Nonlinear quadratic dynamic matrix control of a fluidized catalytic cracking unit

A.T. BOUM[*], D. BINGONG[**], J.P. CORRIOU[***]
[*] University of Douala,
ENSET, B.P 1872 Douala,
CAMEROON
boumat2002@yahoo.fr
[**] University of Douala,
EDSFA, UFD MIAPF,
CAMEROON
davidbingong@yahoo.fr
[***] University of Lorraine
LRGP, UMR 7274, Nancy,
FRANCE
jean-pierre.corriou@univ-lorraine.fr

Abstract: This paper present the application of a nonlinear model predictive control strategy to an fluidized catalytic cracking (FCC) unit. The FCC is a complex nonlinear process that has been the subject of many models and control studies. The present dynamic model of the FCC process, inspired from Blacken model, uses three lump kinetics to describe the cracking reactions in the riser considered as a plug-flow system. The riser behaviour is described by gasoil, gasoline, coke and energy balances. The separator is considered as a CSTR. The regenerator mainly constituted by a dense and a dilute zone is also considered as a CSTR to represent the catalyst and its dynamic behaviour is described by coke, oxygen and energy balances. This model is sufficiently complex to capture the major dynamic effects that occur in an FCC and to control the key variables that are the riser outlet temperature and the regenerator dense bed temperature. The manipulated inputs are the air inlet flow rate in the regenerator and the regenerated catalyst flow rate. Hard constraints are imposed with respect to the manipulated variables. In spite of the important nonlinearity of the FCC, Nonlinear quadratic dynamic matrix control is able to maintain a smooth multivariable control of the plant, while taking into account the constraints. The comparison study with linear quadratic dynamic matrix control shows a better following of the set point.

Key-Word: Nonlinear, Predictive control, fluid catalyst

1. Introduction

Fluid Catalytic Cracking (FCC) is one of the most important processes in a refinery, in particular due to its economic importance [1]. An FCC is used to crack heavy atmospheric residues and vacuum distillate into lighter molecules that yield more valuable products such as gasoline, kerosene, light gas oil …The FCC unit is a complex process due to the composition of the feed and the dynamic mass and heat interactions between its main components, namely riser, separator and regenerator, with recycling effects. Thus, while respecting the environmental regulation and operating constraints, the gains that can come from an improvement in the optimal control of this process make it a challenge to science and engineering in the field of automation and call for an advanced control tool. Nonlinear Model Predictive Control (NMPC) is presently used due to its capacity to easily handle multivariable processes while also taking into account hard and soft constraints with respect to the manipulated variables, their moves and the controlled variables and also the better following of set point.

FCC control has been performed by means of different approaches [10, 12, 13, 15]. In practice, FCC units are frequently regulated using PID controllers based on the knowledge

and experience of operators in the refinery.
In this work, Nonlinear Model Predictive Control with the algorithm named nonlinear quadratic dynamic matrix control (NQDMC) is used to control the FCC using two manipulated variables and two controlled variables. Section 3 describes the FCC model. Section 4 deals with NQDMC principles. Section 5 deals with the control of the FCC unit and presents the simulation results. Section 6 deals with the comparison study between QDMC and NQDMC. Finally, the conclusions of the paper are presented in Section 7.

2. Description of a modern FCC process

A modern FCC unit mainly consists of three units [3]. The cracking reactions of the hydrocarbon feed take place in the riser while the catalyst is reactivated in the regenerator by combustion of the coke deposited on the catalyst in the riser reactor.
The feed is preheated at a temperature in the range 450-600K. Thereafter, this feed is injected in the bottom part of the riser with a small quantity of vapor. The feed is vaporized at the contact of the hot catalyst. The hydrocarbon vapors undergo an endothermic reaction while rising to the top of the riser. The residence time of the catalyst and the hydrocarbon vapors in the riser is a few seconds. The temperature at the top of the riser is between 750 and 820K. The disengagement part of the reactor is used to separate the catalyst from the vapors, then the vapors enter the main fractionator. The spent catalyst is separated from the vapors by cyclones and flows in the extraction part where the remaining hydrocarbons on its surface are removed by stripping steam. The catalyst flows through a transport line to the regenerator.
In the regenerator, the catalyst is reactivated by burning the deposited coke using air entering at the bottom of the regenerator. This partial or total exothermic combustion reaction reactivates the catalyst and maintains the bed temperature between 950-980K for future gasoil cracking. The regenerated catalyst flows continuously in the riser through another circuit and the heat transported by the catalyst is used to compensate the endothermic reactions in the riser.

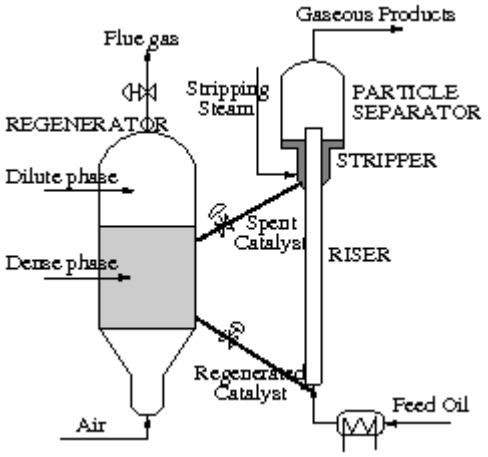

Fig. 1. Schematic diagram of FCC unit.

3. Mathematical model of the FCC

The FCC model that is used in this work is inspired and adapted from [2, 8, 9], this model derives in a great part from the model proposed by [11].

3.1 Riser model

The riser is considered as a plug flow reactor. The residence time of catalyst and feed in the riser is supposed to be a few seconds. Consequently, the riser is only described by spatial equations and considered as an algebraic system. The kinetic model makes use of a three lump scheme [16] to describe the cracking in the riser [5].
The feed temperature $T_{ris}(z=0)$ at the entry of the riser results from the energy balance. z is a dimensionless height $\in [0,1]$.

Mass balance of gas oil

$$\frac{dy_{go}}{dz} = -k_1\, y_{go}^2\, C_{owr}\, \phi\, t_{c1} \qquad (1)$$

where k_1 is the kinetic constant for gasoil consumption, $COWR$ is the catalyst to oil ratio, y_f is the mass fraction of gasoil in the riser, t_{c1} is the residence time of the catalyst in the riser at top. ϕ is the deactivation factor of the catalyst due to coke deposition

Mass balance of gasoline

$$\frac{dy_g}{dz} = (\alpha_2\, k_1\, y_{go}^2 - k3\, y_g)\, C_{owr}\, \phi\, t_{c1} \qquad (2)$$

Energy Balance

$$\frac{dT_{ris}}{dz} = \frac{\Delta H_{crack} F_{feed}}{(F_{regcat} C_{pcat} + F_{feed} C_{po} + \lambda F_{feed} C_{psteam})} \frac{dy_{go}}{dz} \qquad (3)$$

Where ΔH_{crack} is the heat of reaction, F_{feed} and F_{regcat} are the flow rates of gasoil and catalyst respectively. The kinetic constants follow Arrhenius law. The catalyst deactivation by coke deposition is given as

$$\phi = (1 - m\, C_{cokereg})\, \exp(-\alpha\, t_{c1}\, z\, C_{owr}) \quad (4)$$

The produced coke concentration is empirically given by

$$C_{cokeprod} = k_c \sqrt{\frac{t_{c1}}{C_{rc}^N} \exp\left(\frac{-E_{acf}}{RT_{ris,1}}\right)} \quad (5)$$

where $T_{ris,1}$ is the temperature at the riser outlet. The amount of coke concentration leaving the riser is

$$C_{cokeris,1} = C_{cokereg} + C_{cokeprod} \quad (6)$$

3.2 Separator model

The residence time of catalyst in the separator is frequently of the order of one minute. This separator can be modelled as a perfectly mixed tank.

Mass balance of coke on catalyst

$$\frac{dC_{cokesep}}{dt} = \frac{F_{regcat}\,(C_{cokeris,1} - C_{cokesep})}{m_{catsep}} \quad (7)$$

Energy balance

$$\frac{dT_{sep}}{dt} = \frac{C_{pcat}\, F_{regcat}\,(T_{ris,1} - T_{sep})}{m_{catsep}\, C_{pcat}} \quad (8)$$

3.3 Regenerator model

The regenerator model is inspired from [7]. The regenerator is a fluidized bed where air bubbles cross the dense bed formed by the catalyst. This bed is considered as a CSTR where the residence time of catalyst is frequently between ten to twenty minutes. The air bubbles through the bed could be modelled as a plug flow, but for ease of simulation, they are modelled as a CSTR. The temperature and amount of coke are considered uniform throughout the dense bed as well as the oxygen concentration. An important feature of the FCC is that the reactions in the riser are mainly endothermic whereas those in the regenerator are exothermic, thus the heat released in the regenerator is used by the riser by means of the transported catalyst. As the FCC process involves catalyst recycling, its behavior is difficult to simulate correctly in steady state and transient state.

Mass Balance of coke on the catalyst

$$\frac{dC_{cokereg}}{dt} = \frac{(F_{spentcat}\, C_{coksep} - F_{regcat}\, C_{cokereg}) - \mathcal{R}_{cb}}{m_{catreg}} \quad (9)$$

Energy balance in the regenerator

$$\frac{dT_{reg}}{dt} = \frac{1}{(m_{catreg}\, C_{pcat})}[(T_{sep}\, F_{spentcat}\, C_{pca} + T_{air}\, F_{masregair}\, C_{pair} - T_{reg}\,(F_{regcat}\, C_{pcat} + F_{masregair}\, C_{pair}) - \Delta H_{cb}\, \frac{\mathcal{R}_{cb}}{M_{wcoke}}] \quad (10)$$

The kinetics of coke combustion is given by

$$\mathcal{R}_{cb} = k_{cb} \exp\left(-\frac{E_{acb}}{RT_{reg}}\right) x_{O2}\, C_{cokereg}\, m_{catreg} \quad (11)$$

Mass balance of oxygen in the dense bed

$$\frac{dx_{O2}}{dt} = \frac{1}{m_{airreg}}[F_{masregair}/M_{wair}\,(x_{o2,in} - x_{o2,reg}) - ((1+\sigma)\, n_{CH} + 2 + 4\,\sigma)/(4\,(1+\sigma))\, r_{cb}/M_{wcoke})] \quad (12)$$

Table 1. FCC data

Symbol	Meaning	value
F_{regcat}	mass flowrate of catalyst (kg.s^{-1})	294
F_{feed}	mass flow rate of feed (kg.s^{-1})	40.63
$F_{masregair}$	mass flow rate of air to regenerator (kg.s^{-1})	25.378
T_{air}	temperaure of air to regenerator (K)	360
T_{feed}	feed temperature (K)	434.63
T_{boil}	boiling temperature of the feed (K)	700
H_{vap}	heat of feed vaporization (J.kg^{-1})	1.5610^5
C_{po}	heat capacity of oil (J.kg^{-1}.K^{-1})	2671
C_{psteam}	heat capacity of steam (J.kg^{-1}.K^{-1})	1900
E_{af}	activation energy for cracking of gas oil (feed) (J.mol^{-1})	$101.5\ 10^3$
E_{ag}	activation energy for cracking of gasoline (J.mol^{-1})	
t_c	residence time in the riser(s)	$112.6\ 10^3$
E_{acf}	activation energy for coke formation (J.mol^{-1})	9.6
C_{pair}	heat capacity of air (J.kg^{-1}.K^{-1})	2089.5
H_{crack}	heat of cracking (J.kg^{-1})	1074
α_2	fraction of gas oil that cracks to gasoline	$506.2\ 10^3$
m_{catsep}	holdup of catalyst in separator (kg)	0.75
m_{catreg}	holdup of catalyst in regenerator (kg)	17500
m_{airreg}	holdup of air in the regenerator (mol)	175738
n_{CH}	number of moles of hydrogen per mole of carbon in the coke	20000
M_{wcoke}	molar weight of coke (kg.mol^{-1})	2

The parameters of the present FCC model are given in Table 1. A complete description can be found in [9]. The model is simulated in Fortran90.

4. Nonlinear quadratic matrix control

The principle used for nonlinear quadratic dynamic matrix control is shown in (Figure 2). The principle of operation of this nonlinear model predictive strategy is based on a successive linearization of a nonlinear model and the use of a linear model predictive control algorithm namely the quadratic dynamic matrix control during each samplingperiode to generated control inputs.

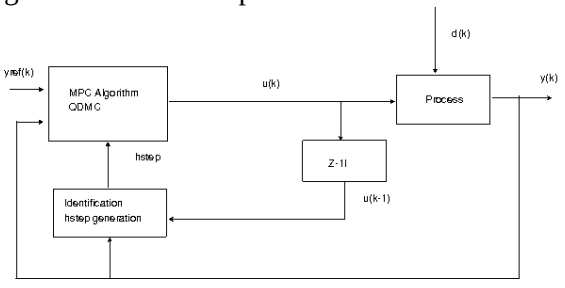

Fig. 2. Nonlinear mpc algorithm

For explanation purposes, first DMC is presented in a SISO framework [6]. A quadratic criterion taking into account the difference between the estimated output and the reference on the prediction horizon H_p is given by

$$J = \sum_{i=1}^{H_p} (\hat{y}(k+i|k) - y^{ref}(k+i))^2 \quad (13)$$

This criterion is minimized with respect to the variation of $\Delta u(k)$ of the input considered over a control horizon H_c.

The prediction of the ouput based on past and future inputs is

$$\hat{y}(k+l|k) = \underbrace{y_{ss} + \sum_{i=l+1}^{H_m-1} h_i \Delta u(k+l-i) + h_M(u(k+l-M) - u_{ss})}_{\text{past inputs effect}} + \underbrace{\sum_{i=1}^{l} h_i \Delta u(k+l-i)}_{\text{future inputs effect}} + \underbrace{\hat{d}(k+l|k)}_{\text{predicted disturbances}} \quad (14)$$

where h_M is the model horizon that must be larger than or equal to the prediction horizon. The output prediction based on past inputs is defined as

$$y^*(k+l|k) = y_{ss} + \sum_{i=l+1}^{M-1} h_i \Delta u(k+l-i) + h_M(u(k+l-M) - u_{ss}) \quad (15)$$

The vector of output predictions $\hat{y}(k+l|k)$ is related to the vector of ouput predictions $y^*(k+l|k)$ based on past inputs, to the vector of inputs $\Delta u(k)$ and to the vector of predicted disturbances as

$$\begin{bmatrix} \hat{y}(k+1|k) \\ \vdots \\ \hat{y}(k+H_p|k) \end{bmatrix} = \begin{bmatrix} y^*(k+1|k) \\ \vdots \\ y^*(k+H_p|k) \end{bmatrix} + A \begin{bmatrix} \Delta u(k) \\ \vdots \\ \Delta u(k+H_c-1) \end{bmatrix} + \begin{bmatrix} \hat{d}(k+1|k) \\ \vdots \\ \hat{d}(k+H_p|k) \end{bmatrix} \quad (16)$$

where A is the dynamic matrix made of step response coefficients h_i of the plant outputs to the manipulated inputs.

$$A = \begin{bmatrix} h_1 & 0 & \dots 0 \\ h_2 & h_1 & \vdots \\ \vdots & \vdots & \ddots \\ h_M & h_{H_c-1} & \dots h_1 \\ \vdots & \vdots & \vdots \\ h_M & h_{M-1} & \dots \quad h_{M-H_c+1} \\ \vdots & \vdots & \vdots \\ h_M & h_M & \dots h_M \\ \vdots & \vdots & \vdots \\ h_M & h_M & \dots h_M \end{bmatrix} \quad (17)$$

For a multivariable system of dimension $n_u \times n_y$ the dynamic matrix is simply composed of submatrices. As

$$A = \begin{bmatrix} A_{11} & \dots & A_{1n_u} \\ \vdots & & \vdots \\ A_{n_y1} & \dots & A_{n_yn_u} \end{bmatrix} \quad (18)$$

According to past equations, the vector of future input moves is given as

$$\Delta u(k) = [\Delta u_1(k)^T \dots \Delta u_{n_u}(k)^T]^T \quad (19)$$

which is the least-squares solution of the following linear system

$$\begin{bmatrix} y^{ref}(k+1) - y^*(k+1|k) - \hat{d}(k|k) = e(k+1) \\ \vdots \quad (20) \\ y^{ref}(k+H_p) - y^*(k+H_p|k - \hat{d}(k|k) = e(k+H_p) \end{bmatrix}$$

$$= e(k+1) = A\Delta u(k) \quad (21)$$

In the absence of constraints, the least-squares solution is

$$\Delta u(k) = (A^T A)^{-1} A^T e(k+1) \quad (22)$$

In order to take into account the constraints, QDMC is used instead of DMC. Furthermore, a modification of the quadratic criterion as the sum of a performance term and an energy term is introduced in QDMC. Hard constraints affecting the manipulated variables and their moves are taken into account

$$u_{min} \le u \le u_{max} \quad \Delta u_{min} \le \Delta u \le \Delta u_{max} \quad (23)$$

These constraints can be gathered as a system of linear inequalities incorporating the dynamic information concerning the projection of constraints

$$B\,\Delta u(k) \le c(k+1) \quad (24)$$

In the presence of constraints, the QDMC problem can be formulated as quadratic programming such as

$$\min_{\Delta u(k)} [\frac{1}{2}\Delta u(k)^T H \Delta u(k) - g(k+1)^T \Delta u(k)] \quad (25)$$

subject to constraints. H is the Hessian matrix which is equal to

$$H = A^T \Gamma^T \Gamma A + \Lambda^T \Lambda \quad (26)$$

where A is the dynamic matrix, Γ is a diagonal matrix of weights for the outputs, Λ is a diagonal matrix of weights for the inputs, g is the gradient vector that is equal to

$$g(k+1) = A^T \Gamma^T \Gamma e(k+1) \quad (27)$$

This quadratic programming problem can be solved efficiently by available subroutines [14]. The present MPC code has been developed in Fortran90 and is able to take into account any number of inputs and outputs, any type of constraint, with respect to the inputs, their moves or the outputs [6]. The version used in this article is based on step responses. The strategy to implement nonlinear quadratic matrix control is to carry out at each sampling time the identification of the process and use this algorithm to come out with a control law that is applied to the process.

5. Control of the FCC Process

In order to identify the FCC process, step responses are used. These coefficients of the step responses are generated in each sampling period and are used to build a dynamic matrix during each sampling period . As the process is multivariable and as imposed constraints on the manipulated variables are considered, the nonlinear quadratic dynamic matrix control algorithm is used. The controlled outputs are the riser temperature and the regenerator temperature. The manipulated inputs are the air flow rate to the regenerator and the regenerated catalyst flow rate

5.1 Identification

Step inputs are successively applied to the FCC model [3, 4] and the outputs are sampled with a sampling period 250s in order to obtain the step response coefficients according to Figure 3. The model horizon is equal to 60.

The identified step responses are represented in Figures 4, 5. The indicated normalized time is the number of sampling periods. The manipulated inputs are respectively the

regenerated catalyst flow rate u_1 and the air flow rate to the regenerator dense bed u_2. The controlled outputs are the temperature at the top of the riser y_1 and the regenerator temperature y_2. The step responses to u_1 show an algebraic effect followed by an inverse response. The algebraic effect is due to the immediate influence of the catalyst flow rate variation as the dynamic influence is neglected in the riser. The inverse response is more complex, the temperature first decreases due to the endothermic reactions in the riser, then it increases due to the exothermic reactions in the regenerator, but with a larger time constant in this latter. The influence of u_2 is simpler and the responses are close to first-order transfer function responses. For nonlinear quadratic dynamic matrix control, the identification process will be carried at each ampling period.

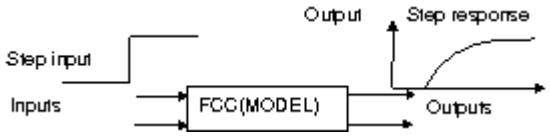

Fig. 3. Schematic diagram of Identification Process

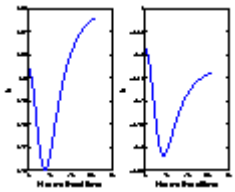

Fig. 4. Coefficients of the step responses between u_1 and y_1 (left) and between u_1 and y_2 (right)

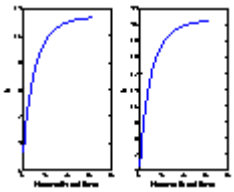

Fig. 5. Coefficients of the step responses between u_2 and y_1 (left) and between u_2 and y_2 (right)

5.2 Selection of the manipulated controlled variable pairings

The relative gain array is a valuable tool for the pairing of manipulated and controlled variable in a multivariable process. The selection of the manipulated and controlled variable are describe in [4].

5.3 Simulation results and discussions

The process is operated in partial combustion mode, opposite to complete combustion, i.e. the catalyst is not completely regenerated in the regenerator and some coke remains on the catalyst before entering the riser. The algorithms used to control the FCC unit are NQDMC and QDMC. The sampling period is 250s, the prediction horizon 60 (sampling periods) and the control horizon 3. Constraints are imposed on the manipulated variables ($u_1 \in [270, 320]$, $u_2 \in [24, 50]$). The two algorithms are executed and the results are compared. The simulation results (Figures 6, 7, 8, 9) show that, despite changes in the set points, the outputs follow the set points with small deviations, lower than 1 or 2K at the most, while the manipulated variables remain within the constraints.

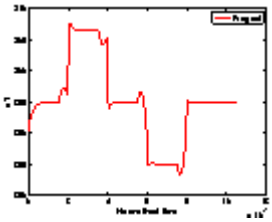

Fig. 6. Flow rate of regenerated catalyst u_1 (kg.s^{-1})

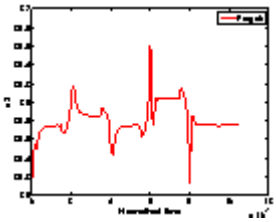

Fig. 7. Flow rate of air to the regenerator u_2 (kg.s^{-1})

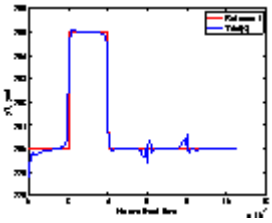

Fig. 8. Temperature at the top of the riser y_1 (K)

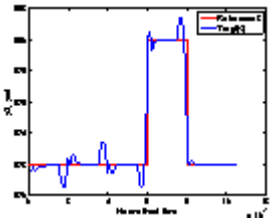

Fig. 9. Temperature in the regenerator y_2 (K)

Decoupled set points were imposed to put into evidence the coupling effects between inputs and outputs. Thus, the NQDMC controller used with the successive identification through step response coefficients is able to maintain the complex process outputs close to their respective variable sets points with very acceptable deviations.

The weights used in the criterion ($\Gamma = 10$, $\Lambda = 1$) were introduced to give more importance to the performance part than to the energy part of the criterion. The consequence is that the tracking is very correct, but that at the same time some rather steep variations of the inputs are imposed, such as clearly shown around set point changes.

6. Comparison between QDMC and NQDMC

The results of NLQDMC algorithm and QDMC algorithm are presented in 10, 11 12, 13, 14, 15, 16, 17. These results shows a great improvement in the control of the FCC unit by the nonlinear quadratic dynamic matrix control algorithm compare to quadratic dynamic matrix control which is a linear mpc algorithm.

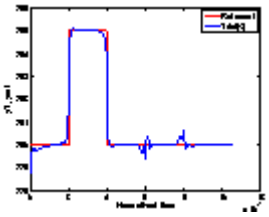

Fig. 10. Temperature at the top of the riser with nlqdmc y_1 (K)

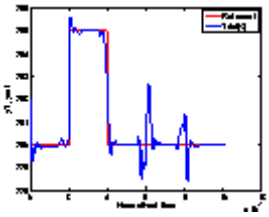

Fig. 11. Temperature at the top the riser with qdmc y_1 (K)

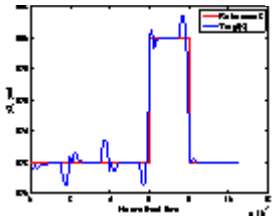

Fig. 12. Temperature a the top of the riser witl nlqdmc y_2 (K)

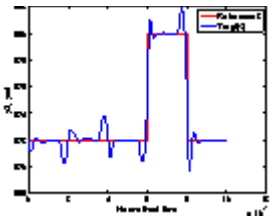

Fig. 13. Temperature at the top of the riser with qdmc y_2 (K)

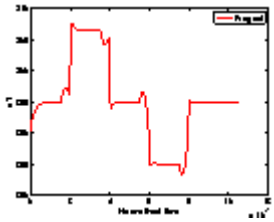

Fig. 14. Flow rate of regenerated catalyst with nlqdmc u_1 ($kg.s^{-1}$)

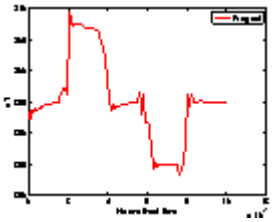

Fig. 15. Flow rate of regenerated catalyst with qdmc u_1 ($kg.s^{-1}$)

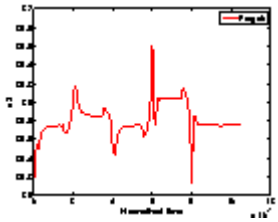

Fig. 16. Flow rate of air with nlqdmc u_2 ($kg.s^{-1}$)

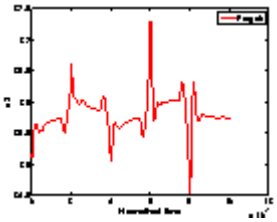

Fig. 17. Flow rate of air with qdmc u_2 ($kg.s^{-1}$)

Table 2. Quantitative comparative data

Parameters	NLQDMC	QDMC
Average time of simulation for one period of sampling (s)	5.21	0.07
Maximum going beyond on output 1 (K)	0.4	2.7
Maximum going beyond on output 2 (K)	1.5	2.2

7. Conclusion

In this work, a multivariable nonlinear quadratic dynamic matrix control algorithm based on successive step responses was implemented to control the FCC process with the regenerated catalyst flow rate and the flow rate of air to the regenerator as manipulated variables. The simulation results show a very good tracking of the temperatures at the top of riser and in the regenerator, despite strong interactions between the riser and the regenerator. The yield of products such as gasoline and, more generally, the overall yield of an FCC unit can be improved while taking into account the different constraints of the process. A comparative study was carried out with the quadratic dynamic matrix control algorithm and the results show an improved control of the FCC process with the use of the NLQDMC algorithm rather than the QDMC algorithm.

References:

[1] Ali, H., Rohani, S., and Corriou, J. (1997). Modelling and control of a riser type fluid catalytic cracking (FCC) unit. *Trans. IChemE.*, 75, part A, 401–412.

[2] Balchen, J., Ljungquist, D., and Strand, S. (1992). State- space predictive control. *Chem. Eng. Sci.*, 47(4), 787–807.

[3] Boum, A.T., Latifi, A., and Corriou, J.P. (2013). Model predictive control of a fluid catalytic cracking unit. In *Process Control (PC), 2013 International Conference on,*

335–340. doi:10.1109/PC.2013.6581433.
[4] Boum, A.T., Latifi, M., and Corriou, J. (2015). Multivariable control and online state estimation of an FCC unit.
[5] Corma and Martinez-Triguero (1994). Kinetics of gas oil cracking and catalyst decay on SAPO-7 and USY molecular sieves. *App Catal,* 118, 153-162.
[6] Corriou, J. (2003). *Commande des procédés.* Lavoisier, Tec. & Doc., Paris.
[7] Errazu, A., de Lasa, H., and Sarti, F. (1979). A fluidized bed catalytic cracking regenerator model grid effects. *Can. J. Chem. Engng.,* 57, 191-197.
[8] Hovd, M. and Skogestad, S. (1991). Controllability analysis for the fluid catalytic cracking process. *AIChE Annual Meeting.*
[9] Hovd, M. and Skogestad, S. (1993). Procedure of regulatory control structure selection with application to the FCC process. *AIChE J.,* 39(12), 1938-1953.
[10] Kurihara, H. (1967). *Optimal Control of Fluid Catalytic Cracking Process.* Ph.D. thesis, MIT.
[11] Lee, E. and Groves, F. (1985). Mathematical model of the fluidized bed catalytic cracking plant. *Trans. Soc. Comput. Sim.,* 2, 219-236.
[12] Moro, L.L. and Odloak, D. (1995a). Constrained multivariable control of fluid catalytic cracking converter. *Journal of Process Control,* 5, 29-39.
[13] Moro, L.L. and Odloak, D. (1995b). Constrained multivariable control of fluid catalytic cracking converters. *Journal of Process Control*, 5, 29-39.
[14] Schittkowski, K. (1985). NLPQL: A Fortran subroutine solving constrained nonlinear programming problems. *Ann. Oper. Res.*, 5, 485-500.
[15] Shridar, R. and Cooper, D. (1998). A novel tuning strategy for multivariable model predictive control. *ISA Transactions*, 36(4), 273-280.
[16] Weekman, V. and Nace, D. (1970). Kinetics of catalytic cracking selectivity in fixed, moving and fluid bed reactors. *AIChE J.*, 16(3), 397-404.

Journal of Engineering Science and Technology Review, 8(3), 158-168.