Dynamic modeling and improvements in the tuning of PI Controllers for Fluidized Catalytic Cracking Unit

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Abstract: - The Fluidized Catalytic Cracking Unit is one of the most important dynamic and complex process in a refinery that cracks down longer chain hydrocarbons to yield Gasoline. The process is highly nonlinear and multi variable with severe interactions. The input to the Cracking reactor is a mixture of hydrocarbons that makes the reaction kinetics very complicated due to the involved reactions. The purpose of this study is to develop a detailed dynamic model of a typical FCC unit that consists of the reactor, regenerator, blower and catalyst transfer lines and to properly select the controller tuning rule so that the preferred performance criteria is achieved. Enough detail is provided in the simulated model to capture the major dynamics including nonlinearities, interactions and constraints. A four lump yield model is plugged to the simulated FCCU model to capture the reaction kinetics. With an objective to satisfy minimum overshoot as the performance criteria, PI controllers implemented for reactor and regenerator temperature control of FCCU were tuned with two different tuning rules for satisfying minimum overshoot as the required performance criteria.

Keywords: Fluidized Catalytic Cracking Unit, Four Lump Yield Model, Gasoline yield, Reactor and Regenerator temperature control, PI Controller Tuning, minimum overshoot

1. Introduction

Fluidized Catalytic Cracking Unit (FCCU), primarily used in producing additional gasoline in the refining process is a chemical process that uses a catalyst to create new, smaller molecules from larger molecules to make gasoline and distillate fuels. After 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. The FCCU includes two most important units namely the reactor where the cracking takes place under intense heat and pressure and the regenerator where regeneration of catalyst from coke takes place Economic operation of FCCUs plays an important role in the overall economic performance of the refinery. Many efforts have been made in many ways by different researchers to evolve and improve the accuracy of the model's predictions with a real process for industrial FCCU, which are mostly based on both the fluid flow of the process and kinetic models. Three of the most commonly used models in the literature which incorporate most of the dynamics of an Industrial type FCCU are the one by Lee and Groves [5], McFarlane et al. [9], and Arbel et al [2] while others consider only the Reactor Model neglecting the Regenerator Dynamics. This work includes the simulation of the Reactor Regenerator Model along with the other auxiliary units [9].The main limitation of this model is that the chemical kinetics behind the formation of Gasoline, coke and other light gases from the feed is not considered. Since the objective of this work is to perform optimization analysis as well, the chemical kinetics behind the conversion of feed into the reactor products mainly the Gasoline and coke is necessary. The complex mixtures were described by many researchers by means of lumping a large number of chemical compounds into smaller groups of pseudo-components [3], [6], [10] and [12] .Week man [13] developed the first three lump model. Lee et al [6] gave the four lump model. Complex models are mathematically more complicated and need more experimental parameters which are difficult to estimate [4]. Here the four lump yield model [6] is simulated and plugged with the simulated FCCU model. Based on the outcome of the open loop study carried out [8] it is inferred that reactor and regenerator temperature control plays a significant role in deciding the yield of Gasoline and in turn the formation of coke. Hence PI controllers were implemented for reactor and regenerator temperature control and the tuning parameters were selected with an objective of minimum overshoot as the performance measure [8].

2. Modeling of FCC unit

The process diagram of Type IV FCCU unit for which the model is developed is shown in Figure 1.

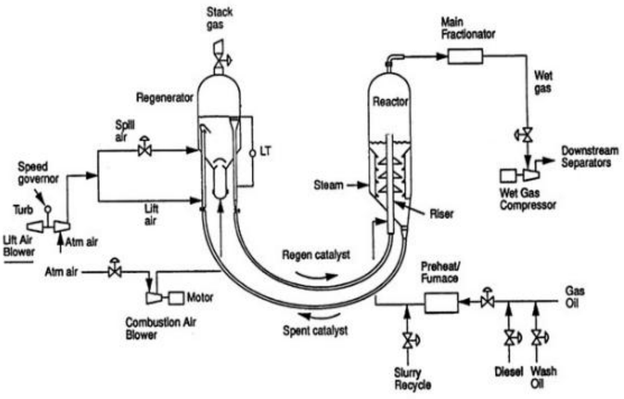

Figure 1. Schematic flow diagram of FCCU

Preheated feed is mixed with hot slurry recycle (from the bottom of the main fractionator) and injected into the reactor riser, where it mixes with hot regenerated catalyst and totally vaporizes. The hot catalyst provides the sensible heat, heat of vaporization and heat of reaction necessary for the endothermic cracking reactions. As a result of the cracking reactions, a carbonaceous material (coke) is deposited on the surface of the catalyst. Coke on spent catalyst is usually 5 to 10% hydrogen, depending on the coking characteristics of the feedstock. Since coke poisons the catalyst, continuous regeneration is necessary. Seperation of catalyst and gas occurs in the disengaging zone of the reactor. Entrained catalyst is removed in cyclones. Catalyst is returned to the stripping section of the reactor where steam is injected to remove entrained hydrocarbons. Reactor product gas is passed to the main fractionators for heat recovery and separation into various product streams. Wet gas from the overheads of the main fractionator is compressed for further separation in downstream fractionators.

Spent catalyst is transported from the reactor to the regenerator through the spent catalyst U-bend. Air is injected into the bottom of the regenerator lift pipe to assist the circulation of catalyst. Catalyst in the regenerator is fluidized with airflow provided by the lift and combustion air blowers. Carbon and hydrogen on the catalyst react with oxygen to produce carbon monoxide, carbon dioxide and water. While most of the reactions occur in the fluidized bed, some reaction does occur in the disengaging section above the bed, where some catalyst is still present. gas travels up the regenerator into the cyclones where entrained catalyst is removed and returned to the bed. The regenerator is run at conditions of temperature and excess oxygen to ensure that virtually all carbon monoxide produced in the bed is converted to carbon dioxide before entering the cyclones(referred to as CO burn)

The model captures the major dynamic effects that occur in a real FCCU plant. The non-linear model was developed for the Feed preheat system, Reactor Riser, Regenerator, Combustion Air Blower, Wet gas Compressor and Catalyst circulation lines.The furnace firebox temperature of the feed and outlet temperature were modelled with the following energy balance equation.

$$\frac{dT_3}{dt} = \left(F_5 \Delta H_{fu} - UAfT_{lm} - Q_{loss}\right)/\tau fb \qquad (1)$$

$$\frac{dT_2}{dt} = (T_{2ss} - {}_{-2})/\tau fo$$

(2)

The coke balance includes the carbon entering the reactor on regenerated catalyst and is given by

$$\frac{dC_{sc}}{dt} = \left\{F_{rgc}C_{rgc} + F_{coke} - F_{sc}C_{sc}\frac{dW_r}{dt}\right\}/W_r \qquad (3)$$

The catalyst balance is given by

$$\frac{dW_r}{dt} = F_{rgc} - F_{sc} \qquad (4)$$

Reactor riser energy balance which also assumes stirred tank dynamics is given by

$$M_{cpeff}\frac{dT_r}{dt} = Q_{in} - Q_{out} \qquad (5)$$

The pressure at the bottom of the reactor riser is needed in the force balance on the regenerated catalyst U bend. Thus the Reactor riser pressure balance is given by

$$P_{rb} = P_4 + \rho_{ris}h_{ris}/144 \qquad (6)$$

The main fractionator and reactor pressure balance is given by

$$\frac{dP_5}{dt} = 0.833\left(F_{wg} + F_{v13} + F_{v11} - F_{v12}\right) \tag{7}$$

$$\frac{dP_7}{dt} = 5(F_{v11} - F_{11}) \tag{8}$$

The catalyst phase of the fluidized bed is assumed to be perfectly mixed. Regenerator energy balance is given by

$$\left[MI + \left(W_{reg} + W_{sp}\right)C_{pc}\right]\frac{dT_{reg}}{dt} = Q_{in} - Q_{out} \tag{9}$$

Carbon balance is given by

$$\frac{dC_{rgc}}{dt} = \left(\frac{dW_c}{dt} - C_{rgc}\frac{dW_{reg}}{dt}\right)/W_{reg} \tag{10}$$

$$\frac{dW_{reg}}{dt} = F_{sc} - F_{sp} \tag{11}$$

$$\frac{dW_c}{dt} = (F_{sc}C_{sc} - F_H) - \left(F_{sp}C_{rgc} + 12F_{air}(X_{co} + X_{co2})\right) \tag{12}$$

Standpipe inventory balance is given by

$$\frac{dW_{sp}}{dt} = F_{sp} - F_{rgc} \tag{13}$$

The Pressure balance in the regenerator assumes ideal gas behaviour. The pressure at the bottom of the regenerator P_{rgb} is required in the calculation of air flow into the regenerator from the air blowers.

$$\frac{dP_6}{dt} = \left\{R\left(n\frac{dT_{reg}}{dt} + \left(T_{reg} + 459.6\right)\frac{d_n}{dt}\right)\right\}/V_{reg} \tag{14}$$

An increase in lift air flow rate lowers the density of catalyst in the lift pipe which in turn lowers the head, resulting in an increase in catalyst flow through the U bend. Changes in density in the lift pipe occur with an assumed time constant, τ_{fill} and are given by

$$\frac{d\rho_{lift}}{dt} = \left(\frac{F_{sc}}{V_{cat}}, lift * Alp + P_{airg}\rho_{lift}\right)/T_{fill} \tag{15}$$

Air is supplied to the regenerator by two centrifugal compressors. The bulk of regenerator air is supplied by the combustion air blower, which supplied air directly to the bottom of the regenerator. The lift air blower injects air into the bottom of the lift pipe.

$$F_{sucn,comb} = 45000 + \sqrt{(1.581 * 10^9 - 1.249 * 10^6 * P_{base}^2)} \tag{16}$$

$$\frac{dP_1}{dt} = \frac{R(T_{atm}+459.6)}{29V_{comb,s}}(F_{v6} - F_6) \tag{17}$$

$$\frac{dP_2}{dt} = \frac{R(T_{atm}+459.6)}{29V_{comb,\text{ジ}}}(F_6 - F_{v7} - F_7) \tag{18}$$

$$F_{base} = 8600 + \sqrt{\left(2.582 * 10^8 - 1.068 * 10^5 P_{base,d}\right)} \tag{19}$$

Circulation of spent and regenerated catalyst is modeled as single phase flow governed by simple force balances. The force balance on the regenerated catalyst U bend is given by,

$$\frac{dv_{rgc}}{dt} = \frac{f_{rgc}}{M_{rgc}} \tag{20}$$

The force balance on the spent catalyst circulation line given by,

$$\frac{dv_{sc}}{dt} = \frac{f_{sc}}{M_{sc}} \tag{21}$$

The complete model of the FCCU is simulated in Matlab Simulink Platform.

3. Four Lump Yield Model

The Reaction scheme of four lump yield model is given in Fig 2.The lumps are feed, gasoline, coke and gas. Gas oil (Y_1) is assumed to crack to gasoline (Y_2), the most desired product, and to the byproducts, coke (Y_4) and wet gas (Y_3). The four lumps and their interactions are shown in figure 2.

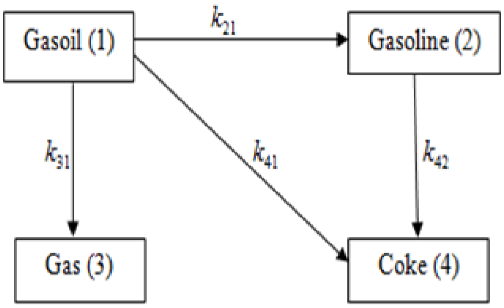

Figure 2. Reaction scheme of 4 lump yield model

The rate constants for the cracking reactions are represented by the k’s and are obtained from the experimental data of Gianetto et al [3] . 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.

$$\frac{dY_1}{dt} = -\varphi(k_{21}+k_{31}+k_{41})\frac{Y_1^2 W_{ris} w_r}{M_A V_r^2} \qquad (22)$$

$$\frac{dY_2}{dt} = \varphi\left[\left(\frac{w_T}{M_A V_T}\right)k_{21}Y_1^2 - k_{42}Y_2\right]\frac{W_{ris}}{V_T} \qquad (23)$$

$$\frac{dY_3}{dt} = \varphi\left[\left(\frac{w_T}{M_A V_T}\right)k_{31}Y_1^2\right]\frac{W_{ris}}{V_T} \qquad (24)$$

$$\frac{dY_4}{dt} = \varphi\left[\left(\frac{w_T}{M_A V_T}\right)k_{41}Y_1^2 + k_{42}Y_2\right]\frac{W_{ris}}{V_T} \qquad (25)$$

Fraction of active sites in catalyst is given by

$$\varphi = \exp\left(\frac{-\alpha Y_4 w_T}{W_{ris}}\right) \qquad (26)$$

Reaction rate constant can be estimated by

$$k_{ij} = k_{ij0}\exp\left(\frac{-E}{RT_r}\right) \qquad (27)$$

4. Control of Reactor and Regenerator Temperature

4.1. Multiloop Control

The reactor temperature and regenerator temperature were selected as a controlled variable since precise temperature control is required for stable production of Gasoline and other product gases . The manipulated variables were flow of regenerated catalyst and flow rate of air. The control structure selection was done based on Relative Gain Array (RGA) analysis.

The input and output relationship are given as

$$T_r = \frac{0.142}{1606s+1}F_{rgc} + \frac{3.2112}{4037s+1}F_{air} \qquad (28)$$

$$T_{reg} = \frac{0.2984}{1602s+1}F_{rgc} + \frac{26.89}{1575s+1}F_{air} \qquad (29)$$

The above transfer functions were found out by using the process reaction curve method.

The steady (gain) model is expressed as

$$k = \begin{bmatrix} k_{11} & k_{12} \\ k_{21} & k_{22} \end{bmatrix} = \begin{bmatrix} 0.142 & 3.2112 \\ 0.2984 & 26.89 \end{bmatrix} \qquad (30)$$

Thus, the relative gain array for a 2 × 2 system can be expressed as given below

$$\Lambda = \begin{bmatrix} 1.335 & -0.335 \\ -0.335 & 1.335 \end{bmatrix} \qquad (31)$$

Figure 3 shows the schematic of the closed loop system with the PI controller.

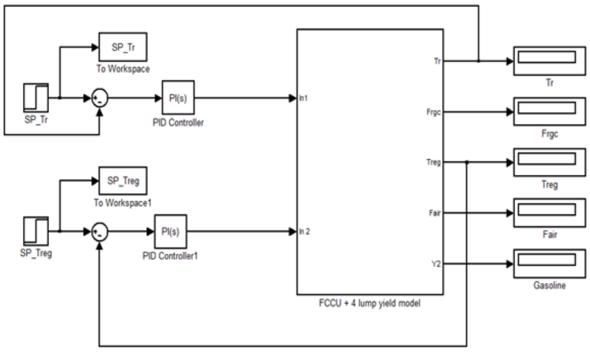

Figure 3. Schematic diagram of closed loop system with PI controller

The reactor temperature must be maintained at a certain level to provide the 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 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 regenerator.

4.2. 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. Having Reactor and regenerator control as the controlled variable, minimum overshoot is chosen as the performance criteria. Initially the PI controllers are tuned using direct synthesis method. The results were compared against Atkinson and Davey tuning rule proposed by A.O'Dwyer[1]. The tuning rule and its parameters are given in table 1.

Table 1 .PI Tuning rules and the parameters

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

The control signal from the tuned PI controllers was given to the whole simulated FCCU model and the closed loop response is studied.

5. Results and Discussions

The open loop response of the simulated FCCU model after plugging the yield model is studied [8]. The formation of Gasoline, Coke and other light gases from Gas oil is shown in Fig 4 and it is inferred that Gasoline and other light gases are produced in equal amount with minimum coke .

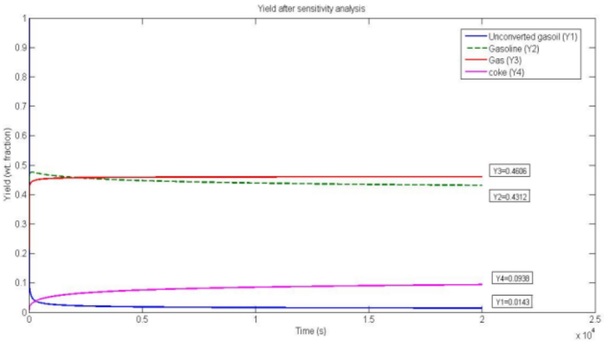

Fig 4:Yield of Gasoline,Coke and other light gases from Gas oil

With the optimized model, the PI controllers were designed with the two proposed tuning rule for the reactor and regenerator temperature control and is listed in table 2 and 3.

Table 2. PI tuning parameters for Reactor temperature control

PI TUNING RULE	(K_P)	(K_I)
Direct synthesis	7.0422	0.004385
Atkinson and Davey	16.001	0.0267

Table 3. PI tuning parameters for Regenerator temperature control

PI TUNING RULE	(K_P)	(K_I)
Direct synthesis	0.017597	0.000037887
Atkinson and Davey	0.082675	0.0001378

Based on the Controller settings, the closed loop response for the reactor temperature is obtained for 993F as the set point and is shown in Figure 5.

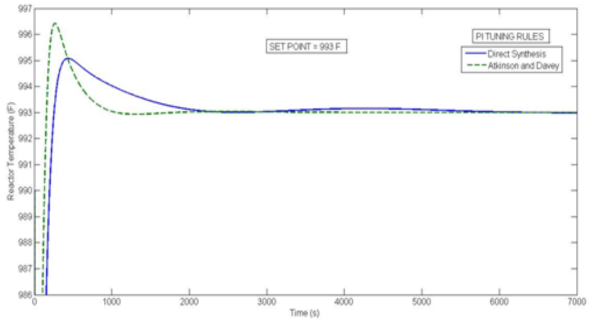

Figure 5. Control of reactor temperature for 993˚F as set point

Controller settings based on direct synthesis method produces minimum overshoot but having a sluggish response where as Atkinson and Davey PI tuning rule provides better response with minimum overshoot and quicker settling time of about 2500 secs. After the steady state was reached, disturbance has been given to the effective coke factor (Ψ_f) from 1 to 1.5 at 7000s and from 1 to 0.5 at 12000s and the controller performance was studied and shown in figure 6.

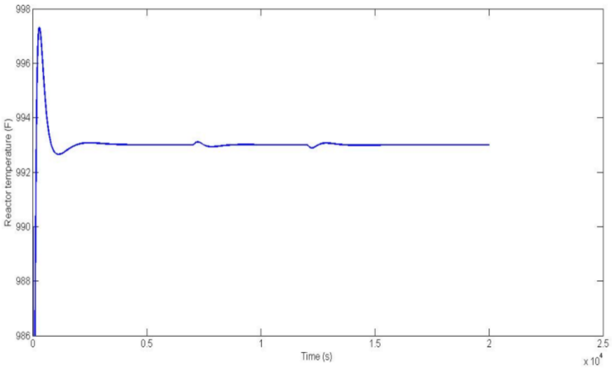

Figure 6. Control of reactor temperature with disturbance in effective coke factor

Similarly the regenerator temperature was operated for 1275˚F as setpoint and the controller performance for the two controller settings is shown in Figure 7.

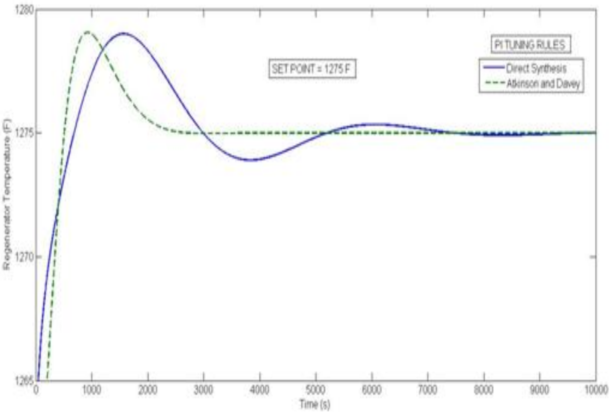

Figure 7. Control of regenerator temperature for 1275˚F as set point

It shows that the direct synthesis method is having minimum overshoot but with a sluggish response. Hence Atkinson and Davey PI tuning rule will provide the best response with minimum overshoot as well as faster settling time of about 5000 secs.

After the steady state was reached, disturbance has been given to the effective coke factor (Ψ_f) from 1 to 1.5 at 7000s and from 1 to 0.5 at 12000s and the controller performance was obtained as in Figure 8.

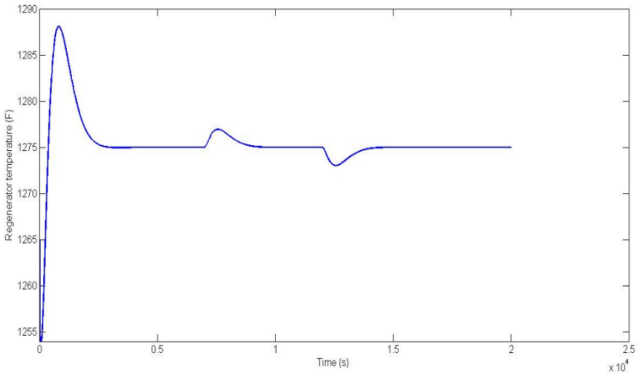

Figure 8. Control of regenerator temperature with disturbance in coke factor

6. 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 conditions to calculate the conversion and the distribution of products. From the closed loop performance study it is concluded that Atkinson and Davey PI tuning rule proves to be the best PI tuning rule for the temperature control when performance criteria of minimum overshoot and faster settling time is considered.

NOMENCLATURE

A_{lp} = Cross sectional area of lift pipe (8.73 ft^2)

A_{reg} = Cross sectional area of regenerator (590 ft^2)

A_{ris} = Cross sectional area of reactor riser (9.6 ft^2)

A_{sp} = Cross sectional area of standpipe (7 ft^2)

$A_{stripper}$ = Cross sectional area of reactor stripper (60 ft^2)

$A_{ubendrgc}$= Cross sectional area of regenerated catalyst U bend (3.73 ft^2)

$A_{ubendsc}$ = Cross sectional area of spent catalyst U bend (5.72 ft^2)

a_1 = Furnace heat loss parameter (.15 btu/s °F)

a_2 = Furnace heat loss parameter (200 btu/s)

C_H = Weight fraction of hydrogen in coke (.075 lb H_2/lb coke)

C_{rgc} = Weight fraction of coke on regenerated Catalyst (wt. coke/wt. catalyst)

C_{rw} = Wet gas compressor compression ratio

C_{sc} = Weight fraction of coke on spent catalyst (wt. Coke/wt. catalyst)

C_{slurry} = Factor representing coking tendency of slurry recycle relative to fresh feed
(3.5 for base base)

$E_{lift,air}$ = Elevation of regenerator lift air injection (134 ft)

$E_{oilinlet}$ = Elevation where oil enters the reactor riser (124.5 ft)

$E_{stripper}$= Elevation of reactor stripper tap (130ft)

E_{tap} = Pressure tap elevation on standpipe (155 ft)

E_{21} = Activation energy, gas oil to gasoline (btu/lb.mol)

E_{31} = Activation energy, gas oil to wet gas (btu/lb.mol)

E_{41} = Activation energy, gas oil to coke (btu/lb.mol)

E_{42} = Activation energy, gasoline to coke (btu/lb.mol)

F_{air} = Air flow rate into regenerator (mol/s)

F_B = Effect of feed type on coke production

F_{base} = Air lift compressor inlet suction flow at base conditions (ICFM)

F_{coke} = Production of coke in reactor riser (lb/s)

$F_{gasoline}$= Flow rate of gasoline (lb/s)

F_{go} = Flow of gas oil to reactor riser (lb/s)

F_H = Burning rate of hydrogen (lb/s)

$F_{lightgas}$ = Light gas flow rate (lb/s)

f_{of} = Overflow factor (424)
f_{rgc} = Force exerted by regenerated catalyst (lbr)
F_{rgc} = Flowrate of regenerated catalyst (lb/s)
f_{sc} = Force exerted by spent catalyst (lbr)
F_{sc} = Flowrate of spent catalyst (lb/s)
F_{sg} = Stack gas flow (mol/s)
F_{sp} = Flow into standpipe (lb/s)
$F_{sucn,comb}$= Combustion air blower inlet suction flow
$F_{sucn,lift}$ = Lift air blower inlet suction flow
$F_{sucn,wg}$ = Wet gas compressor inlet suction flow
$F_{surg,comb}$ = Combustion air blower surge flow (45,000)(ICFM)
$F_{surg,lift}$ = Lift air blower Surge flow (ICFM)
$F_{surg,wg}$= Wet gas compressor surge flow (11,700 ICFM)
F_T = Air flowrate into regenerator (lb/s)
$f_{ubendrgc}$= Regenerated catalyst friction factor (17 lb s/ft^2)
$f_{ubendsc}$ = Spent catalyst friction factor (47 lb s/ft^2)
F_{ugo} = Unconverted gas oil rate (kg/s)
F_{v6} = Flow through combustion air blower suction valve (lb/s)
F_{v7} = Flow through combustion air blower vent valve (lb/s)
F_{v8} = Flow through lift air blower vent valve (lb/s)
F_{v11}= Flow through wet gas compressor suction valve (mol/s)
F_{v12} = Flow through wet gas flare valve (mol/s)
F_{v13}= Flow through wet gas compressor anti-surge valve (mol/s)
F_{wg} = Wet gas production in reactor (mol/s)
F_1 = Flow of wash oil to reactor riser (lb/s)
F_2 = Flow of diesel oil to reactor riser (lb/s)
F_3 = Flow of fresh feed to reactor riser (lb/s)
F_4 = Flow of slurry to reactor riser (lb/s)
F_5 = Flow of fuel to furnace (scf/s)
F_6 = Combustion air blower throughput (lb/s)
F_7 = Combustion air flow to the regenerator (lb/s)
F_8 = Lift air blower throughput (lb/s)
F_9 = Lift air flow to the regenerator (lb/s)
F_{10} = Spill air flow to the regenerator (lb/s)
F_{11} = Wet gas flow to the vapor recovery unit (mol/s)
G = Acceleration due to gravity (32.2 ft lb/s^2)
h_{lift} = Height of lift pipe (34 ft)
h_{ris} = Height of reactor riser (60.0 ft)
h_{sp} = Height of regenerator standpipe (20.2 ft)
H_{wg} = Wet gas compressor head (psia)
k_{avg} = Average ratio of specific heats (1.39)
k_{comb}= Combustion air blower discharge pipe flow resistance factor(40.0lb/s$\sqrt{psia}$)
k_{lift} = Lift air blower discharge factor (5 lb/s$\sqrt{psia}$)
k_6 = Combustion air blower suction valve flow rating (250 lb/s$\sqrt{psia}$)
k_7 = Combustion air blower vent valve flow rating (15 lb/s$\sqrt{psia}$)
k_8 = Lift air blower vent valve flow rating (5 lb/s $\sqrt{psia}$)
k_9 = lift air blower spill valve flow rating (10 lb/s $\sqrt{psia}$)
k_{11} = Wet gas compressor suction valve flow rating (1.5 mol/s$\sqrt{psia}$)
k_{12} = Wet gas flare valve flow rating (0.5 mol/s $\sqrt{psia}$)
k_{13} = Wet gas compressor anti-surge valve flow rating (0.1 mol/s$\sqrt{psia}$)
k_{14} = Regenerator stack gas valve flow rating (1.1 mol/s$\sqrt{psia}$)
k_{21} = Rate constant, gas oil to gasoline (ft^6/ (lbmol.lbcat.s))
k_{31} = Rate constant, gas oil to wet gas (ft^6/ (lbmol.lbcat.s))
k_{41} = Rate constant, gas oil to coke (ft^6/ (lbmol.lbcat.s))
k_{42} = Rate constant, gasoline to coke (ft^3/lbcat.s)
L_{sp} = Level of catalyst m standpipe (ft)
$L_{ubendrgc}$= Length of regenerated catalyst ubend (56 ft)
$L_{ubendsc}$= Length of spent catalyst ubend (56 ft)
M = Polytropic exponent
MC_{peff} = Effective heat capacity of riser vessel and catalyst (10000 Btu/°F)
M_I = Effective heat capacity of regenerator mass (200,000 Btu/°F)
M_{rgc} = Inertial mass of regenerated catalyst (lb.s^2/ft)
M_{sc} = Inertial mass of spent catalyst (lb.s^2/ft)
N = Amount of gas (mol)
P_{atm} = Atmospheric pressure (14.7 psia)
P_{base} = Combustion air blower base discharge pressure (psia)
$P_{base,d}$ = Lift air blower base discharge pressure (psia)
P_{blp} = Pressure at bottom of lift pipe (psi)
P_{rb} = Pressure at bottom of reactor riser (psi)
P_{rgb} = Pressure at bottom of regenerator (psi)
P_{vru} = Discharge pressure of wet gas compressor to vapor recovery unit (101psia)
P_1 = Combustion air blower suction pressure (psia)
P_2 = Combustion air blower discharge pressure (psia)
P_3 = Lift air blower discharge pressure (psia)
P_4 = Reactor pressure (psia)
P_5 = Reactor fractionator pressure (psia)
P_6 = Regenerator pressure (psia)

P_7 = Wet gas compressor suction pressure (psia)
Q_{air} = Enthalpy of air to regenerator (btu/s)
Q_c = Total heat of burning carbon (btu/s)
Q_{catou}= Enthalpy of catalyst out of reactor riser (btu/s)
$Q_{cracking}$= Heat generated from cracking (btu/s)
Q_e = Total heat lost from regenerator to environment (556 Btu/s)
Q_{ff} = Heat required to bring fresh feed to reactor riser temperature (btu/s)
Q_{fg} = Enthalpy of outgoing regenerator stack gas (btu/s)
Q_{fr} = Heat required to raise temperature of fresh feed from 500°F (liq) to 1000°F (Vapor) (309btu/lb)
Q_H = Enthalpy of hydrogen to regenerator (btu/s)
Q_{in} = Enthalpy into regenerator, reactor (btu/s)
Q_{out} = Enthalpy out of regenerator, reactor (btu/s)
Q_{loss} = Heat loss from furnace (btu/s)
Q_{rgc} = Enthalpy of regenerated catalyst (btu/s)
Q_{sc} = Enthalpy of spent catalyst (btu/s)
Q_{slurry} = Heat required to bring slurry to reactor riser temperature (btu/s)
Q_{sr} = Heat required to raise temperature of slurry from 700°F (liq) to 1000°F(Vapor) (412 btu/lb)
R = universal gas constant (10.73 ft^3 psia/lbmol °R)
s_a = Actual speed of the lift sir blower (rpm)
s_a^{max} = Maximum speed of the lift air blower (6320 rpm)
s_a^{min} = Minimum speed of the lift air blower (5090 rpm)
s_a = Base speed of the lift air blower (5950 rpm)
S_f = Slurry factor, takes into account the effect of slurry recycle on the system
t = Contact time (s)
T_{air} = Temperature of air entering regenerator (270°F)
T_{atm} = Atmospheric temperature (75°F)
T_{base} = Base temperature (1100°F)
$T_{base,f}$ = Base temperature of reactor fresh feed (700°F)
$T_{comb,t}$ = Combustion air blower discharge temperature (190°F)
T_{cyc} = Regenerator stack gas temperature at cyclone (°F)
$T_{lift,d}$ = Lift air blower discharge temperature (225°F)
T_{lm} = Furnace log mean temperature difference (°F)
T_r = Temperature of reactor riser (°F)
T_{ref} = Base temperature for reactor riser energy balance (999 °F)
T_{reg} = Temperature of regenerator bed (°F)
T_{sc} = Temperature of spent catalyst entering regenerator °(F)
T_1 = Temperature of fresh feed entering furnace (460.9°F)
T_2 = Temperature of fresh feed entering reactor riser (°F)
$T_{2,ss}$ = Steady state furnace outlet temperature (°F)
T_3 = Furnace firebox temperature (°F)
UA_f = Furnace overall heat transfer coefficient (25btu/s)
$V_{air,lift}$ = Velocity of air in lift pipe (ft/s)
$V_{cat,lift}$ = Velocity of catalyst in lift pipe (ft/s)
$V_{comb,d}$ = Combustion air blower discharge system volume (1000 ft^3)
$V_{comb,s}$ = Combustion air blower suction system volume (200 ft^3)
V_{lift} = Manipulated variable for lift air blower steam valve (0-1)
$V_{lift,d}$ = Lift air blower discharge system volume (200 ft^3)
$V_{reg,g}$ = Regenerator volume occupied by gas (ft^3)
v_{rgc} = Velocity of regenerated catalyst (ft/s)
v_{ris} = Volumetric flow rate m reactor riser (ft3/s)
V_s = Superficial velocity in regenerator (ft/s)
v_{sc} = Velocity of spent catalyst (ft/s)
v_{slip} = Slip velocity (2.2 ft/s)
V_T = Volume of reactor riser (575.713 ft^3)
V_6, V_7 = Combustion air blower suction and vent valve position (0-1)
V_8, V_9 = Lift air blower vent valve and spill air blower valve position (0-1)
V_{11}, V_{13}= Wet gas compressor suction valve and vent valve position (0-1)
V_{12} = Wet gas flare valve position (0-1)
V_{14} = Stack gas valve position (0-1)
W_c = Inventory of carbon in regenerator (lb)
W_r = Inventory of catalyst in reactor (lb)
W_{reg} = Inventory of catalyst in regenerator (lb)
W_{ris} = Inventory of catalyst in reactor riser (lb)
W_{sp} = catalyst Inventory in regenerator standpipe (lb)
w_T = Inventory of hydrocarbon in the riser (lb)
WHSV= Weight hourly space velocity (lb oil/ (lb.cat/s))
$X_{co,xg}$ = Molar ratio of CO to air in stack gas (moles CO/moles air)
$X_{co2,xg}$= Molar ratio of CO_2 to air in stack gas (moles CO_2/moles air)
$X_{o2,xg}$ = Molar ratio of O_2 to air in stack gas (moles O_2/moles air)
Y_1 = Mass fraction, gas oil feed (ft^6/ (lbmol.lbcat.s))

Y_2 = Mass fraction, gasoline (ft^6/ (lbmol.lbcat.s))
Y_3 = Mass fraction, wet gas (ft^6/ (lbmol.lbcat.s))
Y_4 = Mass fraction, coke (ft^3/ (lbcat.s))
Z_{bed} = Regenerator dense bed height (ft)
Z_{cy} = Height of cyclone inlet (45 ft)
Z_{lp} = Height of lift pipe discharge (11 ft)
Z_{sp} = Standpipe exit height from the bottom of the Regenerator (13 ft)

Greek symbols

α = Exponential decay function (391)
ΔH_{crack} = Heat of cracking (btu/lb)
ΔH_{fu} = Heat of combustion of furnace fuel(1000 btu/SCF)
ΔH_H = Heat of combustion of hydrogen (69,960 btu/lb)
ΔH_2 = Heat of formation of CO2 (169,080 btu./mol)
ΔH_1 = Heat of formation of CO (46368btu./mol)
ΔP_{frac} = Pressure drop across reactor main fractionators (9.5 psia)
ΔP_{rgc} = Pressure drop from bottom of standpipe to oil inlet elevation of riser (psi)
ΔP_{RR} = Differential pressure between regenerator and reactor (psi)
ΔP_{SC} = Pressure drop from bottom of reactor to lift air injection elevation (psi)
$\Delta T_{stripper}$ =Temperature drop across reactor stripper (35°F)
ϵ_e = Effective void Fraction in regenerator dense phase bed
ϵ_f = Apparent void Fraction in regenerator dense phase bed
η_p = Polytropic efficiency (1.0**)**
ρ_{airg} = Density of air at regenerator conditions (lb/ft^3)
ρ_c = Density of catalyst in U-bend and regenerator standpipe (45 lb/ft^3)
$\rho_{c,dilute}$ = density of catalyst in the dilute phase (lb/ft^3)
$\rho_{c,dense}$ = Density of catalyst in the dense phase (lb/ft^3)
ρ_g = Density of exit gas ($mole/ft^3$)

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