The Model Predictive Control System for the Fluid Catalytic Cracking Unit

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Abstract: - The fluid catalytic cracking unit (FCCU) is one of the most important and complicated process in the refining industry. The catalyst performance and the advanced control system have contributed to the increase of the gasoline production and to increase of the plant profit. One concept of the advanced control is represented by model based predictive control. The paper studies the predictive controller applied to the FCCU. The topics approached in the paper are: the structure of the catalytic cracking process, the process modeling, the overview of the model based predictive control concept and the development of the predictive controller for the FCCU. In the last part will be outlined the performance that can be obtained using the model predictive controller for FCCU.

Key-Words: - FCC, modeling, simulation, control, model predictive control, optimization

1. Introduction

It is well know that the fluid catalytic cracking unit is a complex process, both from modeling and from the control point of view. The FCCU is difficult to control due: i) the nonlinear character of the process; ii) the strong interaction between the variables of the process; iii) the multivariable character of the process; iv) a big difference between time constants of the process; v) the necessity to control system with changing operating conditions in the presence unmeasured disturbances.

The literature is relatively rich in modeling and simulation studies of the FCCU. Some of the works deal with the kinetic models of the catalytic process [1, 2, 3]. Another category of works is focused on the reactor modeling, in a steady-state or dynamic regime, using a certain kinetic model of the catalytic cracking process [4, 5]. A much more reduced category of works deal with aspects of the advanced process control of the FCCU, the proposed control algorithms being tested by mathematical model of the process [6, 7].

The objective of this work is to elaborate a mathematical model of catalytic cracking, that be used in developing, testing and implementing a predictive control system that can be applied to the FCCU.

2. Process descriptions

The fluid catalytic cracking unit, presented in figure 1, contains two components: the reactor and the regenerator. Because the modeling of the process is very difficult, the authors have proposed the decomposition of the process in four sub-processes, figure 2 [8]. The sub-processes are:

- The interfusion node sub-process is located at the reactor base and is designed for the instantaneous vaporization of the feedstock at direct contact with the regenerated catalyst.
- The riser sub-process is a plug flow tubular reactor where takes place the chemical reactions.
- The stripper sub-process, located at the top reactor, contains a cyclones system for the gaseous phase separation of the feedstock and the reaction products in the from the catalyst particles.
- The regenerator sub-process is represented by a complex system, assimilated to a reactor with perfect mixing, which the target is the catalyst regeneration by the partial burning of the coke deposited on the catalyst.

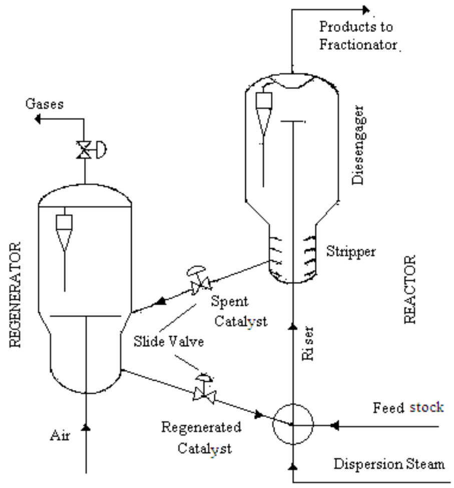

Fig. 1. The industrial fluid catalytic cracking unit.

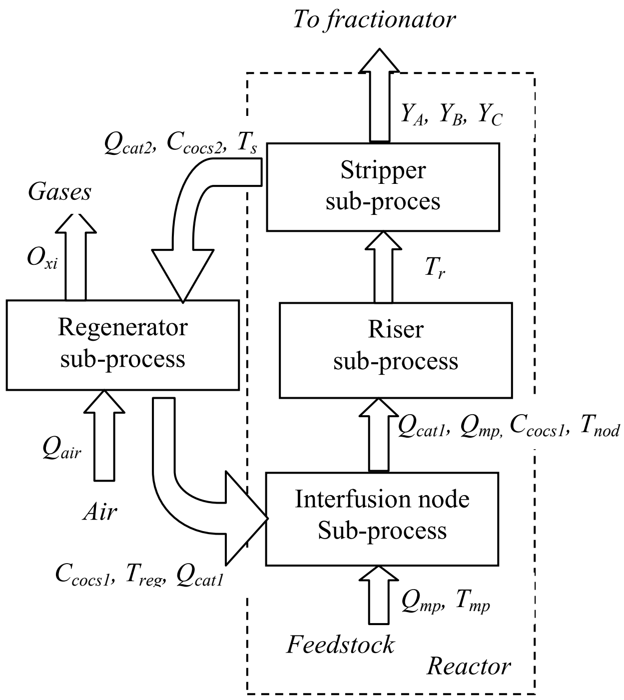

Fig. 2. The sub-process of the FCC.

The significance of the variables is the following: Q_{mp}, T_{mp} – feedstock flow rate and temperature; Q_{cat1} – regenerated catalyst flow rate; T_{nod} - interfusion node temperature, C_{cocs1} – the mass fraction of the regenerated catalyst coke; T_{reg} – the regenerated catalyst temperature T_r –riser outlet temperature; Y_A – the feedstock concentration, Y_B – the gasoline concentration, Y_C - the gas and coke concentration in reactor, C_{cocs2} – the mass fraction of the coke deposited on the catalyst after the cracking reaction, Q_{cat2} – spent catalyst flow rate; T_s – stripper temperature; Q_{air} – mass flow rate air to regenerator; O_{xi} – oxygen mole fraction in regenerator. Each sub-process is characterized by the steady-state model or the dynamical model.

3. The mathematical model of the FCC

The mathematical model of FCC contains four models: the model of the interfusion node, the model of the riser, the model of the stripper and the model of the regenerator.

3.1. The model of the infusion node sub-process

The model of the interfusion node is represented by a heat balance in the steady state regime [9]. The temperature of the interfusion node T_{nod} is calculated with the relation:

$$T_{nod} = \frac{Q_{cat1}\, c_{p,cat}\, T_{reg} + Q_{mp}\, c_{p,mp}\, T_{mp} - \Delta H_{vap}\, Q_{mp}}{Q_{cat1}\, c_{p,cat} + Q_{mp}\, c_{p,mp}} . \qquad (1)$$

where $c_{p,cat}$ - heat capacity of the catalyst; $c_{p,mp}$ - heat capacity of the feedstock; H_{vap} – feedstock vaporization enthalpy.

3.2. The model of the riser sub-process

The mathematical model of the riser subsystem is structured in the next components: kinetic model, material and heat balance.

3.2.1. The kinetic model

In the specialized literature there are know the following kinetic models of the fluid catalytic cracking process: Weekman model [1], Ginetto model [2], Mobil model [3]. The authors have chosen the Weekman kinetic model, because the model is simple and robust kinetic model. The Weekman's kinetic model is a deltoid reaction scheme what describes the cracked the feedstock into gas oil, coke and gases. The rates of the three reactions are definition by the relations

$$\begin{cases} r_1 = -k_1 \cdot Y_A^2 \\ r_2 = -k_2 \cdot Y_B \\ r_3 = -k_3 \cdot Y_C^2 \end{cases} . \qquad (2)$$

Constant rates reaction k_1, k_2, k_3 are dependent on the feedstock nature, the temperature in the riser and the activity of the equilibrium catalyst.

3.2.2. Material balance

The riser is considered a plug flow tubular operated adiabatically and the material balance equations have the form

$$\begin{cases} \dfrac{dY_A}{dz} = -\dfrac{1}{U_v} * (k_1 + k_3) * Y_A^2 \\ \dfrac{dY_B}{dz} = \dfrac{1}{U_v} * (k_1 * Y_A^2 - k_2 * Y_B) \\ \dfrac{dY_C}{dz} = \dfrac{1}{U_v} * \left(k_2 * Y_B + k_3 * Y_A^2\right) \end{cases} \qquad (3)$$

where U_v represents vapor's rate.

3.2.3. Heat balance

The heat balance is represented by differential equation

$$\frac{dT_r}{dz} = \frac{\left(-\Delta H_{r1}\right) * Q_{rA}}{Q_{feed}\left(Y_A c_{p,A} + R_{steam} c_{p,steam} + R_{cat} c_{p,cat}\right)}, \qquad (4)$$

where Q_{rA} is raw material, Q_B - gasoline mass flow, Q_{cat} - catalyst mass flow, Q_{steam} - steam mass flow.

3.3. The model of the stripper

The mathematical model of the stripper sub-process is based on the hypothesis of the perfect mixing. The dynamic model has two components: the material balance associated to the coke deposed on the catalyst and the energy balance in the strippers. The equations have the next form:

$$W_s \frac{dT_s}{dt} = Q_{cat1}\, T_r - Q_{cat2}\, T_s \tag{5}$$

$$W_s \cdot \frac{dC_{cocs2}}{dt} = Q_{cat1} C_{cocs1} - Q_{cat2} C_{cocs2} \tag{6}$$

where W_s – holdup catalyst in separator.

3.4. The model of the regenerator sub-process

The regenerator model used by the authors is according to Erazu's model. This model contains the material balance associated to the coke, the material balance associated to the oxygen and the energy balance [10].

3.5. The process simulation

The mathematical model previously presented was implemented using Matlab® simulation environment. The mathematical model has been validated by authors using industrial data [11].

3.6. Simplified dynamic process model

A key step to the implementation of the model based predictive control structure is to determinate a simplified model of the process. From a point of view of the control algorithms, there is preferred an input-output representation for the simplified models. To determine the simplified model for the catalytic cracking process the authors propose the identification scheme presented in the figure 3.

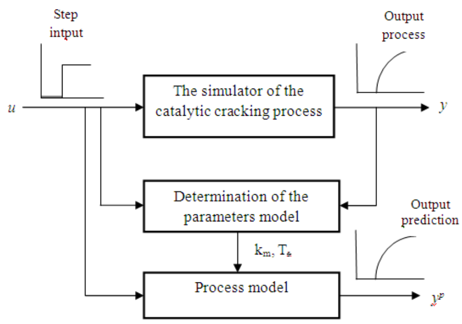

Fig. 3. The identification scheme

This identification method is based on the simulator developed by authors and presented in the paper [8]. Practically, the identification method of the simplified model of the process consist the three steps.

The first step is represented by an input - output informational characterization conform to the sub-process (reactor and regenerator), which build the catalytic cracking process, as well as the interaction that occur between them, illustrated in figure 4.

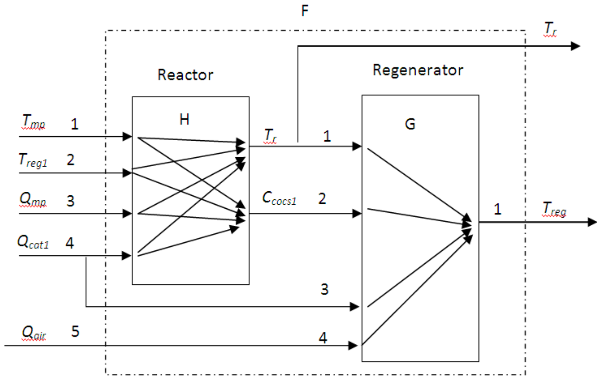

Fig. 4. The input-output informational characterization.

The second step consists in determination of the transfer function type that corresponds to each channel of the both sub-process. In this case, based on information about process is considerate that each channel can be characterized by a first order transfer function without dead time, by the formulation

$$M(s) = \frac{k_m}{T_s \cdot s + 1}\ , \tag{7}$$

where k_m is the gain and T_s time constant.

The transfer functions associated to the reactor are named with ***H***, the transfer functions associated to the regenerator are named ***G*** and the transfer functions of overall process are named ***F***. The ***H*** and ***G*** transfer functions have been determinate for a steady-state operating point. The global transfer function ***F*** was determined by arithmetic calculations.

The last step consists in the determination of the parameters associated to the transfer function for each channel corresponding to the reactor sub-process and the regenerator sub-process. The method used for determination of parameters k_m and T_s associated to transfer function is the graphic method proposed in the paper [12]. In the table 1 are presented the relations which describe the simplified model of the process after the identification procedure.

4. Model based predictive control system of the FCCU

The Model Based Predictive Control is one of the advances control methods, which can handle these control problems efficiently. The predictive controller contains two components: the model process and an optimal module [13, 14]. In figure 5 there is illustrate the structure of a MBPC system.

Table 1. The transfer functions of the simplified model used by implementation of the MBPC.

Input \ Output	Riser outlet temperature	Regenerator temperature
Feedstock temperature	$F_{11}(s)=\dfrac{0.17}{0.048s+1}$	$F_{21}(s)=\dfrac{0.0045s^2+0.105s+0.165}{0.00064s^4+0.029s^3+0.386s^2+1.163s+1}$
Regenerated catalyst temperature	$F_{12}(s)=\dfrac{0.76}{0.048s+1}$	$F_{22}(s)=\dfrac{0.025s^2+0.465s+0.715}{0.00082s^4+0.033s^3+0.401s^2+1.177s+1}$
Feedstock flow	$F_{13}(s)=\dfrac{-7.72\cdot 10^{-4}}{0.052s+1}$	$F_{23}(s)=\dfrac{-2.059\cdot 10^{-4}s^2-0.00045s-0.00072}{0.00072s^4+0.031s^3+0.39s^2+1.165s+1}$
Regenerated catalyst flow	$F_{14}(s)=\dfrac{1.751\cdot 10^{-4}}{0.062s+1}$	$F_{24}(s)=\dfrac{-1.65\cdot 10^{-7}s^4-5.29\cdot 10^{-6}s^3-3.562\cdot 10^{-5}s^2}{0.00035s^5+0.016s^4+0.22s^3+0.95s^2+1.64s+1}-$ $-\dfrac{-8.16\cdot 10^{-5}\cdot s+6.038\cdot 10^{-5}}{0.00035s^5+0.016s^4+0.22s^3+0.95s^2+1.64s+1}$
Air flow	$F_{15}(s)=0$	$F_{25}(s)=\dfrac{0.0028}{0.48s+1}$

It is known that the main objectives of the FCCU are to the maximization of the yield gasoline. This desiderate is achieved if in the reactor take place a good conversion and in the regenerator is obtain a good combustion. In practice, the riser outlet temperature is used to control the conversion and the regenerator temperature is used to control the combustion.

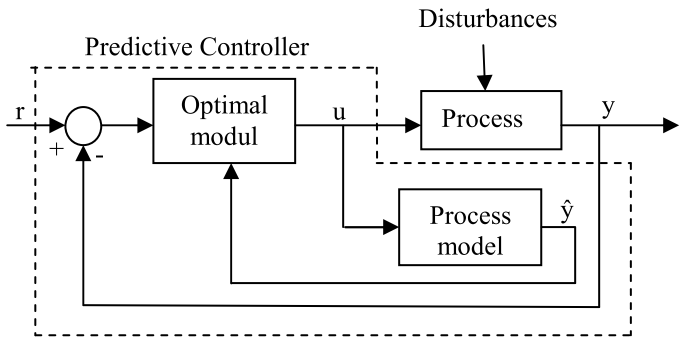

Fig. 5. The MBPC structure.

A conceptual representation of the predictive control structure associated to the catalytic cracking process is presented in figure 6. The input variables of the predictive controller are:

- measured disturbances of the process (the feedstock temperature – T_{mp}, regenerated catalyst temperature - T_{reg1}, feedstock flow - Q_{mp});
- the set point of the controller (optimal riser outlet temperature - T_r^i and optimal regenerator temperature - T_{reg}^i);
- the feedback variables of the process (riser outlet temperature – T_r and regenerator temperature - T_{reg}).

Regarding the manipulated variables of the controller, these are the regenerated catalyst flow – Q_{cat1} and air flow in the regenerator – Q_{air}.

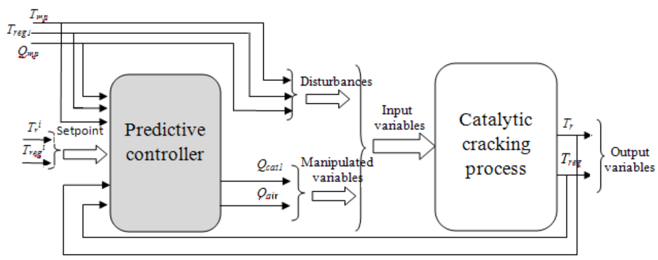

Fig. 6. The predictive control structure of the catalytic cracking process

6. The simulation results

Investigation performance of the predictive control system consists in the modification of the set point (riser outlet temperature T_r, the regenerator temperature T_{reg}) and the disturbances which appears in the process (the feedstock flow Q_{mp}, the feedstock temperature, and the regenerated catalyst temperature T_{reg1}). The investigation was based on the modification of the controller tuning parameters. For the multivariable predictive controller are considered the following default simulation parameters:

- Prediction horizon is p=100 intervals;
- Control interval is T= 0.0012h;
- Control horizon is M=19 control intervals

To determining the performance of the predictive control structure, the authors run three types of tests.

The A test, which consist in modifying the references of the controller (riser outlet temperature T_r, the regenerator temperature T_{reg1}) in step variations. In figures 7 and 8 are presented the evolution in time of this variable, together with the manipulated variables associate (Q_{cat1} and Q_{air}). As can be seen from the above trends, the multivariable controller system successes fully bring the output values to the set point values, without state steady error.

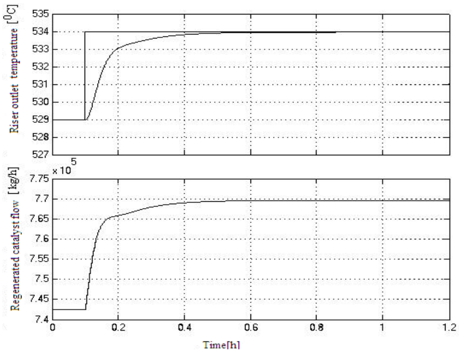

Fig. 7. The dynamic evolution of the riser outlet temperature and regenerated catalyst flow when the controller setpoint - T_r increases from 529 ^{0}C to 534^{0}C.

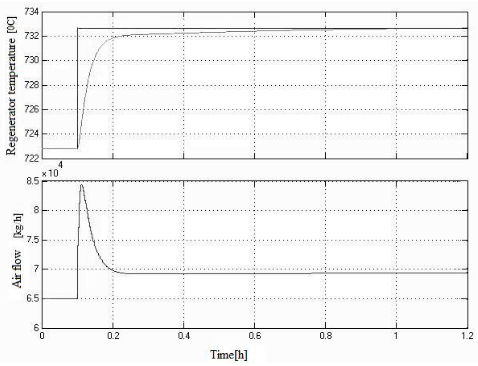

Fig. 8. The dynamic evolution of the regenerator temperature and air flow rate when controller set point - T_{reg1} increases from 722.97^{0}C to 732.97 ^{0}C

The B test consists in to modify the disturbance of the system. In figure 9 and 10 are presented the evolution in time of the riser outlet temperature - T_s, the regenerated catalyst temperature T_{reg1} and the manipulated variable associated when one of the disturbances (here feedstock temperature) is change.

From results associated to the B test can be observed that the control system eliminates the effect of the distributions which appear in the process.

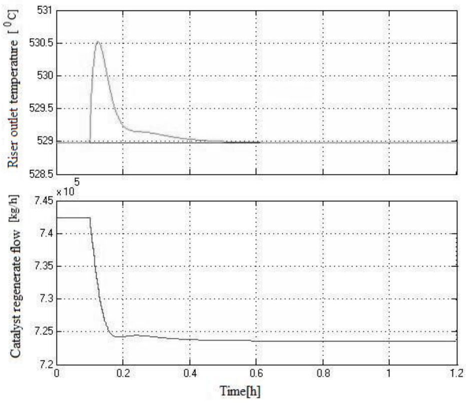

Fig. 9. The dynamic evolution of the riser outlet temperature and regenerated catalyst flow when the feed stock temperature increases from 195 ^{0}C to 215 ^{0}C

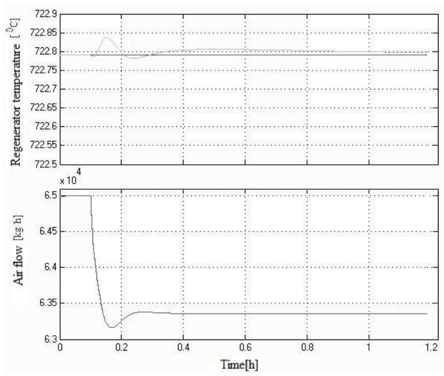

Fig. 10. The evolution in time of the regenerated catalysts temperature and air flow when the feedstock increases from the 195^{0}C to 215 ^{0}C.

The C test consists to modifying the tuning controller parameters. In case when the control interval increases from 0.0012h to 0.0024h, it will be see that the achieve the values of the set point is make with an increasing of the transient time, figure 11 and 12.

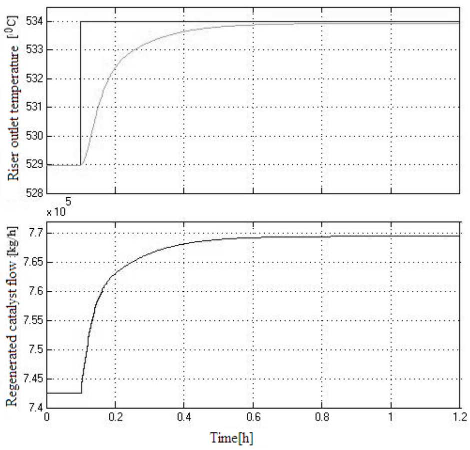

Fig. 11. The dynamic evolution of the riser outlet temperature and regenerated catalyst flow when the temperature riser controller set point increases from 529 ^{0}C to 534^{0}C and the control interval is 0.024h

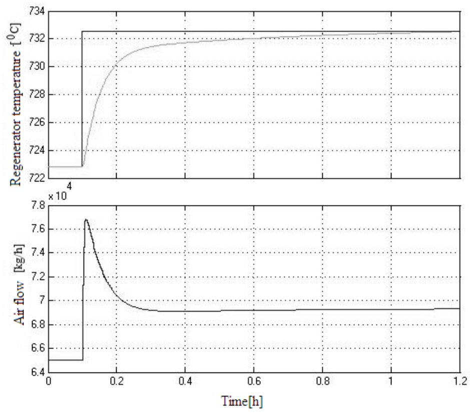

Fig.12. The dynamic evolution of the regenerator temperature and air flow trend when the temperature regenerator controller set point increases from 722.97 ^{0}C to 732.97 ^{0}C and the control interval is 0.0024h.

7. Conclusion

In this paper there are presented aspects of modeling the catalytic cracking fluid process in order to elaborate a predictive control structure associated to the catalytic cracking process. The main contributions brought by the authors within this paper are:

- The mathematical modeling of the fluid catalytic cracking process in a structural manner. This approach implies the decomposition of the whole process into sub-processes on topological and functional criteria.
- The structural approach attributes to the mathematical model robustness, clarity and the possibility of testing and/or modifying independently the mathematical models corresponding to sub processes, without affecting his assembly.
- Determination of simplified model which captures the dynamic of the process, and can be used by the MBPC Controller.
- As can seen from the above trends, the behavior of the process and control system was studied for different values of turning parameters, observing that a increasing of the control interval can lead to an increasing of the transient time. Also can be observed that the process output values follow the setpoint value with the best dynamic performance for the default values of the turning parameters.
- The control system eliminates the effect of the distributions which appear in the process.

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