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On-Line Optimization Applied To Large Scale Plants

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Abstract

In this work, the objective is to discuss the problems of large scale process optimization. The case study is the optimization of the separation section of the Fluid Catalytic Cracking Unit (FCCU). The objective of such unit is to convert residues into high added value products (LPG and gasoline). Factorial Design and Response Surface Methodology were introduced as a tool to evaluate the main effects (process variables with major impact on its behavior) as well as to map suitable regions for successfully applying the SQP method to optimize the process.

Keywords: Optimization, Petroleum Refining, Response Surface Methodology

1. Introduction

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). Most of FCC units were built up before the early's 1970's, when energy cost were considerably lower than today. Low capital costs were the primary investment objective and efficient energy utilization was not considered as important issue.

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 as well as 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

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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.

2. 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 (vapor 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). Simulations were performed using industrial data to validate the whole simulation procedure and to analyze the simulator performance.

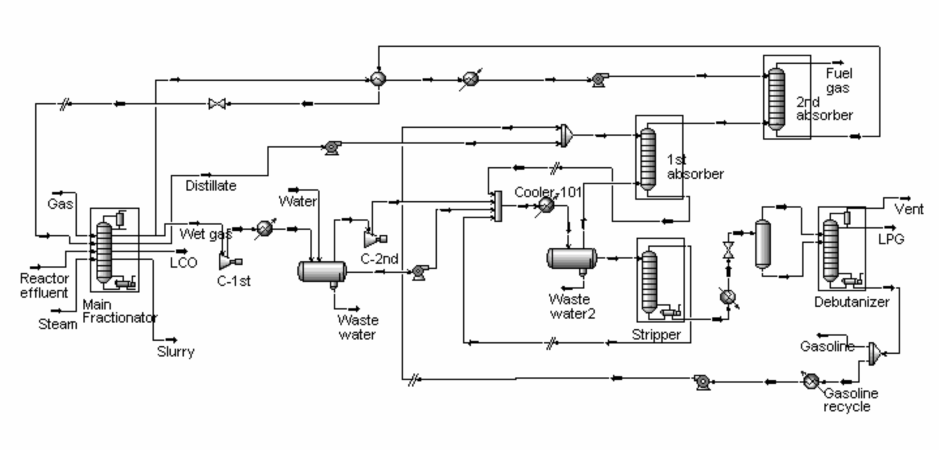

Figure 1 – Vapor recovery section of FCC unit

3. Process Optimization

On-line optimization consists of a technique to continuous reevaluation and alteration of process operating conditions to obtain an objective function subject to operational constraints. Examples of objective function are: maximize the profit or minimize the operating costs.

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 at which 95% of the LPG is vaporized at atmospheric pressure. To introduce this property in the simulator, it was necessary to use a sub-flowsheet 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 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.

$$\mathrm{Pr\ ofit} = \sum_{i=1}^{n} (\mathrm{Flowrate} * \mathrm{value}) - \sum (\mathrm{utility\ cos\,ts}) \qquad (1)$$

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).

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

The main restrictions of the process are the debutanizer products qualities:
-271.17K < LPG weathering < 275.15K
Gasoline RVP < 60 KPa

3.1 Factorial Design and Response Surface Methodology

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. Figure 2 shows the LPG productivity for gasoline recycle and bottom fractionator temperature variations. Increasing the bottom temperature of the main fractionator, the LPG productivity and profit increase too. Increasing the second compressor pressure, the productivity and profit decrease and increasing the gasoline recycle flow rate, the productivity and profit decrease.

Table 1 – Independent variables: low and high levels

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

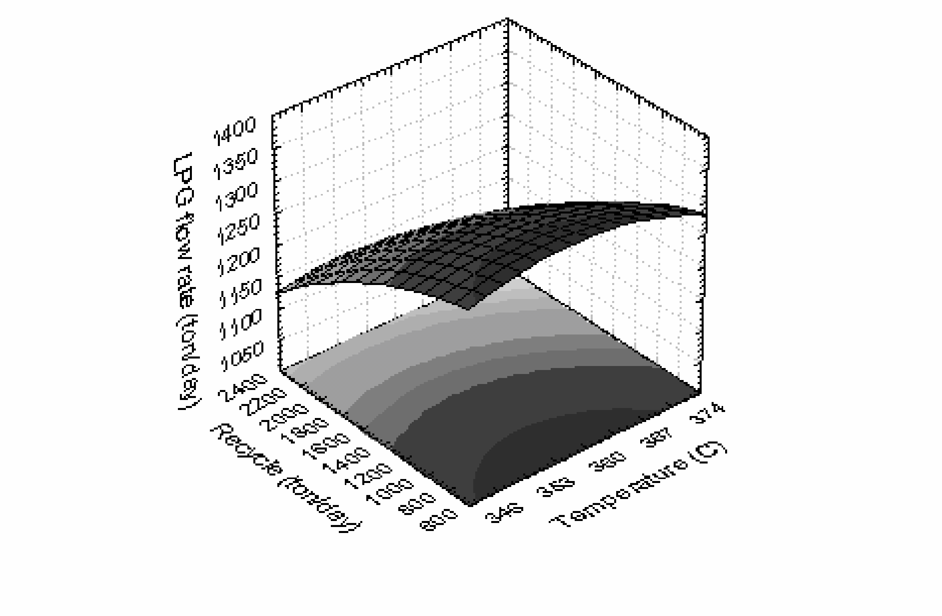

Figure 2 – LPG productivity for gasoline recycle and bottom fractionator temperature variations

3.3 Sequential Quadratic Programming (SQP)

Sequential quadratic programming is an effective method for solving constrained optimization problems with smooth nonlinear functions in the objective and constraints. SQP solves a sequence of quadratic programming sub-problems, where each interaction of the QP sub-problem requires the solution of a large linear system for search direction. For that reason, it does not work well for large scale processes, if poor starting points are given. However, this problem can be minimized, if a previous method, as factorial design, is used to obtain trust regions and then SQP is applied (Vasconcelos et al. 2003; Rezende et al., 2004).

Prior to each step, the optimizer needs to determine the gradient of the optimization surface at the current location. The optimizer moves each primary variable by a value of the product between the variable and a multiplier defined by the user (which due to the size of the multiplier will be a small step). The derivative is then evaluated for every function (Objective and Constraint) using the values for the function at the two locations of the decision variable. From this information and the optimizer history, the next step direction and size are chosen.

Initially, a two level factorial design was used to evaluate which variables cause the most significant impact on the process optimisation. The responses were: the unit profit and LPG and gasoline productivities. Analysing the main effects factor, it was observed that the bottom temperature of the main fractionator, gasoline recycle flow rate, and debutanizer heat duty were important. A new design was proposed and a quadratic model was found for each dependent variable. Response surfaces were analysed and it was observed that the net profit is linear in the variable ranges, while LPG productivity presents a quadratic behaviour. SQP was applied and the optimal point was found for different operation loads and different product prices. Without this approach, SQP tends to fail. Table 2 shows the optimal results.

Table 2 – Optimal results

Fractionator temperature (K)	643.15
Compressor Pressure (Pa)	1470997.5
Gasoline recycle (Kg/s)	17.36
Weathering(K)	272.92
RVP (kPa)	57.96
LPG (Kg/s)	14.90
Gasoline (Kg/s)	43.56
Profit ($)	$1.260\text{x}10^7$

4. Concluding Remarks

Using only SQP method, it was observed that convergence was not possible to obtain the global optimal point. Factorial design was used in order to verify which variables were important to be considered in the optimisation, their weight and to avoid mistakes and convergence problems. An optimised region was determined and, then, SQP was successfully applied. Another advantage was the possibility to know the process behaviour through response surfaces. Factorial design can, also, generate a parametric model that is useful in online applications.

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