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Real Coded GA Tuned Decentralized Decoupled PID for Fluid Catalytic Cracking Unit

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ABSTRACT

Modeling and control of fluid catalytic cracking unit (FCCU) is a challenging problem since it is a highly nonlinear and interacting process. Model of FCCU that describes the dynamic behavior of reactor and regenerator, has been developed by considering energy and material balance equations. A perceptive study has been carried out to determine the interaction between two controlled variables and two manipulated variables and the elements of relative gain array (RGA). RGA analysis suggests that the temperature at the reactor and regenerator can be controlled by manipulating the regenerated catalyst flow rate and air flow rate respectively. Based on this analysis decouplers have been designed to reduce interactions. Two proportional integral derivative (PID) controllers have been used to achieve control of FCCU. Controller parameters are tuned using Ziegler-Nichols and real coded GA. Simulation results are presented to show that the GA-Based optimized PID controller is capable of providing an Improved closed-loop performance over the Ziegler- Nichols tuned PID controller Parameters. Compared to the heuristic PID tuning method of Ziegler-Nichols, the proposed method was more efficient in improving the step response characteristics such as, reducing the steady-states error, rise time, settling time and maximum overshoot in control the reactor and regenerator temperature of FCCU.

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INTRODUCTION

The petroleum industries in the world provide inputs to economic sector including the transport and chemical industries. FCCU is the heart of the modern refineries which is a highly complex and interaction process that cracks high boiling, high molecular weight hydrocarbon fractions of crude oil into more valuable gasoline and other products. FCCU has the impact on the overall refineries profit, so by the implementation of proper control and optimization techniques, the economic benefits can be increased. Threats in the analysis and control of FCCU are (a) Little known and more complex dynamics (b) Complex kinetics of cracking and coke burning reactions (c) Strong interaction between reactor and regenerator and (d) Many operating constraints.

Literatures reveal that most of the available models are empirical and a semi empirical model that reflects the behaviour of the process. Chang-Bock and In-su *(*2001) developed a detailed dynamic model of the reactor and regenerator by considering all the auxiliary units of the process. Elnashaie and Elshini (1993) described the empirical model that has a better insight into the behaviour of the FCC process. Hany and Rohani (1997) developed a simple overall dynamic model of the stacked type FCCU.

1.FCCU:

A typical FCCU is shown in Fig 1. It consists of riser/reactor and regenerator units. In riser/reactor all the endothermic cracking reaction takes place while the regenerator burns off the coke on the spent catalyst, then the fresh catalyst returns to the riser/reactor carrying sufficient heat to supply the heat requirements of the reactor, thus repeats the cycle (Osofisan and Obofaiye, 2007).

The preheated crude oil or feed about 450K-600K is injected in to the bottom of the riser to reactor along with the powdered catalyst and steam. Lighter hydro carbons are produced as the main cracking product, in addition with the by-product coke which deposits on the surface of the catalyst that lowers the catalyst activity. The residence time of the catalyst in the riser is low about 2-5sec. The reactor temperature is typically between 750K-820K. The control valve2 manipulates the quantity of regenerated catalyst flow rate to maintain the riser temperature at predetermined value (Neran and Shayma, 2007).

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The spent catalyst is recycled to the regenerator through the transport lines as shown in Fig 1. The coke is burnt off the catalyst surface by the air blown into the regenerator. This exothermic combustion reaction takes place at the temperature of 950-980K, which is highly sufficient to supply heat requirement of the reactor. The air flow rate to the regenerator could be controlled by a control valve3 (CV3) (Elizabeth and Rafael, 2007).

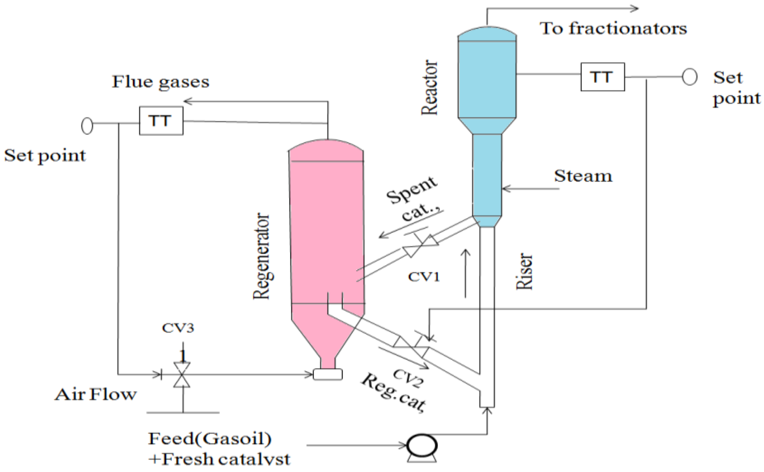


Fig. 1: FCCU process and control configuration.

2.Modelling:

Mathematical model for FCCU is developed by combining or lump the chemical species into 3 pseudo components as shown in Fig 2 (Neran and Shayma, 2007).

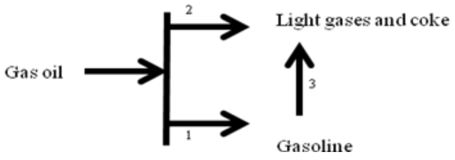


Fig. 2: Three_Lump kinetics.

Assumptions in order to formulate energy balance in reactor and regenerator include,
(a) Neglecting the conduction, convection, and radiated terms and
(b) Heat of reaction and heat of combustion are constant.

Input stream − [Output stream − Heat of reaction] = Rate of Accumulation
Heat of Reg. catalyst + Heat of Feed + Heat of Steam –
{Heat of Effluent – Heat of Spent Catalyst + Heat of reaction} = Rate of Accumulation

2.1Reactor Modeling:

Residence time of feed in the riser is only a few seconds, and hence ideal reactor model is used. The energy balance around the reactor will be,

$$F_{rc}Cp_{rc}T_{reg} + F_f Cp_f T_f + F_{st}H_{st} - F_p Cp_p T_{rea} - F_{sc}Cp_{sc}T_{rea} + \Delta H_R = (M_p Cp_p + M_{sc}Cp_{sc})\frac{dTrea}{dt} \quad (1)$$

*2.1 **Regenerator Modeling:***

Catalyst residence time in the regenerator is generally around 10 to 20min. It is common to assume that the temperature and the amount of coke on catalyst are uniform throughout the regenerator (Sadeghbeigi,2000).

Input stream − [Output stream + Heat of combustion] = Rate of Accumulation

Heat of Spent catalyst + Heat of Air –
{Heat of Combustion − Heat of Reg. Catalyst − Heat of Flue gases} = Rate of Accumulation

$$F_{sc}Cp_{sc}T_{rea} + F_a Cp_a T_a - \Delta H_c - F_{rc}Cp_{rc}T_{reg}F_{fl}Cp_{fl}T_{reg} = (M_{rc}Cp_{rc} + M_{fl}Cp_{fl})\frac{dTreg}{dt} \quad (2)$$

3.Open loop response:

Plant parameters from the literature (Sadeghbeigi,2000, Evelyn and Frank, 1985, Manamalli,2005) are used to simulate and verify the model as given in the equation (1) and (2).

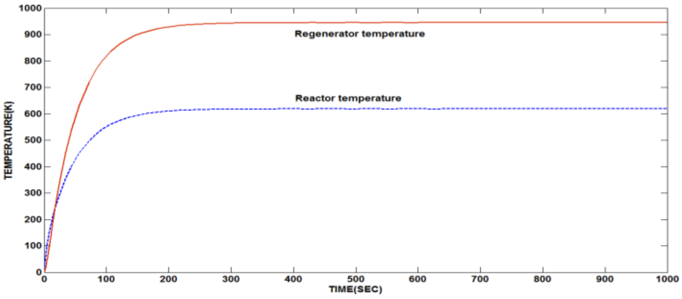


Fig. 3: Open loop response.

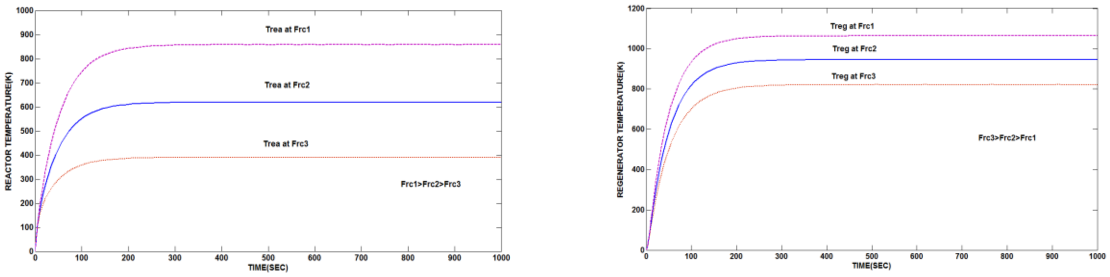
The plant parameters are listed in Table 1. The response of reactor and regenerator temperature is shown in Fig 3.

3.1 Response to the changes in the flow rate of Regenerator Catalyst:

Fig 4 shows the response of the reactor and regenerator temperature for 5% step increase in the F_{rc}. Higher the regenerator catalyst flow rate associated with more heat input to reactor, cracking reaction is accelerated. So, the reactor temperature increases with the decrease of regenerator temperature. Similarly, decrease of F_{rc} has the effect of reduction in heat supply to the reactor thus decelerates the cacking reaction and increase the regenerator temperature.

Table 1: Plant parameters of FCU model.

Parameters	Value
Specific heat capacity of Regenerated catalyst	1.005KJ/KgK
Mass Flow rate of feed(Gasoil)	51.25Kg/Sec
Specific heat capacity of feed	3.1335KJ/KgK
Temperature of feed	420K
Mass Flow rate of Spent catalyst	463.37Kg/Sec
Mass of regenerated catalyst	4547.93Kg
Heat of reaction	506.2KJ/Kg



(a) (b)

Fig. 4: Response of (a) Reactor (b) Regenerator temperature for step Changes in the catalyst flow rate when F_a=constant.

3.2 Response to the changes in the flow rate of air to the Regenerator:

Fig 5 shows the response of the changes in the reactor and regenerator temperature for 5% step increase in the F_a. Due to this, combustion is accelerated and the regenerator and reactor temperature increases. Similarly decrease in F_a leads to decrease in reactor and regenerator temperature.

Thus, the changes in the any one of the manipulated variable affects both the controlled variables and there by confirms the presence of interaction.

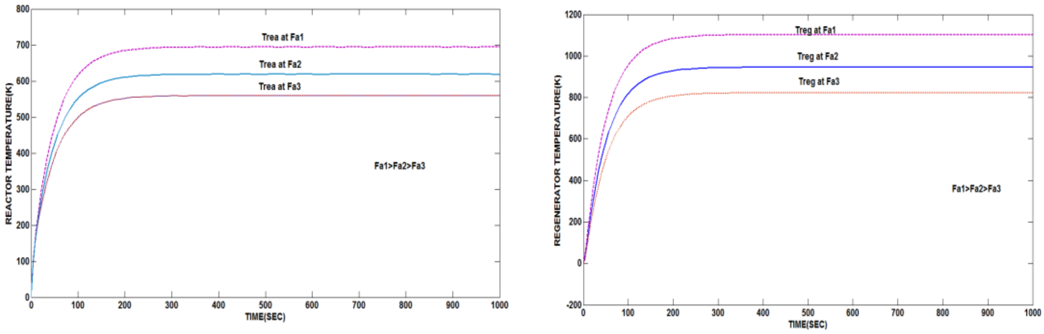
4. Control of FCCU:

To achieve good product quality with maximum yield, FCCU control requires maintaining reactor and regenerator temperature at predetermined values. In this work, the control of temperature in reactor and regenerator is carried out at the regulation level. Two controlled variables and manipulated variables have been taken as T_{reg}, T_{rea} and F_{rc}, F_a respectively.

The reactor temperature is controlled by manipulating the regenerated catalyst flow rate and the regenerator temperature is controlled by manipulating the air flow rate to the regenerator. To carry out this, Decentralized decoupled PID controller is designed and used.

4.1 Decentralized PID Control:

PID controller is a generic control loop feedback mechanism which is widely used in industrial control systems. A PID controller calculates an "error" value as the difference between a measured process variable and a desired set point. The controller attempts to minimize the error by adjusting the process control inputs (Bequette,1998).



(a) (b)

Fig. 5: Response of (a) Reactor (b) Regenerator temperature for step Changes in air flow rate when F_{rc}=constant.

4.2 Decoupling Control System:

To design controller for FCCU process, two characteristics should be investigated.

(1) Interaction among the loops as shown in Fig 6 and

(2)The number of feasible, alternative control loop configuration that gives minimal interaction (RGA analysis).

RGA is defined as the ratio of open loop gain in terms of (M_j, j^{th} manipulated variable) with all other M's are constant to the gain in terms of (Y_i, controlled variable)with all other Y's are constant, the term (λ_{ij}) will be used to describe the dimensionless change in (Y_i) with respect to a change in (M_j).The open loop static gain between T_{rea} and F_{rc} when F_a is kept as constant and the other, when (T_{reg}) is constant by the control loop. The values of the other relative gains could be calculated from above relative gain λ_{11} using the characteristics of the RGA matrix (Stephanopoulos,1984).

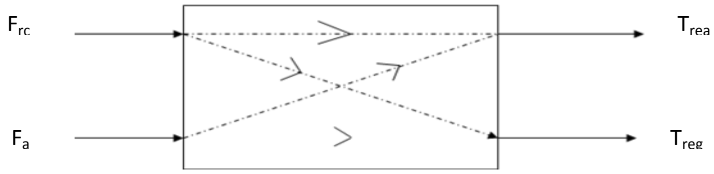


Fig. 6: Interaction between process variables.

The purpose of decouplers is to cancel the interaction effects between the two loops and thus gives non-interacting control loops. Implementation of decouplers with the PID is as shown in fig 7. The interaction from loop1 and loop2 is eliminated by using D2 and the interaction from loop2 to loop1 is eliminated by D1as shown in fig 7.

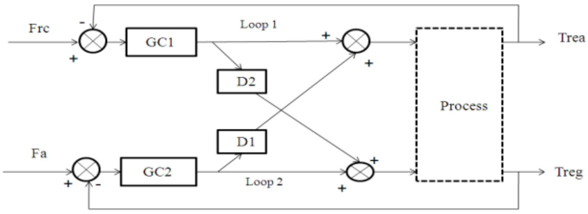


Fig. 7: Implementation of decouplers.

5. *Controller Tuning:*

In this work, Ziegler-Nichols and Real coded Genetic Algorithm tuning methods have been chosen in order to obtain desired response using ISE as a performance index.

5.1 Realcoded GA Tuning:

Genetic algorithm is a heuristic method to search the solution of the optimization problem using technique such as inheritance, mutation, selection and crossover. In this paper genetic algorithm is applied to tune the PID parameters (K_p,K_i,K_d). GA looks for the optimal solution which minimizes the performance index ISE during the search process (Brien and Howe, 2008).

When the variables are naturally quantized, the binary GA fits nicely. However, when the variables are continuous, it is more logical to represent them by floating-point numbers. This continuous GA also has the advantage of requiring less storage than the binary GA because a single floating-point number represents the variable instead of *N_bits* integers. The continuous GA is inherently faster than the binary GA, because the chromosomes do not have to be decoded prior to the evaluation of the cost function. Fig 8 shows the flowchart of RGA operations sequence (Anil Kumar,Dr.Rajeev Gupta,2013).

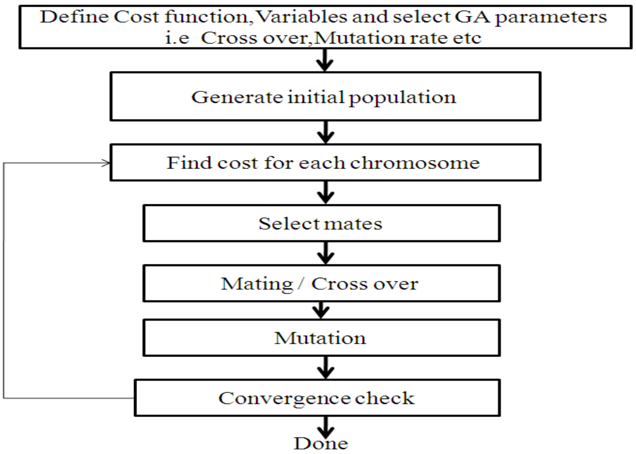


Fig. 8: Flowchart of RGA operation sequenc.

In this work, Roulette wheel selection, non-uniform mutation and single point crossover has been used to obtain the optimal tuning algorithm (Arturo, Y., Jaen-Cuellar, Rene de, J., Romero-Troncoso, Luis Morales-Velazquez and Roque A. Osornio-Rios, 2013). The fitness function of performance index is calculated using equations (3) and (4). Controller parameters shown in Table 2 are obtained using convergence of ISE for number of generations as shown in Fig 9.

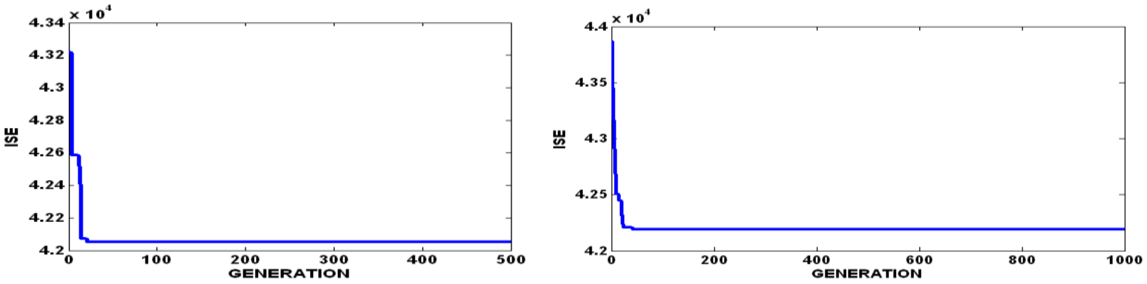
$$F = 1000/(1+J_1) \quad (3)$$

$$ISE=1000/(maxfit(1))-1 \quad (4)$$

Where J_1 = Performance index ISE ,F= fitness function

Table 2: Tuned controller parameters.

Control variable	RGA			Ziegler-Nichols		
	K_p	K_i	K_d	K_p	K_i	K_d
Reactor	23.4	1.3	0.03	25.7	2.25	0.5
Regenerator	34.8	2.41	0.8	32.4	3.8	0.95



(a) (b)

Fig. 9: Convergence of RGA for (a) Generation = 500 (b) Generation = 1000.

The performance criteria (ISE) have become constant after a number of consecutive generations (500 and 1000).

RESULTS AND DISCUSSION

Using MATLAB software tool, the simulink model of FCCU process is designed and open loop response is obtained as shown in the Fig 3 and it is observed that the temperature of the reactor and regenerator (T_{reg}=997K&T_{rea}=630K) settled at steady state values.

The response of PID without decouplers is shown in Fig 10 and Fig 11. It is observed that, due to the interaction present in the process, the response is being highly oscillated and has not reached the specified set points. The response of decentralized decoupled PID using Ziegler-Nichols and RGA tuning are shown in the Fig 12 and Fig 13. From the response it is observed that T_{reg} and T_{rea} are settled at specified set points with less amount of interaction. For multiple step set points, the response of decoupled decentralized PID is shown in Fig 14.

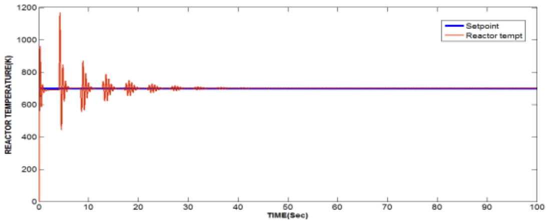


Fig. 10: Response of Reactor temperature at interaction.

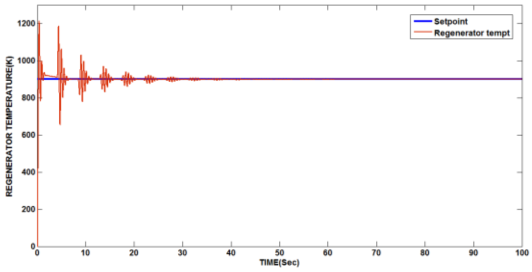


Fig. 11: Response of Regenerator temperature at Interaction.

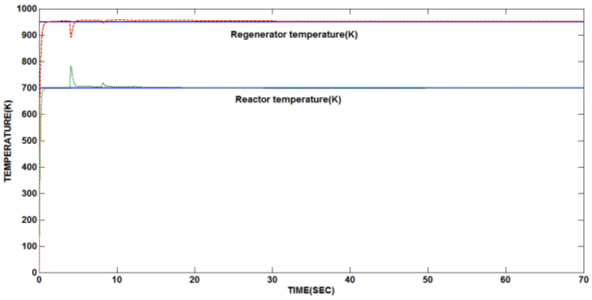


Fig. 12: Ziegler-Nichols tuned decoupled PID response.

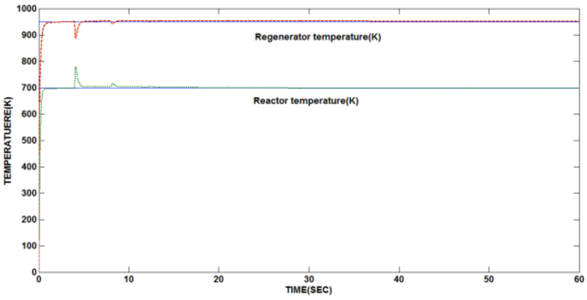
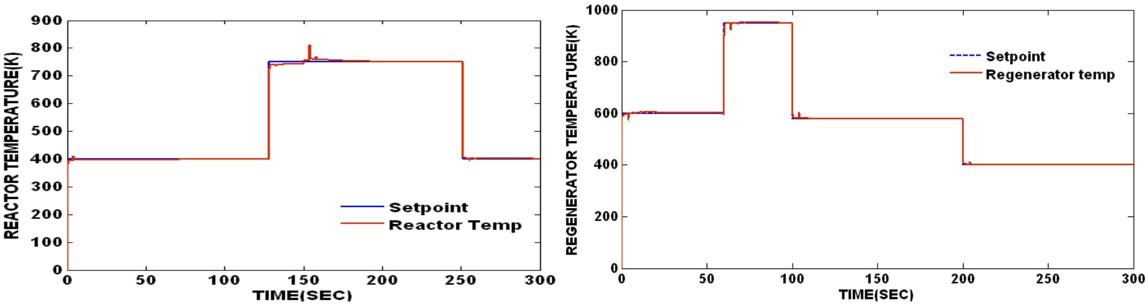


Fig. 13: RGA tuned decoupled PID response.



(a) **(b)**

Fig. 14: Multistep Response of (a) Reactor (b) Regenerator temperature with decoupler.

The performance of the controller without decouplers is highly oscillatory due to the presence of interaction, but the response is less oscillatory with decouplers. From the results the performance indices are tabulated in Tables 3(a) and 3(b).

Table 3: (a) Comparison of performance criteria for the two controllers.

Control variable	Ziegler-Nichols			RGA		
	ITAE	IAE	ISE	ITAE	IAE	ISE
Reactor	5582	390	6900	5135	350	4167
Regenerator	3318	266	2966	2906	244	2445

Table 3: (b) Comparison of performance criteria for the two controllers.

Control variable	Ziegler-Nichols		RGA	
	Setling time (sec)	Overshoot (%)	Setling time (sec)	Overshoot (%)
Reactor	81	7	48	5
Regenerator	70	4	30	3

From the Tables 3(a) and 3(b) the performance index ISE, overshoot, settling time have become reduced in RGA compared to Ziegler-Nichols.

7. Conclusion:

Modelling of FCCU has been done using energy balance equations and open loop response is obtained using steady state values in MATLAB. Pairing of input and output variables in order to reduce the interaction has been done using RGA analysis and decouplers have been designed. The decentralized PID controller has been designed taking ISE as a performance index in MATLAB. Controller tuning has been done using Ziegler – Nichols and RGA optimization method. A comparative study of the two tuning techniques reveals that use of RGA based controllers improves the performance of the process in terms of time domain specifications, set point tracking, and regulatory changes. The simulation results also show that, the performance of PID with decouplers is better than PID without decouplers.

Nomenclature:

D1(s)	Decoupler for loop 1
D2(s)	Decoupler for loop 2
T_{reg}	Regenerator temperature (K)
T_{rea}	Reactor temperature (K)
F_{rc}	Mass flow rate of regenerated catalyst (kg/s)
F_{sc}	Mass flow rate of spent catalyst (kg/s)
F_{st}	Mass flow rate of steam (kg/s)
H_{st}	Enthalpy of steam
F_f	Mass flow rate of feed (kg/s)
ΔH_R	Heat of reaction (KJ/kg)
C_{pa}	Heat capacity of air (KJ/kgK)
C_{pp}	Heat capacity of product (KJ/kgK)
$\mathrm{C}_{\mathrm{pfl}}$	Heat capacity of flue gas (KJ/kgK)
M_{rc}	Mass of regenerated catalyst (kg)
M_{sc}	Mass of spent catalyst (kg)
F_a	Mass flow rate of air (kg/s)
ΔH_c	Heat of combustion (KJ/kg)

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