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Exergy Analysis Applied to Separation Processes in a FCC Plant Using Computational Models

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Exergy analysis is a useful technique that allows in deep discussion of energy utilisation in chemical processes. Furthermore, it helps to discover specific areas in the process subjected to energy degradation (Rivero, 2002). On this work, the results from the analysis to several cases of topology modifications in the separation section of a fluid catalytic cracking (FCC) in a refinery are illustrated.

In the evaluated plant, it was found a high potential for energy optimization in the main fractionator column where exergy losses reached 105 GJ/h and cooling requirements were about 240 GJ/h.

A reduction of 10 % in exergy losses, related to base case, is achievable in according to the proposed modification. Annual savings are estimated between 0.45 and 0.50 M USD/y, and reduction in pollutant emissions are calculated around 5,100 t CO_2e.

The methodology used, included the configuration of a wide process model in a commercial simulation software, the validation of the model by plant test run, the validation of the exergy computation algorithms from modelling applied to several operating scenarios. The model included the separation section of an FCC plant, starting from main fractionator, stripper, debutanizer, depropanizer, the compression system and liquid gas absorbers, as well as the heat transfer section.

1. Introduction

Petroleum refining is an industrial activity with intensive use of energy, highly contributing with greenhouse gas (GHG) emissions. FCC plants have a big impact on gasoline oriented refineries, and there is an interesting opportunity for energy optimization here. Currently, the growing energy demand around the world and stricter regulations on product quality, along with compliance on permissible emission levels by big players in the industry, are strong drivers to research for alternative configurations in hydrocarbon processing plants in order to maximize the resources utilization, minimize the energy consumption and contribute with a positive impact on emissions reduction.

To tackle with this challenge, based on the eco-efficiency concept, the second law analysis was required to find alternative process modifications to reduce exergy losses without compromising the product quality.

A methodology was developed to evaluate several scenarios in a systematic manner, in order to find the equipment or plant section to improve or modify. A model of the industrial plant was made to analyse actual and proposed scenarios by process simulation, in order to find key sections to improve by using of exergy analysis.

As the result, it was found that in the FCC separation system plant the highest potential for energy optimization is the main fractionator column, where energy losses were in order of 105 GJ/h, and cooling requirements of 240 GJ/h. From several proposed modifications, a potential reduction of around 10 % in exergy losses, compared with the base case is achievable. This represents annual savings estimated around 0.45 M USD, and emissions reductions of 5,100 t CO_2e.

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2. Theoretical frame or State of the technique

2.1 Impact of the selected process in refinery energy consumption

In general terms, refining processing of hydrocarbons is very intensive in energy use, being the most energy demanding processes the lube oil plant, alkylation and isomerisation, as shown in Table 1. However, these units do not process as much material as crude distillation (CDU) or fluidized catalytic cracking (FCC) plants, which have bigger impact in the refinery energy consumption due to their high processing capacity.

Table 1: Energy demand in refining process, MJ/bbl

Process Unit	Min	Max	Process Unit	Min	Max
Atmospheric Distillation	90	200	Visbreaking	100	150
Vacuum Distillation	50	120	Delayed Coking	120	250
Fluidized Cat Cracking	50	180	Hydrocracking	170	340
Hydrotreating	60	180	Cat Reforming	220	360
Alkylation, H2SO4	350	360	Alkylation, HF	430	430
Isomerization, iC4	360	360	Lube Oil Plant	1,500	1,500

Source: Author adaptation, based on Energy and Environmental Profile of US Petroleum Refining Industry, 2007. US DOE and Energetics Inc.

In absolute terms, as Schaeffer mentioned in 2006, the energy consumption in a refinery is concentrated in a few processes that are not the more intensive in energy use; however they use high rates of feedstock. For example, crude distillation units (CDU) and vacuum distillation units (HVU) spent between 35 to 45 % of energy used in a refinery, (API Roadmap, 2000). The Colombian case is very similar. Ecopetrol’s Barranca refinery is the largest industrial facility processing 250 kbbl/d of crude oil, and due its historical oriented production to gasoline, there are several FCC units with a total capacity of 102 kbbl/d. Any effort to reduce energy losses in the FCC process will have a high economical and environmental impact to the refinery margin.

FCC technology is used to convert heavy oil fractions (350 to 550 °C) into lighter hydrocarbons by cracking long chains of hydrocarbon in a fluidized bed reactor. The typical FCC products are: cracked naphtha, LPG, and petrochemical precursors, and by-products like Light Cycle Oil and Slurry to Fuel Oil.

The FCC reactor requires high energy quantities, and continuous catalyst addition from regenerator. Once re-activated, the catalyst is mixed with the feed just before the riser, and starts flowing upward to the reaction zone. As mentioned by Sadeghbeigi (2000), the catalytic cracking reactions are predominantly endothermic, and the required energy is supplied by the regeneration system that burns the spent catalyst. Just after the catalyst promoted the reactions occurring, the vapour effluent flows through several distillation systems, starting from the main fractionator, in order to separate the valuable products.

The scope of this work was to demonstrate that is possible to use exergy analysis to reduce the energy losses in the system, and therefore mitigate the CO_2 emissions.

The energy consumption proportionally affects the emission of greenhouse gases (GHG), mainly represented by carbon dioxide (CO_2), product of the complete combustion of the hydrocarbons. Consequently, the energy generation causes more CO_2 emissions during this process. This can be quantified using the metrics from the United States Department of Energy (DoE). The emission factors calculated by DoE are in the range of 0.147 to 0.909 (t CO_2)/MWh of energy generated. For the US this factor is 0.676 (t CO_2)/MWh and in contrast, for Latin America is an average of 0.189 and specifically 0.228 (t CO_2 per)/MW-h for Colombian case. The difference between these values depends on the type of power generation used, in example the hydraulic energy used in Latin America is less pollutant than the thermal energy used in the United States.

2.2 Fundamental concepts

Eco-efficiency concept is based on the relationship between economic and ecology aspects. As mentioned by WBCSD (1992) it is possible to reach eco-efficiency when a product or service is made with the minimal generation of contamination, and using the minimum quantity of natural resources. Under this definition, eco-efficiency is achieved when goods are made with competitive prices, satisfying human needs and providing quality of life, while progressively reducing the impact on the environment.

From the point of view of eco-efficiency, there are two aspects of high interest for the society. First, the impact caused by productive processes with low efficiency and intensive use of energy, and secondly, the growing trends of global energy consumption that forecasts higher demands in the near future.

The most direct way to increase the productivity in an industrial process is to reduce the energy consumption and for this purpose, basics of thermodynamics that govern the process transformations are highly required. With an energy balance the net consumption or generation of energy in the process is defined, however, by exergy balance it is possible to describe the quality of the energy, and the possibility to modify the interactions in the process configuration in order to reduce inefficiencies in the process. In fact, exergy concept helps in the optimisation of industrial processes because it is a combination of the conservation energy law (first law) and the entropy generation law (second law).

Exergy is defined as the maximum quantity of useful work that can be obtained as process changes reversibly from a given state to another equilibrium state with the environment. Kotas (1995) stated that exergy is the maximum work that can be obtained from any amount of energy, or the maximum work that can be removed from a system in interaction with the environment.

It is known that only irreversible processes occur in the real world, and thanks to this theoretical concept, it is possible to find energy degradation processes that may be potentially useful. Although exergy balance only exist for reversible or ideal processes, the calculation of exergy losses allows to visualize the required modifications to improve the processes. As general rule, the higher exergy losses are the first process to improve. However, as all the sections in the system are interrelated, it is possible to find exergy losses similar or bigger than the modified process in comparison with the original process. (Gong and Wall, 1997).

In 1997, Rivero stated that exergy calculations are based on the determination of two thermodynamics functions of state: Enthalpy and Entropy. Therefore, considering a system that is defined by its independent variables like pressure, temperature or composition, etc., and the system is set-up in a level “0” environment, the exergy or the system can be defined by the following expression, Eq.1:

$$\text{Exergy} = (H - H_0) - T_o\,(S - S_0) \qquad (1)$$

With H as enthalpy, S as entropy and T the temperature, the sub index “$_0$” indicates the condition of environment that surrounds the system. In other words, the exergy is calculated as the difference between total enthalpy and total entropy.

$$\text{Exergy} = \text{Total Enthalpy} - \text{Total Entropy} \qquad (2)$$

In 1998, Sorin et al, settled that it is possible to calculate the exergy content for each stream at the inlet and outlet of each process system, in order to establish a global exergy balance. Furthermore, the total exergy incoming to the system is always higher than the outlet streams.

Later on Rivero (2002) defined the exergetic analysis as “a technique that allow us to discuss in deep about the use of energy in the processes, and discover in what part of the system can exist energy degradations”

Several related studies had been done up-to-date, but latest were focused on applications to renewable fuels, like Jaimes and Kafarov (2010) that applied exergy analysis to palm oil biodiesel plant or Peralta, Sanchez and Kafarov (2010) who used similar analysis to biodiesel plant from microalgae biomass. Most recently, Tarighaleslami et al. (2011) worked on Exergy Analysis in a Crude Distillation Column, and compared the effect of varying the feed quality, the configuration of pump around in the column, and splitting the vapor and liquids in the feed to the column.

3. Methodology for analysis - Experimental development

As scope of this work, a methodology was developed to analyze and determine alternatives and its hierarchy, in order to define the best scenario from the options. The flow chart in the Figure 1 summarizes the methodology path-way.

Based on process simulation and analysis techniques, the thermodynamic properties of the inlet and outlet streams in a subsystem or in the global system were estimated. With these properties, the evaluation of energy uses in the entire process was made, with the respective determination of energy usage in the process by first and second law balances.

A process model of the FCC separation section was configured in a commercial software PRO/II, and the exergy calculations built in the software were validated with a simple case model.

The model included the main distillation column and vapour recovery unit in the plant. As shown in the Figure (2), the columns involved were: main fractionator and side stripper columns, compression train, main absorber column, sponge absorber column, lights stripper column, debutanizer and depropanizer columns.

4. Results and discussion

From the simulation report, the Unit Availability Balance (exergy) let to rank which process to tackle first, in order to get and optimized solution. The proposed modification allowed reducing the exergy losses in the main fractionator by 8.9 % versus the base case, and 5.9 % diminish in cooling water services.

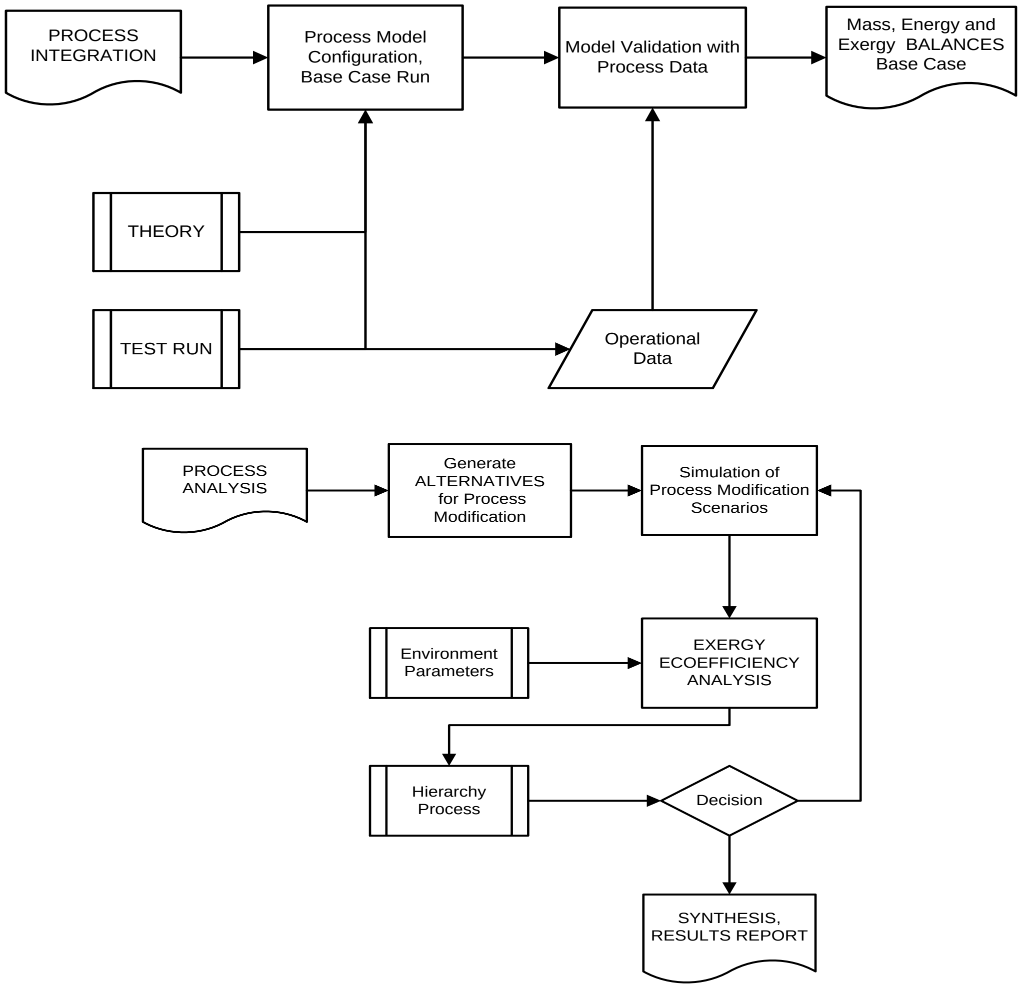

Figure 1. Methodology to evaluate different process configurations by the use of eco-efficiency criteria, Source: Author 2013

Table 2: Unit Availability Balance, Base Case versus Optimized Case

Process Unit	UID	Delta B GJ/h	Ext-Work GJ/h	Duty GJ/h	Delta B GJ/h	Ext-Work GJ/h	Duty GJ/h
Main fractionator	T701	**105.088**	0.000	**-239.615**	**95.757**	0.000	-**225.389**
Naphtha stripper	T702	0.043	0.000	0.000	0.039	0.000	0.000
LCO stripper	T703	0.202	0.000	0.000	0.202	0.000	0.000
Main absorber	T751	0.450	0.000	-0.415	0.449	0.000	-0.4153
Sponge absorber	T752	0.048	0.000	0.000	0.049	0.000	0.000
Stripper	T753	-4.597	0.000	21.567	-4.583	0.000	21.489
Debutanizer	T754	-3.157	0.000	3.118	-3.155	0.000	3.113
Depropanizer	T755	-0.683	0.000	0.934	-0.683	0.000	0.934
Total Exergy Loss		**97.394**			**88.076**		

Source: Author 2013, from model simulation Output Results

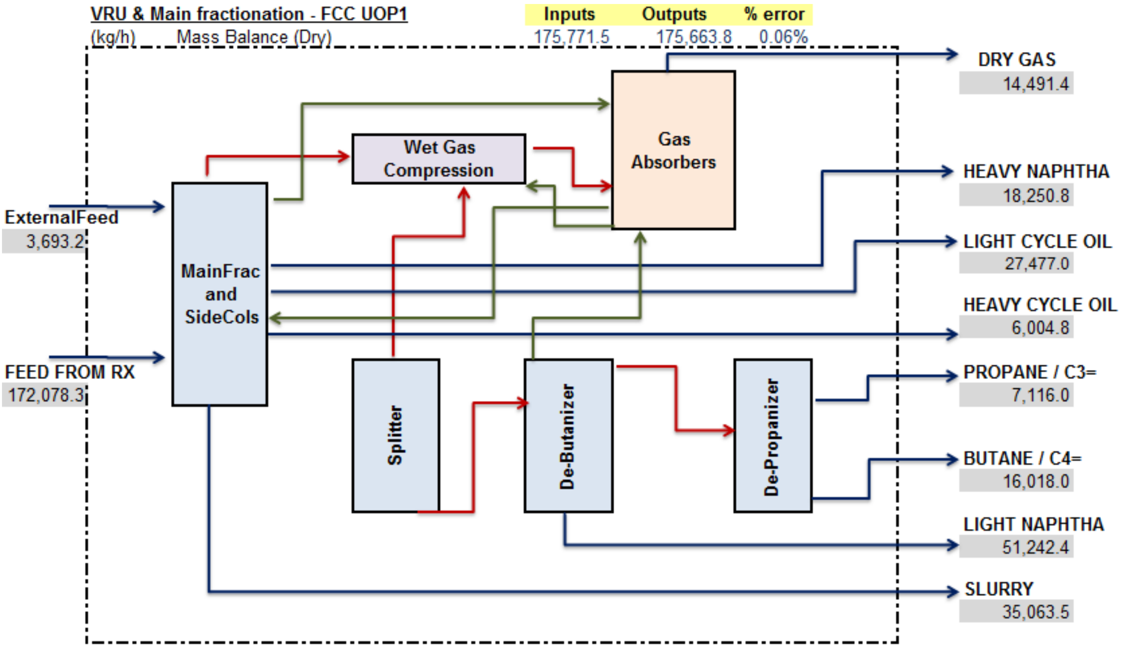

Figure 1. Block diagram and mass balance of the plant section as configured in the model. Source: Author 2013

The total exergy loss in the plant was reduced by 9.6 % as the result of the modification. Considering an emission factor of 0.228 (t CO_2)/MW-h applied to the Colombian case, it gives an equivalent factor 0.0633 (t CO_2)/GJ/h. As there are 9.331 GJ/h potential energy recovered in the process, this means an equivalent amount of 0.5898 (t CO_2)/h reduced, or 5,101 t CO_2 Equivalent yearly in 360 d basis.

The economical impact on this modification reflects the pollutant reduction, and less fuel oil consumption. With an optimistic scenario of CERTs or penalties for GHG emissions of 35 USD/(t CO_2E), gives around 0.18 M USD/y. And, from the savings of energy in the fuel of 9.331 GJ/h means about 0.32 M USD/y. The sum of these two savings accounts for **0.5 M USD/y**.

The stated hypothesis was verified: It is possible to find a new process configuration in the plant in order to reduce the energy losses and consequently reducing the pollutant emissions without compromise the yields or quality of the products.

Exergy analysis is a powerful technique that helps in ranking which section of the plant is the focus for energy optimization and allows defining in a quick manner the gross benefits to the process.

The emission factors for energy (power) generation give a gross indication of how much pollution is generated depending on the technology used. Using the adequate value according the country or region or interest, allows estimating in a good manner how much CO_2 Equivalent pollution is caused by any process.

5. Conclusions

(1) An integral methodology for evaluating processes was developed applying the eco-efficiency concept. That is having in count parameters like energetic efficiency, economic sustainability, and minimizing the use of equipments in the process.

(2) A powerful rigorous model of the FCC plant was configured and tested, specifically for the separation section. The model included the main fractionator and auxiliary side strippers, the compression system, the main and sponge absorber, as well the stripper, debutanizer and depropanizer columns

(3) The exergy calculation module built in the process simulator PRO/II was validated along with a hand calculation. An accurateness of 99.97 % was found.

(4) It was determined that the largest energy losses occur in the main fractionator and due to the great difference with other systems, the relevant equipment in the studied plant was this column.

All the alternatives evaluated shown a reduction in the total exergy losses.

(5) With the proposed modification, there is a significant decrease in exergy losses obtaining a potential of 9.33 GJ/h energy savings.

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