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Comparison of Decoupler with PID Controller and Model Predictive Controller for the Fluid Catalytic Cracking Unit in Petroleum Refinery

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Abstract: The proposed study has been examined and reviewed the published experimental results related to reactor-regenerator system of Fluid Catalytic Cracking Unit (FCCU). It also focuses the limitations of existing methods for controlling the temperature in the reactor-regenerator system. In the present study, complex dynamic model of the reactor regenerator system has been developed and subsequently used with the controller. FCCU is widely used to convert the high-boiling, longer chainhydrocarbon fractions of petroleum crude oils to more valuable gasoline, olefinic gases and other products.Because of its feed processing tractability, the FCC process is considered as a primary conversion unit in a unified refinery and ideal FCC operation can have a significant impact on the refinery profitability. Control of the FCC continues to be a challenging and significant problem due to interaction between the loops. So, there is a real need for a control logic that effectively utilizes the available process measurements and model information characteristic of the process. Relative gain array is used to minimize the interaction and select the variable pairings and then decoupler is developed to remove interaction completely.Stabilization can be achieved through simulated implementation of a Model Predictive Control (MPC).

Key words: Fluid Catalytic Cracking Unit (FCCU), relative gain array, decoupler, Model Predictive Control (MPC)

INTRODUCTION

The fluid catalytic cracking is one of the utmostimperative processes in the oil refineries. Its design and operation are principally aimed for the production of gasoline with a higher octane rating and olefinic gases. The rate of cracking and the end products are sturdilyreliant on on the temperature and presence of catalysts. The Fluid Catalytic Cracking Unit (FCCU) has become the testingworkbenchof many progressive control methods. Today, both academia and industry are expressing great interest in the improvement of new control algorithms for their efficient industrial FCC implementation. Analysis and control of FCC process have been instigate challenging problems owing to the following process characteristics, very convoluted and diminutive known hydrodynamics,composite kinetics of both cracking and coke burning reactions, sturdy interaction between the reactor and regenerator, many operating constraints. FCCU's steady state behavior is exceedingly nonlinear, leading to multiple steady states, input multiplicities etc. This is more complex problem, since the numeral of process variables that one would like to control extensively exceeds the number of manipulated variables that are presented for the task.

Literature survey: Numerous papers relating the FCC process can be found in the published literature. They present various aspects of mathematical modeling and simulation, stability, optimization and optimal control.

Several studies on dynamic modeling of the whole FCC unit have been accessible in recent papers. Fundamental modeling work on FCCU has been reported by Lee and Groves (1985). Alhumaizi and Elnashaie addresses the main problem associated with the control of industrial fluid catalytic cracking units. Six simple feedback control strategies are proposed using two controlled and two manipulated variables. Han *et al.* (2000) developed a dynamic model of the reactor, regenerator, catalyst transport lines and other auxiliary units of modern riser type FCC unit was developed on the basis of conservation principles.

Abul-Hamayel used four lump model to demonstrate the new methodology for modeling the kinetics data that

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was composed using micro-activity test (MAT) method. Instead of the traditional methodology of concurrent regression analysis of the rate equations, consecutive regression of each rate equation was performed.

Raluca presents dynamic simulations for the FCCU aggregate system that comprises the main fractionator and a kinetic model for the riser leading to a 2144th order ODE Model. Grounded on this model an inferential control scheme is anticipated that is able to control the product distribution resulted from the fractionator based on straightforwardlyquantifiable variables in the regenerator-reactor system.

Osofisan and Obafaiye regulate a definite relationship between the vital variables (reactor temperature/riser outlet temperature, regenerator temperature, regenerated catalyst feed rate and the airflow rate) through the use of fuzzy logic control scheme is focused and designed a fuzzy model capable of managing the characteristic uncertainties and imprecision typicallyallied with the catalytic cracking process in an FCCU.

Ahari *et al.* (2008) established one-dimensional adiabatic model for FCC unit riser that combines with predictive riser hydrodynamic model and a four-lump dynamic model with modification of the kinetic parameters based on Patience correlation. The chemical reactions were categorized by a four-lump dynamic model, (Han *et al.*, 2000) and the optimization techniques applied.

Roman *et al.* (2009) presents new model and dynamic replication results for the FCCU reactor regenerator main fractionator aggregate system using a five lump kinetic model for the riser. The model comprises in a set of 933 ODEs. Based on this complex nonlinear model, different Model Predictive Control based algorithms have been examined for the FCCU control. A 5×5 control scheme is anticipated and attested as being able to control the gasoline attained from the main fractionator.

Process description: The FCCU is a pillar of the present refinery, in that its role of converting heavy hydrocarbons to more usable products such as gasoline impacts heavily on the refinery's economic performance. FCCU is a complex nonlinear, time varying exothermic process challenges multivariable control problems. The selection of good inputs (manipulated variables) and outputs (measured variables) is an significant issue, as the pairing of chosen controlled and manipulated variables for distributed control. A shortened process schematic and instrumentation diagram is shown in the (Fig. 1).

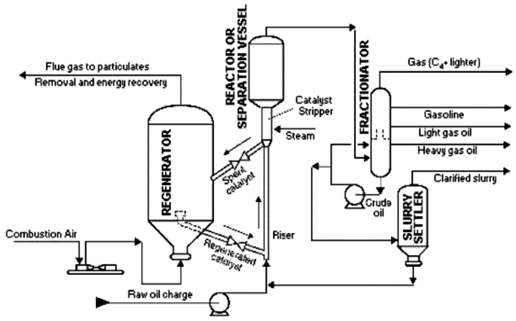

Fig. 1: Schematic representation of FCC unit

The FCC unit comprises of three stages: a riser reactor, a catalyst stripper and a regenerator (along with other accessories).The refinery produced gas oil and supplemental feed stocks are generally combined and send to surge drum which provides the steady flow of feed to FCC unit charge pumps. From the surge drum feed is normally heated to a temperature of 270-375°C. Almost all reactors consists of riser in which there is short contact time (<5 sec) of catalyst and feed. From the preheater feed enters the riser, where it is vaporized and cracked into smaller molecules of vapor by interaction and mingling with the very hot powdered catalyst from the regenerator. All of the cracking reactions take place in the catalyst riser. The control valve manipulates the quantity of hot regenerated catalyst in order to maintain a predetermined outlet reactor temperature. The hydrocarbon vapors “fluidize” the powdered catalyst and the mixture of hydrocarbon vapors and catalyst streams upward to arrive the reactor. The reactor is in fact simply a vessel in which the catalyst elements are detached from vapor products by cyclones and the spent catalyst flows downward through a steam shedding section to eliminate any hydrocarbon vapors before the spent catalyst returns to the catalyst regenerator. The flow of spent catalyst to the regenerator is organized by a slide valve in the spent catalyst line. In the regenerator, carbonaceous particles which moderate the catalytic activity are burned with the presence of air. The air flow rate to the regenerator is measured by a control valve that outlets portions of the air to the atmosphere. The combustion of the coke is exothermic and it produces a hugequantity of heat that is partially absorbed by the regenerated catalyst and delivers the heat prerequisite for the vaporization of the feedstock and the endothermic cracking reactions that take place in the catalyst riser. Aimed at that intention, FCC units are frequentlymentioned to as being heat balanced. The hot flue gas exoduses the regenerator after evanescent through multiple sets of two-stage cyclones that eliminate entrained catalyst from the flue gas.In this practice the significant measured variables are chosen to be the reactor temperature/riser vent temperature (T_{RA}) and the regenerator temperature (T_{RG}). The manipulated variables are flow rate of regenerated catalyst (R_{RC}), flow rate of spent catalyst (R_{SC}) and flow rate of air to the regenerator (R_{AI}).

MATERIALS AND METHODS

Development of model: The typical FCC unit involves of three mechanisms, a riser reactor, a catalyst stripper and a regenerator. Reactor-regenerator section is painstaking as heart of the FCC unit. For modeling FCCU, these mechanisms should be deliberated separately then they are integrated to simulate the entire FCC unit. In this method the essential measured variables are preferred to be the reactor temperature/riser outlet temperature (y_1) and the regenerator gas temperature (y_2). The manipulated variables are flow rate of regenerated catalyst (m_1), flow rate of spent catalyst and flow rate of air to the regenerator (m_2). The representing of composite chemical systems for the replication of process dynamics and control has been motivated by the economic enticements for enhancement of plant operation and plant design, as in the case of FCCU.

Most of the commercial gain from FCC mechanism improvement has come from the optimization level with the regulation system simply providing stable, responsive and safe operation. The delinquent is to find official schemes that are Operative, Economically reasonable, Related to prevailing practice and able to afford adequate operator interface when preferred.

A static model is hand-me-down for the riser. In this toil, an operativeapplied control scheme of Joseph Bromley and Thomas Ward is cast-off. In this arrangement, feed is gasoil which be able tofissure into gasoline or light gas. The equilibrium equation for Hold up of catalyst is:

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

Note:

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

The balance equation for concentration of spent catalyst:

$$\frac{dC_{SC}}{dt} = \frac{1}{H_{RA}\begin{bmatrix} R_{RC}C_{RC} - R_{RC}C_{SC} \\ +100R_{CF} \end{bmatrix}}$$

And also:

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

The balancing equation for concentration of catalytic carbon:

$$\frac{dC_{CAT}}{dt} = \frac{1}{H_{RA}\begin{bmatrix} -R_{RC}C_{CAT} \\ +100R_{CF} \end{bmatrix}}$$

The balancing equation for concentration of carbon on regenerated catalyst:

$$\frac{dC_{CAT}}{dt} = \frac{1}{H_{RG}\begin{bmatrix} R_{SC}(C_{SC} - C_{RC}) \\ -100R_{CF} \end{bmatrix}}$$

Where:

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

Reactor model of FCCU: The catalyst is steam exposed in the reactor vessel to eliminate hydrocarbons. The reactor overhead is separated in a cyclone to eradicate catalyst and the product vapors pass to a product fractionator. The balance equation of reactor temperature is given by:

$$\frac{dT_{RA}}{dt} = \frac{R_{RC}}{H_{RA}}\left(T_{RG} - T_{RA}\right) + \frac{1}{S_c H_{RA}}\left[-S_F D_r\right.$$

And also:

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

$$\frac{C_{TF}}{1 - C_{TF}} = \frac{K_{CR}P_{RA}H_{RA}}{R_{TF}}$$

Regenerator model of FCCU: The reactor pressure can be continued by operating the fractionator overhead gas compressor speed or the overhead gas recycle rate. The flue gas rate can be operated to uphold the regenerator pressure. The hot flue gas in the regenerator is toodetached from catalyst in a cyclone and utilized for retrievalof thermal and combustion energies. The balance equation of regenerator temperature is given by:

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

Controlling of FCCU: The control of obtainable variables is imperative for the efficient and safe operation of the unit and has direct influence on the products yield. Mechanism of the FCC has been and unremitting challenging and chief problem. As will be grasped, its steady state performance is highly nonlinear, prominent to multiple steady states, input multiplicities and all that entails. The reactor temperature has to be preserved at a

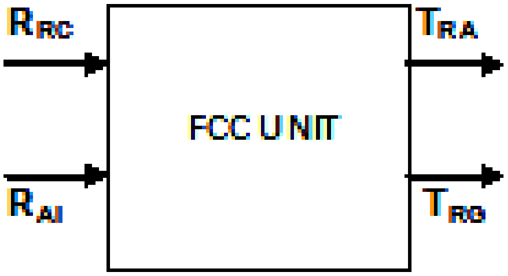

Fig. 2: MIMO system

certain level to provide a desired maximum transformation of the feed oil. A suitable reactor temperature control means also a good management of thermal energy. Control of reactor catalyst catalogue is fundamental to provide stabilization and safety in the catalyst circulation. Reactor pressure control openlystimuli the coke and gases formation. Composition of the products must be maintained at preferred definite values to promise the products quality and plant productivity.

Interaction of control loops: Consider a method with two measured outputs and two operated inputs in Fig. 2. The input-output relationships are given by:

$$Y_1(s) = G_{11}(S)m_1(S) + G_{12}(S)m_2(S)$$
$$Y_2(s) = G_{21}(S)m_1(S) + G_{22}(S)m_2(S)$$

where, $G_{11}(S)$, $G_{12}(S)$, $G_{21}(S)$ and $G_{22}(S)$ are the four transfer functions relating the two inputs and the two outputs. These equations designate that the transformation in m_1 or m_2, will affect both controlled outputs. Two potential problems arise from this process interaction it may disrupt the closed loop system and It tends to make controller tuning furtherproblematic.

Relative gain array: Relative gain array affords a quantity ofinteraction based on steady state conditions. It is used to select the pairs of input and output variables in decree to lessen the measure of interaction among the resulting loops. Relative gain array is expressed as:

$$\lambda = \begin{bmatrix} \lambda_{11} & \lambda_{12} \\ \lambda_{21} & \lambda_{22} \end{bmatrix}$$

Where:

$$\lambda_{11} = \frac{(\Delta y_1 / (\Delta m_1) m_2)}{(\Delta y_1 / (\Delta m_1) Y_2)}$$

$$\lambda_{12} = \frac{(\Delta y_1 / (\Delta m_2) m_1)}{(\Delta y_1 / (\Delta m_2) Y_2)}$$

$$\lambda_{21} = \frac{(\Delta y_2 / (\Delta m_1) m_2)}{(\Delta y_2 / (\Delta m_1) Y_1)}$$

$$\lambda_{22} = \frac{(\Delta y_2 / (\Delta m_2) m_1)}{(\Delta y_2 / (\Delta m_2) Y_1)}$$

The sum of relative gains in any row or column of the array is equal to one. Thus:

$$\lambda_{11} + \lambda_{12} = 1$$
$$\lambda_{11} + \lambda_{21} = 1$$
$$\lambda_{12} + \lambda_{22} = 1$$
$$\lambda_{21} + \lambda_{22} = 1$$

If one value is known the other three values can be easily computed. In particular:

- If λ_{11}= 0, then Y_1 does not respond to m_1 and m_2 should not be used to control Y_1
- If λ_{11}= 0, then m_2 does not affect Y_1 and the control loop between Y_1 and m_1 does not interact with loop of Y_2 and m_1
- If $0<\lambda_{11}<1$,then the interaction exists and as m_2 varies it affects the steady state value of Y_1 the smaller value of λ_{11}, the larger interaction becomes
- If $0<\lambda_{11}<1$, then $m_2$from that caused by m_1

Design of decoupling control system: The relative gain array specifies how the inputs should be coupled with the outputs to form loops with the smaller quantity of interaction. To cancel the interaction properties between two loops, a decoupler is used.Basic idea is to practicesurplus controllers to compensate for process interaction and thus reduce control loop interaction. Ideally, decoupling control permits set point changes to disturb only the preferred controlled variables. Usually, decoupling controllers are considered using a simple process model (transfer function model). Two control loops by coupling m_1 with $y_1$and m_2 with y_2 is formed assume that initially both the outputs are at the desired set point values. Suppose that a disturbance or set point Changes cause the controller of loop 2 to vary the value of m_2, this will generate an undesired disturbance for loop 1 and will cause y_1 to differ from its preferred. From Fig. 2, to keep T_{RA} constant, R_{RC} should be changed by the following amount:

$$m_1 = \frac{G_{12}(S)}{G_{11}(S)} m_2$$

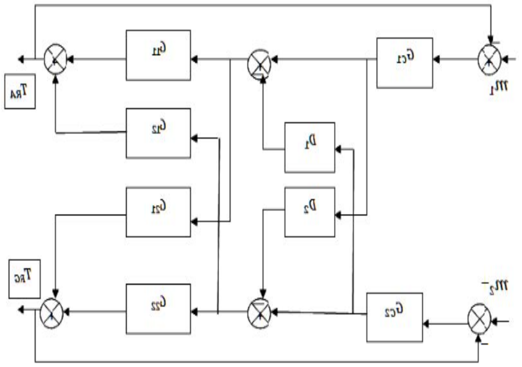

Fig. 3: Block diagram of decoupler

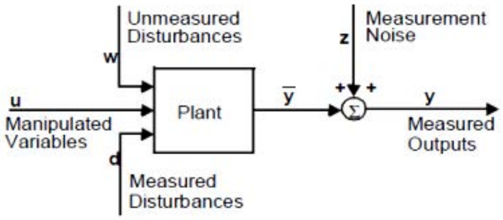

Fig. 4: Block diagram for process

Above equation implies a dynamic component with transfer function:

$$D_1(S) = \frac{G_{12}(S)}{G_{11}(S)}$$

This dynamic component is called a Decoupler. It abandons any effect that loop 2 might have on loop 1. To eliminate the interaction from loop 1-2, use the dynamic element D_2 (Fig. 3):

$$D_2(S) = \frac{G_{12}(S)}{G_{11}(S)}$$

Model predictive controller: In the precedingera, Model Predictive Control (MPC) has become a preferred control strategy for a large number of methods. The main details for this realizationreside in its ability to handle constraints in an optimal way and the flexibility of its formulation in the time domain. At each sampling time, the model is updated based on new measurements and state variable estimates. Consider the process shown in the below block diagram (Fig. 4). The universal Linear Time Invariant (LTI) state-space representation used in the MPC Toolbox is given by:

$$\begin{aligned} X(k+1) = x(k) + T_u U(k) \\ + T_d d(k) + T_w W \end{aligned}$$

$$y(k) = t(k) + 2(k)$$

$$\begin{aligned} y(k) = C_x(k) + D_u u(k) \\ + D_d d(k) + D_w W(k) \end{aligned}$$

Where:

x = A vector of n state variables
u = Signifies the n_u manipulated variables
d = Signifies n_d measured then spontaneously changing inputs, (i.e., measured disturbances)
w = Denotes n_w unmeasured disturbances
y = Vector of n_y plant outputs
z = Measurement noise and F, G_u, etc. are constant matrices of appropriate size

The variable (k) denotes the plant output prior the accumulation of measurement noise. The MPC mechanisms with state-space models in a special presentation, called the mod format. The mod format is a single matrix that covers the state-space F, G, C and D matrices plus some additional information. The MPC includes a number of commands that make it easy to generate models in the mod format.

In contrast to other feedback controllers that compute the control action based on present or past information, MPC determines the control action based on the predicted future dynamics of the system being controlled.. The MPC algorithm is able to find the best solution to satisfy all constraints.MPC is able to obtain better control performance, as it can determine the current control action for minimizing errors caused by reaching the constraints that are predicted to become active in the future.

RESULTS AND DISCUSSION

The research on the dynamic characteristics of FCC unit reveals that FCC processes consist of two inputs and two outputs.In practical combustion mode, the common choice of variables have been regulated are the riser outlet Temperature (T_{RA}) and regenerator's Temperature (T_{RC}). If the pairings T_{RA}-T_{RC} and T_{RC}-R_{AI} were selected to design a decentralized control strategy, a classical rise-regenerator control structure has been obtained. The mathematical model considered in this work simulates the main features of the behavior of FCC units as shown in Fig. 5 and 6. By relative gain array technique, the input-output relationship have been derived as:

$$T_{RA} = \frac{6.3175}{45.18s+1} m_1 + \frac{0.576}{336.9s+1} m_2$$

$$T_{RG} = \frac{69.235}{31.875s+1} m_1 + \frac{6.774}{1456.2s+1} m_2$$

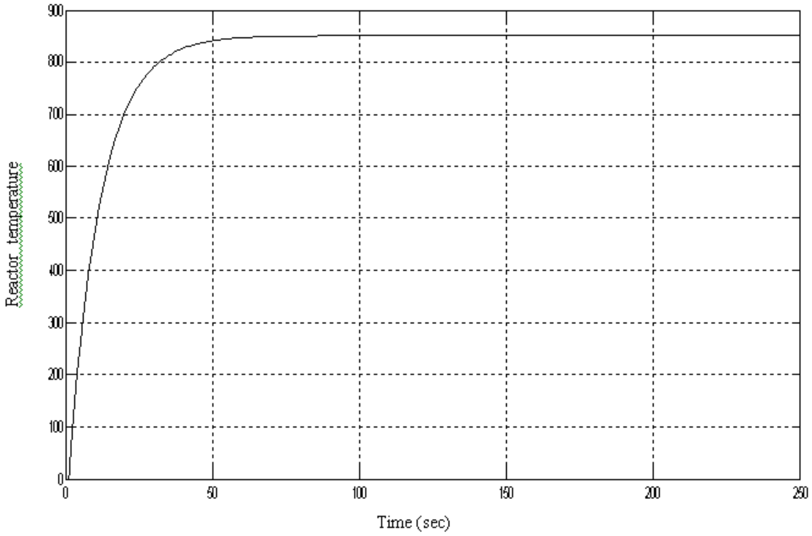

Fig. 5: Steady state response of reactor temperature

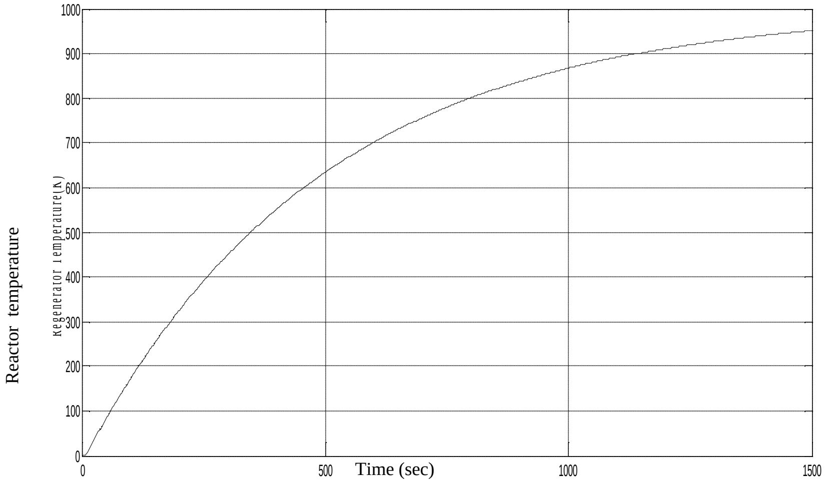

Fig. 6: Steady state response of regenerator temperature

The choice of pairing has been recommended is to couple R_{RC} with T_{RG} and R_{AI} with T_{RG}. The characteristic responses have been shown in Fig. 7 and 8. Temperature using RGA technique while y_2 constant. For this choice of pairing the relative gain matrix obtained is:

$$\lambda\begin{bmatrix}0.98 & 0.02\\ 0.02 & 0.98\end{bmatrix}$$

So, the desirable pairing is to couple m_1 with y_1 and couple m_2 with y_2. Since, there is some interaction between two loops, decoupler is used to cancel the interaction. The dynamic elements of decoupler are designed using the formula's and derived as:

$$D_1 = -\frac{3692.4s+10.96}{45.18s+1}$$

$$D_2 = -\frac{14883.35s+10.22}{31.87s+1}$$

The simulation result using decoupler has been shown in Fig. 9 and 10. While using the Decoupler, the interaction between the two loops have been eliminated. But the response shows some deviates with lower value of set point for the reactor temperature and which deviates with higher value of set point for the regenerator temperature. So, to improve the performance or to achieve the desired value decide to use integral controller in combination with proportional controller (PI controller)

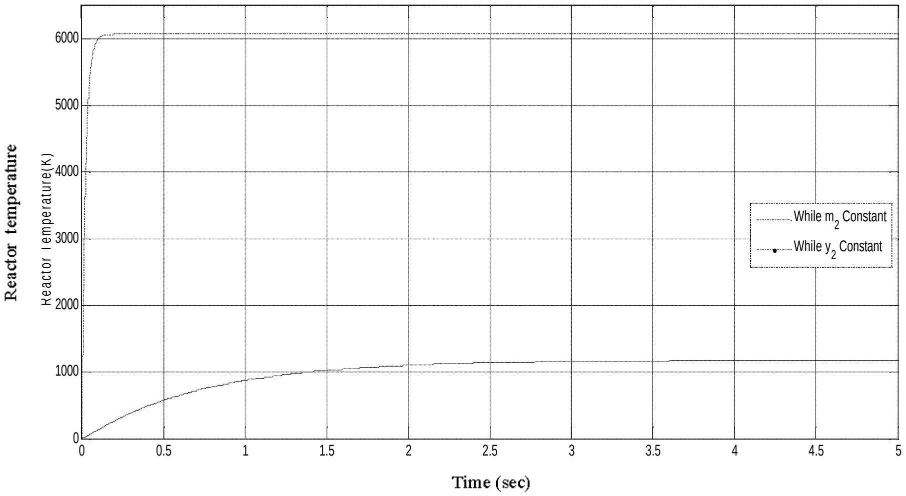

Fig. 7: Response of reactor temperature using RGA technique while m_2 and y_2 constant

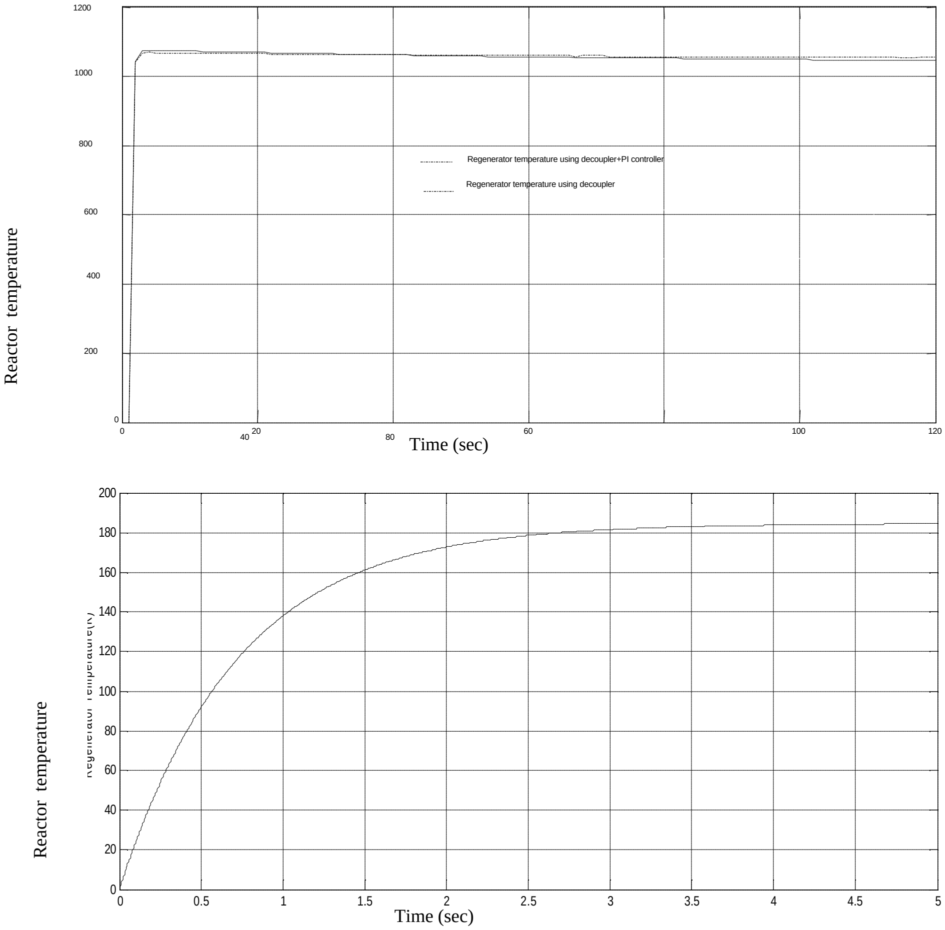

Fig. 8: Response of regenerator

to achieve the set point. In simulation,the PI controller have enriched the enactment while relating with PI controller. To verify the performance of PI with an advanced control scheme model predictive controller

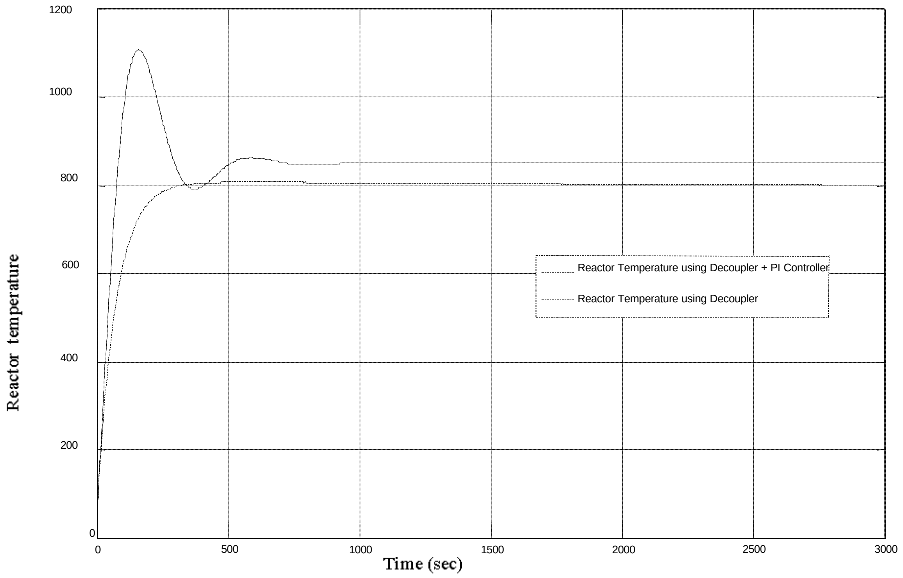

Fig. 9: Response of Reactor Temperature using Decoupler and Decoupler with PI Controller

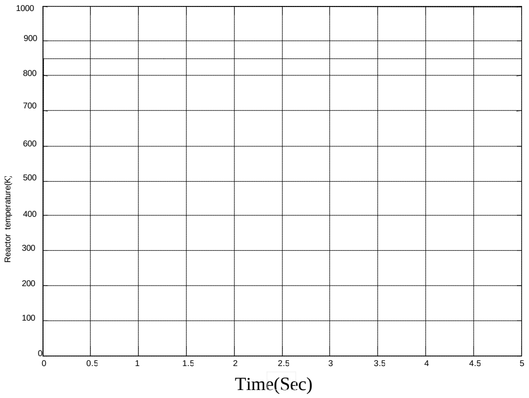

Fig. 10: Response of reactor temperature using MPC

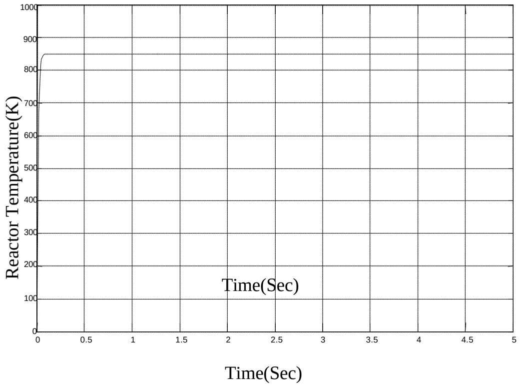

Fig. 12: Response of reactor temperature using MPC with various control block moves

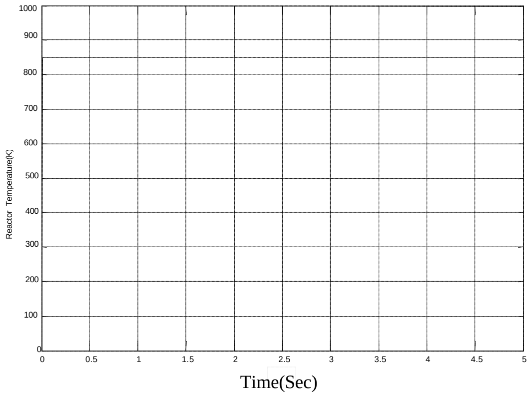

Fig. 11: Response of Regenerator Temperature using MPC

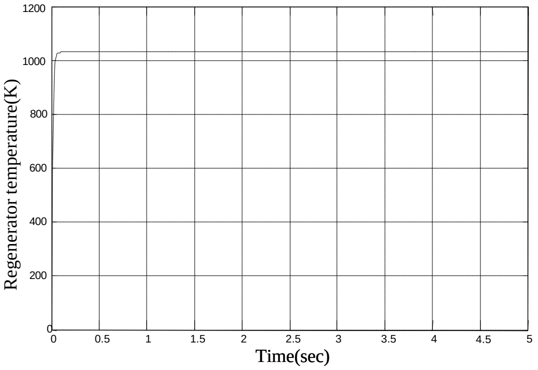

Fig. 13: Response of Regenerator Temperature using MPC with various control block moves

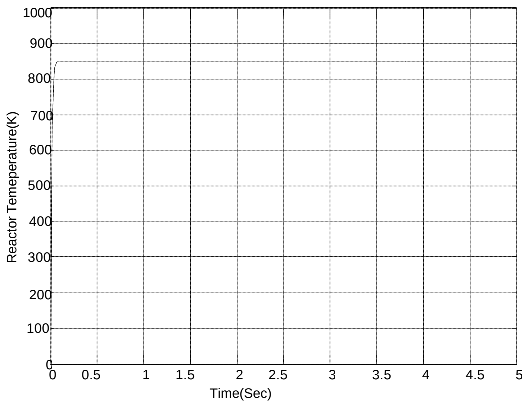

Fig. 14: Response of reactor temperature using MPC with disturbances

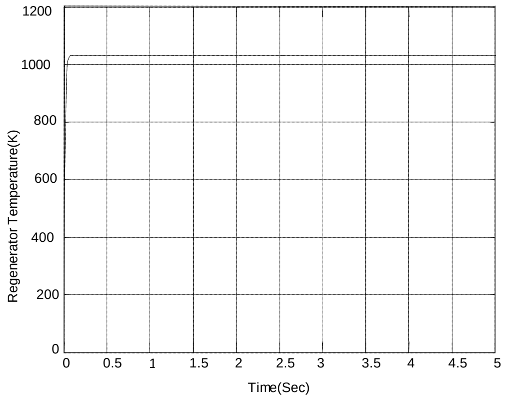

Fig. 15: Response of regenerator temperature using MPC with disturbances

have been implemented.Their simulation results have been shown in Fig.11 and 12. The model predictive controller have tracked the response and achieved the desired value for the both the reactor temperature and regenerator temperature with the short settling time. For often effective the blocking have been used in steps and their responses have been shown in Fig. 13 and 14. The response of Reactor Temperature and Regenerator Temperature control with noise using MPC have been shown in Fig. 15 and 16.

Performance analysis: The character of the complete closed-loop response, since time t = 0 until steady state has been reached, might be used for the formulation of dynamic performance criterion. Time-Integral performance criteria are based on the entire response of the process. The most often used are:

Table 1: Comparison of reactor temperature performance using decoupler and model predictive control

Performance criterion	Decoupler with PI controller	Model predictive controller
Error	0.344	0.10
Settling time	28.00	3.58
ISE (Integral of the square error)	4.35×10^{-5}	0.10
IAE (Integral of the absolute error)	1470	1.00
ITAE (Integral of time weighted absolute error)	41160	3.58

Table 2: Comparison of regenerator temperature performance using decoupler and model predictive control

Performance criterion	Decoupler with PI controller	Model predictive controller
Error	1.808	0.1
Settling time	40	0.2
ISE (Integral of the square error)	3.53×10^{-4}	0.1
IAE (Integral of the absolute error)	438.2	1.0
ITAE (Integral of time weighted absolute error)	17528	0.2

- Integral of the square error
- Integral of the absolute error
- Integral of Time weighted Absolute Error

For decoupler and model predictive controller, the parameter values are compared in Table 1 and 2.

CONCLUSION

This study has addressed the critical issues that describe the interaction of variables in the reactor and regenerator of fluid catalytic cracking unit in a petroleum refinery. The process description has been included. Animproved mathematical model has been proposed that will better describe the kinetics of variables. The following conclusions have been drawn from the present study. For the interaction process, selection of pairing is done by relative gain array. According to RGA matrix, the variables are paired and again loop response is found. Recommended pairing is used to minimize the interaction.

To remove the interaction completely, decoupler are designed and implemented in the simulink which provides effective implementation of the model to control the FCCU process. Further, the model of FCCU has been implemented with model predictive controller and better stabilization can be achieved while using MPC. In future, the effect of reactor temperature and regenerator temperature through conversion of total feed(volume fraction) using MPC.

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
D_{TF} = Density of total feed (kg m^{-3})
F_{CF} = Factor for carbon formation of feed, (kg carbon/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 sec^{-1})
R_{CB} = Rate of coke burning (kg sec^{-1})
R_{CC} = Rate of catalytic carbon formation in the reactor (kg sec^{-1})
R_{CF} = Rate of carbon forming on catalyst (kg sec^{-1})
R_{OC} = Rate of gas oil cracking (kg sec^{-1})
R_{RC} = Rate of regenerated catalyst (kg sec^{-1})
R_{SC} = Rate of spent catalyst (kg sec^{-1})
R_{TF} = Rate of total feed
S_A = Specific heat of air (Jkg-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)
ΔH_{CR} = Heat of cracking (J kg^{-1})
ΔH_{FV} = Heat of feed vaporization (J kg^{-1})
ΔH_{RG} = Heat of regeneration (coke burning) (J kg^{-1})

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