"BABES–BOLYAI" UNIVERSITY
CLUJ-NAPOCA

Faculty of Chemistry and Chemical Engineering

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ADVANCED CONTROL OF THE HEAT INTEGRATED COMPLEX PLANTS

PhD THESIS ABSTRACT

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Contents

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Chapter 1. The Motivation and the Objectives of the Thesis

Due to the first world-wide oil crisis occurred in ’70 and due to the global energy crisis started in 1973 the energy recovery became a priority for the industry and in the same time a challenge for the scientists. They identified the necessity to redesign the industrial processes in terms of energetic efficiency, and discovered that this goal could be achieved by energy saving using the retrofit and the recovery of the extra energy from all secondary sources of a process (Rev & Fonyo, 1986).

During the time the scientists’ strategy to achieve energy efficiency changed. Until 10-20 years ago, the general research interest in order to improve the energy efficiency was to redesign and then to optimize each equipment from a plant. Nowadays, the idea is to treat the process as a whole; moreover, the analysis being extended to an industrial platform in the way that each process can be integrated by itself or in interdependence with other processes from the same platform. (Cerda et al. 1983)

By now, in the field of processes heat integration, all the studies (Douglas, 1988, Linnhoff, 1997, Dimian, 2003, Seider, 2004, etc.) are limited to the steady state analysis without taking into consideration the dynamic behavior of all processes.

This limitation was used to simplify the analysis of an integrated complex process because the more rigorous the heat integration is the heavier is to obtain and maintain its stability, as a consequence of its dynamic behavior. Therefore the implementation of an advanced control scheme became a very challenging task.

As a consequence, the objectives of this thesis are the application of the heat integration techniques and of the advanced control techniques to complex chemical processes in order to study the possibility of reducing the energy consumption in an industrial scale plant. In this purpose, the analysis considers a real fluid catalytic cracking process from a Romanian refinery.

Chapter 2. Heat Integration

The second chapter contains a literature review regarding the heat integration field and a discussion of the level approached by now of the heat integrated process controllability.

The development of the process integration techniques conferred important advantages for the industrial processes in terms of process improvement, increased productivity, energy resources management and conservation, pollution prevention, and reductions in the capital and operating costs of chemical plants. Process integration through heat integration due to its economical and environmental benefits became a very important field in chemical engineering. The quantities of the necessary utilities in the process and consequently the total cost can be reduced through the heat integration using one of the two main heat integration techniques: the pinch analysis and the mathematical programming.

The formulation of the concept of heat integration was introduced for the first time by Linnhoff and Flower in 1978. The heat integration techniques have had a fast and beneficial evolution along time once the technology developed.

The development of the pinch technique represented the starting point for the concept of saving and conservation of the energy techniques. Firstly used as a simple heat exchanger network analysis the pinch technique evolved being applied on large scale, complex industrial plants.

In parallel with the pinch technique, the mathematical programming evolved due to the evolution of computation technology. Firstly this technique started with the formulation of Papoulias and Grossmann (1983). The continuous interest in developing and use of this technique resulted in strong representations of it in several algorithms like linear programming (LP), mixed integer linear programming (MILP), non-linear programming (NLP) and mixed integer non-linear programming (MINLP).

Therefore, nowadays, the heat integration techniques and implicitly the process integration field became an important tool to economically improve a plant without being constrained by its complexity.

Software packages implementing the heat integration techniques were developed to facilitate the HEN retrofit design and process design development in order to improve energy consumption and reducing the total cost (ex. Sprint, Aspen, ProII, etc.).

Further, the development of the heat integration field has to take into consideration also the dynamic behavior of the processes because, nowadays, all the heat integration studies were based only on the steady state of a process.

The research group of Morari made important steps in describing the dynamic behavior of the HENs (ex. Saboo et al., 1986, Saboo et al., 1987, Coldberg et al., 1989, Mathisen et al., 1994). They proposed that the dynamic behavior of the HENs to be analyzed using a procedure called the "Resilience index". The resilience index is defined as the maximum arbitrary disturbance load a network can tolerate yet achieve the target temperatures while maintaining the ΔT_m and other level of the energy recovery constants (Saboo et al., 1986). They made comparison of controllability measures and dynamic simulations and concluded that the most important model feature for heat exchanger networks is the residence time of the material in the connecting pipes (Mathisen et al., 1994).

Gonzalez et al. (2006a, 2006b) developed a MPC controller to attain the economical and controllability targets of a HEN. The HEN was simulated through a rigorous nonlinear model. The MPC controller selected model was a linearized state-space model. This controller was tested only for a small dimension HEN system.

Tellez et al. (2006) proposed a five step method for determining the controllability of some potential HENs for a particular plant. The aim of this work was to provide a simple and practical method for process and control systems design engineers that use commercial simulators.

Analyzing either by parts or as a whole, the heat integrated processes is more instable and hard to control after the integration due to the reduction of freedom degrees and this problem need to be solved finding a solution for the control scheme (advanced control algorithms or traditional PID control) in concordance with the design proposed after heat integration and retrofitting a process.

Chapter 3. The Advanced Control of Complex Processes

The third chapter provides an inventory of the advanced control techniques developed during time. Also, a detailed discussion of the control of the heat integrated complex processes in presented. A detailed control scheme development of a HEN and the basic rules are presented. The sensitivity and controllability of the HEN is approached.

The entire heat integrated plant control problem is extremely complex and challenging. It is necessary to understand the chemistry, physics, and economics of the real processes.

The goal of complex plants control is to find the necessary logic, instrumentation, and strategies to operate the plant safety and achieve its design objectives.

In industry, a plant control strategy should be simple enough at least conceptually so that everyone from the operator to the plant manager can understand how it works. The more complex the process, the more desirable it is to have a simple control strategy.

However, the modern process plants are continuously improved for a flexible production and for maximization of the energy and material savings. These plants are becoming more complex with a strong interaction between the process units. Consequently, the failure of one unit might have a negative effect on the overall productivity. This situation reveals important control problems. Another problem is that the techniques developed by now can't solve all the control problems that appear in modern plants because different plants have different requirements.

The appearance and the continuously development of the advanced control techniques provide better solutions for plants control at any level of complexity of the process.

Applied on the complex chemical processes, the advanced control is able to improve product yield, to reduce the energy consumption, to increase the plant capacity, to improve the product quality and consistency, to improve the process safety and to reduce the environmental emissions. The benefits of the advanced control implementation can be observed first in the operating costs of the plant. The operating costs can decrease with 2% - 6% (Anderson, 1992). The second benefit is the reduction of the process variability. As a consequence, the plants can be operated to their designed capacity.

The main advanced control techniques, developed during the time, are presented in Figure 3.1.

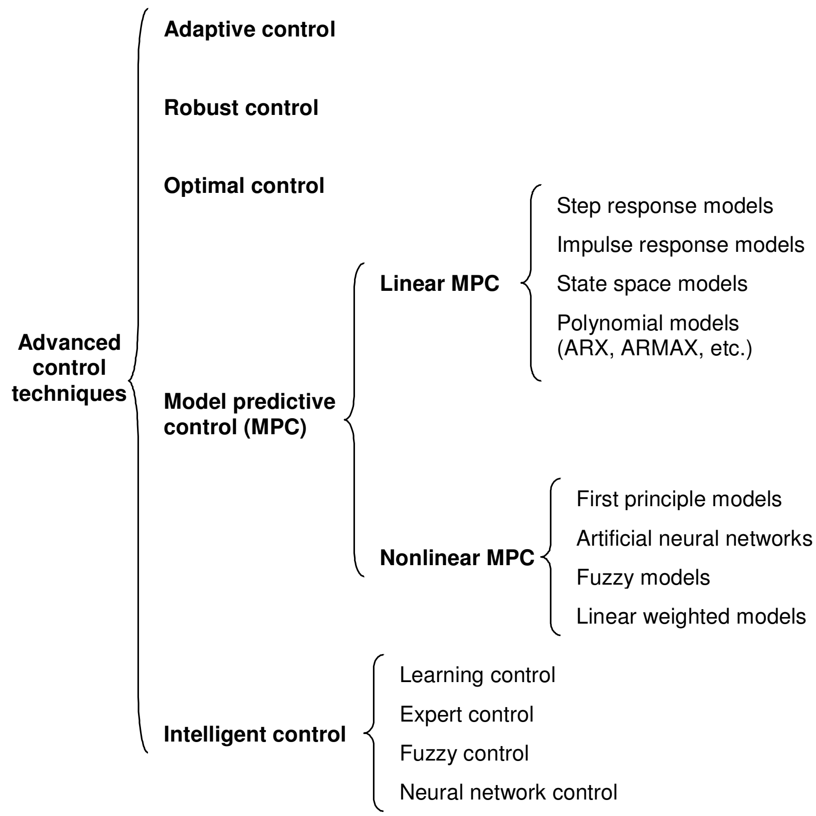


Figure 3.1. The main techniques of advanced control

The model predictive control (MPC) is one of few advanced control methods used successfully in industrial control applications. This technique represents an advanced method of optimal process control since 1980s when it was developed to meet the specialized control needs of power plants and petroleum refineries. Nowadays, can also be found in a wide variety of application areas like: chemicals, food processing, automotive, aerospace, metallurgy, pulp and paper, etc.

The model predictive control is differentiated from the other advanced control techniques by three key elements: the predictive model, the optimization in range of a temporal window, and the feedback correction. The performance of a process control depends on the precision of the model built to copy the dynamic behavior of the process.

The model predictive control (MPC) technique can be successfully applied on the heat integrated processes.

In the case of the heat integrated plant it is necessary that the control system to prevent the propagation of the thermal disturbances through the entire plant. The heat transfer between the process streams can lead to positive feedback and even instability. A viable solution is that the thermal disturbances should be transferred to the plant utility system whenever is possible for removing the source of instability from the process units.

The sensitivity analysis together with the controllability analysis are powerful tools in the development of a control scheme for a heat integrated plant. At industrial scale, these analyses are recommended to be used for the development of the whole plant control system and not by parts.

Chapter 4. Case study - Fluid catalytic cracking process

The fourth chapter describes the case study selected for this work. The case study is a fluid catalytic cracking plant from a Romanian refinery. Therefore, the FCC process, the FCC plant, the FCC technologies and the FCC catalysts are emphasized in this chapter.

Compared with other heavy oil catalytic cracking processes the Fluid Catalytic Cracking (FCC) process is the most common used in a modern oil refinery.

There are approximately 400 catalytic cracking units operating worldwide. The total processing capacity of those units is over 12 million barrels of oil per day.

The design of the cracking units, during the time, was different from plant to plant. Companies like Exxon, Shell, and TOTAL developed and used their own designs of cracking units. Nowadays however, most of the current operating cracking units have been designed or revamped by three engineering companies: UOP, M.W. Kellog and Stone & Webster. The existent FCC plants designs differ only in small details generally from the point of view of security and/or process control, depending on the company that designed them. The design engineering companies' most common objectives are to upgrade low-value feedstocks to more valuable products.

The cracking units are very complex systems. In order to make an idea of the complexity of a FCC plant in Figure 4.1 is shown a schematic view of such a plant. The main units in a FCC plant are: the riser-regenerator, the main fractionator and the pre-heating train of the feedstock.

The main products of the FCC process are:

Light gas	Contains primarily H_2, C_1, C_2s, normally an undesirable by-product of thermal cracking
LPG	C_3s and C_4s – includes light olefins valuable for alkylation
Gasoline	C_5+ high octane component for gasoline pool or light fuel
LCO	Light cycle oil blend component for diesel pool or light fuel
HCO	Optional heavy cycle oil product for fuel oil or cutter stock
CLO	Clarified oil slurry for fuel oil

Coke By-product consumed in the regenerator to provide reactor heat demand

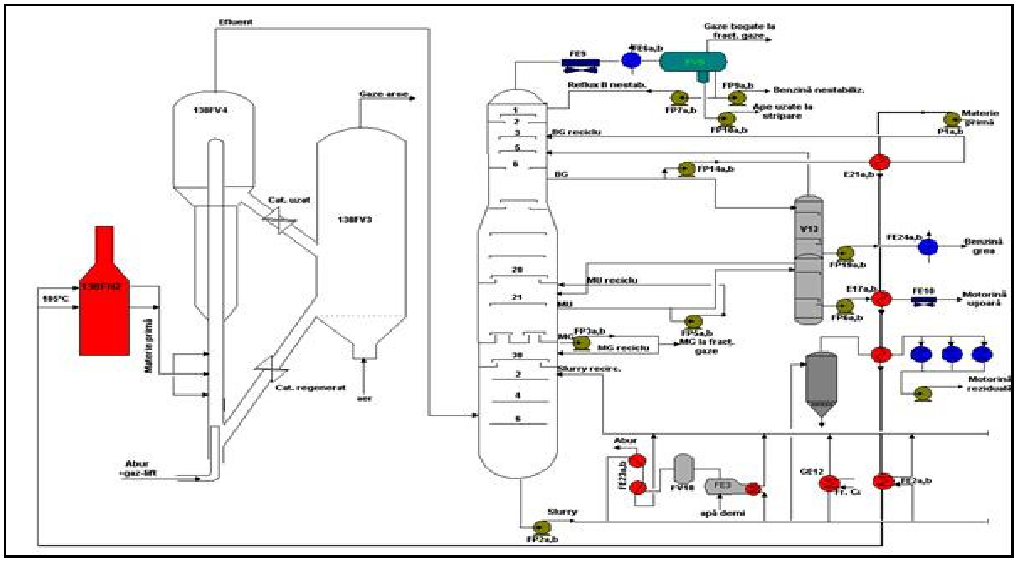


Figure 4.1. The process flow scheme of the fluid catalytic cracking plant

The commercial FCC catalysts are fine powders with the size of particles around 75 microns. In their composition four base components are found: the zeolite, the matrix, the binder and the filler.

Being an old process, the fluid catalytic cracking process, needs to be improved frequently for obtaining modern products according to the market demands.

Nowadays the only manufactures that are continuously improving the FCC tehnology are ExxonMobil, M.W. Kellog and UOP.

The existent FCC plants are different only in small design details, security or process control. The main difference between the manufacturers technology consists in the reaction block design.

Chapter 5. Heat integration of the real FCC plant

An important chapter is the fifth chapter in which an analysis of the real HEN of the FCC plant is presented together with the optimization from the point of view of costs of the real HEN. A new HEN design is developed managing to reduce the total cost with approx. 9%/yr.

First of all, the analysis of the existing heat exchanger network (HEN) of an industrial catalytic cracking plant (FCC) is developed. The method used for energy integration is the Pinch Analysis. This technique is the simplest, easy to use, with immediate results and demonstrates its efficiency and applicability in many industrial saving energy problems.

The study starts with the investigation of the actual HEN and the determination of the minimum necessary of heating and cooling utilities. The system was simulated in ASPEN Plus with the real process data collected from a Romanian refinery (UOP Fluid Catalytic Cracking Process).

The analysis using Aspen HX-Net revealed that the pinch temperature of the process is 144.5^{0}C and the ΔT_{min} for the process is 129^{0}C. The need of hot utility is 19858 kW and of cold utility is 22234.79 kW. These data are provided by Figure 5.1 and Figure 5.2.

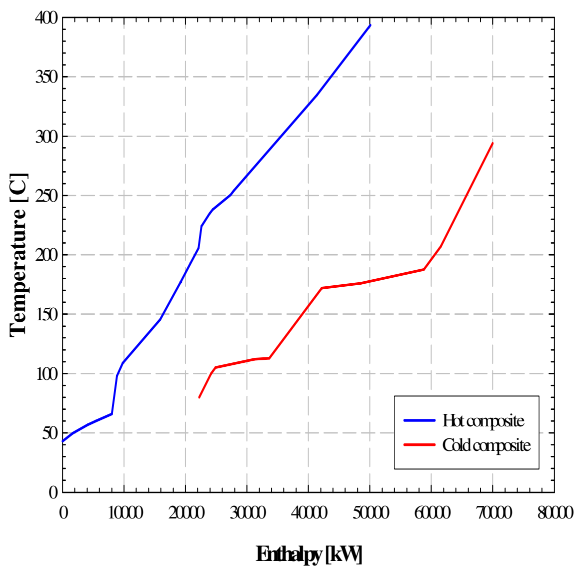


Figure 5.1. The composite curves of the real HEN

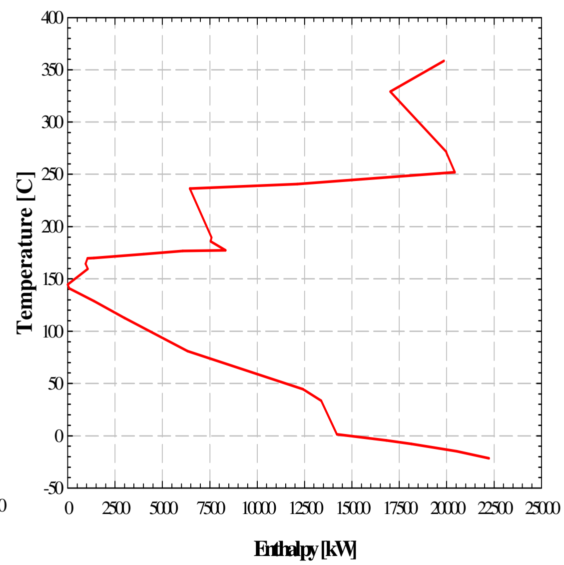


Figure 5.2. The Grand composite of the real HEN

In order to improve the real heat exchanger network the optimization of the total cost of FCC process in function of the minimum approach temperature - ΔT_{min} was done. As it can be seen in Figure 5.3, the optimum minimum approach temperature for the retrofit target was identified to be $\Delta T_{min}=12^0C$.

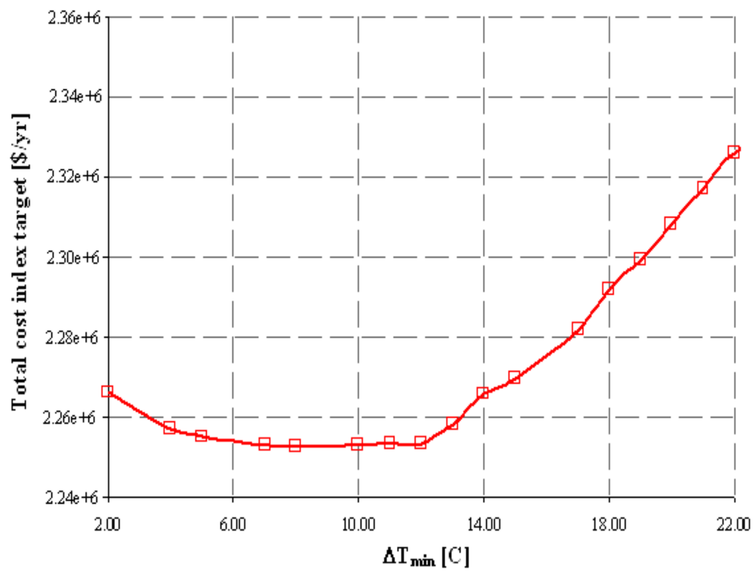


Figure 5.3. Total cost vs. ΔT_{min}

Considering that the actual HEN is operated with $\Delta T_{min}=129^0C$, decreasing it to 12^0C it is possible to improve the actual heat exchanger. The reduction of the ΔT_{min} reduces the heating and cooling needs approximately with 32% and 39% respectively.

In order to improve its operation and to recover a quantity of energy, the FCC process must go through some structural changes (retrofitting). Retrofitting represents changes (new heat transfer area, re-piping, changing the heat exchangers place, etc) in the actual structure of the HEN in order to reduce the operation cost and in this way to increase the capital cost, indicating that there is a trade-off between the operational and capital costs.

Therefore, Aspen HX-Net was used to generate the retrofitted designs of the HEN. Five designs were proposed (A,B, C, D, E). The designs were compared in terms of their operation costs and efficiency.

As it can be observed from Figure 5.4 and Figure 5.5, the design E is the best design comparative with the existing industrial HEN. The HEN operating cost is decreased with approximately 14 % meanwhile the total annual costs are decreased with approximately 9%.

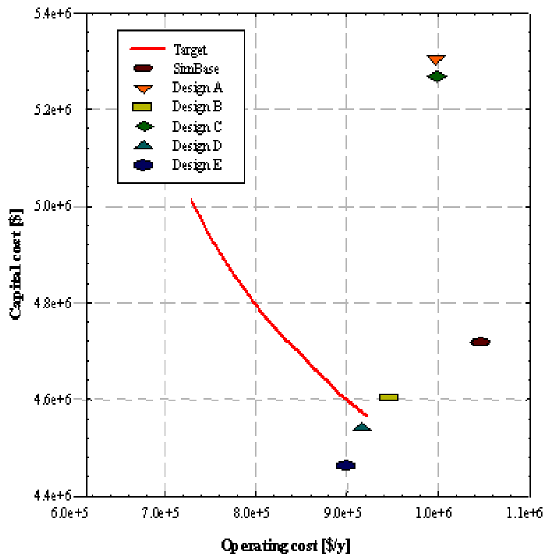


Figure 5.4. The performance of the designs respect to the ideal

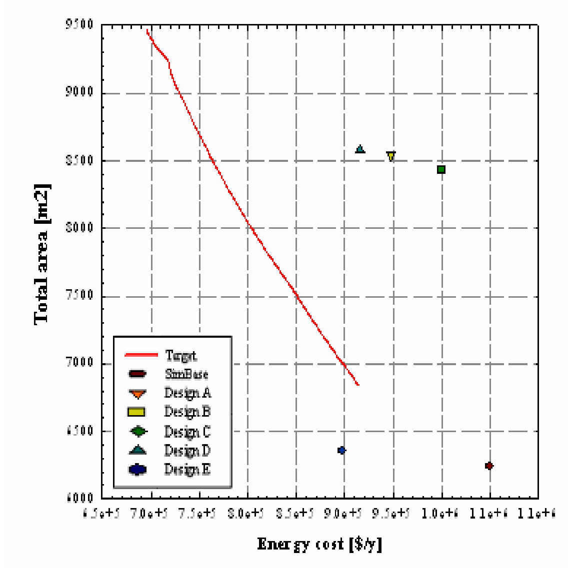


Figure 5.5. The efficiency of the proposed designs

By implementing the new HEN, respectively the Design E, in the industrial plant, no drastic changes are suggested. The new design was done trying not to modify the process-to-process heat exchangers, assuring that the process would not be affected and the energy loss through the pipes minimized.

This optimization of the HEN in terms of the economical point of view gives a starting point to continue with the improvement of the industrial process. Further the new HEN design must be analyzed in terms of dynamic behavior and controllability.

Chapter 6. Modeling and simulation of fluid catalytic cracking heat integrated plant

Chapter 6 describes the development of the FCC heat integrated plant simulator in steady state and in dynamic state using Aspen HySys. A PID control scheme is also implemented and the simulation results revealed stability and an appropriate heat transfer through the FCC plant.

Because of the importance of the FCC process in a refinery, considerable efforts have been done in the field of modeling of the behavior of this kind of unit. A better understanding of its behavior and a continuous improvement of the mathematical model describing the process has a direct effect on the overall plant productivity. It is difficult to develop a model for an entire plant and it is even harder to describe the operation of an integrated one.

The FCC process description is very difficult due to several reasons: the complexity of the chemical reactions mechanism, complex hydrodynamics, strong interaction between the operation of the main reactor and of the regenerator and due to the operation constrains imposed by the new HEN.

Therefore, commercial software specialized for simulating refining processes, Aspen HYSYS provided by AspenTech, was used in order to simulate the heat integrated FCC plant. The model (simulator) considers real industrial data related to material streams, temperatures, pressures, equipments size and geometry, etc. The data have been provided by a Romanian refinery

In the HYSYS interface the FCC model appears as a main flowsheet and two sub-flowsheets. The main flowsheet contains the FCC reaction block with the riser and the regenerator, a simplified scheme of the FCC column and the preheating train for the raw material – the HEN.

Therefore, in steady state, the new HEN design works properly and the heat transfer is made in the imposed conditions by the real plant. The simulation of the new HEN design provided good results. This demonstrates that the new HEN design can successfully be implemented in the real plant, the followed effect being the reducing plant total costs.

The schematic model of the heat integrated FCC plant built in Aspen HYSYS can be seen in Figure 6.1.

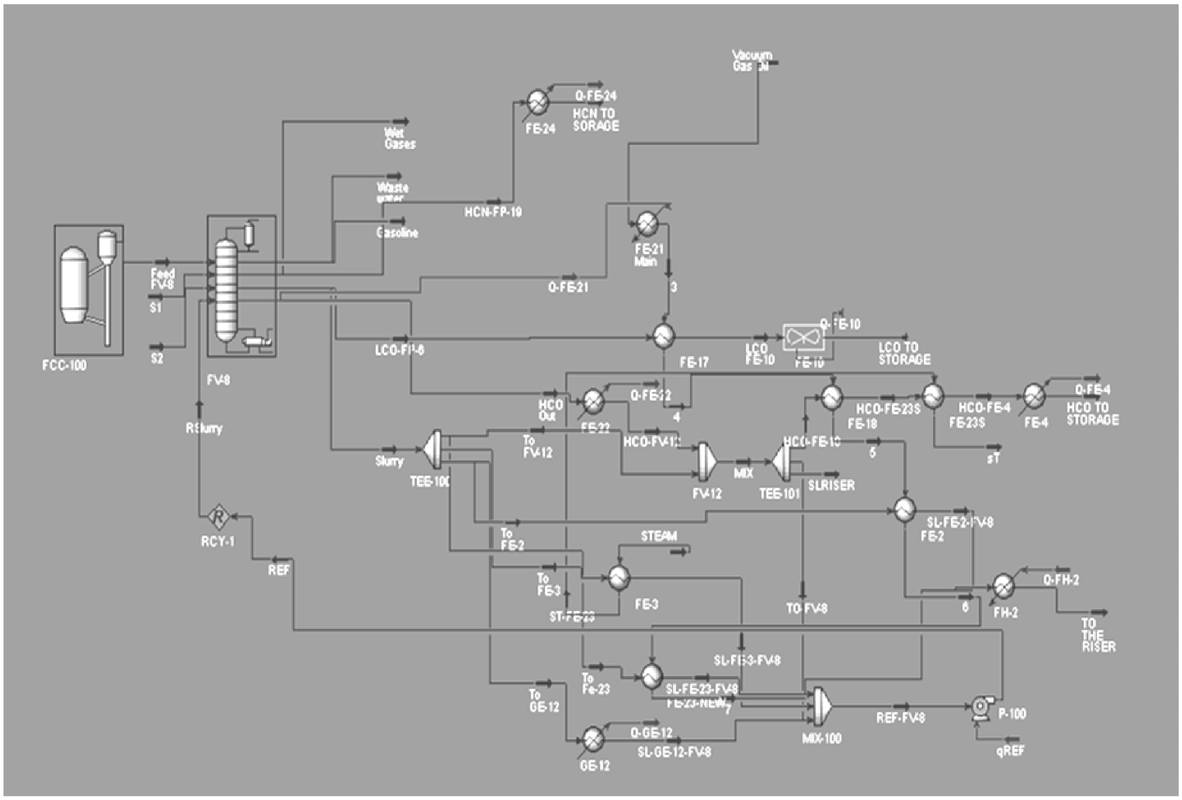


Figure 6.1. The main flowsheet of the FCC heat integrated plant simulation

Beside the steady state, with the new developed heat integrated FCC plant model, it is possible to simulate dynamic behavior. But, this implies several adjustments of the model establishing the P/F relationship in the simulation flowsheet, the equipment sizing, the PID control scheme implementation, etc.

One of the important things for the transition from the steady state to dynamic state is the implementation of an appropriate control scheme. A PID control scheme was implemented and the tuning of the PID controllers has been done using the Ziegler-Nichols method. The Kc, Ti and Td were successfully obtained for each controller.

The importance of the plant operation is found in the quality and quantity of the FCC products and, consequently, in the production price of the products. If is imposed a specific quality of the final products, different operation conditions are necessary. For example, to obtain gasoline Euro 4, the temperature of the output stream from the top of the column is necessary to be 133^0C. To obtain gasoline Euro 5, the temperature of the output stream from the top of the column is necessary to be 108^0C.

In both plant operations is important to maintain the imposed temperature at the setpoint to achieve the requested gasoline quality. Moreover, the variation of the temperature comparing with the setpoint implies energy consumption that, finally, is reflected in the production price of the products. Consequently, the increasing of the production price imposes the increasing of the total costs of the plant.

Therefore, the temperature variation needs to be maintained as lower as possible in order to have lower costs.

For reaching a better plant operation a good developed MPC control scheme is necessary. The MPC applied for the heat integrated FCC industrial plant can decrease the operating costs with approximately 2% - 6% of the existing one related to the real PID control scheme which is presently implemented in the real plant from the Romanian refinery.

The MPC controllers are capable to maintain the variation of the controlled variables much closer to the setpoint than the PID controllers. This may be possible due to the fact that the MPC is based on the process model and can predict the process behavior.

The next step must be the development of the MPC controller for controlling the FCC column based on the data provided by those 5 PID controllers that proved to be able to set the FCC column behavior at normal functioning conditions.

Chapter 7. The advanced control of the heat integrated FCC plant

The main goal of the thesis is to develop an advanced control scheme for the heat integrated plant in order to have more stability of the system and the heat transfer through the entire plant to be done in optimal conditions. Therefore, the chapter 7 contains the development of a MPC control scheme in order to maintain the heat transfer and to exploit the entire plant at its maximum capacity.

The real FCC plant which is presently exploited in a Romanian refinery has implemented a PID control scheme. This type of control reveals different operation problems.

The most important one is the maintaining of minimum pressure drops between the riser and the regenerator through two valves. These pressure drops between these two units assure good catalyst flow. Often, during the FCC process, the PID control scheme failed to assure the pressure drops because when the pressure increases in the riser or regenerator over a maximum allowed limit the PID controller opens completely the two valves losing the pressure drops.

Another problem appears when the oil feedstock is changed because the refinery exploited two different types of oil with different properties.

The refinery processes are continuous processes. Therefore the oils are replaced with the plants in function. The oil feedstock changing needs the adjustment of the PID controllers' parameters. Therefore, the period in which the transition between feedstocks is made, the FCC plant is manually operated and constrained to reach its operation parameters in concordance with the new feedstock.

A good operation of the FCC plant without the interference of the operators can be achieved only using the advanced control techniques, especially the ones which imply using of controllers based on the model of the process because in this way, at every moment of time, the process behavior could be known and the controller could act promptly.

Based on the results obtained with PID control strategy, 5 inputs (process /controlled variable – PV/CV) and 5 outputs (output target objects/manipulated variable – OP/MV) MPC is used. The chosen controlled and manipulated variables are summarized in the following table.

MPC control scheme selected variables

Controlled Variable		Manipulated Variable	
CV1	To Condenser stream temperature	**MV1**	Reflux flow rate
CV2	Condenser Liquid % Level	**MV2**	Gasoline flow rate
CV3	FV-13 bottom HCN flow rate	**MV3**	FV-13 HCN feed flow rate
CV4	FV-10 bottom LCO flow rate	**MV4**	FV-10 LCO feed flow rate
CV5	Slurry temperature	**MV5**	Column recycle slurry flow rate

Comparing with PID controller, the MPC controller presents the necessity to build a process model. Based on the control demands of the heat integrated FCC plant and on the results obtained with PID control strategy, 5x5 MPC controller was developed using the First Order model. In this case the estimation of model states and parameters is critical. The successful implementation of the MPC controller depends on them.

The identification of the process parameters that are needed for the first order model development (the process gain - Kp, the process time constant - Tp and the delay) was realized by developing step response tests for each manipulated variable.

After the parameter were calculated they were used to build the 5x5 MPC step response matrix necessary for determining the MPC controller internal model. In this way arise a new MPC controller capable to handle the control of the FCC column. The performance of the new MPC controller can be observed in Figures 7.1 – 7.5. In these figures the red line represents the setpoint, the blue line represents the manipulated variable and the green line represents the controlled variable.

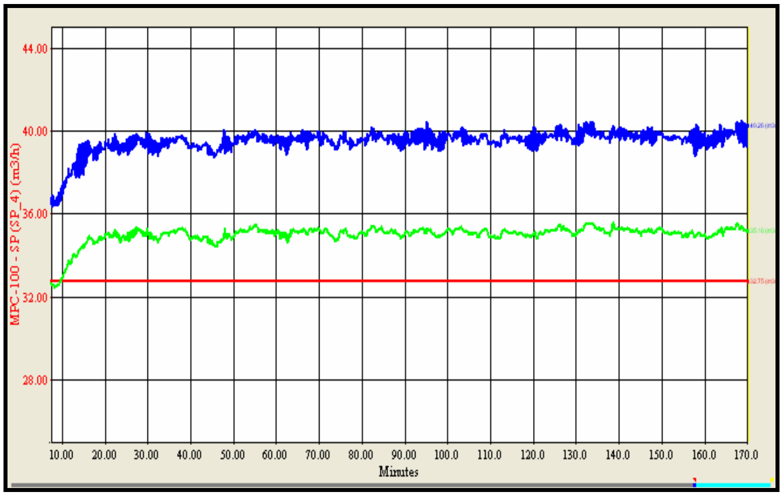


Figure 7.1. The performance of the LCO FP-6 flow control

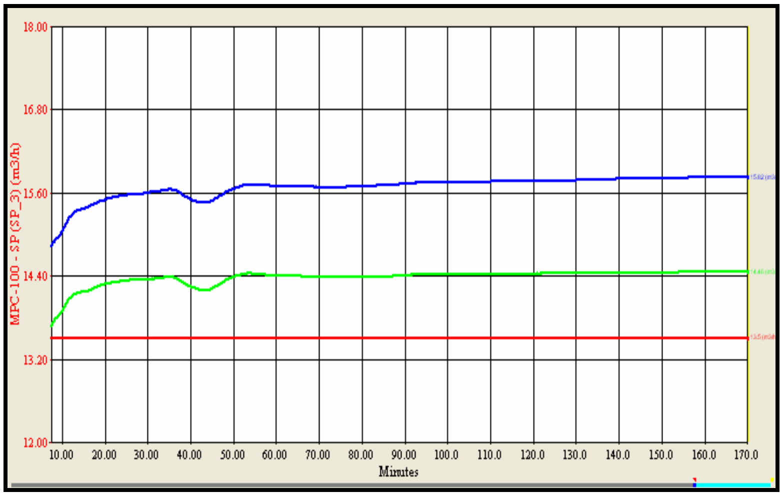


Figure 7.2. The performance of the HCN-FP-19 flow control

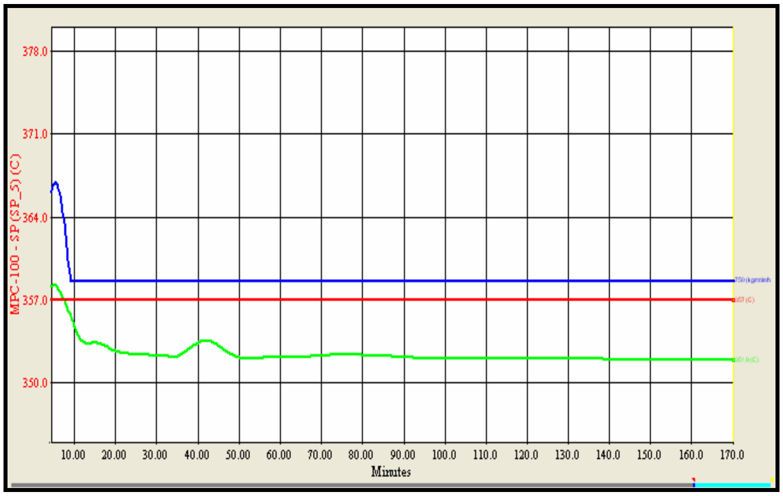


Figure 7.3. The performance of the Slurry temperature control

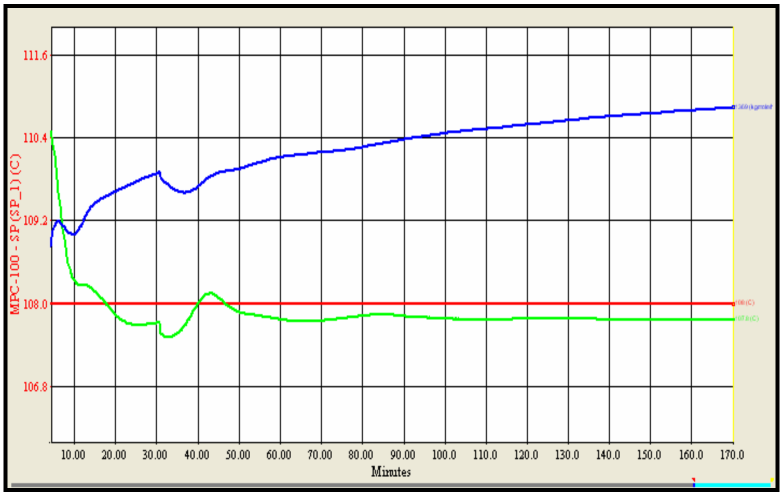


Figure 7.4. The performance of the temperature control of the column top product

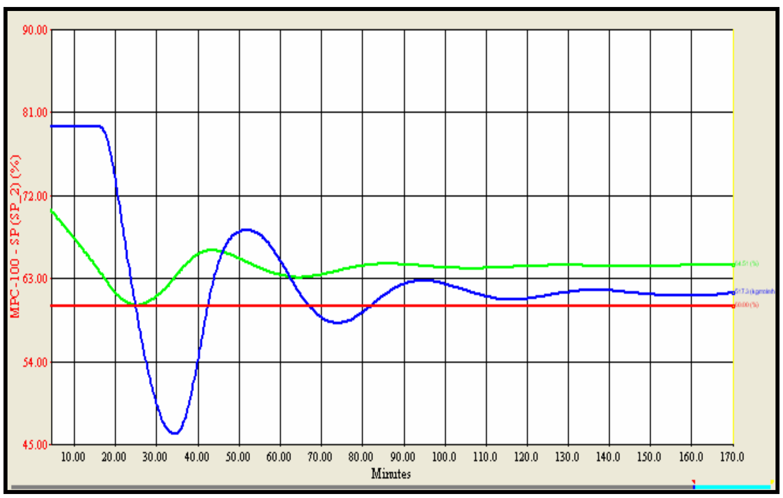
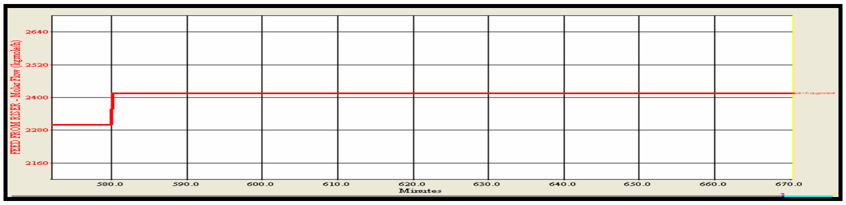
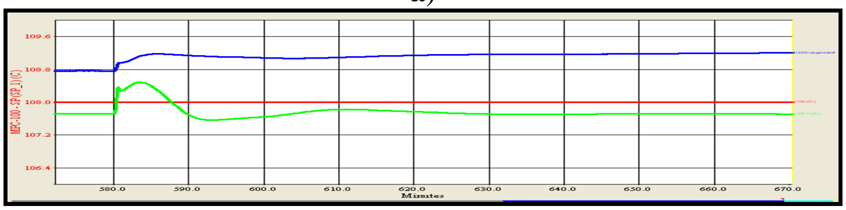


Figure 7.5. The performance of the condenser liquid percent level control

The MPC controller performance was tested in rejecting the disturbances and the results obtained after a +5% disturbance applied on the column feed molar flow are presented in Figure 7.6. The developed MPC controller results enable to establish that the strategy of the advanced control imposed is a very efficient one in case of a FCC heat integrated plant. The MPC controller is capable to maintain the variation of the controlled variables much closer to the setpoint than the PID controllers. This is possible due to the fact that the MPC is based on the process model and can predict the process behavior.



a)



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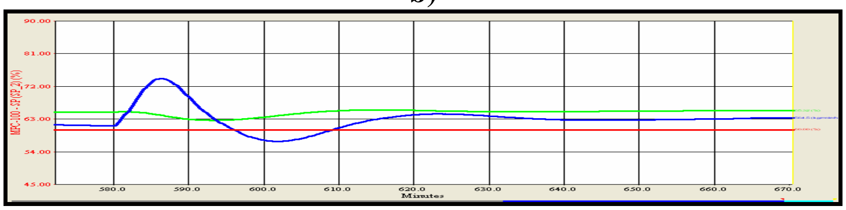

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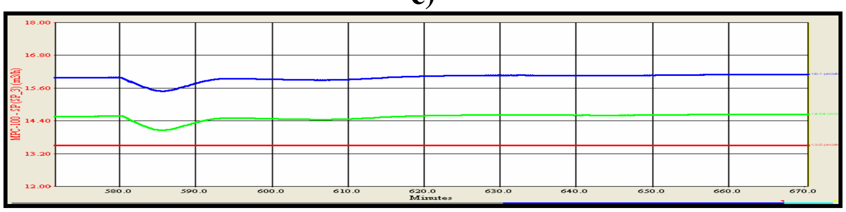

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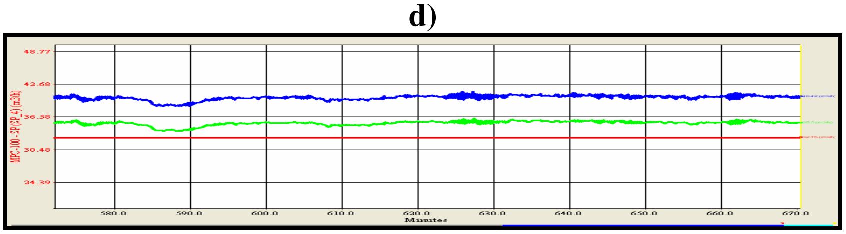
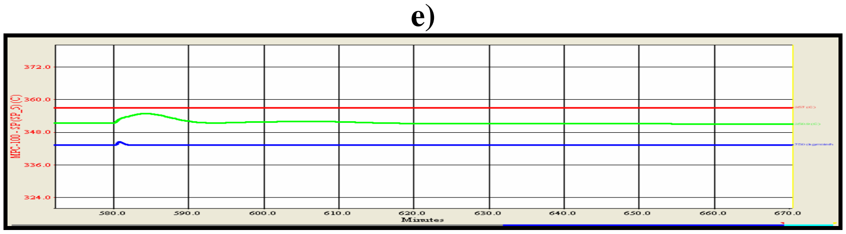


e)



f)

Figure 7.6. MPC controller disturbance test

a) +5% column feed molar flow step disturbance;
b) Top column product stream temperature control;
c) Condenser liquid level control;
d) HCN stripper bottom product stream flow control;
e) LCO stripper bottom product stream flow control;
f) Slurry temperature control.

The method presented in this chapter for developing the MPC controller is an easy and faster method capable to be applied in any industrial plant. Moreover, this method is frequently used in developing advanced control in industry.

The developed MPC controller can decrease the operating costs with approximately 2% - 6% of the existing operating cost related to the real PID control scheme of the real plant.

Chapter 8. Conclusions and future work

The present thesis represents a new perspective in approaching the retrofit problem and advanced control problem of any complex industrial plants.

The thesis study was based on a real industrial case. The data for modeling and design have been obtained from a FCC plant that is in function at this time in a Romanian refinery.

The importance of this study consists in the stabilization of the dynamic behavior of a heat integrated FCC plant obtained by implementation of a MPC control scheme.

It was observed that the appropriate control of the FCC column induces the necessary heat transfer through entire plant. Consequently, in order to develop an advanced control scheme of the plant it is necessary to identify the main influence on the heat transfer through the HEN and controlling it for obtaining stability of the plant and good results regarding the heat transfer.

A particularity of this study is represented by the use of specialized software developed for studying complex systems. This kind of software is capable to reduce the engineers' time for design or improvement of any process.

Regarding the MPC controller development, a simple method was used for the internal MPC model development. This method is fast and very useful in implementing an advanced control scheme at industrial scale. The step response tests in the real plant are insecure and costly especially in a continuous process. Any kind of these step control tests are able to compromise the quality of the products and to destabilize the industrial plant followed by undesirable incidents and costs.

Taking into account the amount of the work presented in this thesis, some important conclusions can be formulated regarding the implementation of the advanced control on a heat integrated plant.

1. It is necessary to establish an appropriate integration design for an industrial plant in order to have both energy savings and economical benefits because, in some cases, the best heat integration can increase the plant total costs.

2. After the implementation of the integrated design, it is important to identify the main disturbances that can affect the new HEN. The sources of the disturbances can be

other units (ex. reactors, distillation columns, etc.) which are direct or indirect connected with the HEN.

3. If an optimal control is applied for maintaining the disturbances sources in the range of the operation parameters a good heat transfer through the new HEN is assured.

4. It is important to emphasize the fact that even if the heat integration induces more instability in the process, an optimal control scheme can be obtained for the entire heat integrated plant with the proviso that the plant is approached as a whole and not by parts.

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