Modeling and Control of Fluid Catalytic Cracking Unit in Petroleum Refinery

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1. INTRODUCTION

For over 60 years, catalytic cracking has been one of the main   processes in petroleum refining, having passed through spectacular development. The fluid catalytic cracking unit (FCCU) has become the "test bench" of many advanced control methods. Today, both academia and industry are expressing great interest in the development of new control algorithms and in their efficient industrial FCC implementation. Analysis and control of FCC process have been known as challenging problems due to the following process characteristics, (i) very complicated and little known hydrodynamics, (ii) complex kinetics of both cracking and coke burning reactions, (iii) strong interaction between the reactor and regenerator, (iv) many operating constraints.

FCCU's steady state behavior is highly nonlinear, leading to multiple steady states, input multiplicities etc. In earlier years before the development of zeolite catalysts, the major control problem was   one of stabilization, of just keeping the unit running. Later with zeolite catalysts, the emphasis is shifted to increasing production rates in the face of unit constraints and to handle heavier feeds. The requirements for reformulated gasoline have added the need to control product composition. This is more complex problem since the number of process variables that one would like to control substantially exceeds the number of manipulated variables that are available for the task.

2. FCCU UNIT

Fluidized catalytic cracking (FCC) is an important process in oil refineries. It upgrades heavy hydrocarbons to lighter more valuable products by cracking, and is the major producer of gasoline in refineries. FCCUs present challenging multivariable control problems. The selection of good inputs (manipulated variables) and outputs (measured variables) is an important issue, as is the pairing of chosen controlled and manipulated variables for decentralized control. The model consists of subsystems: feed and preheat system, reactor, regenerator, air blower, wet gas compressor and catalyst circulation lines. The reactor and regenerator are more important for the FCCU process. It consists of

multiple sophisticated   chemical/physical processes. Example: catalytic cracking chemical reactions, three phase (gas-liquid-solid) fluid dynamics, unsteady state heat transfer, etc. In this process the catalytic activity, multiphase mass fluidized status and other operating parameters (e.g. reaction temperature and system pressure etc. are critical for stabilizing the operation and producing the qualified oil products with high efficiency.

2.1.Process Description

The schematic flow diagram of a typical modern FCC unit shown in Fig.1 below is based upon the "side-by-side" configuration. The preheated high boiling petroleum feedstock (at about 315 to 430 °C) consisting of long chain hydrocarbon molecules is combined with recycle slurry oil from the bottom of the distillation column and injected into the catalyst riser where it is vaporized and cracked into smaller molecules of vapor by contact and mixing with the very hot powdered catalyst from the regenerator. All of the cracking reactions take place in the catalyst riser.
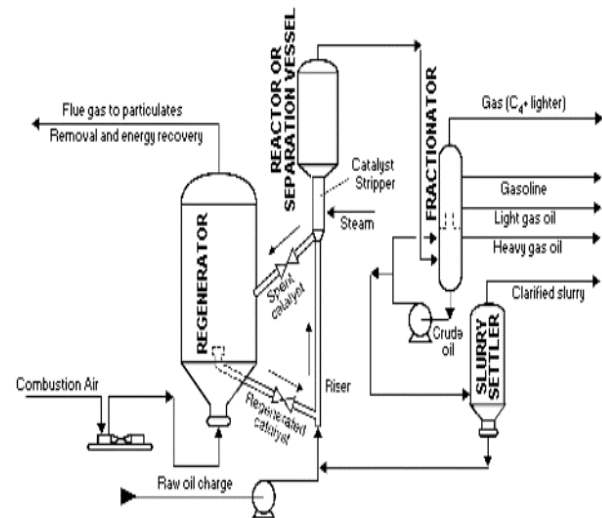

Figure 1: Schematic Representation of FCC Unit

The hydrocarbon vapors "fluidize" the powdered catalyst and the mixture of hydrocarbon vapors and catalyst flows upward to enter the reactor at a temperature of about 535 °C and a pressure of about

1.72 barg. The reactor is in fact merely a vessel in which the cracked product vapors are: (a) separated from the so-called spent catalyst by flowing through a set of two-stage cyclones within the reactor (b) the spent catalyst flows downward through a steam stripping section to remove any hydrocarbon vapors before the spent catalyst returns to the catalyst regenerator. The flow of spent catalyst to the regenerator is regulated by a slide valve in the spent catalyst line. Since the cracking reactions produce some carbonaceous material (referred to as coke) that deposits on the catalyst and very quickly reduces the catalyst reactivity, the catalyst is regenerated by burning off the deposited coke with air blown into the regenerator. The regenerator operates at a temperature of about 715 °C and a pressure of about 2.41 barg. The combustion of the coke is exothermic and it produces a large amount of heat that is partially absorbed by the regenerated catalyst and provides the heat required for the vaporization of the feedstock and the endothermic cracking reactions that take place in the catalyst riser. For that reason, FCC units are often referred to as being heat balanced.

The hot catalyst (at about 715 °C) leaving the regenerator flows into a catalyst withdrawal well where any entrained combustion flue gases are allowed to escape and flow back into the upper part to the regenerator. The flow of regenerated catalyst to the feedstock injection point below the catalyst riser is regulated by a slide valve in the regenerated catalyst line. The hot flue gas exits the regenerator after passing through multiple sets of two-stage cyclones that remove entrained catalyst from the flue gas. In this process the important measured variables are chosen to be the reactor temperature/riser outlet temperature (T_{ra}) and the regenerator gas temperature (T_{rg})

3. MODEL FOR FCCU

The modeling of complex chemical systems for the simulation of process dynamics and control has been motivated by the economic incentives for improvement of plant operation and plant design, as in the case of FCCU. Most of the economic gain from FCC control development has come from the optimization level, with the regulation system simply providing stable, responsive, and safe operation. The problem is to find regulator schemes that are **(1)** Effective, **(2)**Economically justified, **(3)** Related to existing practice, and **(4)** Able to provide adequate operator interface when desired. Most studies concerning FCC units have been dealt with the process control based on simplified reactor - regenerator model which in principle incorporate major observed dynamics. Any FCC control should maintain a suitable

reactor temperature distribution so as to achieve good product characteristics. The regenerator temperature profile should also be bounded so as to prevent abnormal combustion and excessive temperatures. At the same time, energy and material balances must be maintained between the two parts of the unit.

3.1.Development Of Model

A static model is used for the riser .In this work, an effective practical control scheme of Joseph A.Bromley and Thomas J.Ward (1981) is used. In this scheme, feed is gasoil which can crack into gasoline or light gas.

The balance equation for Hold up of catalyst:

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

Note:

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

3.1.1.Reactor Model

The catalyst is steam-stripped in the reactor vessel to remove hydrocarbons. The reactor overhead is separated in a cyclone to remove catalyst and the product vapors pass to a product fractionator.

The balance equation of reactor temperature is given by,

$$\frac{dT_{RA}}{dt} = \frac{K_{RC}}{H_{RA}}(T_{RC} - T_{RA}) + \frac{1}{S_c H_{RA}}[-S_p D_{TF} R_{TF}(T_{RA} - T_{TP}) - \Delta H_{FV} D_{TF} R_{TP}] - \frac{\Delta H_{CR} K_{DC}}{S_c H_{RA}}$$

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

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

3.1.2.Regenerator Model

FCC control unit should maintain a suitable reactor temperature distribution so to achieve good product characteristics. The regenerator temperature profile should also be bounded so as to prevent abnormal combustion and excessive temperatures. At the same time, energy and material balances must be maintained between the two parts of the unit. The reactor pressure can be maintained by manipulating the fractionator overhead gas compressor speed or the overhead gas recycle rate. The flue gas rate can be manipulated to maintain the regenerator pressure. The hot flue gas in the regenerator is also separated from catalyst in a cyclone and used for recovery of thermal and combustion energies.

The balance equation of Regenerator temperature is given by,

$$\frac{dT_{RG}}{dt} = \frac{R_{RC}}{H_{RG}}(T_{RA} - T_{RG}) + \frac{1}{S_p H_{RG}}[-S_a R_{AI}(T_{RG} - T_{AI}) + \Delta H_{RG} R_{ca}]$$

$$R_{ca} = \left(\frac{R_{AI}}{C_1}\right)(21 - O_{FG})/100$$

4. CONTROL OF FCCU

The control of presented variables is important for the efficient and safe operation of the unit and has direct impact on the products yield. Control of the FCC has been and continuous challenging and important problem. As will be seen, its steady state behavior is highly non linear, leading to multiple steady states, input multiplicities, and all that implies.

The reactor temperature has to be maintained at a certain level to provide a desired maximum conversion of the feed oil. A proper reactor temperature control means also a good management of thermal energy. Control of reactor catalyst inventory is necessary to provide stabilization and safety in the catalyst circulation. Reactor pressure control directly influences the coke and gases formation. Composition of the products must be maintained at desired certain values to assure the products quality and plant productivity. The stream transfers the reaction products overhead to the products recovery section. The standpipe transfers spent catalyst continuously from the separator to the regenerator by a control valve. In the regenerator, spent catalyst particles are burned in the presence of air. The air flow rate to the regenerator is controlled by a control valve that vents portions of the air to the atmosphere. On the top of the regenerator, cyclones perform the catalyst separation from the flue gas stream.

4.1.MIMO System

The mathematical model of FCCU is developed from equations given in the literature (Bromley et al 1981).The important feedback that provide automatic control of FCCU are,(i)Control of reactor temperature (T_{RA}) by manipulation of the regenerated catalyst rate (R_{RC}) and (ii)Control of regenerator temperature(T_{RG}) by manipulation of the air flow rate(R_{AI}).

Figure2-MMIO system

4.2.Interaction Of Control Loops
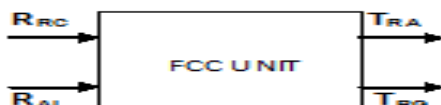
Consider a process with two controlled outputs and two manipulated inputs in fig. The input-output relationships are given by

$$y_1(s) = G_{11}(s)m_1(s) + G_{12}(s)m_2(s) - (4.1)$$
$$y_2(s) = G_{21}(s)m_1(s) + G_{22}(s)m_2(s) -$$
(4.2)

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 indicate that the change in m_1 or m_2 , will affect both controlled outputs. Two potential problems arise from this process interaction:

- It may destabilize the closed loop system

- It tends to make controller tuning more difficult.

4.3. Relative Gain Array

Relative gain array provides a measure of interaction based on steady state conditions. It is used to select the pairs of input and output variables in order to minimize the amount of interaction among the resulting loops.Relative gain array is expressed as

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

4.4.Design Of Non Interacting Control Loops

The relative gain array indicates how the inputs should be coupled with the outputs to form loops with the smaller amount of interaction. To cancel the interaction effects between two loops, a Decoupler is used.

4.5. Decoupling Control System

Basic Idea is to use additional controllers to compensate for process interaction and thus reduce control loop interaction. Ideally; decoupling control allows set point changes to affect only the desired controlled variables. Typically, decoupling controllers are designed using a simple process model (e.g. steady state model or transfer function model).Two control loops by coupling m_1 with y_1 and m_2 with y_2 is formed .From fig [2], to keep y_1 constant, m_1 should be changed by the following amount:

$$m_1 = -\frac{G_{12}(s)}{G_{11}(s)}m_2 \qquad - \qquad (4.3)$$

Above equation implies a dynamic element with

$$D_1(s) = -\frac{G_{12}(s)}{G_{11}(s)} \qquad - \qquad (4.4)$$

This dynamic element is called a Decoupler. It cancels any effect that loop 2 might have on loop 1. To eliminate the dynamic elem... 58

$$D_2(s) = -\frac{G_{21}(s)}{G_{22}(s)} \qquad - \qquad (4.5)$$

4.6. Model Predictive Control

In the wide variety of chemical processes, nonlinearity is rather the rule than the exception. Although it is well recognized that the performance of a control system is most dependent on how successfully it can cope with the nonlinearity of the process, chemical processes have been traditionally controlled by algorithms based on linear time-invariant approximate process models, the most common being step and impulse response models derived from the convolution integral. In the past decade, model predictive control (MPC) has become a preferred control strategy for a large number of processes. The main reasons for this success consist in its ability to handle constraints in an optimal way and the flexibility of its formulation in the time domain. Nonlinear model predictive control is an optimisation-based multivariable constrained control technique that uses a nonlinear dynamic process model for the prediction of the process outputs. At each sampling time, the model is updated based on new measurements and state variable estimates.
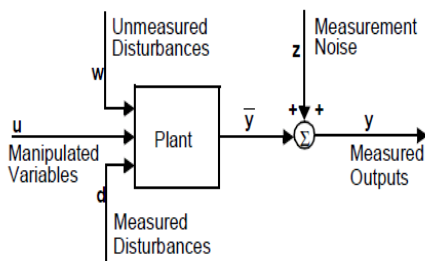

Figure-3 Block diagram for an process

Consider the process shown in the above block diagram. The general discrete-time linear time invariant (LTI) state-space representation used in the MPC Toolbox.

$$x(k+1) = x(k) + T_u u(k) + T_d d(k) + T_w W(k)$$

$$y(k) = \hat{y}(k) + z(k)$$
$$= Cx(k) + D_u u(k) + D_d d(k) + D_w w(k) + z(k)$$

freely-varying inputs (i.e., measured disturbances), w represents n_w unmeasured disturbances, y is a vector of n_y plant outputs, z is measurement noise, and F, G_u, etc., are constant matrices of appropriate size. The variable (k) represents the plant output before the addition of measurement noise.

Define

$$T = [T_u T_d T_w]$$

$$D = [D_u D_d D_w]$$

the MPC Toolbox assumes that the y vector and the C and D matrices are arranged such that the measured outputs come first, followed by the unmeasured outputs.

5. RESULT

The research on the dynamic characteristics of FCC unit reveals that FCC processes consist of two input and two outputs. For pratical combustion mode, a common choice of variables to be regulated is the riser outlet temperature (T_{RA}) and the temperature of regenerator's temperature (T_{RG}). If the pairings T_{RA} - R_{RC} and T_{RG}- R_{AI} are selected to design a decentralized control strategy ,a classical rise-regenerator control structure is obtained .

6. CONCLUSION

The modeling of fluidized catalytic cracking is presented here. For this 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 to minimize the interaction is found by RGA analysis. To remove the interaction completely, decouplers are designed and implemented in the simulink. The feature of simulink manipulation provides a simulation environment for effective implementation of the model to control the FCC process. The state space model of FCCU has to be extended for dynamic model and the Model Predictive Control scheme has to be implemented for the same.

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