EFFECT OF INDEPENDENT VARIABLES ON THE MAXIMIZATION OF GASOLINE YIELD AND CLOSED LOOP STUDIES IN CATALYTIC CRACKING UNIT

By

R. RAJA NANDHINI * M. MYTHILY ** D. MANAMALLI ***

* Department of Instrumentation Engineering, Madras Institute of Technology, Anna University, Chennai, India.
** Department of Instrumentation Engineering, Madras Institute of Technology, Anna University, Chennai, India.
*** Department of Instrumentation Engineering, Madras Institute of Technology, Anna University, Chennai, India.

ABSTRACT

Fluid Catalytic Cracking Unit (FCCU) is an important processing unit in an oil refinery. Fluid catalytic cracking is a process used to convert heavy petroleum products to light products such as gasoline, light fuel oil, and petroleum gas. In the fluid catalytic cracking reactor, heavy gas oil is cracked into more valuable lighter hydrocarbon products. The reactor input (the gas oil fed to the reactor) is a mixture of hydrocarbons that makes the reaction kinetics very complicated due to the involved reactions. The process is highly nonlinear and multi variable with severe interactions. For the simulated dynamic model of FCCU plugged with yield model, sensitivity studies has been carried out to study the effects of independent variables such as feed preheat temperature, feed flow rate and air flow rate in maximizing gasoline yield. With the optimized model, the closed loop studies have been carried out for reactor and regenerator temperature control of FCCU with minimum overshoot as the performance criteria.

Keywords: FCCU, Sensitivity Analysis, Gasoline Yield, Reactor And Regenerator Temperature Control, Minimum Overshoot - Performance Criteria.

INTRODUCTION

Fluidized Catalytic Cracking Unit (FCCU) of gasoil is one of the most important processes in the petroleum refineries. As shown in Figure 1, FCCU receives multiple feeds consisting of high boiling point components from several other refinery process units and cracks these streams into lighter and more valuable components [6]. After further processing, the FCCU product streams are blended from other refinery units to produce a number of products, e.g. distillate and various grades of gasoline. Economic operation of FCCUs (a large refinery may have more than one) plays an important role in the overall economic performance of the refinery. Gasoline yield is an important product from FCCU process since it has a very high market value. Gasoline yield in FCCU depends on various parameters like reactor temperature, regenerator temperature, air flow into regenerator, catalyst circulation rates, etc. Therefore, sensitivity analysis is needed to determine the variable which has strong influence on gasoline yield.

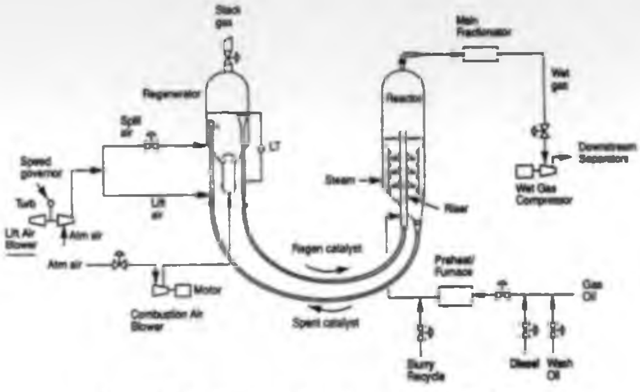

Figure 1. Schematic flow diagram of FCCU

1. Modeling of FCC Unit

The model captures the major dynamic effects that occur in a real FCCU plant. It is multivariable, strongly interacting and highly non-linear. The non-linear model was developed for the following sub models and integrated.

- Feed, Preheat system
- Reactor
- Wet gas compressor

- Regenerator
- Air blowers
- Catalyst circulation line

The simulated model captures the major dynamic effects that occur in a real FCCU plant. The complete FCCU model was simulated in MATLAB Simulink and is validated [1].

Many complex reactions occur during the FCC process and the product consists of a mixture of many compounds. The description of complex mixtures by lumping large number of chemical compounds into smaller groups of pseudo-components has been widely used by researchers to provide number of kinetic equations. The simulated 4-lump model plugged with FCCU model is similar to the 3-lump model of Weekman, the main difference being that coke is independently considered as a lump. Other lumps are feed, gasoline and gas.

It is assumed that the gas oil is cracked into the most desired gasoline, and the by-products of gas and coke. The reaction scheme of 4- lump yield model is shown in Figure 2 [5,7,8,9]. Since the FCC reactor is operating at high temperature, the secondary cracking reaction occurs for gasoline to form coke and gas. There is no inter-reaction between coke and gas [2].

2. Sensitivity Analysis In FCCU

For the simulated model, the sensitivity studies have been carried out i.e., the effects of the following independent variables on gasoline yield have been analyzed [3].

- Temperature of the fresh feed entering the furnace
- Flow of the fresh feed into the reactor riser
- Stack gas valve position which has influence on the air flow into the regenerator

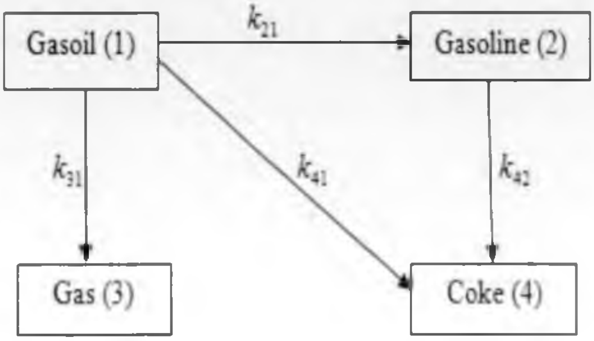

Figure 2. Reaction scheme of 4 lump yield model

To carry out these sensitivity studies, these independent variables were operated between -30% and +30% of their nominal values. The nominal values of temperature of fresh feed entering the furnace is 461°F, flow of fresh feed entering the reactor riser is 126 lb/s and the stack gas valve position is 0.64.

The values of those variables at which the maximum yield has been obtained were fixed as the optimum values. For the optimized model, the closed loop studies have been carried out with PI controller at the regulatory level.

Feed preheat temperature plays an important role in controlling the temperature in the riser reactor and hence the cracking reactions.

When the temperature of the fresh feed entering the furnace increases, the gasoline yield gets decreased, keeping feed flow into reactor riser (126 lb/s) constant.

When the flow of fresh feed to the reactor riser increases, the gasoline yield gets increased because increase in flow rate will lead to more amount of feed taking part in the reaction inside the reactor riser unit, keeping the temperature of fresh feed entering the furnace (461°F) constant.

Increase in the stack gas valve position will lead to a decrease in pressure inside the regenerator, which demands more amount of air flow into regenerator, keeping the feed flow rate (126 lb/s) and feed temperature (461°F) constant. Increase in air flow rate into the regenerator will cause an increase in the regenerated catalyst flow rate due to which the reactor temperature gets increased. When the reactor temperature crosses its optimum temperature, it will lead to decrease in the gasoline yield.

It has been observed from the sensitivity analysis that optimum yield (Figure 3) is obtained at the temperature of fresh feed entering the furnace = 401.2°F, the flow of fresh feed to reactor riser = 100.3 lb/s and the valve position at 0.448 (air flow into regenerator = 2.1236 moles/s).

The following Table 1 shows the operating ranges of the independent variables used for the study of the sensitivity effect on the gasoline yield and their impact on it.

The Figures 4 and 5 show the responses of the yield and

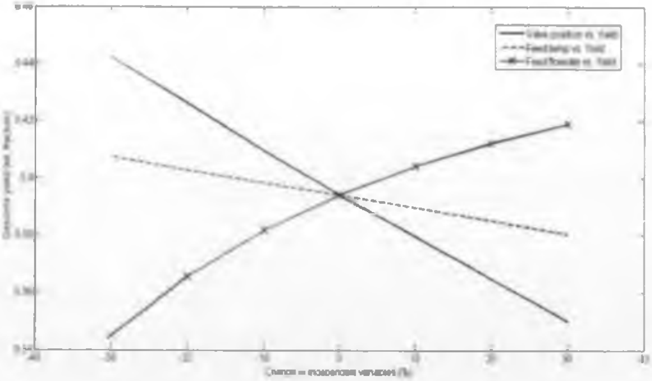

Figure 3. Optimum yield based on the sensitivity analysis

Independent Variables	Range	Impact On Gasoline	Remarks
Temperature of fresh feed entering furnace (F)	320 to 560	Decreases	Flow of fresh feed to reactor riser is having more influence on the gasoline yield
Flow of fresh feed to reactor riser (lb/s)	88 to 164	Increases	
Valve position	0 to 1	Decreases	

Table 1. Effect Of Independent Variables On The Gasoline Yield

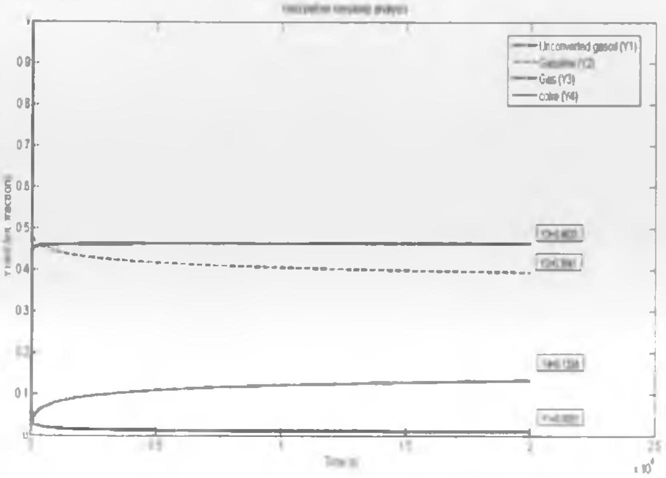

Figure 4. Yield response before sensitivity analysis

their variations before sensitivity analysis and after sensitivity analysis.

Table 2 lists the response of the gasoline and coke yield before and after sensitivity studies.

It has been observed from Table 2 that, there is a considerable increase in gasoline yield and decrease in the coke formation after fixing the values of independent variables for maximizing gasoline in the simulated model.

3. Control Of Reactor And Regenerator Temperature

3.1 Multiloop Control

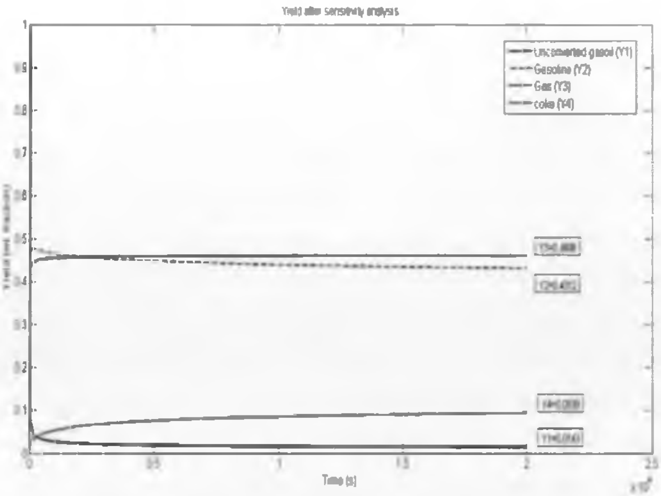

Figure 5. Yield response after sensitivity analysis

Yield (wt. fraction)	Before Sensitivity Analysis	After Sensitivity Analysis	% Increase / % Decrease
Gasoline (Y2)	0.3941	0.4312	+9.4
Coke (Y4)	0.1334	0.0938	-29.7

Table 2. Yield Of Gasoline And Coke Before/After Sensitivity Analysis

Each manipulated variable depends on only a single controlled variable i.e., a set of conventional feedback controllers. In most of the chemical industries, the processes are basically MIMO systems. The controlled variables have been selected to provide, through control, a safe and economic operation. The reactor temperature and regenerator temperature are selected as a controlled variable. The manipulated variables are flow of regenerated catalyst and flow rate of air [4].

The control structure selection was done based on Relative Gain Array (RGA) analysis and is shown in Figure 6.

The input and output relationship are given as The above transfer functions were found out by using the process reaction curve method.

The steady (gain) model is expressed as,

$$T_r = \frac{0.142}{1606s+1} F_{rgc} + \frac{3.2112}{4037s+1} F_{air}$$

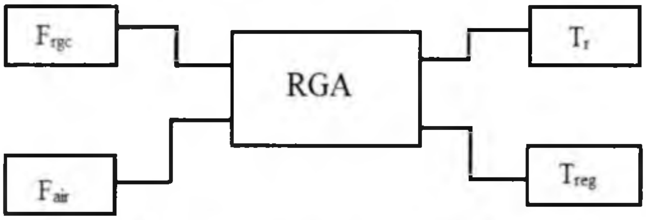

Figure 6. Control structure based on RGA analysis

Thus, the Relative Gain Array for a 2 × 2 system can be expressed as given below

$$\Lambda = \begin{bmatrix} 1.335 & -0.335 \\ -0.335 & 1.335 \end{bmatrix}$$

Pair the controlled and manipulated variables so that, the corresponding relative gains are positive and are as close to one as possible. From this RGA matrix, we can conclude that pairing of manipulated variables with control variables (i.e., flow rate of regenerated catalyst is used to control reactor temperature and flow rate of air is used to control regenerator temperature) is best.

Figure 7 shows the schematic diagram of the closed loop system with PI controller.

The reactor temperature must be maintained at a certain level to provide a desired maximum conversion of feed oil. The regenerator temperature must be maintained at a certain level in order to allow a stable coke from the catalyst. Permanent catalyst deactivation is produced by exceeding the high temperature limit. The proportional-integral (PI) controller is used at regulatory level. The specified reactor temperature is maintained by using a PI controller to adjust the flow of regenerated catalyst. Also the specified regenerator temperature is maintained by using a PI controller to adjust the air flow into the regenerator.

3.2 PI Tuning Rules

Before performing closed loop studies on any dynamic model, the best performance criteria for the specific control variable need to be studied. As per the conversation with experts working in CPCL (Chennai Petroleum Corporation Limited), minimum overshoot was chosen as the performance criteria for the reactor and regenerator temperature control of FCC unit.

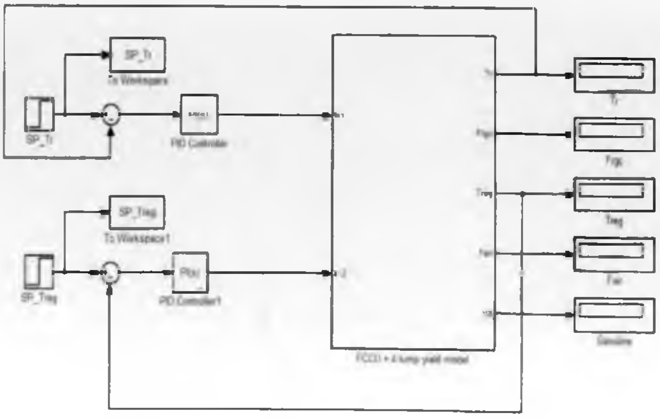

Figure 7. Schematic diagram of closed loop system with PI controller

With minimum overshoot as the performance criteria, the following tuning rules listed in Table 3 have been used to tune the PI controller [10].

where K_c = Proportional gain

τ_I = Integral time constant

λ = Adjustable parameter

K_u = Ultimate gain of the sustained oscillations

T_u = Ultimate time period of the sustained oscillations

The control signal from the tuned PI controller has been applied to the whole simulated FCCU model and not to the transfer function that has been obtained through process reaction curve method. The transfer function was used only to establish the input-output relationship between the controlled variable and the manipulated variable.

3.3 Control of Reactor Temperature (T_r)

The reactor temperature must be maintained at a certain level to provide a desired maximum conversion of feed oil. The Pi tuning parameters for the reactor temperature control process for different PI tuning rules listed in Table 4.

The reactor temperature was operated for three different set points (990°F, 993°F and 995°F) and their responses for the different PI tuning rules have been shown below.

From Figures 8, 9 and 10, it can be inferred that the same tuning parameters as given in Table 4 can be applied to any operating point. Also it shows that the direct synthesis method is having minimum overshoot but having a sluggish

Sl. No	Rule	K_c	τ_I
1	Direct synthesis	$\dfrac{\tau}{k_p\lambda}$	τ
2	Atkinson and Davey	$0.25K_u$	$0.75T_u$

Table 3. Pi Tuning Rules And The Parameters

Pi Tuning Rule	Proportional Gain (K_p)	Integral Gain (K_i)
Direct synthesis	7.0422	0.004385
Atkinson and Davey	16.001	0.0267

Table 4. Pi Tuning Parameters For Reactor Temperature Control

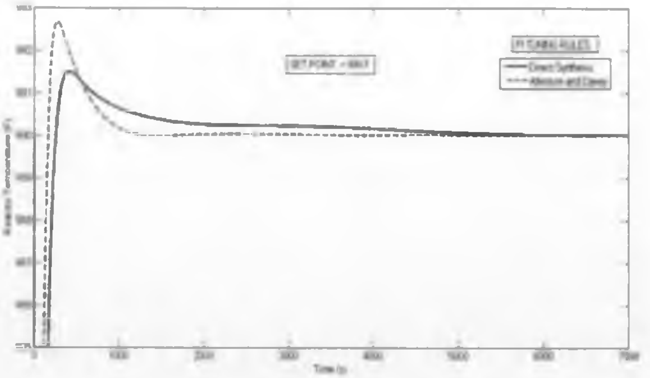

Figure 8. Control of reactor temperature for different PI tuning rules (990°F set point)

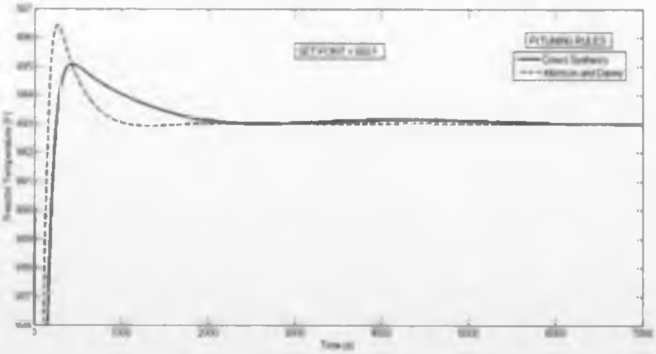

Figure 9. Control of reactor temperature for different PI tuning rules (993°F set point)

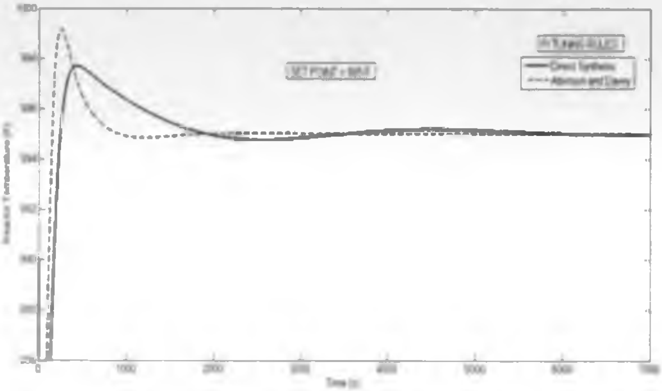

Figure 10. Control of reactor temperature for different PI tuning rules (995°F set point)

response. So it is better to choose the Atkinson and Davey PI tuning rule for the controller as it gives the next best response with minimum overshoot and quicker settling time.

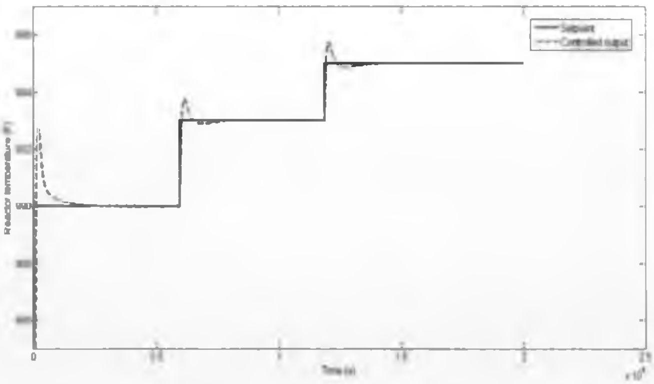

Figure 11. Reactor temperature control for different operating points using Atkinson and Davey PI tuning rule

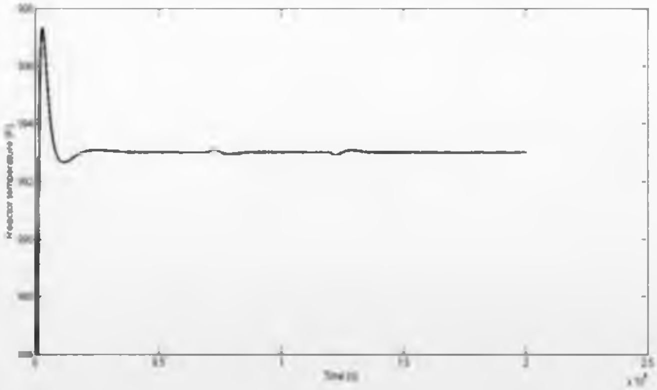

Figure 12. Control of reactor temperature with disturbance in effective coke factor

Figure 11 shows the reactor temperature control for different operating points using Atkinson and Davey PI tuning rule. After the steady state was reached, disturbance has been given to the effective coke factor ($\square_f$) from 1 to 1.5 at 7000s and from 1 to 0.5 at 12000s and the controller performance was studied and is given in Figure 12.

3.4 Control of Regenerator Temperature (T_r)

The PI tuning parameters for the regenerator temperature control process for different PI tuning rules is listed in the following Table 5.

The regenerator temperature was operated for three different set points (1265°F, 1275°F and 1285°F) and their responses for the different PI tuning rules have been shown below.

From Figures 13, 14 and 15, it can be inferred that the same tuning parameters as given in Table 5 can be applied to any operating point. Also, it shows that the direct synthesis method is having minimum overshoot but having a sluggish response. So, the Atkinson and Davey PI tuning rule is better to

Pi Tuning Rule	Proportional Gain (K_p)	Integral Gain (K_i)
Direct synthesis	0.017597	0.000037887
Atkinson and Davey	0.082675	0.0001378

Table 5. Pi Tuning Parameters For Regenerator Temperature Control

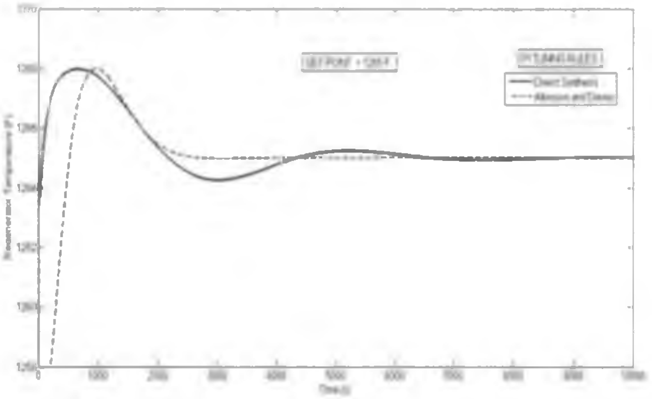

Figure 13. Control of regenerator temperature for different PI tuning rules (1265˚F set point)

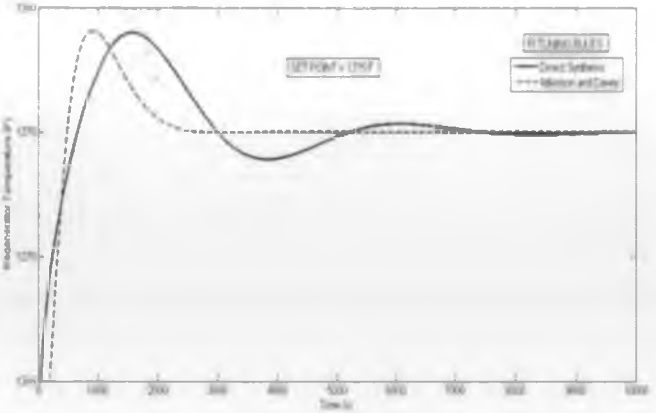

Figure 14. Control of regenerator temperature for different PI tuning rules (1275˚F set point)

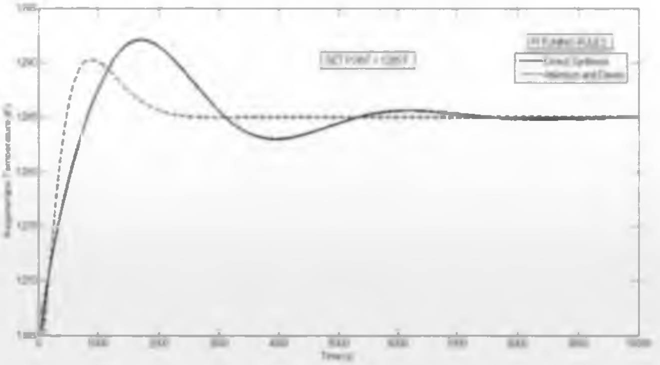

Fig. 15 Control of regenerator temperature for different PI tuning rules (1285˚F set point)

choose for the controller as it gives the next best response with minimum overshoot and quicker settling time.

Figure 16 shows the regenerator temperature control for different operating points using Atkinson and Davey PI tuning rule. Again, when the steady state was reached, disturbance has been given to the effective coke factor ($\square_f$) from 1 to 1.5 at 7000s and from 1 to 0.5 at 12000s and the controller performance was studied and is shown in Figure 17.

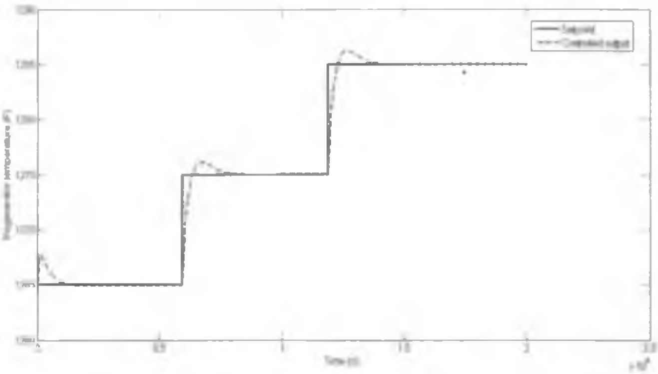

Figure 16. Regenerator temperature control for different operating points using Atkinson and Davey PI tuning rule

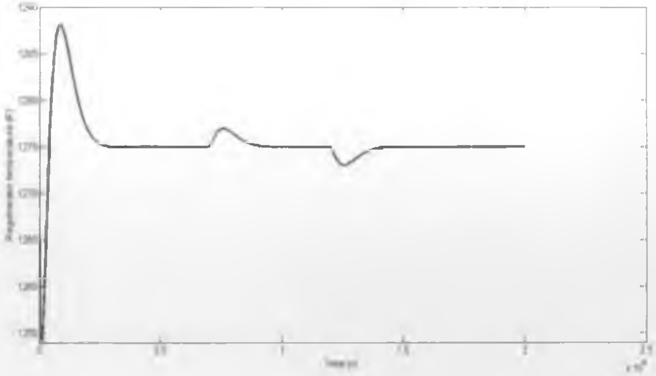

Figure 17. Control of regenerator temperature with disturbance in effective coke factor

3.5 Yield Response Under Closed Loop Condition

Table 6 describes the variation of gasoline yield and coke yield for different PI control tuning methods when the reactor temperature is controlled at 993˚F and regenerator temperature Is controlled at 1275˚F.

Conclusion

The "process" is represented by a simulated dynamic model of a model IV FCC unit which is combined with a steady-state yield model for the FCC reactor. The dynamic model will calculate the time-varying states of the FCC unit at any point in time, while the yield model uses the reactor

Yield (wt. fraction)	Before Sensitivity Analysis	After Sensitivity Analysis PI Tuning Rules	
		Direct synthesis	Atkinson and Davey
Unconverted gasoil (Y1)	0.0122	0.0137	0.0147
Gasoline (Y2)	0.4215	0.4268	0.4316
Gas (Y3)	0.4619	0.4557	0.4497
Coke (Y4)	0.1038	0.1038	0.1040

Table 6. Variation Of Gasoline Yield With Different PI Tuning Rules

conditions to calculate the conversion and the distribution of products.

The sensitivity analysis of certain independent variables performed results show that the gasoline yield can be increased by decreasing the temperature of the fresh feed entering the furnace and air flow into regenerator (by minimizing the valve opening), when the flow of fresh feed to the reactor riser is increased.

From the closed loop performance study, it is concluded that Atkinson and Davey PI tuning rule proves to be the best PI tuning rule when the performance criteria of minimum overshoot was considered.

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ABOUT THE AUTHORS

R. Raja Nandhini is pursuing her postgraduate in Department of Instrumentation, MIT Campus, Anna University, India. She completed her graduate in Electronics and Instrumentation. Her areas of research include Modeling and control of Petrochemical Processes.

M. Mythily is working as an Assistant Professor in the Department of Instrumentation, MIT Campus, Anna University, India. She completed her graduate in Electronics and Instrumentation and postgraduate in Applied Electronics and currently pursuing her PhD in Control of Petrochemical Processes. She has published papers in one National Journal and five International Conferences. Her area of research includes Modeling and control of Petrochemical Processes.

Dr. D. Manamalli is working as an Associate Professor in the Department of Instrumentation, MIT Campus, Anna University, India. She completed her graduate in Electronics and Instrumentation and postgraduate in Instrumentation. She received her PhD in Modeling and Control of Petrochemical Processes. She has also published papers in more than 5 International Journals and around 15 International Conferences. Her area of research includes Modeling and control of Refinery Processes.