}{dt} = \frac{R_{SC}}{H_{RG}} (T_{RA} - T_{RG}) + \frac{1}{S_C H_{RG}} [-S_A R_{AI} (T_{RG} - T_{AI}) + \Delta H_{RG} R_{CB}]$$

### Nomenclature

$C_1$  – Fitting constant for particular data  
 $C_{CAT}$  – Concentration of catalytic carbon on catalyst [wt%],  
 $C_{RC}$  – Concentration of regenerated catalyst [wt%],  
 $C_{SC}$  – Concentration of spent catalyst [wt%],  
 $C_{TF}$  – Conversion of total feed [volume fraction],

$$\frac{dC_{CAT}}{dt} = \frac{1}{H_{RA}} [-R_{RC}C_{CAT} + 100R_{CC}]$$

The carbon concentration on regenerated catalyst is governed by:

$$\frac{dC_{RC}}{dt} = \frac{1}{H_{RG}} [R_{SC}(C_{SC} - C_{RC}) - 100R_{CB}]$$

where:

$$R_{CB} = \left(\frac{R_{AI}}{C_1}\right) (21 - O_{FG})/100$$

### Reactor Model

The FCC riser reactor is divided into two functional zones. The lower portion is the feed-injection zone, where catalyst addition, feed vaporization, and initial cracking begin. The upper zone completes the cracking reactions involving multiple species, simplified into pseudo-components: gas oil, gasoline, and light gases.

The riser, operating with modern zeolite catalysts, is treated as an adiabatic plug flow reactor. Catalyst stripping and product separation via cyclone precede further product fractionation. Cracking reactions are assumed to follow first-order kinetics.

The reactor temperature balance is:

damage. Reactor pressure is typically managed by regulating compressor speed or recycle rate, while flue gas flow controls regenerator pressure.

Cyclone separators remove catalyst particles from hot flue gases, enabling heat and energy recovery. Reactor-regenerator models are combined, assuming constant pressure and neglecting riser time lag, which is minimal (under 10 seconds).

The regenerator temperature balance is:

$D_{TF}$  – Density of total feed [kg/m<sup>3</sup>],  
 $F_{CF}$  – Factor for carbon formation of feed [kg carbon/s] / [m<sup>3</sup>/s],  
 $H_{RA}$  – Hold up of catalyst in the reactor [kg],  
 $H_{RG}$  – Hold up of catalyst in the regenerator [kg],  
 $O_{FG}$  – Oxygen in flue gas [mol%],  
 $R_{AI}$  – Rate of regenerator air [kg/s],

$R_{CB}$  – Rate of coke burning [kg/s],  
 $R_{CC}$  – Rate of catalytic carbon formation in the reactor [kg/s],  
 $R_{CF}$  – Rate of carbon forming on catalyst [kg/s],  
 $R_{OC}$  – Rate of gas oil cracking [kg/s],  
 $R_{RC}$  – Rate of regenerated catalyst [kg/s],  
 $R_{SC}$  – Rate of spent catalyst [kg/s],  
 $R_{TF}$  – Rate of total feed [m<sup>3</sup>/s],  
 $S_A$  – Specific heat of air [J/kg-k],  
 $S_C$  – Specific heat of catalyst [J/kg-k],  
 $T_{AI}$  – Temperature of air [K],  
 $T_{RA}$  – Temperature of Reactor [K],  
 $T_{RG}$  – Temperature of Regenerator [K],  
 $T_{TF}$  – Temperature of feed [K],  
 $\Delta H_{CR}$  – Heat of cracking [J/kg],  
 $\Delta H_{FV}$  – Heat of feed vaporization [J/kg],  
 $\Delta H_{RG}$  – Heat of regeneration (coke burning) [J/kg].

### First Order Process Systems

A first-order system is characterized by a response that can be described using a first-order differential equation. For a linear or linearized system, the general form of the governing equation is:

$$a_1 \frac{dy}{dt} + a_0 y = b f(t)$$

where  $f(t)$  represents the input or forcing function applied to the system.

Provided that  $a_0 \neq 0$ , the equation can be rearranged as:

$$\frac{a_1}{a_0} \frac{dy}{dt} + y = \frac{b}{a_0} f(t)$$

$$x(k+1) = x(k) + T_u u(k) + T_d d(k) + T_w W(k)$$

$$y(k) = \hat{y}(k) + z(k) = Cx(k) + D_u u(k) + D_d d(k) + D_w w(k) + z(k)$$

Here,

- $x(k)$ : state vector
- $u(k)$ : manipulated inputs
- $d(k)$ : measured disturbances
- $w(k)$ : unmeasured disturbances
- $y(k)$ : system outputs
- $z(k)$ : measurement noise
- $T_u, T_d, T_w, D_u, D_d, D_w$ : system matrices
- $\hat{C}$ : output matrix

These equations form a linear time-invariant (LTI) model in state-space form derived from a set

This form can be simplified further by introducing two important parameters:

$\tau_p = \frac{a_1}{a_0}$  known as the process time constant

$K_p = \frac{b}{a_0}$  referred to as the process gain or steady-state gain. With these definitions, the equation becomes:

$$\tau_p \frac{dy}{dt} + y = K_p f(t)$$

This standard form is commonly used to describe the dynamic behavior of first-order systems in process control.

The corresponding transfer function in the Laplace domain, representing the system's output-to-input ratio, is expressed as:

$$G(s) = \frac{\overline{y(s)}}{f(s)} = \frac{K_p}{\tau_p s + 1}$$

This transfer function provides a compact representation of the system's dynamics and is fundamental in control system analysis and design.

### Model Predictive Control (MPC)

Model Predictive Control (MPC) is an advanced control strategy that utilizes a process model to predict future system behavior and compute control actions by solving an online optimization problem at each sampling interval. Unlike conventional control techniques, MPC can explicitly handle multivariable interactions and constraints on both inputs and outputs. A standard discrete-time state-space model used in MPC is:

of ordinary differential equations (ODEs) linearized and discretized using standard methods such as forward Euler or zero-order hold. The ODE system described in the above Sections should be discretized to derive the above algebraic form, which is critical in implementing MPC.

This function penalizes deviations from reference values and changes in control signals. MPC accounts for system constraints and disturbances in real-time, offering superior control for nonlinear or multivariable processes.

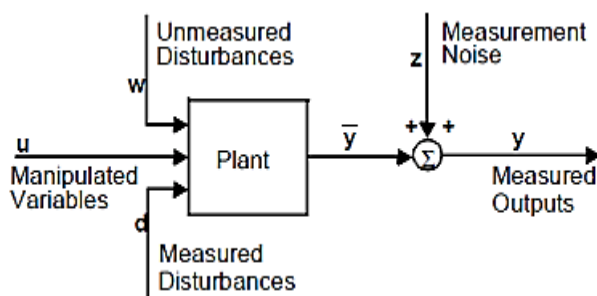


Fig. 3 – Structure of MPC.

To clarify, the mod format used in tools like MATLAB groups matrices  $F$ ,  $G$ ,  $C$ ,  $D$  into a single structure for efficient computation.

## RESULTS AND DISCUSSION

The modeled results integrated reaction kinetics with hydrodynamic conditions to estimate the molar output of each pseudo-component from the riser reactor. Model validation was performed using contemporary data cited in the literature. The outcomes of the proposed design can be fine-tuned by adjusting certain parameters. The influence of parameters such as regenerated catalyst velocity and air flow rate on the overall performance of the FCC unit was also analyzed.

Heat and mass transfer within the reactor and regenerator are inherently complex. The regenerator is typically divided into two zones: a dense bed (comprising both solid and gas phases) and an entrained flow region. Mass transfer occurs as gas moves upward through the bed. In the dense region, it is generally assumed that mixing is ideal and temperature remains uniform. Meanwhile, the gas phase in this zone is assumed to be in thermodynamic equilibrium with the solid phase. Catalyst particles, due to entrainment, also populate the region above the dense bed, known as the disengagement zone, where catalyst concentration decreases with height.

According to studies from the United States, FCC technology contributes to about 35–45% of gasoline production in modern refineries. While older refineries relied on thermal cracking, the adoption of catalytic cracking has improved both yield and selectivity – producing gasoline with higher octane ratings and lower quantities of heavy oils and light gases. The light gases generated contain more olefins compared to thermal cracking.

In catalytic cracking, coke (carbon) is deposited on the catalyst, leading to deactivation. To sustain

catalyst activity, the deposited coke must be burned off in a separate regenerator unit. Since the cracking reactions are endothermic, the heat needed is provided by the exothermic combustion of coke in the regenerator. Systems like FCC are designed to efficiently transfer this heat back to the riser reactor, using configurations known as “heat-balanced designs”.

The FCC process uses finely powdered catalysts (average particle size around 70 micrometers), which behave like a fluid when aerated with steam. This catalyst facilitates both mass and heat transfer. The regenerated catalyst transfers heat to the riser, while spent catalyst returns to the regenerator.

Different FCC unit configurations are used in industrial practice, including side-by-side and stacked arrangements. In the side-by-side layout, the reactor and regenerator are housed in separate vessels. Crude oil is pre-treated through distillation to yield products like LPG, naphtha, kerosene, and diesel. The residue is then vacuum-distilled to separate vacuum gas oil (VGO), which constitutes about 25–30% of the crude and is the primary feedstock for FCC.

The riser reactor is modelled as a series of interconnected zones. At each level, mass and energy balances are calculated based on kinetics, flow hydrodynamics, and catalyst deactivation. The model predicts catalyst activity, product distribution, and temperature along the riser height. Published experimental data is used to validate the model.

Efficient mixing of feed and catalyst is crucial for achieving optimal cracking reactions. Steam is injected to atomize the feed, improving contact with the active acidic sites of the catalyst. Most of the cracking reactions occur in the riser in the presence of high-activity zeolite catalysts.

Globally, around 400 FCC units are in operation, collectively processing over 12 million barrels per day. Product yields and conversion efficiency are highly sensitive to temperature and catalyst quality. Feedstock characteristics can vary widely across

units, even those designed to process similar vacuum gas oil.

A sensitivity analysis was conducted to assess how changes in tuning parameters affect product yields. It was found that product distribution remained stable across a range of parameter adjustments.

The regenerator model includes mass and heat balance equations for both the solid and gas phases. These are linked with equations describing entrained catalyst behavior, flow dynamics, and pressure distribution. The model accounts for complete combustion conditions.

Figures illustrate the variation in carbon concentration on spent catalyst over time (Fig. 4),

on regenerated catalyst (Fig. 5), and on the catalyst during reaction (Fig. 6). Additional plots (Figs. 7 and 8) depict the self-regulating response of the reactor and regenerator temperatures.

Simulation results from MATLAB (Fig. 9) were used to evaluate the dynamic performance of the FCC unit. The system features two major control inputs and two outputs, typically the riser outlet temperature ( $T_{RA}$ ) and the regenerator temperature ( $T_{RG}$ ). Pairing  $T_{RA}$  with regenerated catalyst flow rate and  $T_{RG}$  with air input enables decentralized control strategies. The model highlights that riser temperature decreases significantly with height.

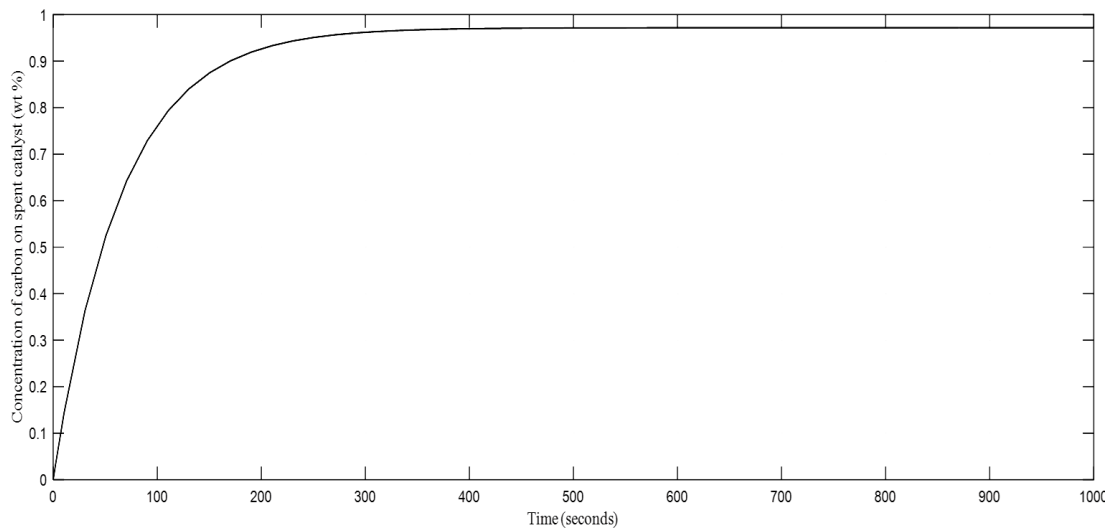


Fig. 4 – Plot for  $C_{SC}$  versus Time.

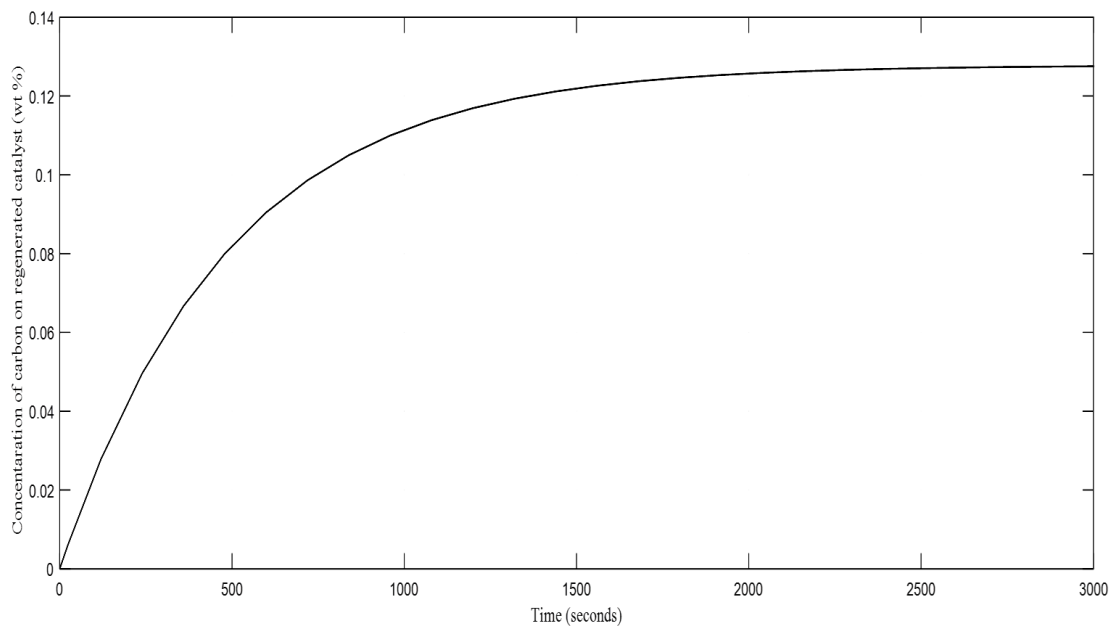
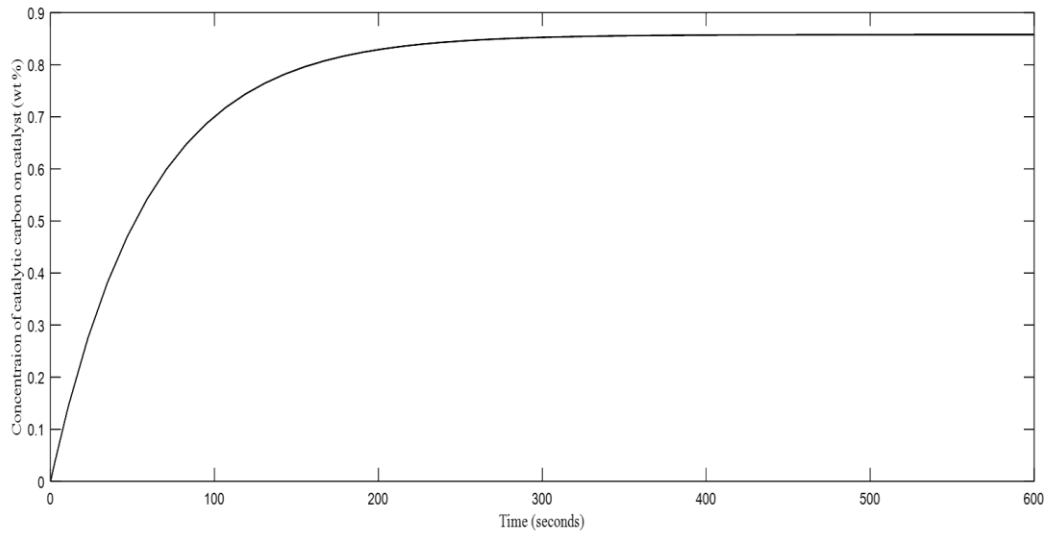


Fig. 5 – Plot for  $C_{RC}$  versus Time.

Fig. 6 – Plot for  $C_{CAT}$  versus Time.

The mathematical model considered in this work simulates the main features of the

behavior of FCC Units, as it is shown in Fig.7 and Fig. 8.

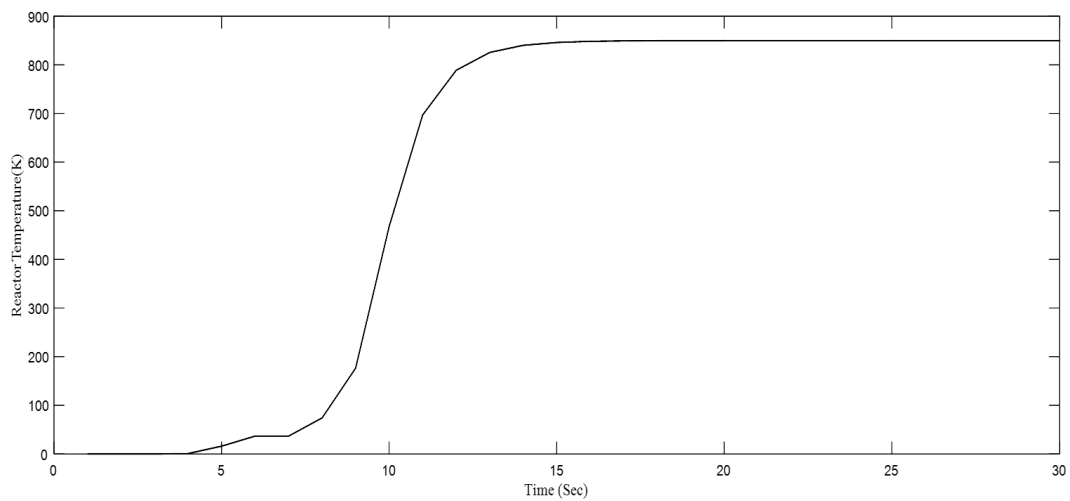


Fig. 7 – Self-Regulatory Response of Reactor Temperature.

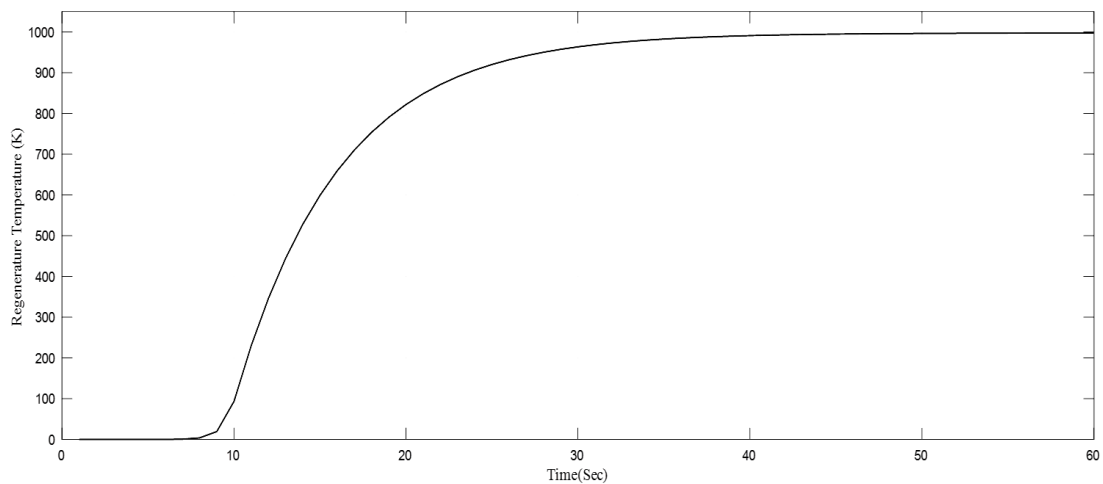


Fig. 8 – Self-Regulatory Response of Regenerator Temperature.

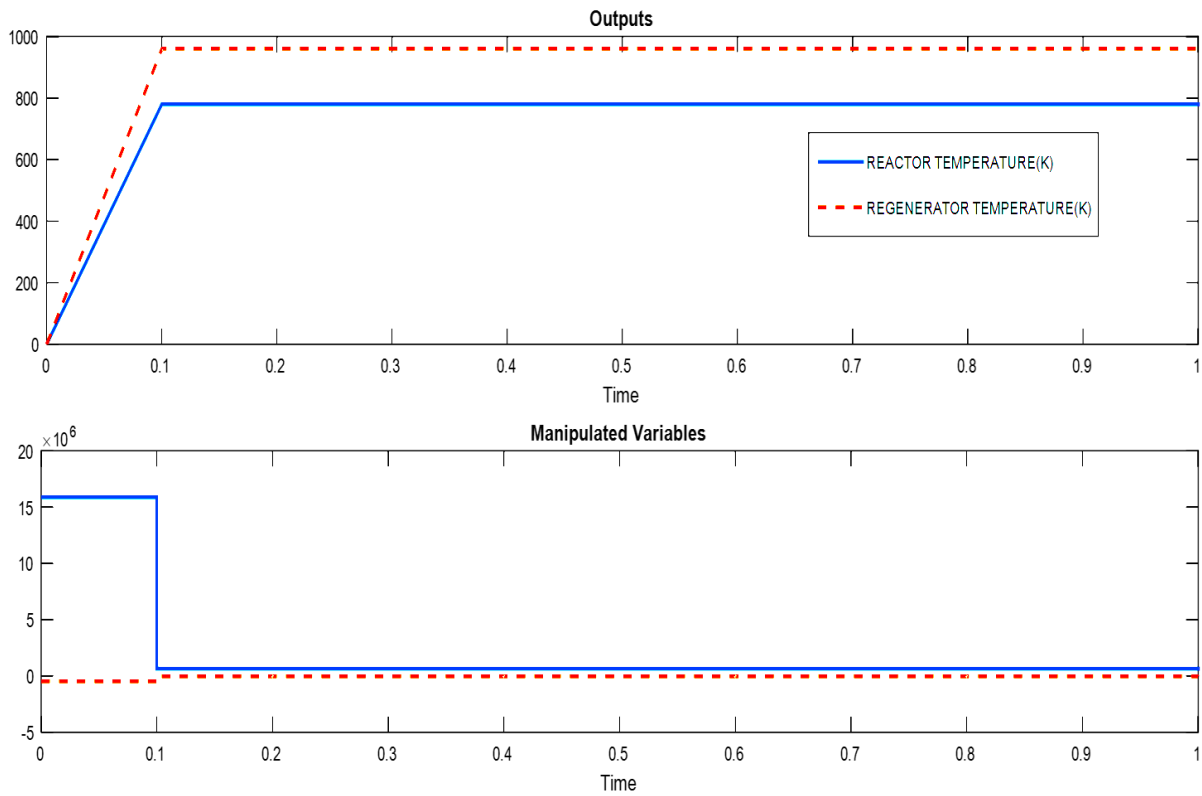


Fig. 9 – Matlab M-file programming output.

Table 1 and Table 2 confirm the sensitivity of product yields to tuning parameter values. Therefore, small increments were

employed in adjusting these parameters during the Model Predictive Control (MPC) simulations.

Table 1

Comparison of reactor temperature performance using MPC

Performance Evaluation	Model Predictive Controller
Error	0
Integral Square Error	0
Integral Absolute Error	0
Integral Time Weighted Absolute Error	0
Settling Time (Sec)	0.1
Delay Time (Sec)	0.06
Rise Time (Sec)	0.1
Peak Time (Sec)	0.1
Peak Value	780

Table 2

Comparison of regenerator temperature performance using MPC

Performance Evaluation	Model Predictive Controller
Error	0.4
Integral Square Error	0.04
Integral Absolute Error	0.4
Integral Time Weighted Absolute Error	0.04
Settling Time (Sec)	0.1
Delay Time (Sec)	0.05
Rise Time (Sec)	0.1
Peak Time (Sec)	0.1
Peak Value	960.1

## CONCLUSION

This research outlines a comprehensive modeling strategy for the Fluidized Catalytic Cracking Unit (FCCU). Control variable pairing was determined using Relative Gain Array (RGA) analysis to identify the most effective input-output combinations. Based on the RGA results, suitable pairings were chosen to reduce process interaction, and decoupling controllers were designed and implemented in a Simulink environment. Simulink's robust simulation tools facilitated the dynamic modeling and control of the FCCU.

In addition, a state-space model of the FCCU was developed to apply a Model Predictive Control (MPC) framework, which contributed to improved system performance and stability. Simulation outcomes indicated that, within the reactor-regenerator system, the regenerator exhibited greater sensitivity than the reactor. Future investigations may explore the influence of temperature variations in both the reactor and regenerator on feedstock conversion efficiency, measured as volume fraction, using advanced MPC techniques.

## REFERENCES

- Ahari J. S., Farshi A. and Forsat K., *Petroleum & Coal*, **2008**, *50*, 15–24.
- Bromley J. A. and Ward J. T., *Industrial & Engineering Chemistry Process Design and Development*, **1981**, *20*, 74–81. <https://doi.org/10.1021/i200012a01>
- Zheng Y. Y., *Computers and Chemical Engineering*, **1994**, *18*, 39–44.
- Nagy Z. K. and Braatz R. D., *AIChE Journal*, **2003**, *49*, 1776–1786. <https://doi.org/10.1002/aic.690490715>
- Elamurugan P. and Dinesh Kumar D., *Int. J. Computer Comm. Information System*, **2010**, *2*, 55–60.
- Heydari M., Ebrahim H. A. and Dabir B., *Am. J. Appl. Sci.*, **2010**, *7*, 221–226. <https://doi.org/10.3844/ajassp.2010.221.226>
- Khandalekar P. D. and Riggs J. B., *Comput. Chem. Eng.*, **1995**, *19*, 1153–1168.
- Elamurugan P. and Siva K., *J. Adv. Chem.*, **2016**, *12*, 5088–5095. <https://doi.org/10.24297/jac.v12i18.605>
- Elamurugan P. and Siva K., *Asian J. Info. Technol.*, **2016**, *15*, 3356–3365.
- Roman R., Nagy Z. K., Cristea M. V. and Agachi S. P., *Comput. Chem. Eng.*, **2009**, *33*, 605–617.
- Weekman V. W. Jr., *Ind. Eng Chem. Process Design and Development*, **1968**, *7*, 90–95.
- Xu O., Su H., Mu S. and Chu J., *J. Zhejiang Univ. Sci. A*, **2006**, *7*, 1932–1941.
- Skogestad S. and Morari M., *Ind. Eng. Chem. Research*, **1987**, *26*, 2323–2330.
- Roman R., Nagy Z., Cristea M. and Agachi P. S., *Comput. Chem. Eng.*, **2009**, *33*, 605–617.
- Singh R., Bala R. and Bhatia B., *Int. J. Adv. Research in Computer Sci. and Software Eng.*, **2014**, *4*, 915–922.
- Ren J., Weng H. X. and Liu F. Y., *Petroleum Processing*, **1993**, *24*, 56–61.
- Skogestad S. and Morari M., *Chem. Eng.*, **2009**, 206–241.
- Tatrai F. Z., Lant P. A., Lee P. L., Ian T. C. and Newell R. B., *J. Proc. Control*, **1994**, *4*, 3–14.
- Li H., Zhang, Q. Xu, W., Wang R. and Qiu T., *Processes*, **2024**, *12*, 2474. <https://doi.org/10.3390/pr12112474MDPI>
- Atiyah S. K., Aljanabi A. Y. A., Ahmed M. S. and Al-Timimi B. A., *Petroleum Chem.*, **2024**, *64*, 83–92. <https://doi.org/10.1134/S0965544124020154SpringerLink>
- Ayotamuno I., *J. Chem. Petrol. Eng.*, **2025**, [https://jchpe.ut.ac.ir/article\\_101533.htmljchpe.ut.ac.ir](https://jchpe.ut.ac.ir/article_101533.htmljchpe.ut.ac.ir)
- Ahmed D. F. and Ateya S. K., *J. Chem. Eng. Proc. Technol.*, **2021**, <https://www.longdom.org/abstract/simulation-and-ratio-control-of-fluid-catalytic-cracking-unit-83799.htmlLongdom>
- Santander O., Kuppuraj V., Harrison C. A. and Baldea M., *Ind. Eng. Chem. Research*, **2023**, *62*, 10587–10600. <https://doi.org/10.1021/acs.iecr.3c01110>