DYNAMICS AND ADVANCED CONTROL OF A FLUID CATALYTIC CRACKING PLANT

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Abstract

In this paper, the separation section of the fluid catalytic cracking unit (FCC) is studied. The objectives of this work are the simulation, the optimization and the control of the separation equipment (which include the main fractionator, absorbers and the debutanizer column). Conventional PID controllers and a proposed predictive controller were considered in a regulatory control problem. Plant-wide control concepts were used. The aim is to control the whole plant taking into account the effect of recycle streams. The simulations were performed using HYSYS.Plant process simulator, version 2.2 (Hyprotech, Ltd).

Keywords

Petroleum refining, PID controller, Optimization, Dynamic simulation, Model predictive control.

Introduction

The fluid catalytic cracking unit (FCCU) is one of the most important processes in the petroleum refineries. The objective of this unit is to obtain products of high added value (gasoline and liquefied petroleum gas - LPG) from raw materials of low commercial value (gasoil) coming from the distillation unit (atmospheric and vacuum columns).

Large number of works can be found in the open literature on modeling and control of the reactor-regenerator system. Zanin et al (2000) presented a real-time optimization strategy and Ansari and Tadé (2000) proposed a multivariable control to the reactor-regenerator. On the other hand, relatively few publications are concerned with the separation tasks. Lu et al (2000) proposed a new configuration for the product recovery section of the FCCU, Dolph (2000) demonstrated the use of dynamic simulation to control emergency situations in the main fractionator and in the compressor and Al-Riyami et al (2001) studied the heat integration of this unit.

On the other hand, control system analysis and design of chemical and hydrocarbon processes have traditionally followed the unit operation approach - control loops were established for each individual unit operations within the plant. The assumption is that by controlling each unit operation the whole plant could be controlled. This can be detrimental. In contrast, plant-wide control procedures enable the entire, complex and highly integrated plants to meet specified manufacturing objectives.

Furthermore, it should be noted that the use of commercial simulator (such as Hysys.Plant) allows the entire flowsheet calculation and representation (such as thermodynamic and physical properties, unit operations, pseudo-component calculation used for representing the petroleum composition, and controller functionality), facilitating and robusting the data to be treated.

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Process Description

Generally, the FCCU contains three main sections:

1. Reactor and regenerator: The gasoil feed (coming from the distillation unit) and recycle from the fractionator are cracked down in the reactor. The reactor effluent feeds the main fractionator.
2. Main fractionator (Main Frac – Figure 1): The reactor effluent is separated into various products and the heat of the reactor effluent is recovered. The overhead product includes gasoline and lighter materials.
3. Gas concentration section (vapour recovery section – this section includes all of the equipment after the Main Frac on Figure 1): This section consists of two absorbers, a rectifier and a debutanizer column besides pumps, compressors(first stage and second stage) and liquid split vessels. The overhead of the main fractionator is separated into fuel gas, liquefied petroleum gas (LPG) and gasoline.

It is important to mention the complex behavior of such separator set due to the equipment effect interactions. External disturbances can propagate not only downstream from one equipment to the next, but upstream through recycle loops.

Figure 1 shows the flowsheet for the second and third sections of the FCCU. The process simulations (steady state and dynamic) were performed using HYSYS.Plant process simulator version 2.4.1 (Hyprotech, Ltd). Moreover, both the steady state and dynamic simulation models have matched the industrial data.

Optimization

The manufacturing objective for the FCCU is to produce LPG and gasoline in the required market specifications. The weathering is the property related to the amount of C5+. It is defined as the temperature on which 95% of the LPG is vaporized at atmospheric pressure. To introduce this property in the simulator, it was necessary to use a subflowsheet environment: the weathering was calculated using successive flashes. The Reid Vapor Pressure (RVP) measures the amount of C5- present in hydrocarbon streams. For gasoline the specification is RVP lower than 60 kPa. Higher values imply in material loss in reservoirs. The simulator has a routine to calculate RVP.

Both weathering and RVP can not be used as controlled variables. They are used as restrictions to find the process conditions in the optimization procedure. It is common to find in the open literature, LPG and gasoline compositions as controlled variables, but this is not possible in practice and will not be used in this work.

The proposed optimization problem was the maximization of the unit profit considering the main product (LPG and gasoline) productivities. The objective function (Equation 1) takes into account the product recovery value (product flow rate multiplied by its commercial value) and the operating costs.

$$\mathrm{Profit} = \sum_{i=1}^{n}(\mathrm{Flowrate} * \mathrm{value}) - \sum(\mathrm{utility\ costs}) \qquad (1)$$

n = number of products

Σ (utility costs) = the sum of the costs related to: steam, reboiler and condenser duties, pumps and compressors.

In Equation (1), the variable 'flow rate' means all product streams (LCO, Slurry, Fuel Gas, LPG and Gasoline). An internal routine presented in the simulator, calculates mathematically Equation (1).

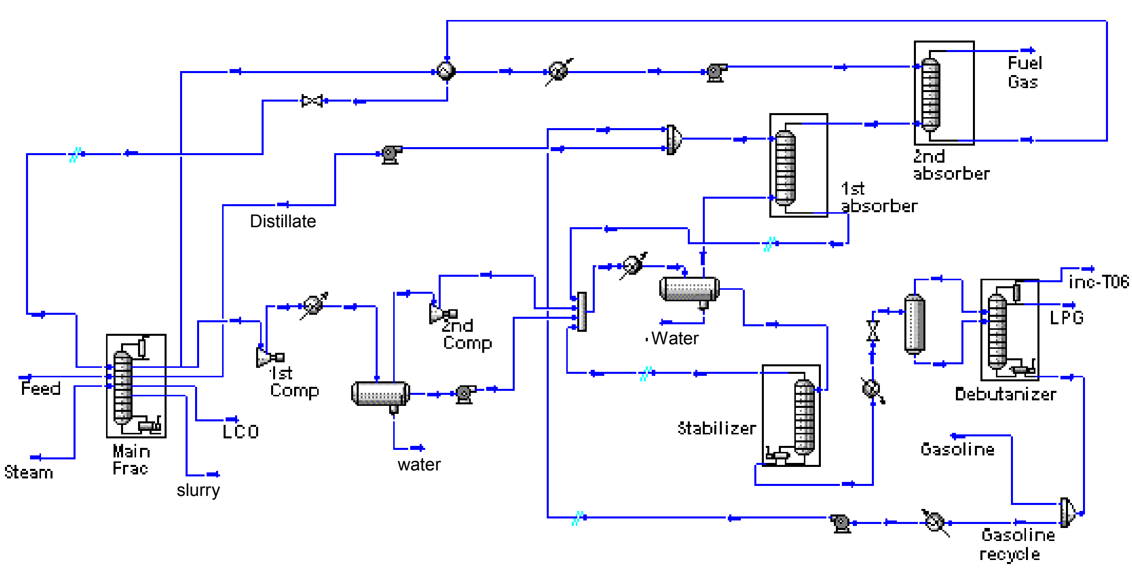


Figure 1. Separation process flowsheet of the FCCU

The variables used in the process optimization were:
1. Bottom temperature of the main fractionator
2. Compressor pressure
3. Gasoline recycle flow rate

The main restrictions of the process are the debutanizer products qualities:
- $-2^oC <$ LPG weathering $< 2^oC$
- Gasoline RVP < 60 KPa

Factorial design procedure was used in order to verify the influence of the variables on process responses (Rodrigues et al, 1993). Independent variable levels are shown on Table 1. Results of the final factorial design are on Table 2.

Table 1 – Independent variables low and high levels

Variable	Low level	High level
Fractionator temperature (^oC)	330.0	350.0
Compressor Pressure (Kg/cm^2)	12.00	24.00
Gasoline recycle (ton/day)	2000	4000

Analyzing the results of Table 2, it can be seen that increasing main fractionator bottom temperature, the LPG productivity and profit increase too. Increasing second compressor pressure, the productivity and profit decrease and increasing the gasoline recycle flow rate, the productivity and profit decrease. The complete factorial design was carried out and the optimal conditions are presented on Table 3.

The steady state simulation and the optimization are used to calculate the set points of the PID controllers.

Table 3 – Optimal results

Fractionator temperature (^oC)	370
Compressor Pressure (Kg/cm^2)	15
Gasoline recycle (ton/day)	1500
Weathering(^oC)	-0.2279
RVP (kPa)	57.96
LPG (ton/day)	1287
Gasoline (ton/day)	3764
Profit ($)	1.260×10^7

Dynamics and Plant-wide Control Strategy

Forty control degrees of freedom are presented in this process. They include: level control for the columns and vessels, pressure control for the columns, pumps and compressors, temperature control for coolers, reflux flow rate for the debutanizer, temperature control for the first absorber, for the stabilizer and for the debutanizer.

In this section, the process behavior is described and the control problems are discussed. Results are given for the main fractionator and for the debutanizer column.

Main Fractionator

The main fractionator column is shown in detail in Figure 2. There are three pumparound (PA_1, PA_2 and PA_3) which are used to control the temperature profile, and one side stripper to stabilize the LCO product stream.

Table 4 shows the controlled and the manipulated variables. Good results were obtained using only PID controllers (Figure 3). Note that the bottom temperature does not move far from the set point (350^oC) and the manipulated variable does not present abrupt changes.

Table 2 – Factorial design results: initial intervals

Fractionator temperature (^oC)	330	330	330	330	350	350	350	350
Compressor Pressure (Kg/cm^2)	12	12	24	24	12	12	24	24
Gasoline recycle (ton/day)	2000	4000	2000	4000	2000	4000	2000	4000
Weathering (^oC)	-1.696	0.4482	-1.270	-1.358	-0.9683	-0.9081	-0.7619	-0.9197
RVP (kPa)	58.27	58.56	58.27	58.18	58.74	58.38	58.79	58.39
LPG (ton/day)	1299	1276	1293	1105	1328	889.4	1289	839.4
Gasoline (ton/day)	3369	3361	3369	3376	3544	3561	3552	3562
Profit ($)	1.141×10^7	1.125×10^7	1.137×10^7	1.098×10^7	1.199×10^7	1.119×10^7	1.193×10^7	1.110×10^7

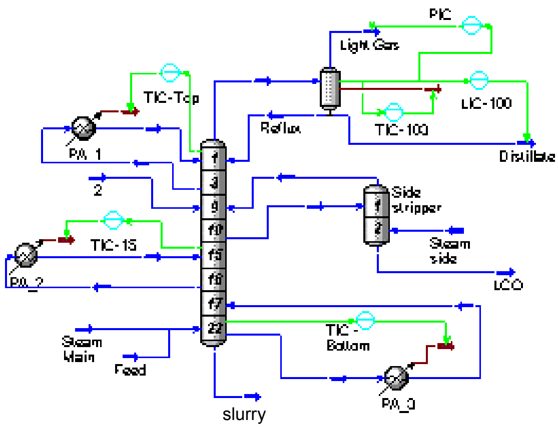
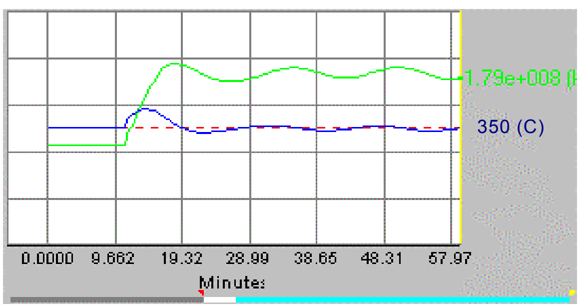


Figure 2 – Details of the main fractionator

Table 4 – Controlled and manipulated variables

Controlled variables	Manipulated variables
Top Pressure (kg/cm^2_g)	Light flow rate (ton/day)
Vessel Temperature (°C)	Condenser duty (KJ/h)
Top temperature (°C)	Reflux (m^3/day)
Stage 15 temperature (°C)	PA_2 duty (KJ/h)
Bottom temperature (°C)	PA_3 duty (KJ/h)



Bottom temperature SP (°C) Bottom temperature (°C)

PA_3 duty (KJ/h)

Figure 3 – Main fractionator bottom temperature control

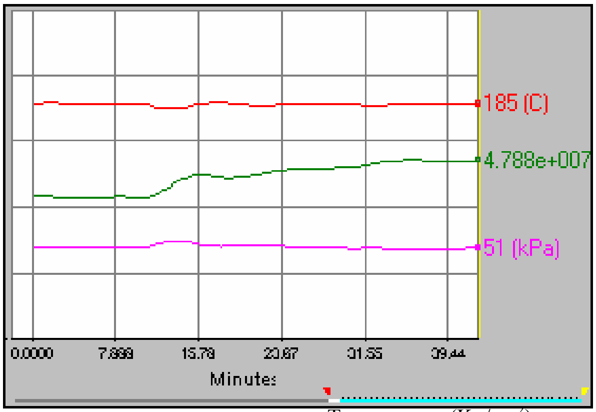
Debutanizer

The debutanizer column separates the products of high added value in the FCCU. It is important to implement an efficient control strategy to maintain products on the required specification. Table 5 shows the controlled and the manipulated variables for the debutanizer.

Table 5 – Controlled and manipulated variables for the debutanizer column

Controlled variable	Manipulated variable
Top temperature (°C)	Reflux flow rate (m^3/day)
Bottom temperature (°C)	Reboiler duty (KJ/h)
Top pressure (kg/cm^2_g)	Light gas flow rate (m^3/day)
Vessel temperature (°C)	Condenser duty (KJ/h)

Figure 4 shows the Model Predictive Control applied to the debutanizer column. A first order model was used to represent the debutanizer.



Bottom temperature Top pressure (Kg/cm^2)

Reboiler duty (KJ/h)

Figure 4 – Model predictive control applied to the debutanizer column.

Conclusions

Using available design information, the FCCU was solved in steady state and the model was validated with industrial data of a Brazilian refinery. The steady state model was used to determine controller set-points and to propose the control strategy. A proposed plant-wide control strategy was devised and implemented to ensure that the process could meet manufacturing objectives. External disturbances are added to the model in order to be possible to evaluate how they propagate through the plant.

Contributions for the optimization of the operating conditions of the separation section of the FCCU were achieved. The main fractionator was controlled with conventional PID controllers and a first order model predictive control was used for the debutanizer.

References

Al-Riyami B. A. (2001)Heat integration retrofit analysis of a heat exchanger network of fluid catalytic cracking plant. *Applied Thermal Engng*,**21**,1449-1487.

Ansari, R. M. and Tadé, M. O. (2000). Constrained nonlinear multivariable control of a fluid catalytic cracking process. *J. Proc. Control* , **10**, 539-535.

Rodrigues, M.I.; Maciel Filho, R.; Maugeri Filho, F. (1993) Optimization of a Process of Continuos Enzyme Purification by Surface Response Analysis. *Food Control Journal*, **4**, 144-148.

Dolph, G. (2000). The use of dynamic simulation to develop control strategies for emegency situations. *Comp and Chem Engng*., **24**, 1181-1186.

Lu, E., Zhang, H. and Zhu, X. (2000) A novel design for vapor recovery units. *Comp and Chem Engng*., **24**, 1317-1322.

Zanin, A. C., Gouvêa, M. T. and Odloak, D. (2000). Industial implementation of a real time optimization strategy for maximizing production of LPG in a FCC unit. *Comp and Chem Engng*., **24**, 525-531.