



RESEARCH ARTICLE - ENGINEERING (MISCELLANEOUS)

A Hybrid Intelligent Control Design for Improving the Quality of Petroleum Products

Ghada A. Mutuab¹, Mohammed Y. Hassan^{2*}

¹Department of Control Engineering, College of Control and Systems Engineering, University of Technology-Iraq, Baghdad, Iraq

²Department of Intelligent Control Engineering, College of Artificial Intelligence Engineering, University of Technology-Iraq, Baghdad, Iraq

* Corresponding author E-mail: mohammed.y.hassan@uotechnology.edu.iq

Article Info.	Abstract
<i>Article history:</i> Received 22 February 2026 Revised 21 May 2026 Accepted 01 June 2026 Published 30 June 2026	One of the most crucial parts of the oil refining process is the Fluid Catalytic Cracking Unit (FCCU). This system is essential for transforming heavy hydrocarbon fractions into valuable lighter products such as propylene, diesel, and gasoline. This method helps to remove impurities, enhance the quality of finished goods, and increase the yield of desirable products. The unit encounters uncertainties in its model dynamics, cross-coupling between its axes and sub-units, and extremely nonlinear effects. This study discusses the design of four hybrid controllers comprising two PD-Like Interval Type-2 (PDLIT2) fuzzy logic controllers and two Nonlinear Proportional-Integral-Derivative (NPID) controllers for controlling the reactor and regenerator temperatures in FCCU processes. The parameters of the NPID controller and each Fuzzy controller are tuned using the Firefly Optimization algorithm. These controllers make up for the model's nonlinearities, uncertainty, chattering, and cross-coupling. The overshoot of the reactor temperature response is enhanced by up to 85%, while that of the generator is enhanced by up to 60%, compared with previous published work.

This is an open-access article under the CC BY 4.0 license (<http://creativecommons.org/licenses/by/4.0/>)

Publisher: Middle Technical University

Keywords: Type-2 Fuzzy Logic Controller (T2FLC); Fluid Catalytic Cracking Unit (FCCU); Nonlinear Control; Petroleum Quality; Firefly Optimization.

1. Introduction

Among other industries, the transportation and chemical sectors depend on input from the global petroleum industry. The Fluid Catalytic Cracking Unit (FCCU) undergoes a highly intricate, interactive process, transforming crude oil fractions with higher heating values and higher molecular-weight hydrocarbons into more valuable products, including gasoline and other products [1]. The control of the fluid catalytic cracking unit, which uses fuzzy logic and nonlinear PID techniques, has garnered significant attention in the field of process control. By using fuzzy logic and nonlinear techniques, this control method maximizes the efficiency of the catalytic cracking process, which is essential to the petroleum industry's production of high-quality gasoline and other important products. Fuzzy logic handles the nonlinearity and uncertainties inherent in the FCCU process, thereby improving stability and response. Additionally, custom control algorithms that adapt to specific operating conditions effectively address the process's nonlinear characteristics. To obtain high-quality products by improving temperature control in this unit, which produces various essential compounds, including gasoline, a widely used motor fuel, addressing the challenges of coupling, system nonlinearity, and process uncertainty is crucial.

Dey and Ayyagari [2] presented a fuzzy pole placement-based fuzzy-PID controller with the primary objective of eliminating or reducing parameter uncertainties. The researchers conducted numerous simulations to demonstrate the controller's efficiency in monitoring and rejecting disturbances, solving a set of fuzzy linear equations to derive the controller coefficients. However, this controller structure resembles that of a traditional PID controller and lacks self-tuning capabilities. Dettori et al. [3] reported the design of a two-layer controller consisting of a traditional fuzzy logic controller and a PID controller that monitors PID gains. Similar to [2], their Fuzzy classifications, membership functions, and rule base closely resembled those of [2]. The researchers demonstrated the fuzzy supervisor's complementary role in mitigating the shortcomings of the conventional PID controller through simulation-based case studies. Rodríguez-Castellanos et al. [4] claimed that PID controller response deteriorates in nonlinear systems, particularly when adapting to variations in operating procedures. They proposed a fuzzy-PID design that uses fuzzy logic to enhance PID controller response behavior. Ahmad et al. [5] improved the dynamic behavior of the workstation liquid controller across a range of operating scenarios using a Fuzzy PID controller.

Nomenclature and Symbols			
Cp	Feed Ability to Retain Heat (KJ/Kg.K)	Hs	Heat of Steam(K)
Cpfl	Flue Gas Heat Capacity (KJ/Kg.K)	K _d	Gain in Derivative Control
C _{pp}	Product Heat Capacity (KJ/Kg.K)	K _p	Gain in Proportionate Control
C _{psc}	Spent Catalyst Heat Capacity (KJ/Kg.K)	K _i	Gain of Integral control
ed	Derivative Error	li	Light Intensity
ei	Integral Error	Mp.	Mass of Product (Kg)
ep	Proportional Error	Msc	Mass of Spent Catalyst (Kg)
Fd	Nonlinear Function of Derivative Control	n	Number of Geometrical Components
Ff	Feed Mass Flow-Rate (Kg/sec)	Npop	Number of Fireflies
Ffl	Mass Flow Rate of Flue Gas (Kg/sec)	T _{ai}	Air Temperature (K)
Fi	Nonlinear Function of Integral Control	Tf	The Feed Temperature (K)
F _p	Proportional Control of a Non-Linear Function	Trea	Reactor Temperature (K)
F _{rgc.}	Catalyst Mass Flow Rate (Kg/sec)	Xi	Initial Population of Fireflies
F _s	Steam Mass Flow Rate (Kg/sec)	ximax	Maximum Value
Hrea	Heat of Reaction (K)	ximin	Minimum Value
Fsc	Rate Mass Rate of Used Catalyst (Kg/sec)	y	Light Absorption Coefficient
Hco	Heat of Combustion (K)		

However, they reported that steady-state characteristics exceeded those of the classical PID. Demidova et al. [6] discussed the control strategy, in which a fuzzy logic controller was monitored by a Genetic Algorithm controller, as demonstrated through simulation. The controller's objective was precise tracking of celestial objects. Ganchev et al. [7] studied and presented a hybrid controller to improve temperature and humidity control in HVAC systems. The controller's strength lay in the Sugeno fuzzy function, constructed using a hybrid of classical decoupling and neuro-fuzzy structure, incorporating decoupling equations into the controller design. Jalali et al. [8] employed a two-layer control strategy to regulate load frequency in a networked audiovisual power system. The process's open-loop simulation results were used to create fuzzy-logic controller rule sets, and PID gains were adaptively adjusted as operating regimes changed. Josiah et al. [9] proposed PID control and demonstrated its ability to control the regenerator and riser temperatures in an FCCU. Mutuab and Hassan [10] designed four nonlinear PID controllers (two for the reactor and two for the regenerator) using a cross-coupling compensation structure and tuned the parameters with the Firefly Optimization Algorithm to address FCCU nonlinearities and interactions, reporting very small overshoot and modest rise times for temperature control. Guo and Yang [11] proposed finite-time nonlinear PID formulations and nonlinear PID designs that prioritize frequency-domain-informed gain tuning for enhanced robustness against nonlinearities and time variation, which are examples of methodological advancements outside FCCU but applicable to FCCU control. Lee et al. [12] designed a Predictive PID controller for nonlinear discrete-time plants, supported by a recurrent polynomial fuzzy broad learning system; the method demonstrated good control performance and computational efficiency and was validated on an experimental heating oven, suggesting suitability for embedded industrial deployment. Rospawan and Tsai [13] conducted simulation studies to compare conventional NN-PID implementations, reported that a model-free control approach that combines PID neural network recognition with multi-innovation error feedback improved convergence and bounded steady-state errors ($\sim \pm 1$). Sun and Su [14] showed that, by automating NPID parameter search in complex landscapes, metaheuristic auto-tuners (Firefly, harmony search) reduce the engineering tuning burden; these techniques have been applied to FCCUs and other nonlinear plants. Rajendran et al. [15] optimized the Fractional Order FOPID controller to test a nonlinear storage tank process. Beşkardeş et al. [16] and Kaya [16] highlighted that when a mathematical model is unavailable, fuzzy logic can be a viable solution. Voskoglou [17] examined how a fuzzy control system operates, using a building's central heating boiler as an example. Atiyah et al. [18] examined and implemented a ratio-control mechanism in two distinct operational contexts. The careful regulation of the riser and regenerator reactors' outlet temperatures is the main concern here. Oloruntoba et al. [19] discussed the importance of uniformly distributing spent catalysts by altering the catalyst distributor's structure and operations. Tian et al. [20] proposed a data-driven and knowledge-based fusion strategy (DL-SDG) for early warning and prediction of aberrant circumstances in the FCC process. Khaldi et al. [21] provided a thorough summary of the state of the art in FCC modeling, control, and optimization. They contrasted the many methods that have been used recently, paying particular emphasis to artificial intelligence techniques. Mastry et al. [22] investigated such a substitute, with particular attention to the FCC process. Five pyrolysis oils derived from biogenic material (olive pits and stones) and municipal solid waste (MSW). Mavukwana et al. [23] examined how the use of FCCU affected the evolutionary behavior and yield of syngas (CO, H₂, and light hydrocarbons), as well as char and energy yields during pyrolysis and CO₂-assisted gasification of waste tires at 900 °C in a fixed-bed semi-batch reactor. Akhtar and Zaman [24] studied the ability of catalytic processes to reduce environmental impacts, which is increasingly acknowledged across various industries. Maroua et al. [25] offered a hybrid strategy for improved microgrid system control that combines a fractional-order method with a Type-2 Fuzzy Logic Controller (T2FLC) optimized by a Genetic Algorithm (GA). Çelik et al. [26] provided a thorough analysis of Non-Linear PID controllers, emphasizing their benefits over Linear PID controllers and their usefulness across a range of engineering applications. They discussed the importance of N-PID controllers, examined significant developments in their structural alterations, and examined various tuning strategies, such as optimization-based, adaptive, and bio-inspired techniques. Alelg et al. [27] presented a feed-aware modeling framework that uses pilot-plant experimental data to enhance the model performance of the FCCU by integrating ensemble anomaly detection, Principal Component Analysis (PCA)-based segmentation coupled with feed chemistry, and Bayesian-optimized regression. Wei et al. [28] proposed a cutting-edge, adaptable Model Predictive Control (MPC) technique to increase light product yield in FCC units. This method successfully handles regenerator temperature fluctuations as an alternative to reaction temperature regulation. Enache [29] described the process used in a commercial FCCU to investigate the causes of afterburning and the technical fixes to reduce it. Thus, it was determined that the non-uniform distribution and mixing of air and catalyst were the primary causes of afterburning, based on analysis of the regenerator temperature profile, the as-built regenerator design, and the regenerator's internal mechanical state. Selalame et al. [30] examined the riser portion of the FCC unit and evaluated conventional modeling techniques for simulating the FCC regenerator. The regenerator's hydrodynamics and kinetics are examined using modeling and experimental data. Additionally, the modeling of constitutive components crucial to the FCC unit, such as catalyst transport lines and gas-solid cyclones, is included. Fuzzy Logic classifiers, Adaptive Fuzzy Logic controllers, and Fuzzy Logic Sliding Mode Control were studied for various industrial applications [31-33].

Previous studies revealed that issues related to coupling, uncertainty, and disturbance compensation in the FCCU unit have not been fully addressed. Solving these problems can significantly enhance the FCCU's efficiency and product quality. Thus, the main goal of this study is to develop a hybrid control system consisting of FLC and Nonlinear PID control for the temperatures of the FCCU reactor and regenerator. This control system employs two nonlinear PID controllers to compensate for disturbances in the system and two PD-Like Type2 (PDLIT2) Fuzzy logic controllers to handle uncertainties in the FCCU. The enhancement is in the overshoot of the reactor temperature response. Firefly Optimization Algorithm is used to tune the controllers' parameters. This paper's remaining sections are organized as follows: Section 2 provides a thorough description of the FCCU procedure, and Section 3 describes the modeling approach. Section 4 delves into the open-loop response process, and Section 5 briefly covers the control design for the FCCU. Section 6 presents the simulation findings, and finally, Section 7 provides the conclusion.

2. FCCU Process

Petroleum refineries consist of numerous processing units, with the FCCU unit being the most crucial one. It transforms heavier fractions, such as gasoline, jet fuel, and diesel, from high-boiling-point, high-molecular-weight fractions like gasoil and residue. A modern FCCU is essential to the economy because it increases the value of the products it produces. This is attributed to its reactivity to changing feedstock and product demands, flexibility in adapting to such changes, and the wide margins between FCCU feedstocks and converted FCCU products. It often serves as the beating heart of the refinery. The catalyst needs regeneration after separation from the product gas due to coke deposition and deactivation. Conversely, hydrocarbon byproducts are entrained, adsorbed, or found on the used Catalyst [34]. The FCCU is described in [1]. It comprises regenerator and riser/reactor components:

- The riser/reactor conducts cracking at endothermic temperatures, while the regenerator burns off the coke on the used catalyst. The amount of catalyst used is regulated via control valve 1.
- Control valve 2, which maintains a fixed temperature of the riser at a predetermined level by modifying the flow rate of the regenerated catalysts.
- The used catalyst is transported back to the regenerator for recycling through the transport lines.
- The air introduced into the coke undergoes combustion on the catalyst surface in the regenerator.

This exothermic combustion reaction occurs between 900 and 970 K, providing ample heat to meet the reactor's heating requirements. The regenerator's airflow rate can be adjusted by control valve 3. Fig. 1 displays the FCCU process schematic diagram [1].

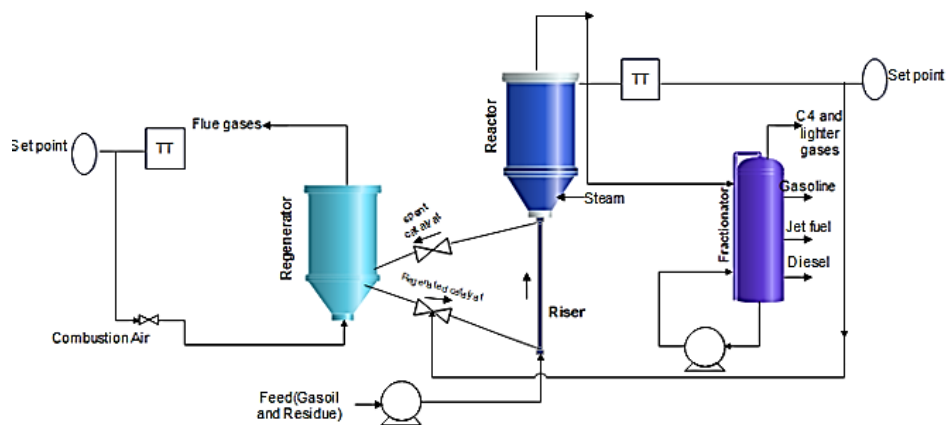


Fig. 1. Process schematic for the FCCU [1]

2.1. Modeling for FCCU process

Considering both material and energy balances, a model of the FCCU that captures the dynamic behavior of both the reactor and the regenerator has been developed. The following assumptions were made to establish a balance of energy between the reactor and regenerator [35]. The Energy Balance Equation of Reactor equations are [35]:

$$\text{Rate of Heat Accumulation} = \text{Input stream} - [\text{Output stream} - \text{Reaction Heat}]$$

$$\text{Regenerated catalyst Heat} + \text{Feed's Heat} + \text{Steam'Heat} - (\text{effluent Spent catalytic Heat}$$

$$\text{Heat of reaction} = \text{Rate of Accumulation}$$

$$Frgc1 Cprgc1 Treg1 + Ff1 Cpf1 Tf1 + Fs1 Hs1 - Fp1 Cpp1 Trea1 - Fsc1 Cpsc1 Trea1 + Hrea1 = \frac{(Mp1 CPp1+Msc1 psc1)dTrea1}{dt} \quad (1)$$

The energy balance equation of the regenerator equation is [35]:

$$\text{Inputs Stream} - [\text{Outputs Stream} + \text{combustion Heat}] = \text{Accumulation Rate} \quad (2)$$

$$\text{Spent catalysts Heat} + \text{Airs Heat} - (\text{Combustions Heat} - \text{Heat of reg catalyts} - \text{Flue gases Heat}) = \text{Rate of Accumulation} \quad (3)$$

$$Fsc1 Cpsc1 Trea2 + Fai2 Cpai2 Tai2 - Hco2 - Frgc1 Cprgc1 Treg2 - Ffl2 Cpf2 Tr = \frac{(Mrgc2 Corgel+Mf12 Cpf12)dTreg2}{dt} \quad (4)$$

2.2. Simulation of the open loop for FCCU

The FCCU open-loop model is simulated using plant parameters in Eq. 1 and Eq. 4. In Table 1, the model's parameters are presented.

Table 1. Plant-related FCCU model parameters [10]

Parameter	Value	Parameter	Value
F_{rgc1}	454.79 Kg/sec	M_{sc1}	2316.86 Kg
$C_{p_{rgc1}}$	1.005 KJ/Kg. K	$C_{p_{sc1}}$	1.9 KJ/Kg. K
F_{f1}	51.25 Kg/sec	F_{sc1}	463.37 Kg/sec
$C_{p_{f1}}$	3.5 KJ/Kg. K	F_{ai2}	66.41 Kg/sec
T_{f1}	420K	$C_{p_{ai2}}$	2.207 KJ/Kg. K
F_{s1}	20.5 Kg/sec	T_{ai2}	773K
H_{s1}	2802K	F_{f2}	75Kg/sec
F_{p1}	62.59 Kg/sec	$C_{p_{f2}}$	3.1335 KJ/Kg. K
$C_{p_{p1}}$	1.15 KJ/Kg. K	M_{rgc2}	4547.93 Kg
H_{rea1}	506.2K	M_{f2}	75 Kg
M_{p1}	314.76 Kg	H_{co2}	950 K

Fig. 2 shows the open-loop response using the regenerator and reactor set points of $T_{reg} = 988.5$ K and $T_{rea} = 776$ K, as shown in Fig. 1.

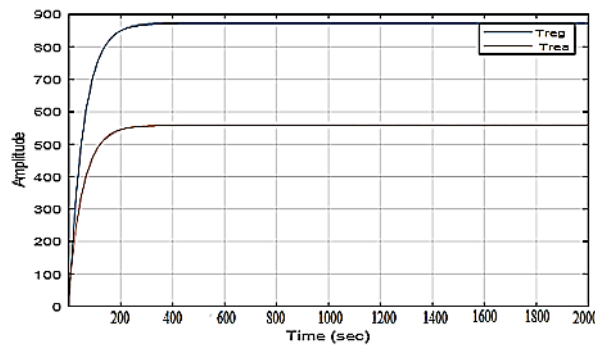


Fig. 2. Reactor and regenerator temperature response in an open loop for the FCCU

The design of the control system is discussed in the next paragraph to achieve high product quality, reduce steady-state error, and minimize overshoot in the FCCU-controlled system's transient responses.

3. Design of Hybrid Intelligent Control for FCCU

In the petroleum industry, FCCU management, or Fluid Catalytic Cracking Unit, is an essential part of refining operations. The FCCU must be carefully monitored and adjusted to maintain the desired operating conditions to guarantee optimal performance and efficiency. In this study, two PDLIT2 Fuzzy Logic Controllers and two nonlinear PID controllers are designed as shown in Fig 3.

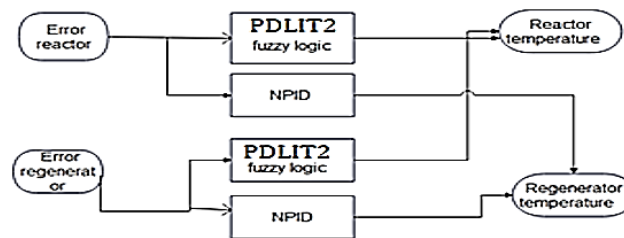


Fig. 3. Hybrid intelligent (PDLIT2 fuzzy logic and NPID) control design [1]

The explanation of the two types of controllers is given in the following sections:

3.1. Nonlinear PID (NPID) control

An effective technique used in many control systems is a nonlinear PID control. It offers an adaptable, effective method for achieving precise control of dynamic systems. The traditional PID control structure can address complex control issues that linear control methods alone cannot handle by incorporating nonlinear elements (Fig. 4).

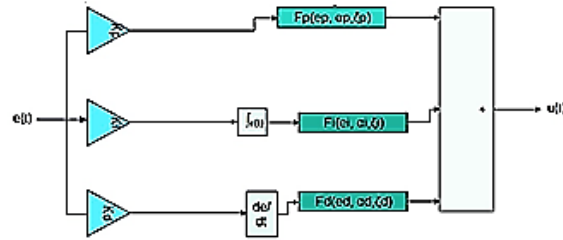


Fig. 4. Elements of Nonlinear PID controller (NPID)

The NPID equation is [36, 10]:

$$NPID = Kp Fp (ep, ap, zp) + Kd Fd (ed, ad, zd) + Ki Fi (ei, ai, zi) \tag{5}$$

where F is a nonlinear function and expressed as [10]:

$$F(e, \alpha, \zeta) = \begin{cases} |e|^\alpha \text{sign}(e), & \text{and } |e| > \zeta \\ e \zeta^{\alpha-1}, & \text{and } |e| \leq \zeta \end{cases}, \quad \zeta > 0 \tag{6}$$

$$\text{sign}(e) = \{1, e \geq 0\} \text{ and } \{-1, e < 0\}$$

e is the error signal, α and ζ are shape parameters controlling the nonlinearity and the linear range of the function F, and Kp, Kd, and Ki are the proportional, derivative, and integral gains of the controller.

3.2. PD-like interval type-2 (PDLIT2) fuzzy logic control

The fuzzy control system is often described as a structure that simulates a human expert. In this case, the human operator's knowledge is represented by a set of fuzzy linguistic rules. Similar to how a human would make decisions, these rules result in an approximation of a decision. However, the efficiency of such a system can suffer due to its inability to leverage the crisp membership functions of traditional fuzzy logic to address the significant consequences of uncertainty and disturbances [37]. The PDLIT2 FLC is a Type 1 Fuzzy Logic generalized three-dimensional controller that handles uncertainty through membership functions [38]. This approach effectively addresses challenging nonlinearities. In 1975, Zadeh developed the Type-2 fuzzy set, which includes a membership function to address uncertainty in three dimensions.

In this study, the FCCU process receives three inputs: the error, the change in error, and the controller output. A set of fuzzy rules is developed using linguistic variables to regulate the reactor and regenerator. Each Fuzzy Controller has seven Type-2 Gaussian membership functions for input and output. Fig. 5 illustrates the membership functions for the fuzzy logic control of the FCCU process. The memberships and rules of this controller were selected to achieve optimal performance of the FCCU, where FOU is the Footprint OF Uncertainty.

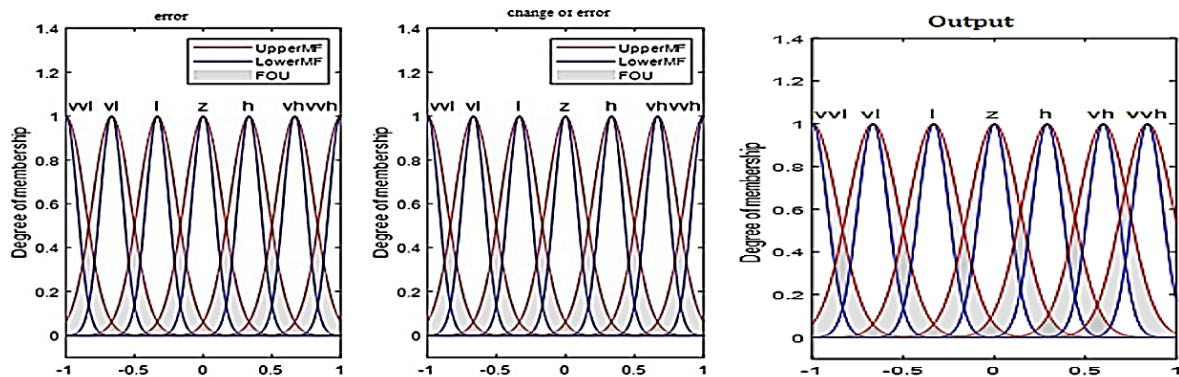


Fig. 5. The membership functions for the two inputs and output for the fuzzy logic control of the FCCU process

Table 2 provides the fuzzy rules for PDLIT2 fuzzy logic control. Seven Gaussian membership functions are utilized in this work for input and output. Using the Number Cruncher Systems (NCSS) software, linguistic variables, intervals, and values for several FCCU inputs and outputs can be obtained. In this study, data from variables with similar input and output are clustered into seven groups using the NCSS software: very very low (vvl), very low (vl), low (l), zero (z), high (h), very high (vh), and very very high (vvh). The controller's inputs are the air and regenerated catalyst flow rates, and its outputs are the reactor and regenerator temperatures. Both input and output membership functions are Gaussian. The aggregation method is Min-Max, and the defuzzification method is the Centroid method. The Karnik-Mendel reduction method is used, and the memberships are normalized to the range (-1, 1). The fuzzy control system is often described as a structure that simulates human expertise. In this case, the human operator's knowledge is represented by a fuzzy linguistic rule set.

Similar to how a human would make decisions, these rules result in an approximation of a decision. However, the efficiency of such a system can suffer due to its inability to leverage the crisp membership functions of traditional fuzzy logic to address the significant consequences of uncertainty and disturbances [37]. These membership functions are also subject to the inherent uncertainty of PDLIT2 fuzzy logic controllers, which extend beyond linguistic variables [38]. This approach effectively addresses challenging nonlinearities. In 1975, Zadeh developed the Type-2 fuzzy set, which includes a membership function to address uncertainty in three dimensions.

Table 2. PDLIT2 fuzzy logic control fuzzy rules [1]

		Error						
		vv1	v1	l	z	h	vh	vvh
change of error	Vv1	vv1	vv1	vv1	vv1	vl	l	z
	V1	vv1	vv1	vv1	vl	l	z	h
	L	vv1	vv1	vv1	l	z	h	vh
	Z	vv1	vl	l	z	h	vh	vvh
	H	vl	l	z	h	vh	vvh	vvh
	Vh	i	z	h	vh	vvh	vvh	vvh
	vvh	vl	h	vh	vvh	vvh	vvh	vvh

4. Firefly Optimization Algorithm (FOA)

The swarm intelligence algorithm family, including the Firefly Optimization Algorithm (FOA), has recently demonstrated impressive performance in solving optimization problems [39]. The primary objective of optimization techniques is to determine the objective functions, or maximum or minimum, of mathematical functions, which might or might not be constrained by variables. The FA is based on the idealized behavior of the firefly's flashing traits. Table 3 illustrates the Firefly pseudo code [39].

Table 3. Firefly optimization algorithm posing as the code [39]

```

Start
Function of interest f(x), x = (x1, ..., xd)
Create the initialized firefly population xi at (i=1, 2,...,n).
f(xi) determines the light intensity I at xi that is associated with f(x)
Define the light absorption coefficient γ

While (t < Maxgeneration)
  For L=1: n, where n is the number of fireflies
    For M=1 : L
      If (IL > IM)
        Vary attractiveness with distance r via e-γr;
        Move it from L to M.
        Calculate fresh approaches and adjust light intensity
      End If
    End for M
  End for L
  Sort fireflies and determine the firefly that is currently the best
End.
    
```

The formula for updating any two fireflies (X_i and X_j) is:

$$X_i^{t+1} = X_i^t + \beta \cdot e^{-\gamma \cdot r_{ij}^2} (X_j^t - X_i^t) + \alpha_t \cdot \epsilon_t \tag{7}$$

α_t is the step size controlling parameter, ϵ_t is a random distribution parameter, r is the distance of attraction, β is the attractiveness firefly value, and γ is the absorption coefficient of the media light. The FOA optimization method is faster and simpler than other optimization methods, such as the Particle Swarm Optimization (PSO) algorithm [40-42], the Social Spider Optimization (SSO) algorithm [43], and the Gray Wolf Optimization (GWO) algorithm [44].

5. Simulation Results

The FCCU control system design employs two NPID controllers to overcome the system's nonlinearity, along with two PDLIT2 fuzzy logic controllers to address the system's uncertainty in controlling the temperature of both the reactor and the regenerator. Fig. 6 illustrates the closed-loop Reactor and regenerator temperature control system.

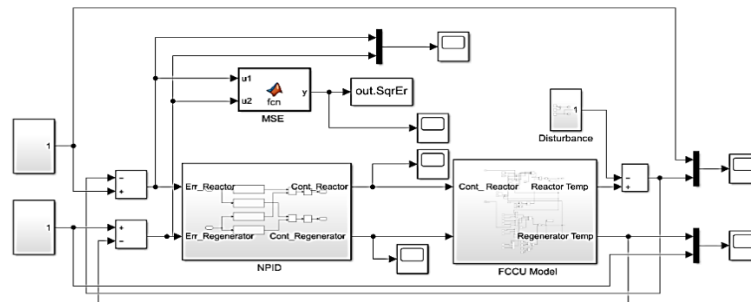


Fig. 6. Simulink of the proposed FCCU-controlled system

The comprehensive block diagram of the suggested FCCU control system, which includes PDLIT2 fuzzy logic control and NPID control, is shown in Fig. 7. A step input of 50 lph (Litter per hour) is introduced to Frge as a disturbance. Moreover, Fig. 8 describes each NPID controller based on Fig. 7, and each Fuzzy controller is described in Fig. 9.

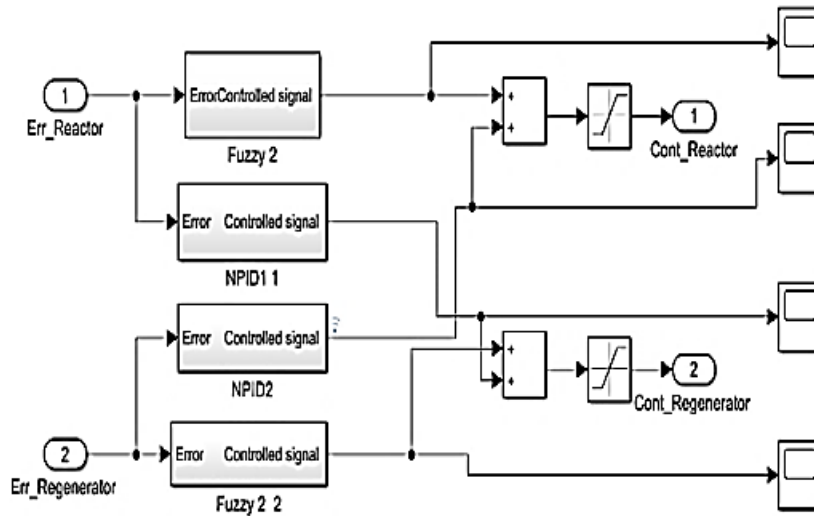


Fig. 7. Nonlinear PID and PDLIT2 Fuzzy controllers

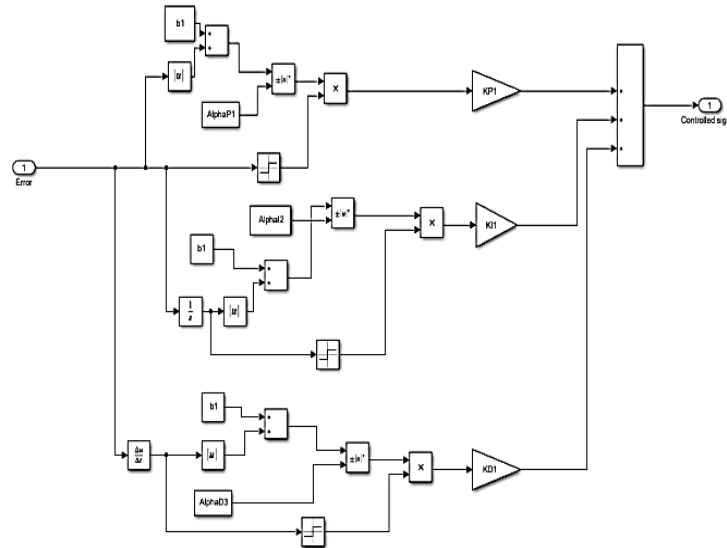


Fig. 8. Simulink of NPID control

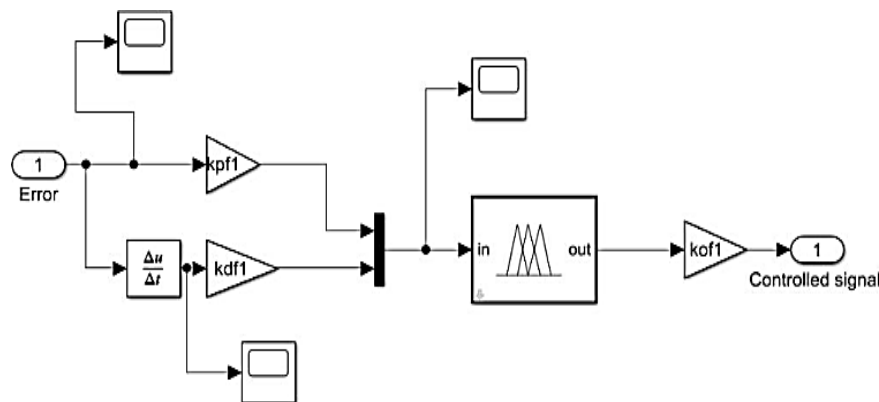


Fig. 9. Simulink of PDLIT2 fuzzy logic control

Each NPID controller has 6 parameters, and each Fuzzy controller has 3. This means that the optimal values for 18 parameters need to be determined. The controller parameters are adjusted using the Firefly Optimization Algorithm (Table 4).

Table 4. Parameters of firefly optimization algorithm

Parameter	Explanation
$\gamma=1$	light absorption coefficient
Maximum generation=100	Maximum No. of Iterations
npop=10	Number of Fireflies
$y = \frac{(e_1^2 + e_2^2)}{2}$	objective functions (Mean Squared Error equation)

The optimal gains and NPID controller parameters following tuning are listed in Table 5.

Table 5. NPID controller optimal parameters and gains

Parameters	Value	Parameters	Value	Parameters	Value
KP1	1	kpf11	0.0016	KP3	1.2
KI1	10	kdf1	0.0033	KI3	30
KD1	1.5	kof1	1000	KD3	1.7
AlphaP1	2	kpf2	0.0011	AlphaP13	0.1
AlphaI2	0.3	kdf2	0.0025	AlphaI23	0.4
AlphaD3	0.6	kof2	1000	AlphaD3	0.7

The ideal controller values are found using the fitness function's Mean Squared Error (MSE), and the goal function is chosen as the Mean Squared Error (MSE) is calculated as:

$$y = \frac{(e_1^2 + e_2^2)}{2} \tag{8}$$

e_1 and e_2 are reactor error and regenerator error in temperature, respectively. The performance of MSE with respect to iterations is shown in Fig. 10. The sudden increase in the MSE is shown in Fig. 10 because of the local minimum phenomena. However, the FOA algorithm overcomes this issue, and the MSE response decreases monotonically.

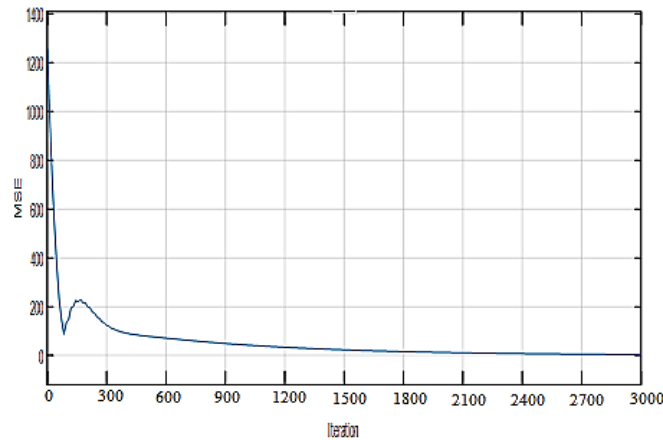


Fig. 10. The firefly optimization algorithm's mean squared error

By selecting a variable set-point temperature for the reactor in the range of (600K-800K) and for the generator in the range (900K-1000K), the output temperature responses are shown in Figs. 11 and 12, respectively. Also, the controlled signals for the reactor and generator systems are shown in Figs. 13 and 14, respectively.

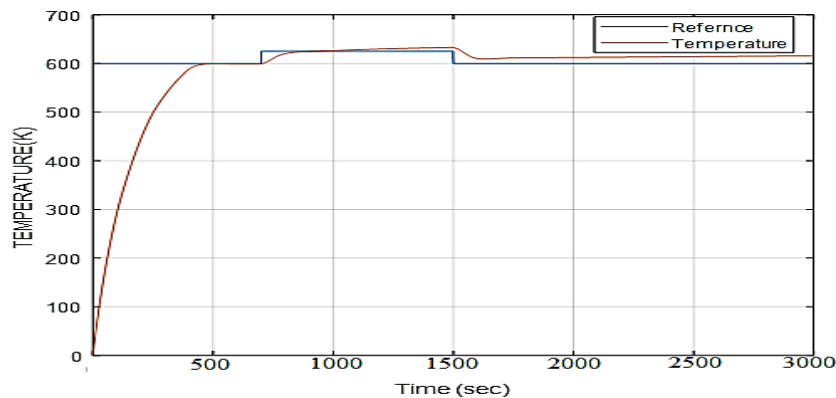


Fig. 11. A variable step-controlled system reactor temperature

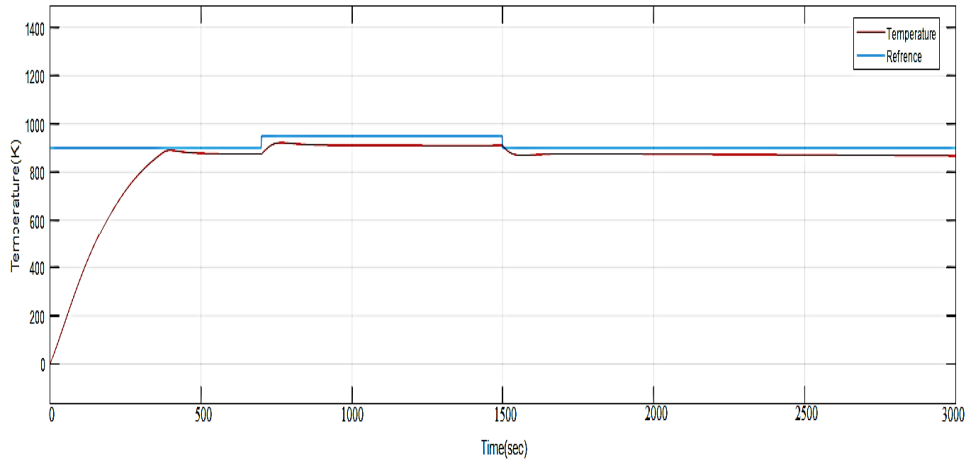


Fig. 12. A variable step-controlled system regenerator temperature

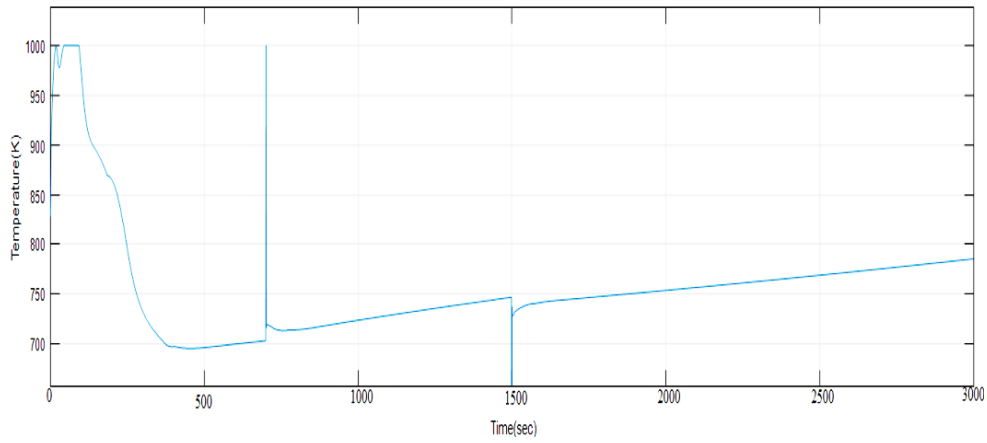


Fig. 13. Response of reactor-controlled signal

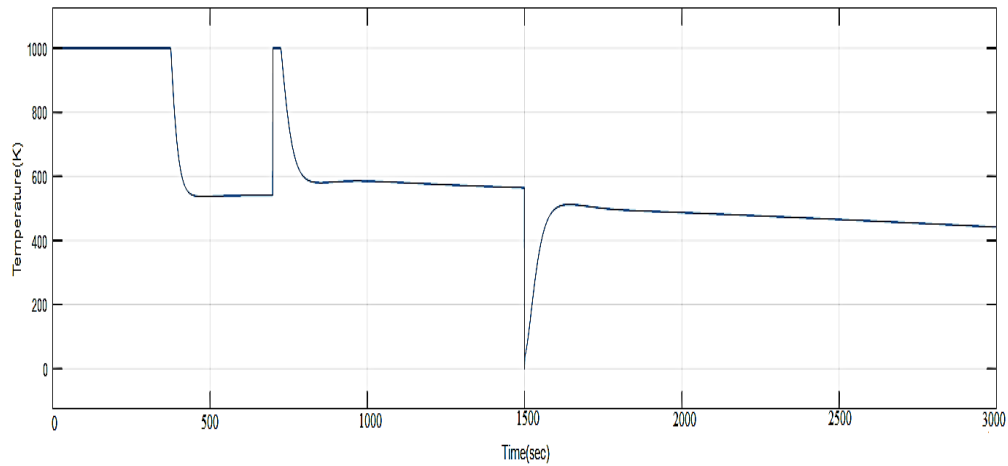


Fig. 14. Response of generator-controlled signal

The spike shown in Fig. 13 is due to a sudden change in the reference temperature. However, the controller compensates for this sharpness in a very short time. Moreover, by applying a disturbance of 50 liters per hour at 2500 seconds and removing it at 2750 seconds to the regenerator catalyst flow rate, using the same step responses explained above, the output temperature responses are shown in Figs. 15 and 16, respectively. The controller compensates for the disturbance in less than 250 seconds.

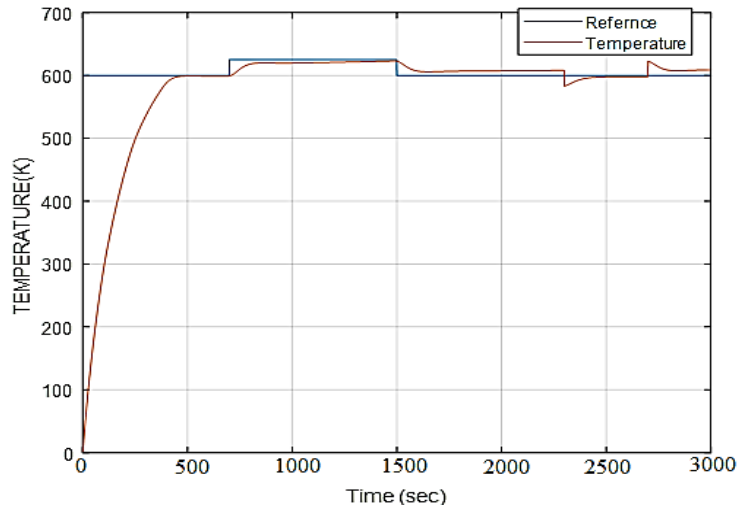


Fig. 15. A variable step-controlled system reactor temperature with the application of a disturbance

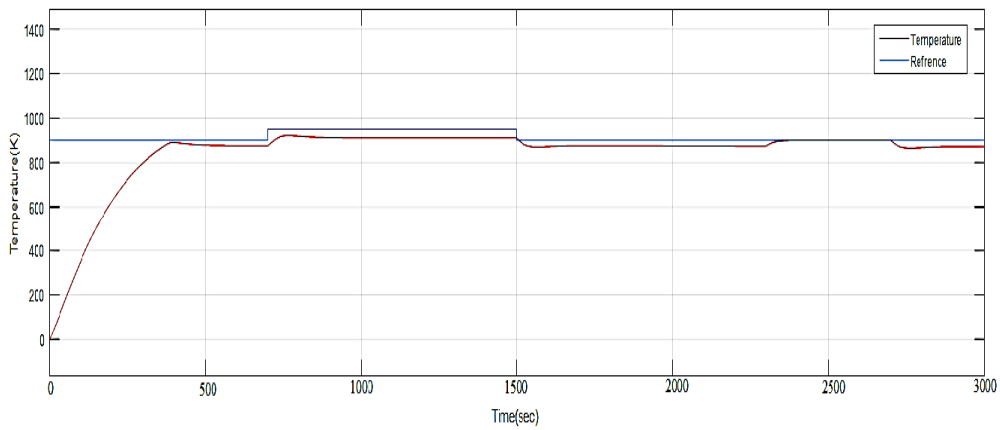


Fig. 16. A variable step-controlled system generator temperature with the application of a disturbance

Also, the controlled signals for the reactor and generator systems under disturbance application are shown in Figs. 17 and 18, respectively.

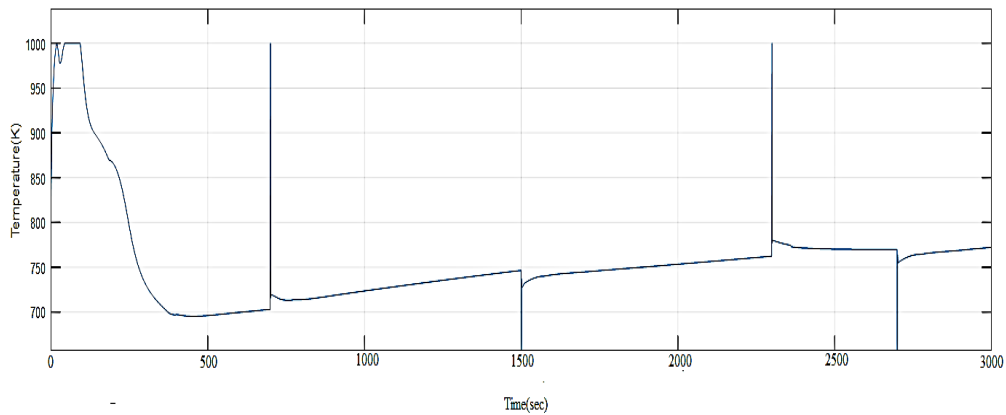


Fig. 17. Response of reactor-controlled signal with the application of a disturbance

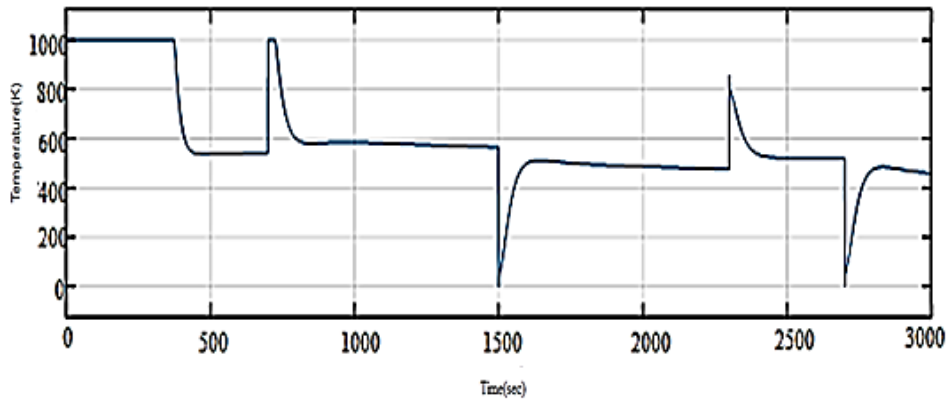


Fig. 18. Response of the generator-controlled signal with the application of a disturbance

The results highlight the significance of two pivotal concepts in the field of process control: nonlinear PID control and fuzzy control, especially when applied to the FCCU. Both of these control strategies are designed to enhance the steadiness, resilience, and flexibility of the control system, thereby improving the overall performance and efficiency of the FCCU. By adding nonlinear characteristics to the FCCU process, PID controllers and nonlinear PID controllers address these complexities. On the other hand, fuzzy control is well-suited for the dynamic and uncertain nature of the FCCU. It leverages fuzzy logic to create a control system that effectively handles uncertain and imprecise information. PD-Like Type-2 Fuzzy logic control (PDLT2) solved the uncertainty and chattering in the system. Also, the disturbance effect has been resolved. The regenerator temperature overshoot is decreased by 85%, and the reduction in the reactor temperature is 60%. Additionally, there was a 0.703% overshoot in regenerator temperature and a 0.239% overshoot in reactor temperature. These enhancements were obtained with respect to the results shown in [1]. To address interference in the system equations for the reactor and regenerator, a cross-coupling approach was used, combining the first and third regulators to regulate the reactor's temperature and the second and fourth controllers to regulate the regenerator's temperature. Based on the simulation results, the overshoot and chattering in control signals have been reduced to minimum values. These controllers address the problem of inherent coupling, uncertainty, chatter, and nonlinearity in the model. The limitation of this work is that the proposed hybrid controller can be used only to control the FCCU. Other operational units of the refinery, such as the Vacuum Distillation Unit, Hydrotreating Unit, and Isomerization Unit, were not considered.

6. Conclusions

This study presented the design of two Type-2 PD-like fuzzy logic controllers and two nonlinear PID controllers for the FCCU. A Firefly Optimization Algorithm was used to tune the controller parameters. Control signal overshoot and chattering have decreased, according to the simulation results. These controllers made up for the model's inherent nonlinearities, chattering, cross-coupling, and uncertainty. Compared to other controllers discussed in the literature review, the proposed controller achieved 60% reductions in regenerator and reactor temperature overshoot. The reactor temperature showed a 0.505% overshoot, whereas the regenerator temperature showed a 1.949% overshoot using the proposed controllers. In a summary, the suggested controller is superior at improving the temperature responses of the regenerator and reactor, thereby improving product quality. For the future work, the proposed controller will be implemented on an FPGA.

Acknowledgment

The authors are grateful to the staff of the College of Control and Systems Engineering at the University of Technology, Iraq, for their support of this study.

References

- [1] Z. Brijet, and N. Bharathi, "Design of type-2 fuzzy logic controller for fluid catalytic cracking unit," *International Journal of Manufacturing Technology and Management*, vol. 35, no. 1, 2021, <https://doi.org/10.1504/IJMTM.2021.114700>.
- [2] A. Dey and R. Ayyagari, "Robust PID controller design using fuzzy pole placement techniques," *IFAC*, Elsevier, vol. 49, no. 1, pp. 789–794, 2016, <https://doi.org/10.1016/j.ifacol.2016.03.153>.
- [3] S. Dettori, V. Iannino, V. Colla, and A. Signorini, "A fuzzy logic-based tuning approach of PID control for steam turbines for solar applications," *Energy Procedia*, vol. 105, pp. 480–485, 2017, <https://doi.org/10.1016/j.egypro.2017.03.344>.
- [4] J. E. Rodríguez-Castellanos, V. H. Grisales-Palacio, and J. E. Cote-Ballesteros, "A tuning proposal for direct fuzzy PID controllers oriented to industrial continuous processes," *IFAC PapersOnLine*, vol. 51, no. 4, pp. 657–662, 2018, <https://doi.org/10.1016/j.ifacol.2018.06.172>.
- [5] S. Ahmed, S. Ali, and R. Tabasha, R., "The design and implementation of a fuzzy gain-scheduled PID controller for the Festo MPS PA compact workstation liquid level control," *Engineering Science and Technology, an International Journal*, vol. 23, no. 2, pp. 307–315, Apr. 2020, <https://doi.org/10.1016/j.jestech.2019.05.014>.
- [6] G. L. Demidova, D. V. Lukichev, A. Y. and Kuzin, "A genetic approach for auto-tuning of adaptive fuzzy PID control of a telescope's tracking system," *Procedia Computer Science*, vol. 150, pp. 495–502, 2019, <https://doi.org/10.1016/j.procs.2019.02.084>.
- [7] I. Ganchev, A. Taneva, K. Kutryanski, and M. Petrov, "Decoupling fuzzy-neural temperature and humidity control in HVAC systems", *IFAC PapersOnLine*, vol. 52, no. 25, pp. 299–304. Nov. 2019, <https://doi.org/10.1016/j.ifacol.2019.12.539>.
- [8] Jalali, N., Razmi, H., and Doagou-Mojarrad, H., "Optimized fuzzy self-tuning PID controller design based on Tribe-DE optimization algorithm and rule weight adjustment method for load frequency control of interconnected multi-area power systems", *Applied Soft*

- Computing Journal, vol. 93, no. 106424, 2020, <https://doi.org/10.1016/j.asoc.2020.106424>.
- [9] P. N. Josiah, I. J. Otaraku, and B. O. Egbuomwan, "Servo and regulatory response of an industrial fluid catalytic cracking (FCC) unit under fuzzy logic supervisory control," *Engineering and Technology Journal*, vol. 41, no. 9, pp. 1139-1151, 2023, <https://doi.org/10.30684/etj.2023.139485.1432>.
- [10] G. A. Mutuab and M. Y. Hassan, "Non-Linear PID control of fluid catalytic cracking unit," *Journal européen des systèmes automatisés*, vol. 56, no. 5, pp. 793-800, Oct. 2023, <https://doi.org/10.18280/jesa.560510>.
- [11] Z. Guo and H. Yang, "Improving model-free control algorithms based on data-driven and model-driven approaches: a research study," *Mathematics*, vol. 12, no. 1:24, 2023, <https://doi.org/10.3390/math12010024>.
- [12] J. Y. Lee, G. G. Jin, and G. B. So, "Adaptive nonlinear Proportional-Integral-Derivative control of a continuous stirred tank reactor process using a radial basis function neural network," *Algorithms*, 1vol. 8, no. 7, pp. 442-442, July 2025, <https://doi.org/10.3390/a18070442>.
- [13] A. Rospawan and C. C. Tsai, "Recurrent polynomial-based FBLS for adaptive predictive PID control of nonlinear discrete-time systems: comparative studies on control performance and time complexity," 2024 IEEE International Conference on Systems, Man, and Cybernetics (SMC), Kuching, Malaysia, 2024, pp. 541-546, <https://doi.org/10.1109/smc54092.2024.10832085>.
- [14] Y. Sun and Z. Su, "Nonlinear finite-time PID control method with gain tuning by frequency domain analysis," 2023 5th International Conference on Intelligent Control, Measurement and Signal Processing (ICMSP), Chengdu, China, pp. 461-466, May 2023, <https://doi.org/10.1109/ICMSP58539.2023.10170956>.
- [15] A. Rajendran, M. Karthikeyan, G. Saravanakumar, "Implementation of FOPID controller with modified harmony search optimization for precise modelling and auto-tuning of nonlinear systems", *Automatika*, vol. 65, no.; 3, pp. 881-893, 2024, <https://doi.org/10.1080/00051144.2024.2307227>.
- [16] A. Beşkardeş, Y. Hameş, and K. Kaya, "A comprehensive Review on Fuzzy logic Control Systems for All, Hybrid, and Fuel cell Electric Vehicles," *Soft Computing*, vol. 28, pp. 8183-8221, 2024, <https://doi.org/10.1007/s00500-023-09454-5>.
- [17] M. G. Voskoglou, "Fuzzy logic in control theory", In: Magdi, D.A., Helmy, Y.K., Mamdouh, M., Joshi, A. (eds) *Digital Transformation Technology. Lecture Notes in Networks and Systems*, vol. 224, Springer, Singapore, 2022, https://doi.org/10.1007/978-981-16-2275-5_13.
- [18] S. K. Atiyah, A. Y. A. Aljanabi, M. S. Ahmed, et al., "Design of a ratio control algorithm for a fluid catalytic cracking system in an universal oil product context," *Petroleum Chemistry*, vol. 64, pp. 83-92, 2024, <https://doi.org/10.1134/S0965544124020154>.
- [19] A. Oloruntoba, Y. Zhang, and C. S. Hsu, "State-of-the-Art review of fluid catalytic cracking (FCC) catalyst regeneration intensification technologies," *Energies*, vol. 15, no. 6:2061, 2022, <https://doi.org/10.3390/en15062061>.
- [20] W. Tian, S. Wang, S. Sun, C. Li, and Y. Lin, "Intelligent prediction and early warning of abnormal conditions for fluid catalytic cracking process," *Chemical Engineering Research and Design*, vol. 181, pp. 304-320, 2022, <https://doi.org/10.1016/j.cherd.2022.03.031>.
- [21] M. K. Khaldi, M. Al-Dhaifallah, O. and Taha, "Artificial intelligence perspectives: a systematic literature review on modeling, control, and optimization of fluid catalytic cracking," *Alexandria Engineering Journal*, vol. 80, pp. 294-314, 2023, <https://doi.org/10.1016/j.aej.2023.08.066>.
- [22] M. C. Mastry, L. Dorazio, J. C. Fu, J. P. Gómez, S. Sedano, S. S. Ail, M. J. Castaldi, and B. Yilmaz, "Processing renewable and Waste based feedstocks with fluid catalytic cracking: impact on catalytic performance and considerations for improved catalyst design," *Front. Chemistry*, vol. 11, no. 1067488, 2023, <https://doi.org/10.3389/fchem.2023.1067488>.
- [23] A. E. Mavukwana, K. G. Burra, C. Sempuga, M. Castaldi, and A. K. Gupta, "Effect of spent fluid catalytic cracking (FCC) catalyst on synga production from pyrolysis and CO₂-assisted gasification of waste tires," *Fuel*, vol. 355, no. 129446, 2024, <https://doi.org/10.1016/j.fuel.2023.129446>.
- [24] M S. Akhtar and W. Zaman, "Advancing sustainable catalysis: catalytic solutions for green chemistry and the energy transition," *Catalysts*, vol. 15, no. 6, pp. 511, 2025, <https://doi.org/10.3390/catal15060511>.
- [25] B. Maroua, Z. Laid, H. Benbouhenni, et al., "Genetic algorithm type 2 fuzzy logic controller of microgrid system with a fractional-order technique," *Scientific Report*, vol. 15, no. 6318, 2025, <https://doi.org/10.1038/s41598-025-90239-1>.
- [26] D. Çelik, N. Khosravi, M. A. Khan, m. Waseem, and H. Ahmed, "Advancements in Nonlinear PID Controllers: A Comprehensive Review", *Computers and Electrical Engineering*, vol. 129 (Part A), no. 110775, 2026, <https://doi.org/10.1016/j.compeleceng.2025.110775>.
- [27] K. Alelg, A. Alfarraj, A. Tanimu, S. A. Ganiyu, and K. Alhooshani, "Data-Driven approach for predicting gasoline yield in an FCC unit charged with light and heavy feedstocks: A PCA-guided grouping for enhanced modeling experience," *Journal of Chemical Information and Modeling*, vol. 66, no. 1, pp. 271-298, 2026, <https://doi.org/10.1021/acs.jcim.5c02281>.
- [28] B. Wei, Z. Wang, Y. Ye, L. Che, H. and Zhou, "Novel flexible model predictive control strategy to improve the yield of light products in fluid catalytic cracking unit," *Chemical Engineering Research and Design*, vol. 217, pp. 467-482, 2025, <https://doi.org/10.1016/j.cherd.2025.04.007>.
- [29] F. Enache, D. Cursaru, and D. Danulescu, "Integration of wet scrubbing system and SO_x additive technologies to reduce the SO₂ emissions generated in FCCU", *Chemical Papers*, vol. 76, pp. 6537-6549, 2022, <https://doi.org/10.1007/s11696-022-02335-5>.
- [30] T. W. Selalame, R. Patel, L. M. Mujtaba, and Y. M. John, "A Review of modelling of the FCC unit—Part II: The Regenerator," *Energies*, vol. 15, no. 1:388, 2022, <https://doi.org/10.3390/en15010388>.
- [31] A. R. Nasser, A. T. Azar, A. J. Humaidi, A. K. Al-Mhdawi, I. K. Ibraheem, "Intelligent fault detection and identification approach for analog electronic circuits based on fuzzy logic classifier," *Electronics*, vol. 10, no. 23:2888, 2021, <https://doi.org/10.3390/electronics10232888>.
- [32] A. K. Al Mhdawi, N. Wright, A. J. Humaidi and A. T. Azar, "Adaptive PI-Fuzzy like control of a stack pneumatic actuators testbed for multi-configuration small scale soft robotics," 2023 International Conference on Manipulation, Automation and Robotics at Small Scales (MARSS), Abu Dhabi, United Arab Emirates, 2023, pp. 1-8, <https://doi.org/10.1109/MARSS58567.2023.10294122>.
- [33] M. K. Hamzah, R. S. Al-Azzawi, A. Al-Jodah, A. J. Humaidi, and A. F. Hasan, "Fuzzy logic-based chattering reduction in sliding mode control of single-link robot using muscle-like actuator," *ICIC Express Letters*, vol. 18, no. 3, pp. 271-283, 2024, <https://doi.org/10.24507/icicel.18.03.271>.
- [34] Z. Brijet, and N. Bharathi, "Design of type-2 fuzzy logic controller for fluid catalytic cracking unit," *International Journal of Manufacturing Technology and Management*, vol. 35, no. 1, pp. 51-68, 2021, <https://doi.org/10.1504/IJMTM.2021.114700>.
- [35] V. Karthika, Z. Brijet, N. and Bharathi, "Design of optimal controller for fluid catalytic cracking unit," *Procedia Engineering*, vol. 38, pp. 1150-1160, 2012, <https://doi.org/10.1016/j.proeng.2012.06.146>.

- [36] S. K. Valluru M. and Singh, "Performance Investigations of APSO tuned linear and nonlinear PID controllers for a nonlinear dynamical system", Journal of Electrical Systems and Information Technology, vol. 5, no. 3, pp. 442-452, 2018, <https://doi.org/10.1016/j.jesit.2018.02.001>.
- [37] M. Y. Hassan, H. I. Ali, and H. M. Jassim, "Hybrid h-infinity fuzzy logic controller design," Journal of Engineering Science and Technology, vol. 15, no. 1, pp. 1–21, 2020.
- [38] S. S. Ghintab and M. Y. Hassan, "PID-like IT2FLC-based autonomous vehicle control in urban areas," Arabian Journal for Science and Engineering, vol. 50, no. 14, pp. 11001-11017, 2025, <https://doi.org/10.1007/s13369-024-09104-4>
- [39] I. Fister, M. Perc, S. M. Kamal, and I. Fister, "A Review of chaos-based firefly algorithms: perspectives and research challenges," Applied Mathematics and Computation, vol. 252, pp. 155-165, Feb. 2015, <https://doi.org/10.1016/j.amc.2014.12.006>
- [40] M. Q. Kadhim and M. Y. Hassan, "Design and optimization of backstepping controller applied to autonomous quadrotor," (2020) IOP Conference Series: Materials Science and Engineering, vol. 881, no. 1, art. no. 012128, 2020, <https://doi.org/10.1088/1757-899X/881/1/012128>.
- [41] A. J. Humaidi, A. A. Oglah, S. J. Abbas, and I. K. Ibraheem, "Optimal augmented linear and nonlinear PD control design for parallel robot based on PSO tuner," International Review on Modelling and Simulations, vol. 12, no. 5, pp. 281–291, 2019, <https://doi.org/10.15866/iremos.v12i5.16298>.
- [42] A. Al-Jodah, S. J. Abbas, A. F. Hasan, A. J. Humaidi, A. Sh. M. Al-Obaidi, A. A. Al-Qassar, and R. F. Hassan, "PSO-based optimized neural network PID control approach for a four wheeled omnidirectional mobile robot," International Review of Applied Sciences and Engineering, vol. 14, no. 1, pp. 58–67, 2023, <https://doi.org/10.1556/1848.2022.00420>.
- [43] M. Y. Hassan and S. S. Ezzaten, "PI-Like interval type-2 fuzzy logic control based social spider optimization for distillation column," 2018 Third Scientific Conference of Electrical Engineering (SCEE), Baghdad, Iraq, art. no. 8684171, 2018, pp. 67 - 71, 2018, <https://doi.org/10.1109/SCEE.2018.8684171>.
- [44] R. G. Ghane and M. Y. Hassan, "Advanced hybrid nonlinear control for morphing quadrotors," Mathematical Modelling of Engineering Problems, vol. 10, no. 4, pp. 1216-1224, 2023, <https://doi.org/10.18280/mmep.100414>.