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SIMULATION OF AN INDUSTRIAL COMPLEX FCCU PART II: STUDY OF THE PROCESS DYNAMIC BEHAVIOR

RALUCA ROMAN*, ZOLTAN KALMAN NAGY**,
VASILE MIRCEA CRISTEA*, ŞERBAN PAUL AGACHI*

ABSTRACT. The fluid catalytic cracking unit (FCCU) is an important processing unit in an oil refinery. A mathematical model for this process has been developed. The novelty of the model consists on the complex global dynamics of the reactor-regenerator-fractionator system as well as complex catalytic cracking kinetics for the reactor. The mathematical model consist of the main subsystems of an industrial unit: feed and preheat system, reactor (riser and stripper), regenerator, air blower, wet gas compressor, catalyst circulation lines and the main fractionator. Based on the mathematical model it was analyzed the dynamic behavior of this complex process that includes also the economical aspects of the process.

1. INTRODUCTION

The Fluid Catalytic Cracking Unit (FCCU) is one of the most important process units in oil refineries for the largest yield of products reached and the importance of them. A small benefit in this process is economically attractive. The (FCC) unit converts gas oils into a range of hydrocarbon products of which gasoline and diesel are the most valuable. The amount of low market-value feedstocks available for catalytic cracking is considerable in any refinery. The ability of a typical FCC unit to produce gasoline and diesel from low market value feedstocks gives the FCC unit a major role in the overall economic performance of the refinery. An overview of the FCC process is given in Figure 1.

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* Babeş-Bolyai University, Faculty of Chemistry and Chemical Engineering, 11 Arany Janos, 400028 Cluj-Napoca, Romania, e-mail: romanr@chem.ubbcluj.ro
** Loughborough University, Department of Chemical Engineering, Loughborough, LE11 3TU, United Kingdom

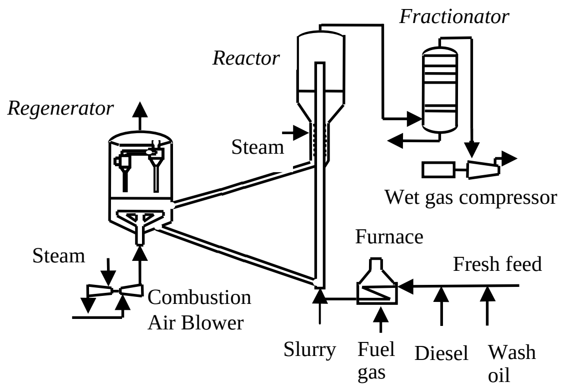

Figure 1. Fluid Catalytic Cracking Unit

The unit consists of a reactor-regenerator section, main fractionator and gas processing facilities. The feed is heated in a fired heater (furnace) and combined with regenerated catalyst in the bottom of the reactor (riser). The catalyst and the reacted hydrocarbon vapors flow up the riser and are separated in the reactor cyclone. The catalyst circulation is achieved by burning off the coke deposit in a fluidized bed inside the regenerator. A steam turbine driven air blower supplies the oxygen needed to burn the coke deposit. The spent catalyst is held up in a small fluidized bed in the upper part of the reactor (stripping section) before being returned to the regenerator. The air flow for combustion was is provided by the combustion air blower. Catalyst in the regenerator is fluidized; carbon and hydrogen on the catalyst react with oxygen to produce CO, CO_2, H_2O. Gas travels up in the regenerator into the cyclones where the entrained catalyst is removed and returned into bed. The flue gas from the regenerator is sent to a waste heat boiler before being discharged to the atmosphere. The FCC unit is operated in full burn mode. Vapor products from the reactor (gases, gasoline, diesel, slurry) are sent to the main fractionator where various boiling point fractions are withdrawn [1].

Numerous studies are concerned with the modeling of this unit, which are very useful in elucidating of the main characteristics of this unit dealing with strong interactions and many constraints from the operating, security and environmental point of view. For the reactor riser, many kinetic models have been proposed. They can be divided in two categories:

heavy lumped models and molecular based models. The later is more generic, but is only applicable with analysis at the molecular scale. Because of this complex analysis, the different groups of molecules are lumped by their boiling point and treated as pseudo-components for a global description of the phenomena taking place in reactor [2].

The potential of yielding more market-oriented oil products, increasing production rate and stabilizing the operation become the major incentives to search for more accurate and practical models and high performance, cost effective and flexible control strategies.

2. MATHEMATICAL MODEL OF THE FCCU

The FCCU complex behavior in the presence of disturbances has been done using the mathematical model of the process. To obtain a mathematical model of the FCC process it was necessary to write mass, energy, moment and conservation equations; equation to describe physical and chemical processes that are taking place in the system and it was obtained, by this way, an analytic mathematical model [3]. It was also studied and identified the equations that correlate the input and output variables by using statistical techniques and it was obtained a new dynamic mathematical model for the FCCU that incorporates process hydrodynamics, heat transfer, mass transfer and catalytic cracking kinetics [4].

The model has been developed on the basis of reference construction and operation data from an industrial unit: ROMPETROL Refinery, Romania. The new FCCU mathematical model includes the main systems: feed and preheat system, reactor (riser and stripper), regenerator, air blower, wet gas compressor catalyst circulation lines and the main fractionator. The novelty of the model consists in that besides the complex dynamics of the reactor-regenerator system it also includes the dynamic model of the fractionator and in this way it can be possible to study the to study its dynamic effects on the overall system. The global model also includes a five lump kinetic model (namely: gas-oil, gasoline, diesel, gases and coke) capable to predict the yields of valuable products and gasoline octane value [5].

The resulted global model of the FCCU is described by a complex system of partial-differential-equations, which was solved by discretizing the kinetic models in the riser and regenerator on a fixed grid along the height of the units, using finite differences. The resulted model is a very high order differential-algebraic equations system (DAE), consists of 933 differential algebraic equatios (ODEs): 133 equations derived from material and energy balances and 800 resulted from the discretization of the kinetic model and with more than 100 algebraic equations. The plant simulator was implemented in C++ programming language for efficient solution and it was compiled in Matlab/Simulink programming language because it has a friendly user graphic interface. The model captures the major dynamic effects that can occur in an actual FCCU system. It is multivariable, strongly interacting and highly nonlinear.

3. SIMULATION RESULTS

The new developed simulator gives useful information regarding the dynamic behavior of the global reactor-regenerator-fractionator system and predicts the composition of the main products (gasoline and diesel) in the case of different disturbances that can appear during the process. Different sets of disturbances have been studied and the evolutions of the most representative process variables in the presence of the slurry recycle flow rate changes in the Figure 2.

The **slurry recycle flow rate** disturbance could appear due to the raw-material fresh feed rate change or due to the changes in the valve position on the slurry circulation line. A decrease by 30% in the slurry recycle rate determine the increase of the regenerated catalyst flow which increase the catalyst-to-oil ratio and this leads to a fast increase of coke in the riser *($coke_{riser}$)*. This coke amount in regenerator decreases the regenerator temperature *(T_{reg})* by 1.5 ^{0}C, and also the reactor temperature *(T_r)* by 0.8 ^{0}C. The increase of the reactor temperature leads to an intensification of the cracking reactions, with the effect of the reactor pressure *(P_r)*. The small increase of the reactor pressure influences the spent catalyst flowrate *(F_{sc})* (0.6% increase). The flowrate of regenerated catalyst (F_{rgc}) increases by 0.3% and for this reasons, reactor catalyst inventory *(Wr)* increases by 2 tons and in the regenerator catalyst inventory *(W_{reg})* increases by 0.07 tons. Because the spent and regenerated catalyst increase and the coke production in riser also increases, the carbon production in regenerator increases and the combustion in the regenerator is performed in an excess of oxygen; the O_2 amount *(X_{O2})* increase with 20% and the CO_2 amount (X_{CO2}) increases with 9.8%. This disturbance influence catalyst-to-oil ratio and also the products profile in main fractionator, gasoline composition on the top of the column decrease by 1.2 % and on top it increases by 0.05% which could have an a significant economical impact on the plant profit.

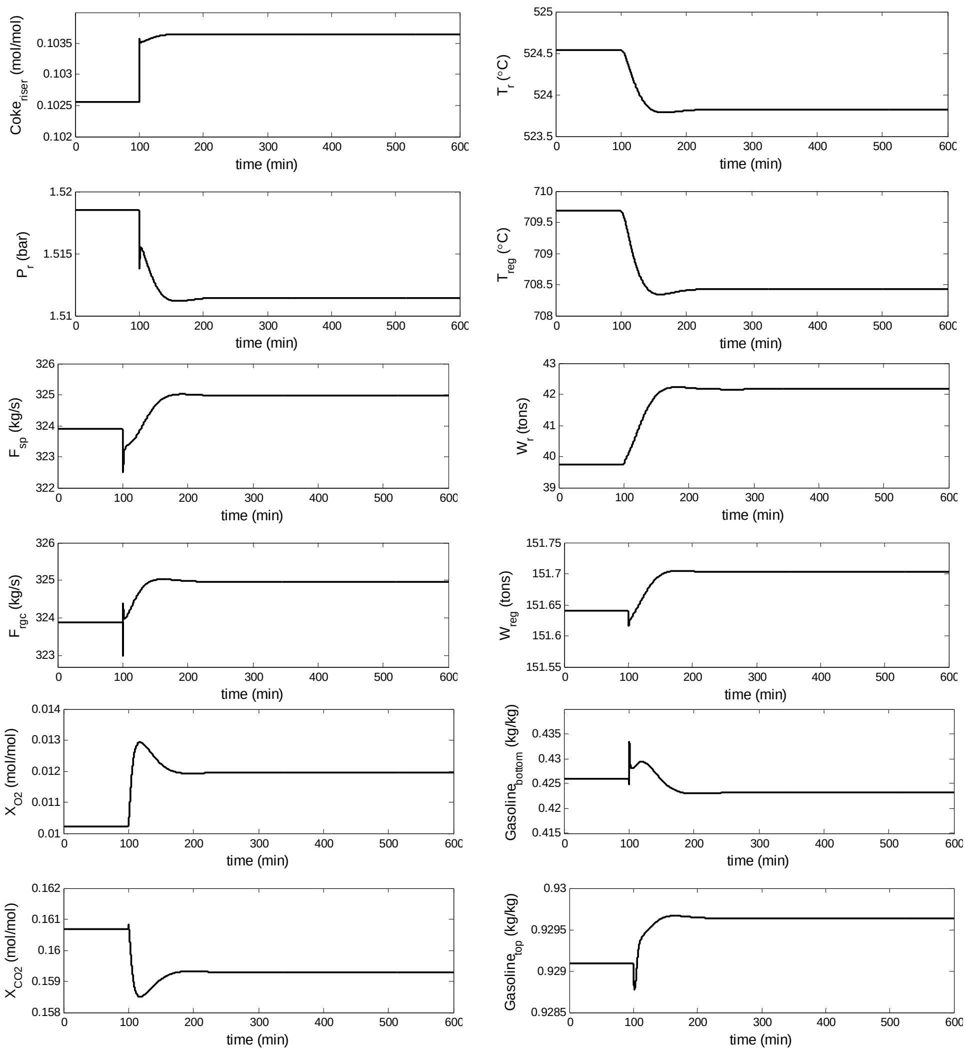

Figure 2. Simulation of FCCU dynamic behavior in the presence of slurry recycle flow rate disturbance (30% decrease at t=100 min)

4. ECONOMICAL ASPECTS

With this simulator it was possible not only to study the process behaviour but it is also possible to investigate the plant gross profit and gasoline octane number, in order to take logical decision concerning the increase in the plant profitability.

Gross Profit of the FCCU can be expressed as follows [6]:

Profit=column flow x gasoline composition x cost gasoline+
+ column flow x diesel composition x cost diesel–
raw material flow x gasoil cost (1)

Gasoline octane number

The motor octane number (*MON*) and the research octane number (*RON*) have the following expressions [6]:

$$MON = 72.5 + 0.05(T_r - 900^0 K) + 0.17(conversion - 0.55) \quad (2)$$

$$RON = 1.29MON + 12.06 \quad (3)$$

The gasoline octane number (CO) can be calculates with the following formula:

$$CO = \frac{MON + RON}{2} \quad (4)$$

The Plant Gross Profit and Gasoline Octane Number are sensitive in the presence of the slurry recycle flow rate changes as follows:

- 30% decrease in the slurry recycle rate can decrease the plant profit with 7.8% and
- 30% decrease in the slurry recycle rate determine the increase of the *CO* from 93.44 to 93.48

5. CONCLUSIONS

The dynamic behavior of this complex petrochemical process in a wide range of operating conditions and in the presence of disturbances was analyzed by using dynamic mathematical modeling. The new FCCU developed model is sufficiently complex to capture the dynamic effects that occur in an actual FCCU system and is able to depict the main dynamic characteristics of a typical commercial FCC process. Simulations demonstrate the process is multivariable, strongly interacting and highly nonlinear. With the new simulator, economical aspects can be studied (Gross Profit and Gasoline Octane Number). The developed complex model is a very efficient tool to study and to improve the design, safe operation and performance of a modern catalytic cracking unit.

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