

Research Article

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Modelling and Simulation of Fluid Catalytic Cracking Unit

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Abstract

This study presents the dynamic model for an industrial Universal Oil Product (UOP) fluid catalytic cracking unit on basis of mass and energy balance and the transfer functions are found. The riser and regenerator are simulated by using Matlab/Simulink software. The dynamic behaviour of the process is carried out by measuring the temperature response of the riser and regenerator to step change in gas oil flow rate, gas oil temperature, catalyst flow rate, air flow rate and air temperature. The simulator is validated by comparing the steady-state behaviour of the system with those in the literature and plant data and the results are found to be in good agreement. The results of simulation show that the process is strongly influenced by the catalyst flow rate, and any increase in the amount of coke on the catalyst and regenerator temperature would be compensated by a larger rate of consumption of the oxygen.

Keywords: Fluid catalytic cracking; Process modelling; Dynamic simulation

Nomenclature

A Constant

A_{cr} Frequency factor in Arrhenius equation for cracking to coke, ($m^3.kg^{-1}.sec^{-1}$)

A_{cr} Frequency factor in Arrhenius equation for coke burning reaction, ($m^3.kmol^{-1}.sec^{-1}$)

B Constant

C Constant

Specific heat capacity, ($kJ/kg.K$) C_p

C/O Catalyst to gasoil ratio

Weight percent of catalytic carbon C_{cat}

Weight percent of carbon on spent catalyst C_{sc}

Weight percent of carbon on regenerated catalyst C_{rc}

D Constant

Diameter of riser, (m) D_R

Diameter of regenerator, (m) D_G

E_{cr} Activation energies for cracking to coke, (kJ/mol)

E_c Activation energies for coke combustion, (kJ/mol)

$E_{activate}$ Activation energies for catalyst, (kJ/mol)

E_i Activation energies, (kJ/mol)

F Flow rate, (kg/sec)

G Transfer function

H_{cr} Heat of cracking to coke, kJ/kg

H_c Heat of coke combustion, kJ/kg

H_v Heat of heat of vaporization, kJ/kg

K_{cr}, K_c Reaction velocity constant for cracking to coke and coke Combustion, (—)

K_i Kinetic rate constant, $i=1, 2, 3$ for cracking to gasoline, light gases, coke respectively, ($m^3.kg^{-1}.sec^{-1}$),

$i=4, 5$ for cracking from gasoline to light gases and coke respectively, (sec^{-1})

K_1 Coke combustion rate constant to form CO , ($1/(kPa \cdot sec)$)

K_2 Coke combustion rate constant to form CO_2 , ($1/(kPa \cdot sec)$)

Proportional gain, $\left(\frac{unit\ of\ response}{unit\ of\ input} \right) K_p$

L_R Length of riser, (m)

L_G Length of regenerator, (m)

O_{fg} Volume percent of oxygen in flue gases P_R Pressure of riser, (kN/m^2)

Pressure in regenerator, (kN/m^2) P_G

R_c Rate of coke combustion, (kg/sec)

R_{cr} Rate of coke formation, (kg/sec)

R Universal gas constant, ($kJ \cdot mol^{-1} \cdot K^{-1}$)

s Laplace transform

tc Catalyst residence time, (sec)

Temperature, (K) T_i

T_G Regenerator temperature, (K)

T_R Riser temperature, (K)

Catalyst holdup in riser, (kg) V_R

Catalyst holdup in regenerator, (kg) V_G

W_{gi}, W_{go} Mass fraction of gasoline and gasoil respectively

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Y_i Mass fraction of products

Subscript

a Air cat Catalyst

f Feed (gas oil)

i Gasoline, light gases and coke

rc Regenerated catalyst

s Solid catalyst

sc Spent catalyst

Greek letters

Δ Difference

τ Time constant, (sec)

ρ_f Density of vaporized feed, (kg/m³)

ρ_{cat} Density of catalyst, (kg/m³)

Φ Catalyst decay function

β_c CO/CO₂ ratio at the catalyst surface in the regenerator

β_{co} Pre-exponent constant in β_c expression

Introduction

The fluid catalytic cracking (FCC) unit is the essential transformation unit done numerous refineries and it is one of the most important and complex processes in the petroleum refining industry. It converts heavy material feeds consisting of high boiling points like gas oil into lighter and more valuable products like gasoline, liquefied petroleum gas (LPG), and olefins by using a zeolite catalyst and it helps to produce about half of the total gasoline output in a refinery. The FCC process vaporizes and breaks the long chain molecules of the high boiling hydrocarbon liquids into much shorter molecules by contacting the feedstock at high temperature and moderate pressure with a fluidized powdered catalyst. The heavy vacuum gas oil (VGO) has a boiling point range of 343- 565°C and an average molecular weight ranging from about 200 to 600 or higher. A wide range of feed stocks can be processed in the FCC unit such as cracked gas oils, deasphalted oils and hydro treated gas oil [1].

Mostly a matter of common sense in modelling the FCC unit is the process assumptions. It consists of riser, regenerator, and main fractionator these three main parts are of particular interests both in industrial and research circles. Since the main parts of the FCC unit that have been modelled are riser and regenerator. The riser of the FCC unit is assumed to be a reactor in which all the complex reactions take place. The regenerator of the FCC unit is assumed to be a constantly stirred tank reactor where combustion reactions take place [2].

The description of the dynamic behaviour of the FCC unit is not easy; the complexity arises from the strong interaction between the reactor where the endothermic cracking reactions and coke deposition take place and the regenerator which supplies the heat load to the reactor by burning off the coke. This difficulty is due to their nonlinear; time varying behaviour and the regenerator and riser are highly interactive with difficult dynamics. Both riser and regenerator mass and heat balance are complex. Additionally, a complex hydrodynamics and a large uncertainty in the kinetics of the cracking reaction and the catalyst deactivation by the coke deposition [3].

In the literature, modelling and simulation of catalytic crackers has been the subject of many papers Saha and Dewangan [4] studied a dynamic model and simulation of FCC unit, and validated by comparing the overall behavior of the system with those in the literature was expected to serve as a valuable tool for various process system studies on fluid catalytic cracking processes.

Sildir et al. [5] developed a dynamic model of the FCC unit which consist of the reactor, the regenerator and the fractionation units. The result showed that a model parameters were estimated from actual industrial data and model predictions match the plant measurements closely.

Bhende and Patil [2] developed a mathematical model of the FCC unit. The developed model contained seven main sections of the entire unit which were the feed and preheating system, riser, stripper, reactor, regenerator and main fractionators. They concluded that the predicted data by the simulator were in close agreement with the industrial data.

Dagde and Puyate [3] presented the models which describe the performance of the riser and regenerator reactors of FCC unit. The simulation results showed that predictions of the models compared very well with plant data for both reactors.

Malay et al. [6] modified the dynamic model that developed by Ali and Rohani to describe the transient behaviour of a FCC unit. The results were found to be in good agreement with the industrial unit. The objective of this study is to develop a FCC mathematical model for a UOP type FCC process on the basis of conservation principles and the associated dynamic simulator using MATLAB-SIMULINK program. The simulation is to be used for dynamic analysis of this process. The behaviour of the system is compared with those in the literature to show the validity of our simulator. The dynamic behaviour of the FCC unit is carried out by measuring the temperature response of the riser and regenerator to step change in gas oil flow rate, gas oil temperature, catalyst flow rate, air flow rate and air temperature.

The mathematical model

There are many mathematical models for the FCC in the literature, some of them use a very simplified cracking process description, and few of them present integration between regenerator and riser. Most of these works is based on model with a high degree of empiricism, and makes use of pseudo-components corresponding to different groups of species, usually called lumps. The FCC unit consists of the riser and the regenerator. The cracking reaction is carried out in the riser where desired reactions include cracking of the high boiling gas oil fractions into the lighter hydrocarbons. The undesired reactions include carbon formation reactions and a regenerator where the carbon removal reactions take place. The effect of the steam on the energy balance is neglected. The reactor catalyst bed is considered to be at incipient fluidization. It was assumed that the catalyst leaving the riser enters the regenerator vessel directly without any delay. The regenerator reactor consists of two regions, the dense region and the free board dilute region. The dilute region is defined as the section of the reactor between the top surface of the dense region and the exit of the regenerator vessel. Most of the coke on the catalyst pellets in this region would be already combusted in the dense region. Thus, further combustion in this region can be neglected. According, the effect of the dilute region on the overall performance of the regenerator is ignored. A schematic of the FCC unit is shown in Figure 1.

The Kurihara model used for this case study is one developed by Ansari and Tade [7]. The first problem for modeling of the FCC is

the selection of the kinetic scheme. One approach to deal with multi-component mixtures, the four lumps suggested by Ahari et al. [8] is used. This is because of its simplicity and popularity. The four lump Scheme are as shown in Figure 2.

According to this scheme, a part of gasoline is also converted to light gases and coke. It is assumed that cracking of gas oil is a second order reaction but that of gasoline is a first order reaction, and that following the reactions take place in the riser and only in the gas phase.

where: $r = \frac{dy}{dt}$ = rate of reaction

$$r_1 = K_1 \cdot \Phi \cdot W_{go}^2 \quad (1)$$

$$r_2 = K_2 \cdot \Phi \cdot W_{go}^2 \quad (2)$$

$$r_3 = K_3 \cdot \Phi \cdot W_{go}^2 \quad (3)$$

$$r_4 = K_4 \cdot \Phi \cdot W_{gl} \quad (4)$$

$$r_5 = K_5 \cdot \Phi \cdot W_{gl} \quad (5)$$

where:

Φ is the catalyst activity.

W_{gl} and W_{go} are the mass fraction of gasoline and gasoil respectively,

K is the Kinetic rate constant.

Since the overall cracking is affected by the catalyst activity, its effect should be incorporated in to the expressions, the deactivation kinetic model of the Weekman is chosen because of its simplicity and popularity in the FCC modeling. The decay of the catalyst activity due to coke deposition is represented by a function Φ , which depends on the temperature and the catalyst residence time.

$$\Phi = \exp(-\alpha \cdot t_c) \quad (6)$$

where:

t_c is the catalysts decay coefficient related to the riser temperature by an Arrhenius equation.

α is the catalysts decay coefficient related to the riser temperature by an Arrhenius equation.

$$\alpha = \alpha_0 \exp(-E/RT) \quad (7)$$

The coke generated by the cracking reaction is usually known as catalytic coke. The mass balance of catalytic coke in the riser, can be written as:

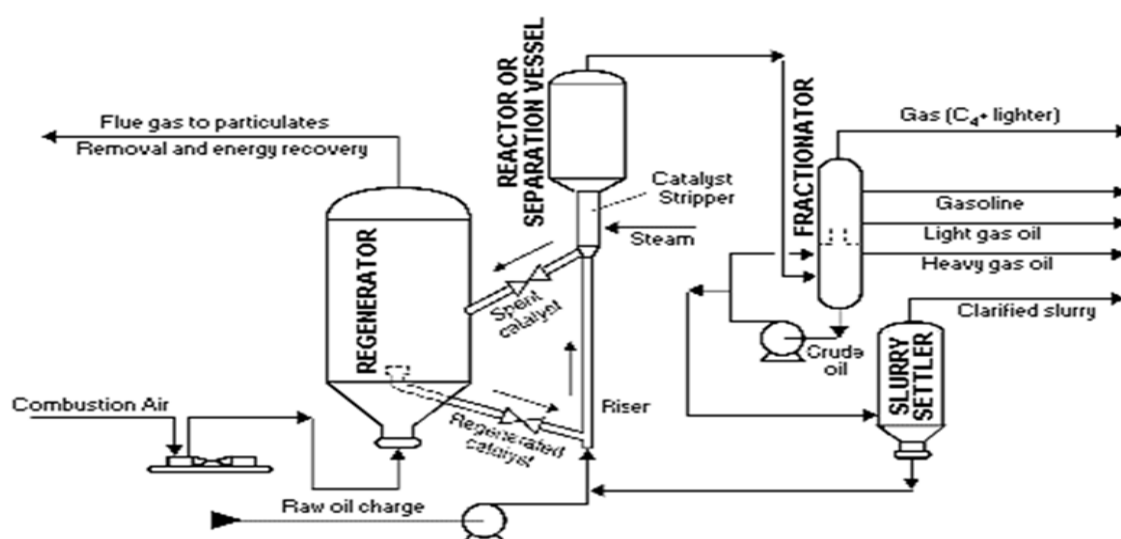


Figure 1: Schematic of the fluid catalytic cracking unit

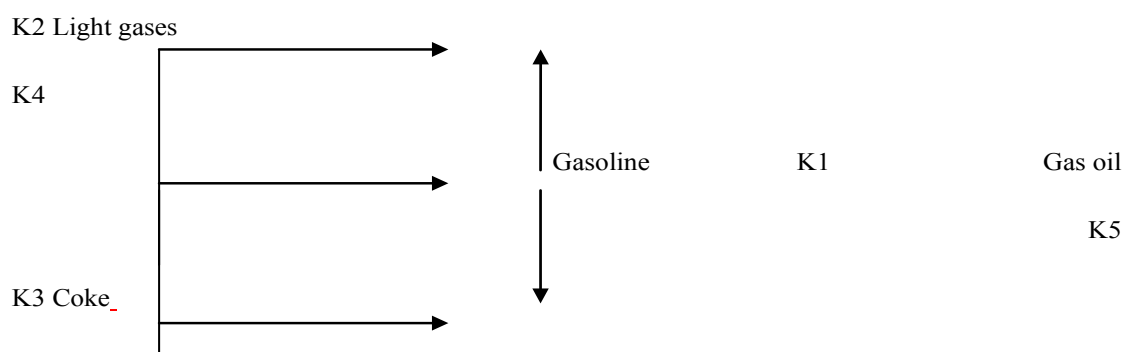


Figure 2: Schematic of four lumped reactions.

$$V_R \cdot \frac{dC_{cat}}{dt} = -F_{rc} \cdot C_{cat}(t) + R_{cr}(t) \quad (8)$$

The total coke on the spent catalyst in the reactor is the sum of the catalytic coke and the residual coke on the regenerated catalyst. Then from Eq. (8) can be given by:

$$V_R \cdot \frac{dC_{sc}}{dt} = F_{rc} (C_{cat}(t) - C_{cat}(t)) + R_{cr}(t) \quad (9)$$

R_{cr} is the specific rate of carbon formation. The dynamics of the cracking reaction in the riser is negligible when compared to the dominant time constants of the system. The reaction term is nonlinear and it must linearization by using Taylor series. The details show in appendix A.

The transfer function of the riser is:

$$C_{sc}(s) = \frac{K_1}{(\tau_1 s + 1)} C_{rc}(s) + \frac{K_2}{(\tau_1 s + 1)} T_R(s) + \frac{K_3}{(\tau_1 s + 1)} G_{GF}(s) \quad (10)$$

The heat balance is handled in accordance with a lumped parameter system. This leads to the following energy balance equation in the riser:

$$CP_R V_R \frac{dT_R}{dt} = CP_R F_{rc} (T_G - T_R) + CP_f \rho_f G_{GF} (T_f - T_R) + (-\Delta H_v) \rho_t G_{GF} + (-\Delta H_{cr}) R_{cr} \quad (11)$$

The transfer function of system can be represented by first order system with steady state gain and the time constant:

$$T_R(s) = \frac{K_4}{(\tau_2 s + 1)} T_G(s) + \frac{K_5}{(\tau_2 s + 1)} T_f(s) + \frac{K_6}{(\tau_2 s + 1)} G_{GF}(s) + \frac{K_7}{(\tau_2 s + 1)} C_{cat}(s) + \frac{K_8}{(\tau_2 s + 1)} G_{GF}(s) \quad (12)$$

The reactions taking place in the regenerator are coke combustion reactions. This coke is the byproduct of the cracking reaction taking place in the riser and get deposited on the catalyst surface in the course of cracking. The intrinsic carbon combustion on the surface of the catalyst corresponds to a couple of reactions producing CO and CO₂ with the second order kinetics [5].

The following reaction that take place in the regenerator are:



Where:

K_1 is the Coke combustion rate constant to form CO [1/(kPa.s)]

K_2 is the Coke combustion rate constant to form CO₂ [1/(kPa.s)].

Then the initial ratio of CO/CO₂ at catalyst surface from the following reaction can evaluate from Eq. (13):

$$\frac{CO}{CO_2} = K_1 / K_2 = \beta c = \beta c_0 e^{-\frac{E\beta}{RT}} \quad (13)$$

Where:

βc is CO/CO₂ ratio at the catalyst surface in the regenerator.

βc_0 is the pre-exponent constant in βc expression.

$E\beta$ is the energy of activation.

T is the temperature, (K).

The equations of the model for the regenerator mass balance are:

$$V_g \cdot \frac{dC_{cat}}{dt} = F_{rc} C_{cat}(t) - R_c(t) \quad (14)$$

Then The mass balance of total carbon on the regenerated catalyst in the regenerator becomes:

$$V_g \cdot \frac{dC_{cat}}{dt} = F_{rc} (C_{sc}(t) - C_{rc}(t)) - R_c(t) \quad (15)$$

Where R_c the carbon burning rate.

The transfer function of system can be represented by first order system with steady state gain and the time constant:

$$C_{rc}(s) = \frac{C_{sc}(s)}{(\tau_3 s + 1)} - \frac{K_9 * F_a(s)}{(\tau_3 s + 1)} \quad (16)$$

Energy balance in the regenerator:

$$V_g \cdot CP_s \cdot \frac{dT_G}{dt} = F_{rc} CP_s (T_R - T_G) + F_a CP_a (T_R - T_G) + (-\Delta H_c) R_c \quad (17)$$

Finally, the transfer function of system can be represented by first order system with steady state gain and the time constant:

$$T_G(s) = \frac{K_{10} T_R(s)}{(\tau_4 s + 1)} + \frac{K_{11} T_a(s)}{(\tau_4 s + 1)} + \frac{K_{12} F_a(s)}{(\tau_4 s + 1)} \quad (18)$$

Simulation work

The riser reactor is a vertical standpipe at about (33 m) in length and (0.8 m) in diameter. Preheated gas oil at about 494°C is sprayed into riser bottom, where it mixes with hot regenerated catalyst at about 695°C to produce a reaction temperature of about 546°C. It is assumed that the vaporization of the gas oil is instantaneous. Vaporized feed pneumatically conveys the catalyst from bottom to the top of the riser. In the riser endothermic cracking takes place at a temperature and pressure of about 546°C and 2.9 bar respectively. The catalyst and product gases from the riser enter the disengaging vessel. The separation of the catalyst from the product streams occurred in this vessel by using deflectors and cyclones. Following this the spent catalyst is transported to the regenerator where coke laid down on the catalyst surface, is burned off using air. The combustion of the carbon and hydrogen coke components is take place in regenerator with (11 m) height and (5.8 m) in diameter, a highly exothermic reaction takes place at a temperature and pressure of about 695°C and 2.9 bar respectively then the regenerated catalyst is recirculated to the reactor and supplies the heat required for cracking reaction.

A simulation program is built for the FCC unit by using the program Matlab/Simulink version (R2011a) from (Math works). It is a software for a simulation of dynamic model analysis. It consists of a Simulink part to build the models and study of the characteristics of dynamic situation. The mathematical model is built for FCC unit in the form of a set of systems and each system component with a set of subsystems which represents the mathematical model equations for FCC unit. Table 1 shows that the input data for simulation work. The hold up of riser was calculated by assuming the riser reactor will be worked as 85% only, the density of feed considered ideal gas and we assume the heat consumed (kJ/sec) for heating up the coke, air and moisture plus heat losses and removed are assumed 6% of total heat of combustion of the coke.

From Figures 3-6 shows the simulation program for the fluid catalytic cracking unit. Ten runs were carried out for the FCC unit (for riser and regenerator). The unsteady step change simulation runs were conducted by introducing gas oil feed rate, gas oil feed temperature, regenerated catalyst flow rate, air flow rate and air temperature, and measuring the output temperature of riser reactor and regenerator reactor. Two step change for this variables (10% - 20%) are taken, Table 2 shows the quantities that are used to make disturbance in the system (shows the layout of the simulation runs).

Parameters	values	Parameters	values
A_{cr} , ($m^3.kg^{-1}.sec^{-1}$)	10.45	F_p , (kg/sec)	20
A_c , ($m^3.kmol^{-1}.sec^{-1}$)	1.4×10^8	F_{cr} , (kg/sec)	144
$A_{activity}$, ($m^3.kg^{-1}.sec^{-1}$)	8.38×10^4	G_{gr} , ($m^3.sec^{-1}$)	0.022
Cp_a , (kJ. $kg^{-1}.K^{-1}$)	2.207	ΔH_{cr} , (kJ/kg)	745
Cp_r , (kJ. $kg^{-1}.K^{-1}$)	3.5	ΔH_c , (kJ/kg)	28700
Cp_s , (kJ. $kg^{-1}.K^{-1}$)	1.15	ΔH_v , (kJ/kg)	96
C/O	7.2	K_1 , ($m^3.kg^{-1}.sec^{-1}$)	1457.59
CO/ CO_2	0.141	K_2 , ($m^3.kg^{-1}.sec^{-1}$)	127.59
C_{sc} , wt%	0.0013	K_3 , ($m^3.kg^{-1}.sec^{-1}$)	1.98
C_{rc} , wt%	0.0002	K_4 , (sec^{-1})	256.81
D_G , (m)	5.8	K_5 , (sec^{-1})	6.29×10^{-4}
D_R , (m)	0.8	L_G , (m)	11
E_{cr} , (kJ/mol)	64.575	L_R , (m)	33
E_c , (kJ/mol)	224.99	P_R , (bar)	2.9
E_{active} , (kJ/mol)	117.72	P_G , (bar)	2.9
E_1 , (kJ/mol)	57.36	R , (kJ. $mol^{-1}.K^{-1}$)	8.3144
E_2 , (kJ/mol)	52.75	T_a , (K)	378
E_3 , (kJ/mol)	31.82	T_r , (K)	494
E_4 , (kJ/mol)	65.73	β_{co}	9.53×10^{-4}
E_5 , (kJ/mol)	66.57	ρ_r , (kg/ m^3)	2.2
F_a , (kg/sec)	16	ρ_{cat} , (kg/ m^3)	1500

Table 1: Data of the fluid catalytic cracking unit.

Run No.	Type of Disturbance	Value
1	Step change in gas oil feed flow rate, kg/sec	20-22
2	Step change in gas oil feed flow rate, kg/sec	20-24
3	Step change in regenerated catalyst flow rate, kg/sec	144- 158.4
4	Step change in regenerated catalyst flow rate, kg/sec	144-172.8
5	Step change in gas oil feed temp., K	494-543.4
6	Step change in gas oil feed temp., K	494-592.8
7	Step change in air flow rate, kg/sec	16-17.6
8	Step change in air flow rate, kg/sec	16-19.2
9	Step change in air temp., K	378-415.8
10	Step change in air temp., K	378-453.6

Table 2: Simulation runs for dynamic systems.

Results and Discussion

The transfer functions were obtained by two methods. First, they were derived from mass and energy balances. Second, they were obtained from step test approximate method and the parameters of transfer function were obtained using sixty-three percent method. Table 3 shows the comparison of transfer functions between two methods. The time constant and steady-state gain were obtained from response curve by using sixty-three percent method. The time constant and steady-gain obtained from sixty-three percent method are compared with those obtained from model.

In this study, the present simulation work was validated by comparing the steady state prediction with the results of simulation of some authors [8,9] and the industrial plant data. The industrial plant data from Universal Oil Product (UOP) type FCC unit finding in [8] were used to verify the present simulation work. The Table 4 shows this comparison. The present simulation results are presented for the riser temperature, regenerator temperature, gasoline yield, light gas yield and coke formed. The results show the best prediction of the gasoline yield, riser and regenerator temperatures but the highest deviation in light gases yield and amount of coke. The deviation percent of the riser and regenerator temperatures from the plant data are 0.855 and 0.864 respectively; these results are in closer agreement with the plant data. However, there are 6.56, -14.18 and -21.72 in gasoline, light gases and

coke yield respectively. The largest deviation, among the five variables, in the amount of coke was obtained. Compared to the simulation of other works, the present simulation results of the gasoline yield, riser and regenerator temperatures are better. However, the percent deviation of the coke amount and light gases yield from the plant data obtained are relatively high but give the lowest deviation from plant data among the other studies. The deviation between the present simulation results and the plant data are attributed to various factors. The simplifying assumptions were imposed on the model such as the adiabatic process, the steam for atomizing and separation were negligible and used values for physical chemical properties (the heats of reactions of the cracking and the combustion reactions) are identified as source of errors. Also, the used kinetic parameters from the literatures depend on the catalyst type, the catalyst activity, the age of the catalyst in operation, and the quality of the feed stock are other source of error. Moreover, the lumping and products represent another source of error. Despite all these, the deviations of the present simulation results from industrial plant data are relatively small.

To study the dynamic behavior of fluid catalytic cracking unit, ten runs were carried out for the FCC unit (for riser and regenerator). The unsteady step change simulation runs were conducted by introducing gas oil feed rate, gas oil feed temperature, regenerated catalyst flow rate, air flow rate and air temperature, and measuring the output temperature of riser reactor and regenerator reactor. Two step change for this variables (10% - 20%) are taken, Table 2 shows the quantities that are used to make disturbance in the system (shows the layout of the simulation runs).

The unsteady-state responses of the riser temperature, regenerator temperature, gasoline, coke and light gases yield product as a result of two steps change increase in the gas oil feed rate from 20 to 22 kg/sec and from 20 to 24 kg/sec are shown in Figures 7-10. The increase in the gasoil feed rate will accelerate the cracking reactions, this results in more gasoline, coke and light gases production as shown in Figures 8 and 9. Since the cracking reactions are endothermic, increasing the extent of the reactions will result in lower riser temperature as shown in Figure 7. This conclusion is in agreement with previous finding of Ali and Rohani [11] who investigated the transient response behavior of FCC unit as shown in Figures 7-9. As a result of lower riser temperature and rates of spent catalyst flowing back to the regenerator at lower temperature, the regenerator temperature decline as shown in Figure 10. Moreover, the drop in the regenerator temperature will decrease rate of combustion reaction.

The responses of the riser and regenerator temperatures to two steps change increase in gas oil feed temperature from 494 to 543.4 K

Parameters	Theoretical	Simulation	Error	system
K_p	0.707	0.447	0.259	Riser
τ_2 (min)	3.166	12	8.834	
K_p	0.581	0.367	0.255	Regenerator
τ_4	6.677	20	13.323	

Table 3: Comparison between the model and step test results of time constant and steady-state gain.

parameter	plant	Ref. [8]	Ref. [10]	Present simulation	%Dev. P	%Dev. [8]	%Dev. [10]
T_R , (K)	795	843	843	801.8	0.855	-4.88	-4.88
T_G , (K)	960	1143	1143	968.3	0.864	-15.28	-15.28
Y_1 , (wt%)	43.9	51.3	51.3	46.78	6.56	-8.81	-8.81
Y_2 , (wt%)	13.82			11.86	-14.18		
Y_3 , (wt%)	5.8	5.8	5.79	4.54	-21.72	-21.72	-21.58

Table 4: Comparison of present simulation results with plant data [8] and [10].

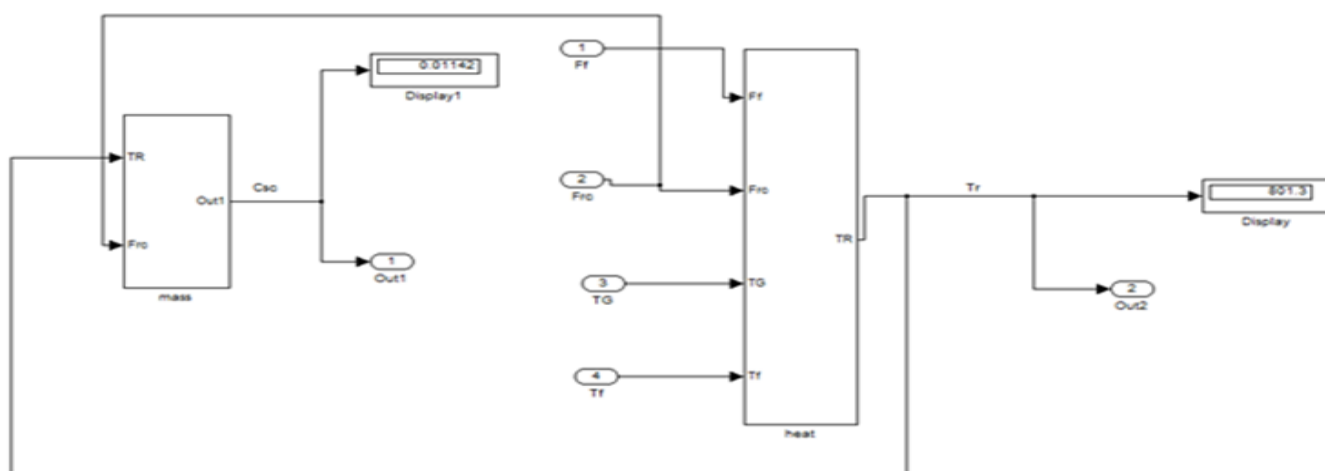


Figure 3: Mass and energy balance for riser reactor.

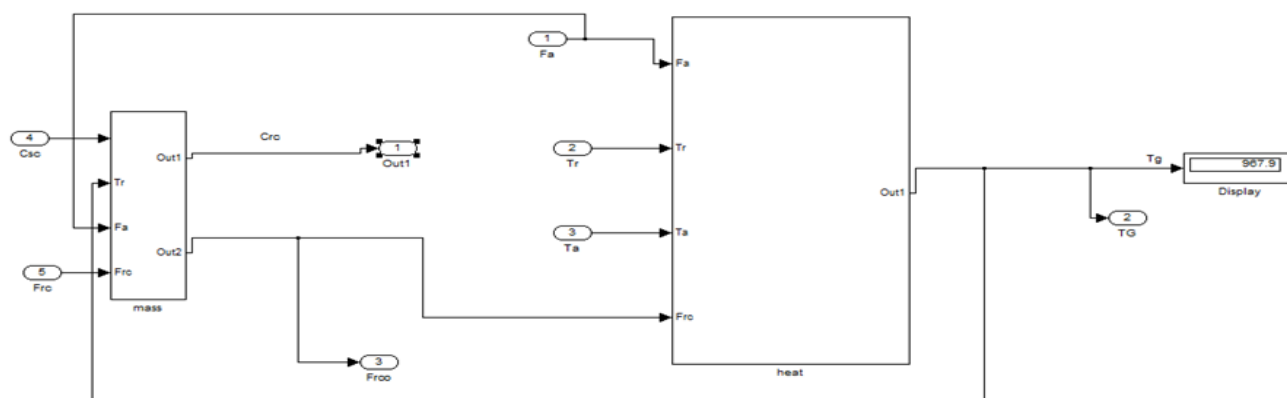


Figure 4: Mass and energy balance for regenerator reactor.

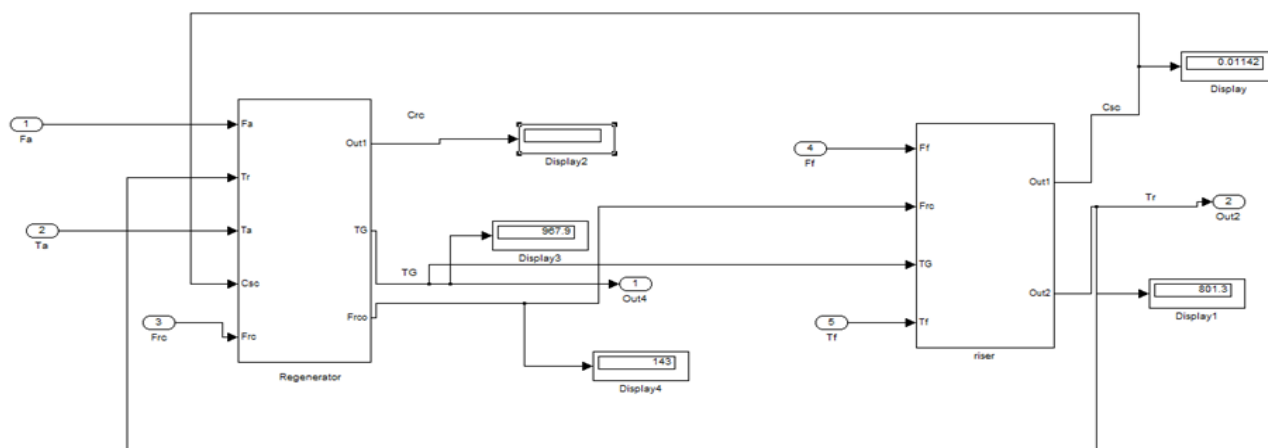


Figure 5: Sub system for mass and energy balance of riser reactor and regenerator reactor.

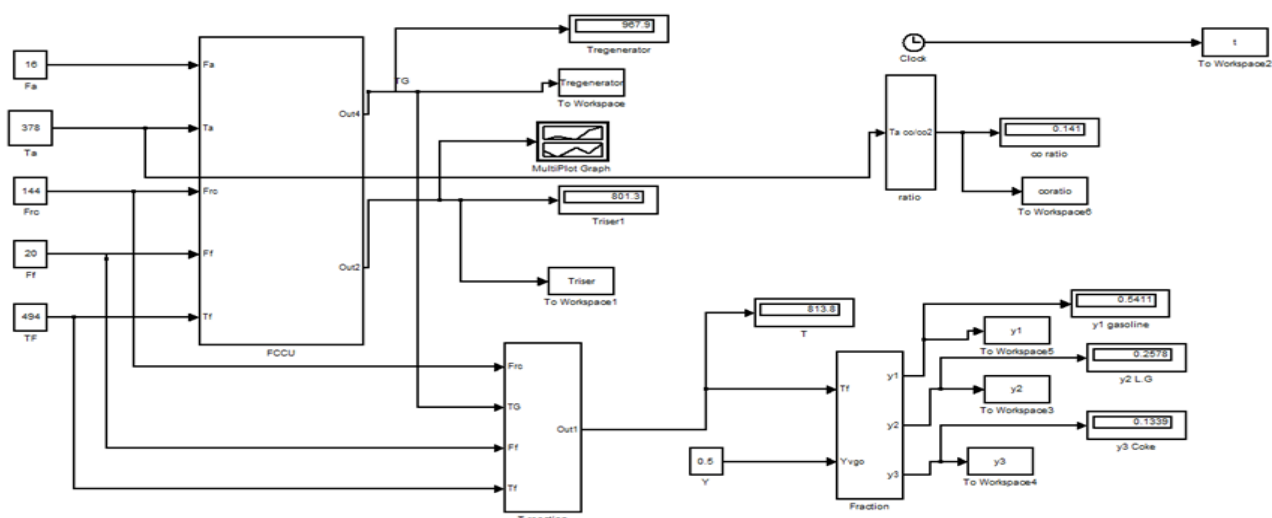


Figure 6: Sub system for mass and energy balance of riser reactor and regenerator reactor.

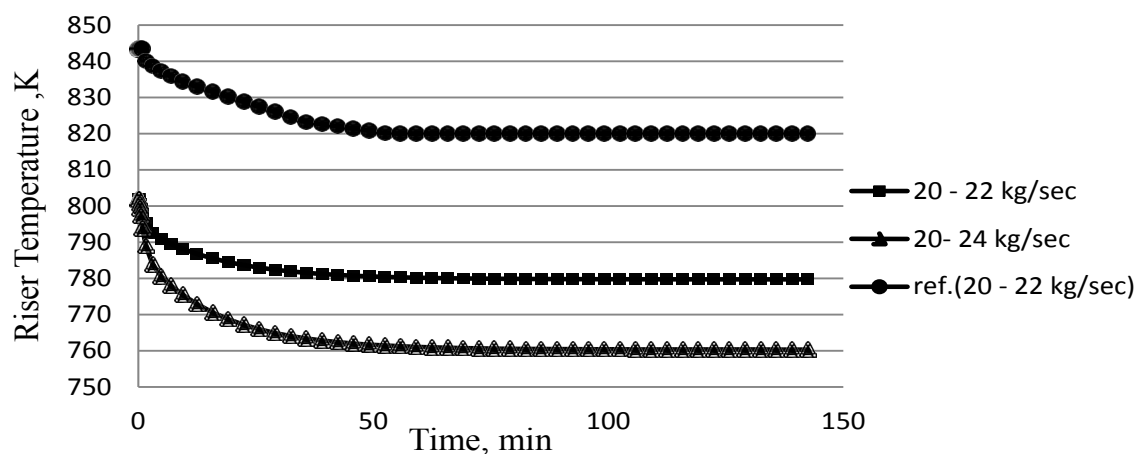


Figure 7: Riser temperature responses to step change in gas oil flow rate for various values of step.

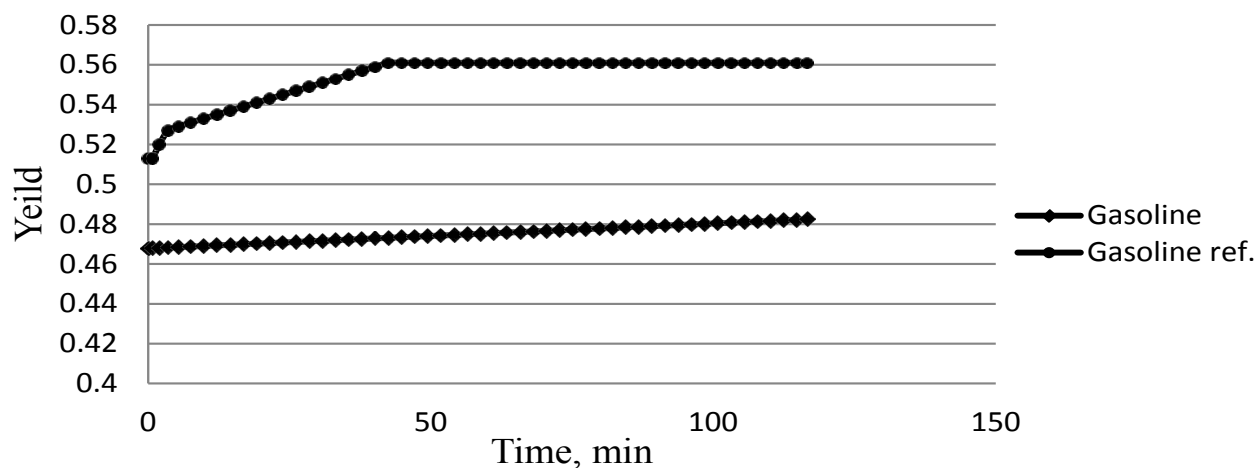


Figure 8: Gasoline yield due to step change in feed gas oil flow rate from 20-24 kg/sec.

and from 494 to 592.8 K are shown in Figures 11 and 12 and responses of the gasoline, light gases, and coke yield due to step change in feed temperature from 494 - 592.8 K are shown in Figures 13-15. As a result of increasing in the gas oil feed temperature the riser temperature increases. The higher gas oil feed temperature will increase the heat available for the cracking reaction increases. Thus, the cracking reactions are accelerated. The increased reaction rates produce more gasoline, light gases and coke as shown in Figures 13-15. The increased reaction rates produce more coke, and the combustion of higher quantities of coke increases the regenerator temperature.

From Figures 16 and 17 shows that the responses of the riser and regenerated temperatures to step change for various regenerated catalyst flow rate. As a result of increasing in the regenerated catalyst flow rate the riser temperature initially increases, however, the decrease in the regenerator temperature compensate the effect of increasing the regenerated catalyst flow rate and eventually the rise temperature will decrease before reaching a new steady-state value. The increase in the regenerated catalyst flow rate is associated with a lower catalyst bed level in regenerator. As the catalyst level in the regenerator drops, the volume occupied by the gases inside the regenerator vessel increases.

Moreover, the drop in the regenerator temperature will decrease the rate of combustion reaction. As a result, the amount of coke on the regenerated catalyst will increase. The higher regenerated catalyst flow rate has two effects on the riser. First, the amount of catalyst and second, the heat available for the cracking reaction increases. The higher regenerated catalyst flow rate due to the increase step change is associated with more heat input and active sites available for the endothermic cracking reaction. Thus, the cracking reactions are accelerated. Initially, the heat associated with the catalyst dominates, and the temperature at the exit of the riser increases. The higher riser temperature together with the presence of more catalyst favors the cracking reactions. The increased reaction rates produce more coke, and the combustion of higher quantities of coke increases the regenerator temperature. On other hand, the endothermic cracking reactions cause a reduction in the riser temperature. Furthermore, as fresh regenerated catalyst flow rate increases, it exerts a spent catalyst flow rate increases. As a result of lower riser temperature and high rates of spent catalyst flowing back to the regenerator at lower temperature, the regenerator temperature decline. This conclusion is in agreement with previous finding of Ali and Rohani [10] who investigated the transient response behavior of FCC unit.

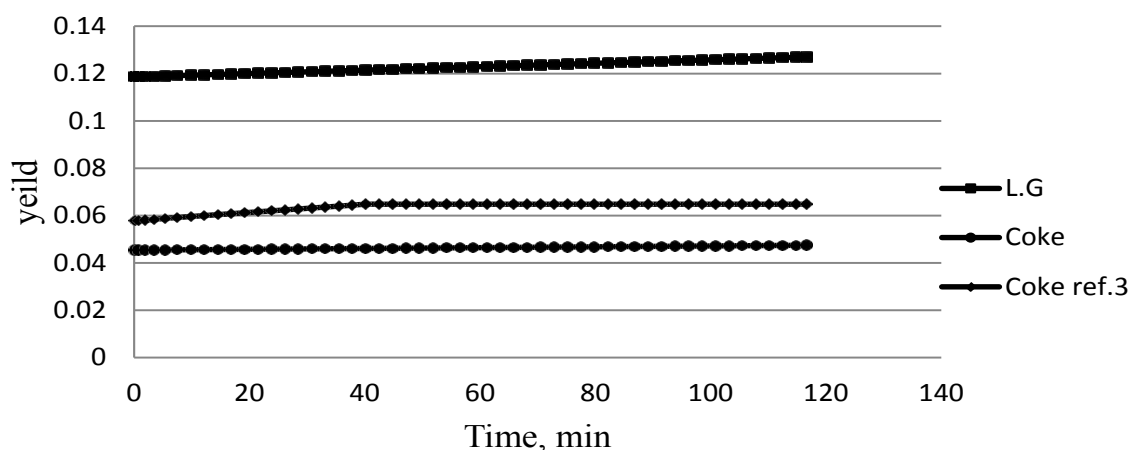


Figure 9: Light gases and coke yield due to step change in feed gas oil flow rate from 20-24 kg/sec.

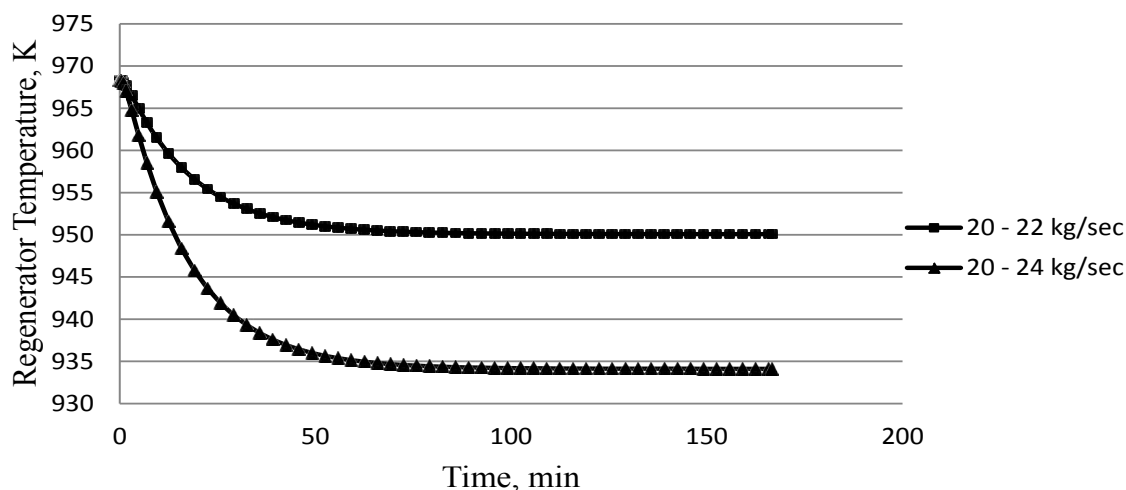


Figure 10: Regenerator temperature responses to step change in gas oil flow rate for various variable.

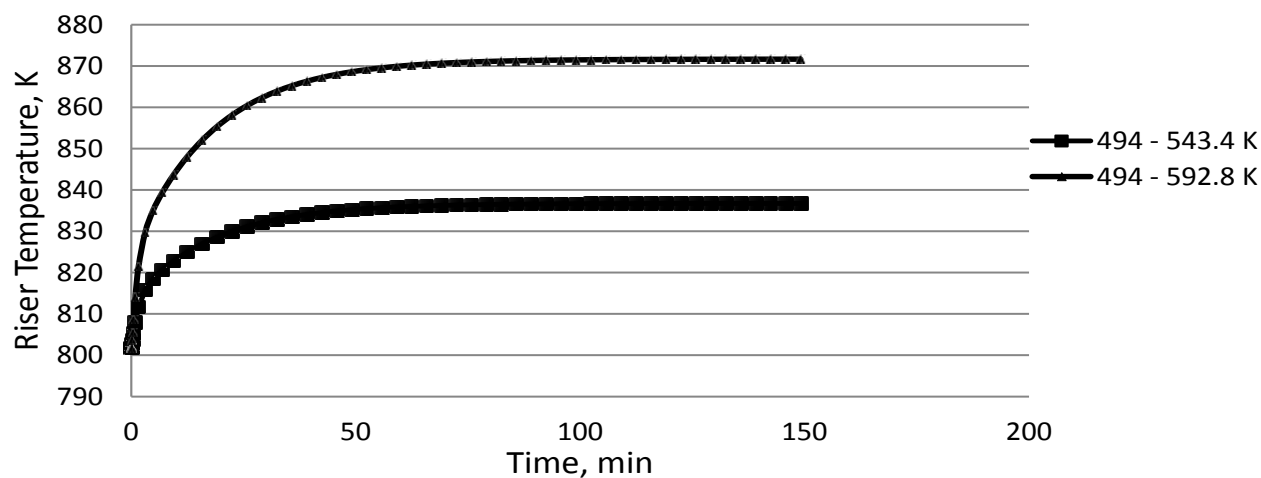


Figure 11: Riser temperature responses to step change in gas oil temperature for various variable.

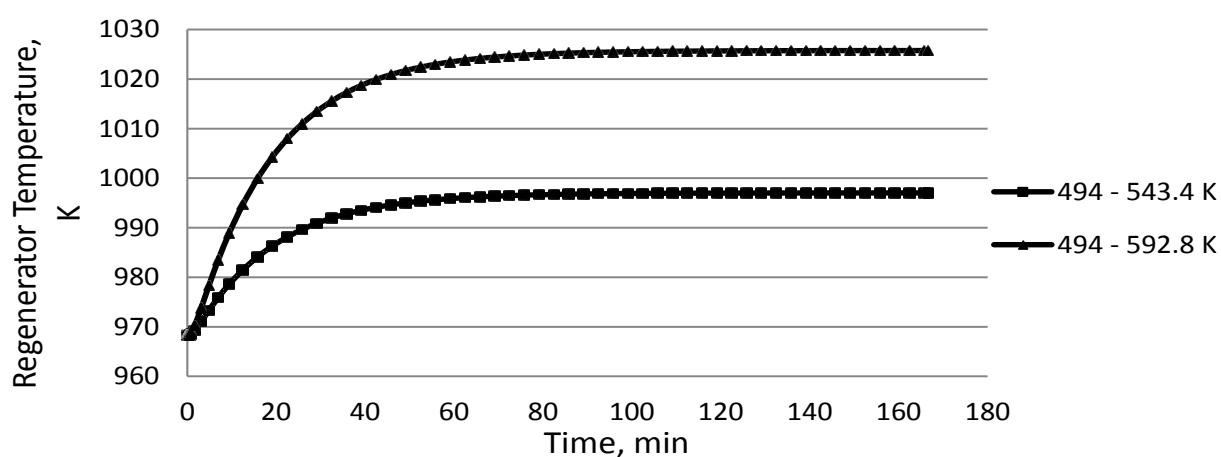


Figure 12: Regenerator temperature responses to step change in gas oil temperature for various variable.

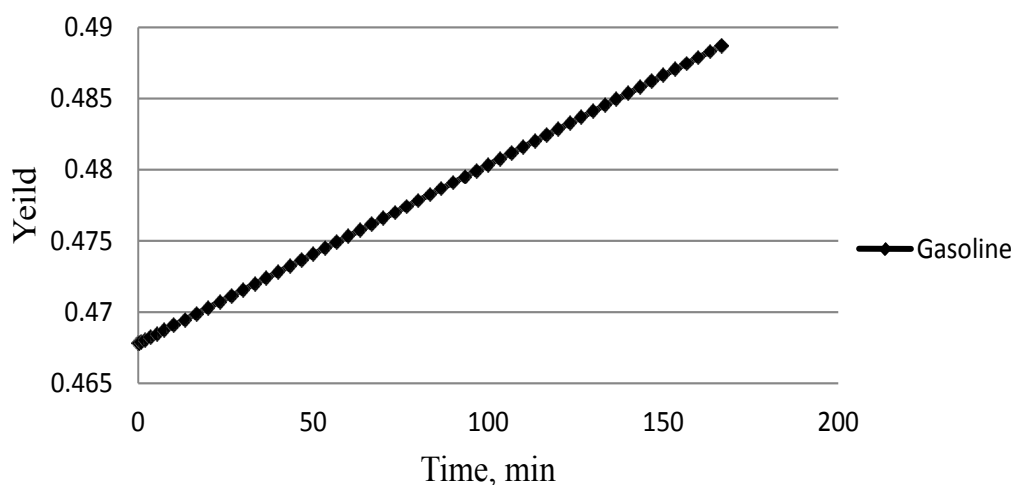


Figure 13: Gasoline yield due to step change in feed gas oil temperature from 494-592.8 K.

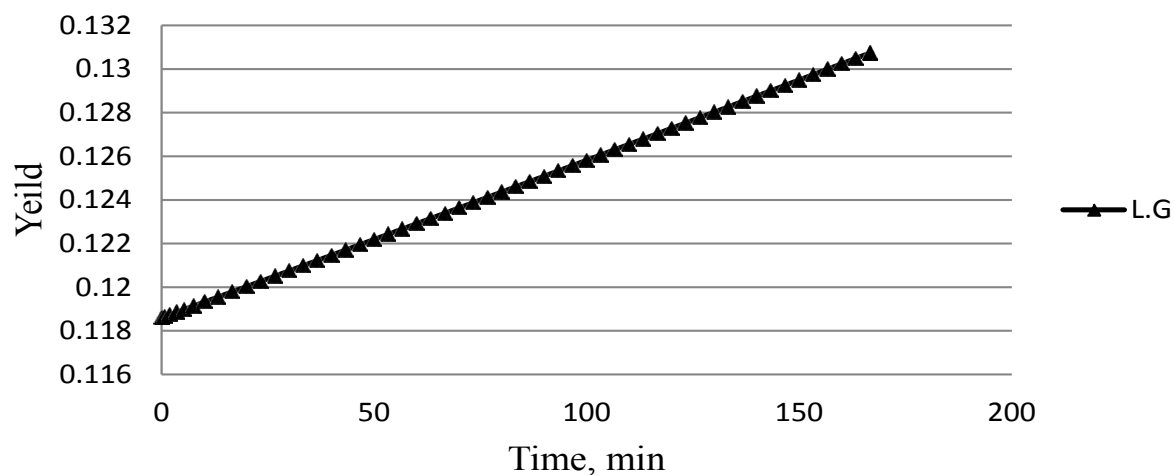


Figure 14: Light gases yield due to step change in feed gas oil temperature from 494-592.8 K.

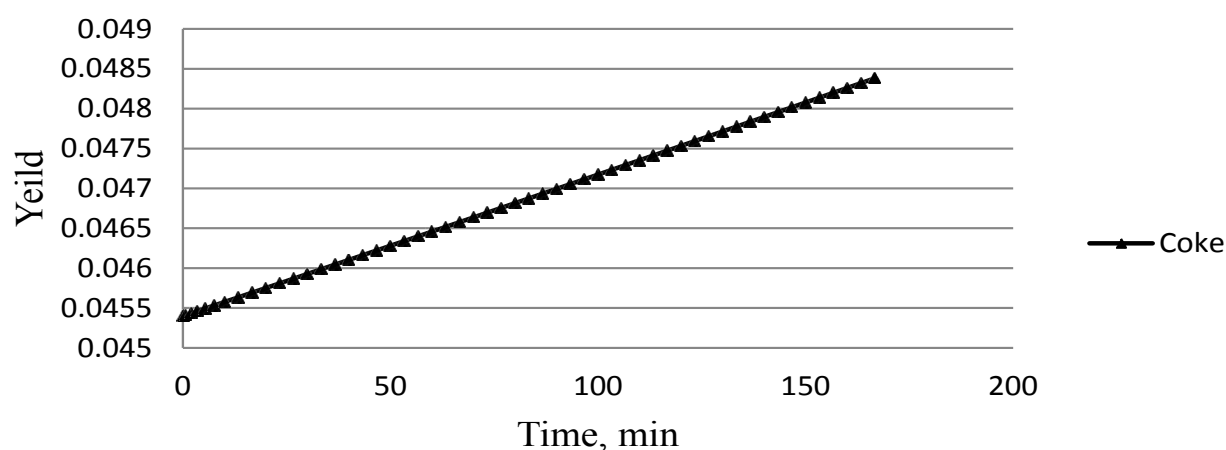


Figure 15: Coke yield due to step change in feed gas oil temperature from 494-592.8 K.

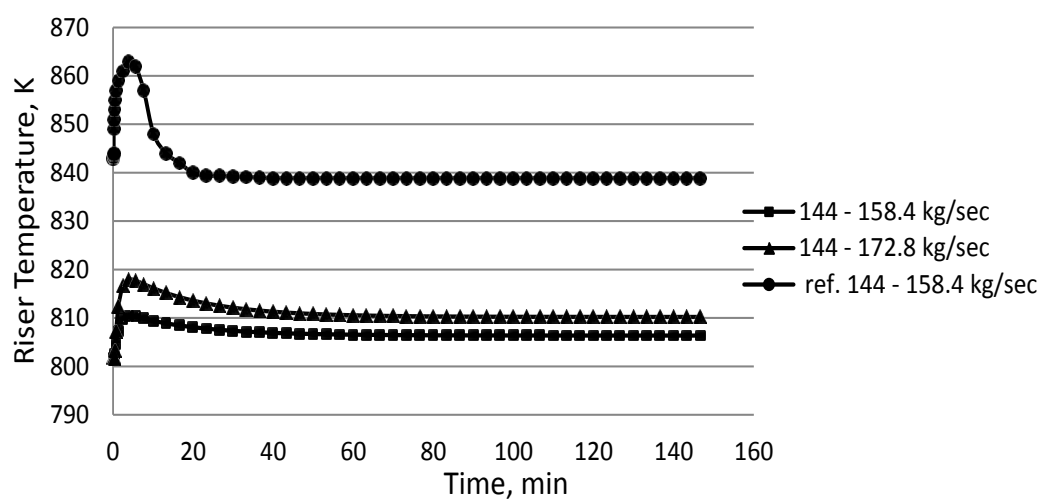


Figure 16: Riser temperature responses to step change in regenerated catalyst flow rate for various variable.

The responses of riser and regenerator temperatures to a two steps change in air flow rate from 16 - 17.6 kg/sec and from 16 - 19.2 kg/sec are shown in Figures 18 and 19. It is seen that the increasing of air flow rate will increase the combustion reaction rate and the amount of coke on the regenerated catalyst decreases. Accordingly, the heat associated with the regenerated catalyst increases and the temperature of the riser increases. Also the yield product increases as the behavior of outlet temperatures because the amount of coke on the regenerated catalyst decreases and more active sites available for the endothermic cracking reaction. Thus, the cracking reactions are accelerated.

The responses of riser and regenerator temperatures to two steps change in air temperature from 378 to 415 K and from 378 to 453.6 K are shown in Figures 20 and 21. As a result of increasing in the air temperature the riser and regenerated temperatures increase. Moreover, the increasing in the regenerator temperature will increase the rate of combustion reaction. As a result, the amount of coke on the regenerated catalyst will decrease. The higher regenerated temperature due to the increasing air temperature is associated with more heat

input and active sites available for the endothermic cracking reaction. Thus, the cracking reactions are accelerated.

Conclusion

From the present study, the following conclusions were drawn regarding to the dynamic behavior of the FCC unit. A simple over all dynamic models for the riser and regenerator were developed. The model simulates the entire FCC unit. The steady-state results of simulation were compared with industrial data and showed a good agreement. The comparison of the simulation results to the industrial plant data at steady-state showed that the simulator predicts the unit's behavior more accurately in comparison with other authors. Transient responses of the riser and regenerator in some of the key operative variables were obtained. The dynamic simulator study showed that the process is strongly influenced by the catalyst flow rate. The dynamic study showed that any increase in the amount of coke on the catalyst and regenerator temperature would be compensated by a larger rate of consumption of the oxygen, if available. Thus it provides a means of self-adjusting the unit.

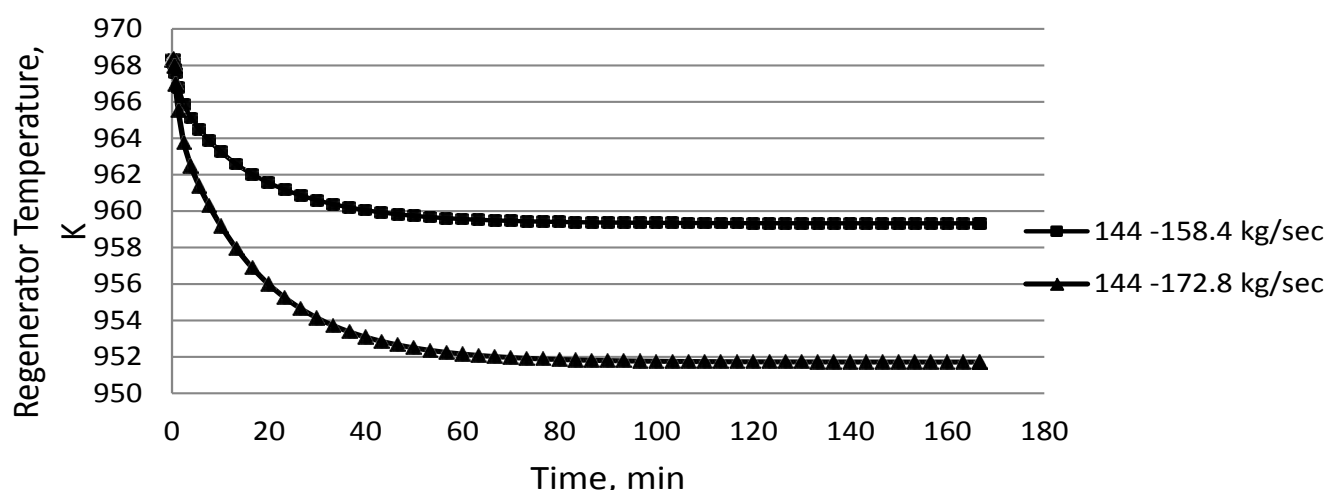


Figure 17: Regenerator temperature responses to step change in regenerated catalyst flow rate for various variable.

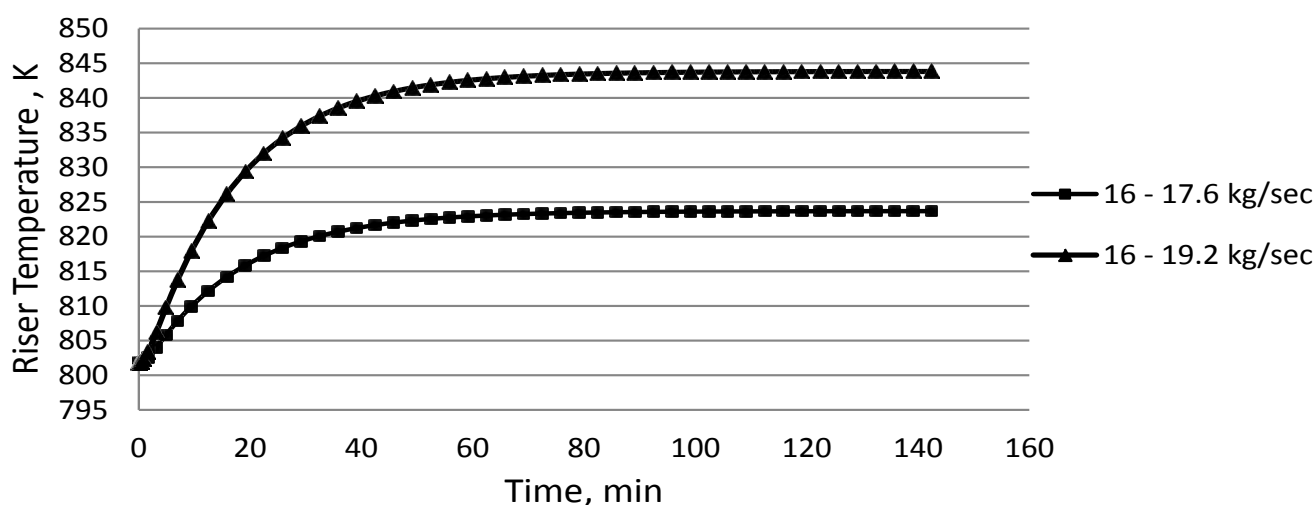


Figure 18: Riser temperature responses to step change in air flow rate for various variable.

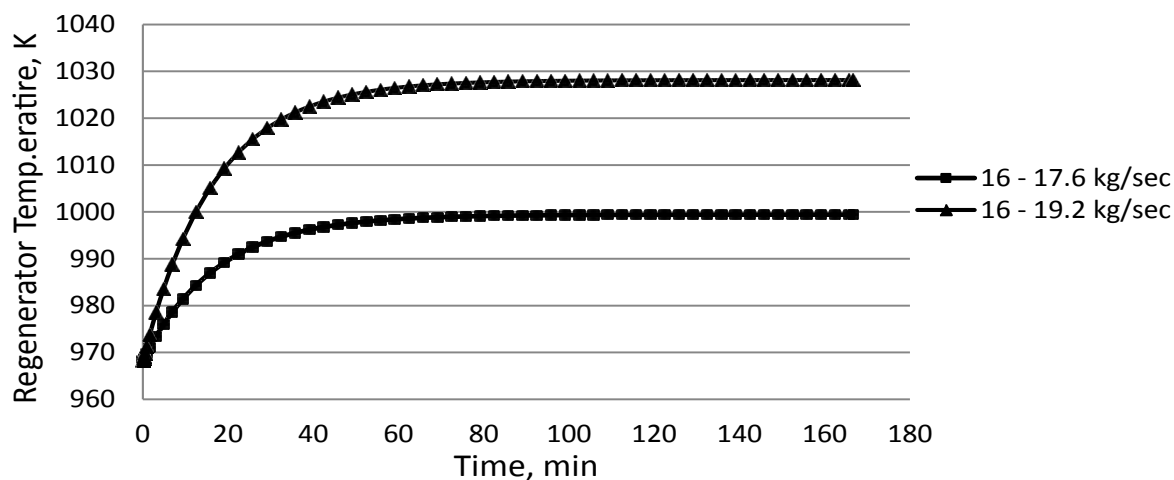


Figure 19: Regenerator temperature responses to step change in air flow rate for various variable.

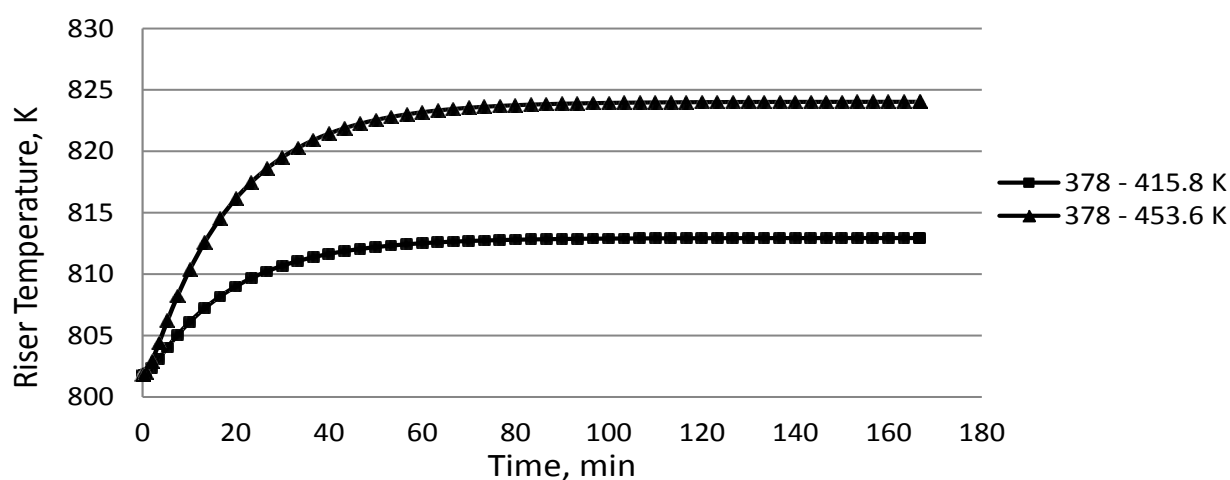


Figure 20: Riser temperature responses to step change in air temperature for various variable.

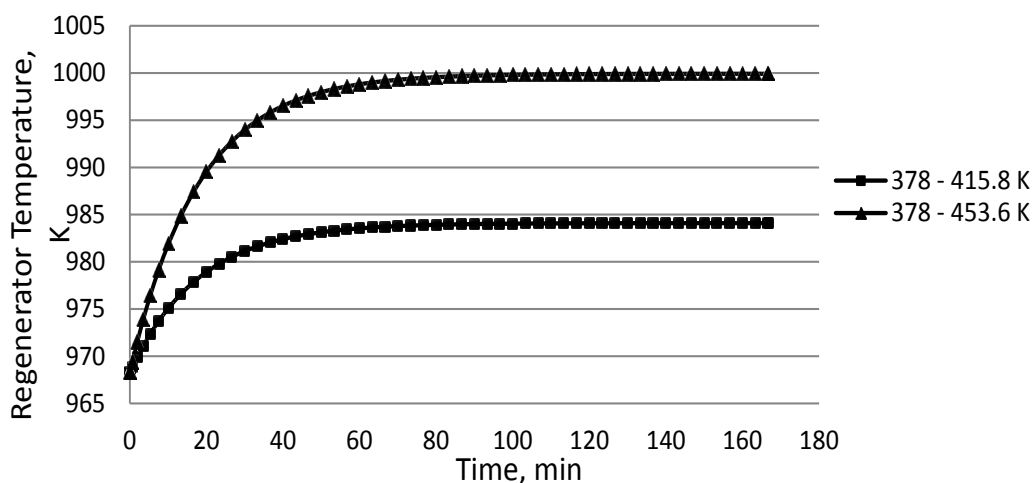


Figure 21: Regenerator temperature responses to step change in air temperature for various variable.

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