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Model predictive controller design of hydrocracker reactors

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Abstract

This study summarizes the design of a Model Predictive Controller (MPC) in Tüpraş Izmit Refinery Hydrocracker Unit Reactors. Hydrocracking process, in which heavy vacuum gasoil is converted into lighter and valuable products at high temperature and pressure is described briefly. Controller design description, identification and modeling studies are examined and the model variables are presented. WABT (Weighted Average Bed Temperature) equalization and conversion increase are simulated, results are discussed.

Key Words: *Refinery, process control, model predictive control, hydrocracker unit, reactor control*

1. Introduction

Turkish Petroleum Refineries Corporation (Tüpraş) is the largest industrial enterprise in Turkey. Tüpraş processes annually 28.1 million tones of crude oil in its four refineries, which are located in Izmit, Izmir, Kirikkale and Batman. Among all, Izmit refinery has the biggest capacity with 11 million tons annual crude oil processing.

Petrochemical industry has a dynamic market condition which tends to shift new areas of different processes for margin improvement. Among the technologies, solid catalyzed hydrocracking processes; converting vacuum gas oils (VGO) into more valuable lower boiling products, such as naphtha, jet fuel and middle distillates; are believed to be a promising technology because of its high product quality [1], [2]. Also, there is a need of high capacity complex controllers for complex multivariable units of hydrocrackers.

After privatization of Tüpraş in 2006, Operations Excellence Program was started for margin improvement. Application of Advanced Process Control (APC) is included in the program. Application of APC to one of the most profitable units; Hydrocracker Unit reactors will be presented in this article. After a brief definition of Hydrocracker unit, controller design in unit reactors will be introduced. After selection of manipulated and controlled variables, identification methods and details are given. Controller design is followed by the conversion control which is the focus of reactor control. In the last part results are represented by the help of the simulation which is constructed by real refinery data.

2. Process definition

An oil refinery is an industrial process plant where crude oil is processed and refined into more useful petroleum products, such as gasoline, diesel fuel, asphalt base, heating oil, kerosene, and liquefied petroleum gas [3], [4]. The growing demand for middle distillates and the increasing production of heavy crude oils have placed hydrocracking as one of the most important secondary and it is commonly practiced in the petroleum refining industry to treat oil residua [5]. Hydrocracking is the process of converting vacuum gas oils (VGO) into more valuable products, under high hydrogen pressure and catalytic condition [6]. Most of the conventional hydrocracking catalysts are dual functional catalysts. They have a hydrogenation- dehydrogenation function as well as an acidic function. The cracking activity is controlled mainly by the support that is acidic in nature, whereas the hydrogenation-dehydrogenation catalyst activity is due to the metals loaded on the support. High acidity tends to cause coking, which leads to deactivation. In order to prepare a suitable hydrocracking catalyst, a good balance between the two functions has to be maintained [7]. According to the catalyst used, the operation can be oriented for the production of gasoline, kerosene or light fuel. These conversions are carried out by three reactors. The first one has three catalytic beds in which the pre-treatment of the charge occurred under high hydrogen pressure.

The pre-treatment or hydro-treatment of the load allows the conversion of the nitrogen, sulphur and oxygen present in the load into harmless molecules. These are ammonia, sulphur acidic and water. Indeed, the nitrogen, sulphur and oxygen could be poison for the catalytic system of the hydrocracking reactor [5]. Pre-treatment effluent is sent to second and third reactors, respectively, for hydrocracking. Cracking reactions take place for gasoline and light hydrocarbon production. Ratio of the valuable products that leaves hydrocracking reactions to total feed flow to unit gives the conversion amount. Inlet temperatures are changed and some variables are monitored for the control of the most important reactor parameter; conversion.

Reactor temperatures are increased for conversion, starting from the fresh catalyst load to completion of catalyst deactivation. Therefore, the quality of the catalyst is not a sufficient condition for the optimal functioning of the hydrocracking reactor. Parameters such as feed flow, temperature, hydrogen partial pressure and recycling rate should be monitored for a good functioning [5]. Figure 1 shows the simplified flow sheet of Hydrocracking Reactors.

2.1. WABT (Weighted Average Bed Temperature)

Weighted average bed temperature (WABT), is generally referred as the sign of catalyst activation. WABT is calculated by the bed temperatures of reactors, each temperature contribute to WABT according to catalyst weight distribution. At each loading, weight of catalyst and its distribution to beds can change, so WABT should be recalculated. To reach the desired product quality pre-treatment and the temperatures of the cracking reactor are changed. This leads to change in the WABT which shows the catalyst deactivation rate and also a good indication for catalyst performance. Increase in temperature versus processed feed or time indicates the catalyst deactivation rate. As unit processes more feed, the reactor needs higher temperatures to attain desired product quality, because of coking reactions and accumulation of catalyst poisonous elements in the feedstock. For example as the deactivation of pre-treatment catalyst increases the amount of sulphur, nitrogen and aromatics increase in the products. WABT calculation example: Assume first reactor consists of 3 parts;

1. Part contains 25% weight of catalyst, at 380 °C
2. Part contains 35% weight of catalyst, at 390 °C

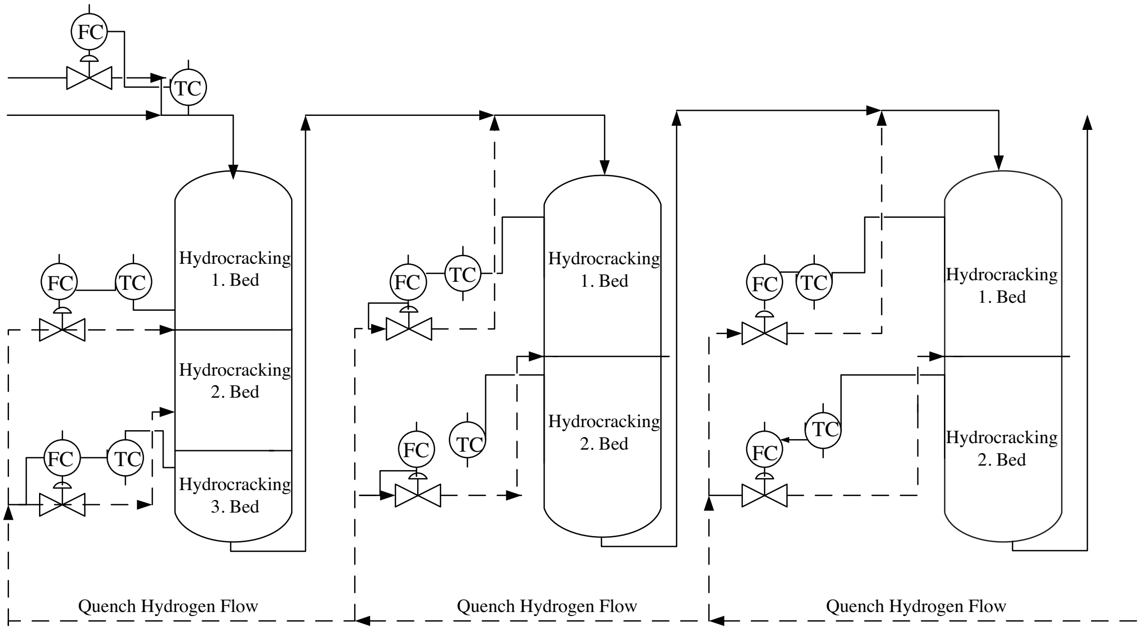

Figure 1. Hydrocracker reactors.

3. Part contains 40% weight of catalyst, at 400 °C

WABT calculated as $= 0.25 \times 380 + 0.35 \times 390 + 0.40 \times 400 = 391$ °C

2.2. Reactor Bed ΔT's (bed wise temperature difference) and conversion

Reactions in the Hydrocracker unit take place at high temperatures (390 °C - 440 °C) and pressures (140 – 160 bars). Exothermic reactions cause the temperatures in the reactors to increase, quench hydrogen gas is used to cool down the reactors. Increase in reactor temperatures is directly proportional to exothermic reactions, which is also an indication of conversion.

3. Controller design

Hydrocracker units' main goal is not only drawing off the desired quality products but also keeping the conversion (total product / total feed) between certain limits. Conversion can only be controlled by manipulation (for example inlet temperatures), monitoring (for example reactor beds' peak temperatures) and controlling of unit variables (quench hydrogen flows).

$$\text{Conversion} = \text{Total Product Draw} \;/\; \text{Total Feed} \tag{1}$$

Controller operators change reactor inlet temperatures to attain the desired conversion. When temperature set value is increased, quench hydrogen is reduced by the cascade set signal.

3.1. Manipulated Variables (MV)

Reactor inlet temperatures are selected as the manipulated variables for reactor control. There are 7 bed inlet temperatures to be used. Main controller gives set values to these 7 reactor inlet temperatures to control temperatures and conversion. Base layer PID control loops of manipulated variables are checked before the implementation of Advanced Process Control (APC). They are retuned where needed, critical instruments are revised, especially controller valves are fixed or renewed, and transmitter reading errors are identified and corrected. Reactor outlet temperatures are related to cracking amount in the beds since the reactions are exothermic.

3.2. Controlled Variables (CV)

3.2.1. Bed ΔT

Hydrocracker units are operated to attain conversion amount which is projected by the catalyst type. As reactor temperatures are changed, its effect on conversion can only be understood after reactor effluent get through of separators, strippers and heat exchangers. In a sense, product draws are only included in the conversion calculation after separated. This means alteration in reactor temperatures affects the conversion after a long dead time. Reactor control algorithm that uses the final product, which is the result of reactions and all separations, would be very slow. For this reason an intermediate, which will be used as the connection between reactor temperatures, reactions and total product draw, is needed. Total temperature difference across the beds (ΔT) which is the result of reactions in each bed is selected as this intermediate. The separation of products is controlled by ΔT, temperature difference along each bed. So, the conversion is controlled by using another controlled variable.

3.2.2. WABT

Weighted average bed temperature is calculated according to the distribution of catalyst in the beds. For the homogenous deactivation of catalyst all WABT must be increased identically throughout its operation life. A higher WABT in one bed and lower in another bed is a sign of maldistribution of reaction in the beds. This will lead to catalyst deactivation of higher temperature WABT faster than the other.

3.2.3. Bed skin temperatures

There are some temperature limitations for reactor column skin wall for safety reasons. Especially, at the end of run of catalyst, temperatures get closer to these limits. Since skin temperatures depend on the reactions taking place in the bed, they can be controlled by reactor inlet temperatures.

3.2.4. Quench hydrogen flow

A certain amount of the quench flow should be kept for emergency situations. For this reason there must be a low limit for the quench valve openings to save some cooling flow for emergency.

3.2.5. Conversion

Conversion, which is the ratio of valuable products that are formed in reactions to the total feed flow, should be controlled to stay in limits, unless the total product draw or feed flow changes. Temperature should be increased for compensating the catalyst deactivation and meanwhile keeping conversion constant.

3.3. Dynamic step tests

After the selection of variables is made, dynamic step tests are done to observe the correlation between manipulated and controlled variables. 7 reactor inlet temperatures in 3 reactors (1. reactor has 3 beds, 2. and 3. reactors have 2 beds) are altered respectively to see the effect of change to each controlled variable. During step tests, only one temperature is altered at a time while all other temperatures are kept constant. All operator interventions are monitored and erased carefully to see the clear effect of each temperature change, which cause the step test period to last 26 days. Step test moves are selected to be small enough not to disturb the system and big enough to see the real effects. Identification is started after the collection of test data to define the relation between the manipulated and controlled variables.

3.4. Identification period

Dynamic step test data is analyzed in the AIDAPro (Advanced Identification and Data Analysis) software, which is a tool in the Process Control Technology Package of Shell Global Solutions International BV. AIDAPro is an empirical dynamic modeling tool which uses dynamic process data to construct linear dynamic models. Even model definition and identification causes a certain understanding of the system behavior, one should analyze the system behaviors' prior to identification. Dual relations of each manipulated variable to controlled variables are created as high order parametric models. Then, effect of two variables to each other is identified from this multivariable matrix. A matrix which consists of all dual relations is constructed by mathematical validation of each correlation. Manipulated 7 variables and controlled 28 variables make a matrix of 7×28, 196 correlations. Final multivariable response matrix is selected from 196 relations according to their magnitude, robustness, dynamic test results and process information.

3.5. Controller design

Constructed models derived from the dynamic tests are used in design of Tüpraş Izmit Refinery Hydrocracker Reactor Controller. SMOCPro (licensed by Shell) is used for the design of Model Predictive Controller (MPC) of reactors. The SMOC algorithm includes several features that are now considered essential to a 'modern' MPC formulation and summarized by Qin and Bagdwell [8] as:

State-space models are used so that the full range of linear dynamics can be represented.

An explicit disturbance model describes the effect of unmeasured disturbances.

A Kalman filter is used to estimate the plant states and unmeasured disturbances from output measurements.

A distinction is introduced between controlled variables appearing in the control objective and feedback variables that are used for state estimation.

Input and output constraints are enforced via a Quadratic Program formulation.

Industrial MPC controllers generally evaluate future CV behavior over a finite set of future time intervals, the prediction horizon. Future output behavior is controlled by penalizing deviations from the desired output trajectory which is a prediction horizon of length P. Controller objective function of MPC [8] is:

$$\min_{\Delta u(n)\ldots\Delta u(n+C-1)} \sum_{i=1}^{P} \left\| \hat{y}(n+i) - r(n+i) \right\|^2 w_1 + \sum_{j=1}^{C} \left\| \Delta u(n+i-1) \right\|^2 w_2 \tag{2}$$

Table 1. Manipulated (MV) and controlled (CV) variables used in controller design.

		MV	CV
Reactor Inlet Temperatures	1. Reactor 1. Bed	♠	
	1. Reactor 2. Bed	♠	
	1. Reactor 3. Bed	♠	
	2. Reactor 1. Bed	♠	
	2. Reactor 2. Bed	♠	
	3. Reactor 1. Bed	♠	
	3. Reactor 2. Bed	♠	
WABT	1. Reactor 1. Bed		♠
	1. Reactor 2. Bed		♠
	1. Reactor 3. Bed		♠
	2. Reactor 1. Bed		♠
	2. Reactor 2. Bed		♠
	3. Reactor 1. Bed		♠
	3. Reactor 2. Bed		♠
Quench Hydrogen flow valve opening	1. Reactor 2. Bed		♠
	1. Reactor 3. Bed		♠
	2. Reactor 1. Bed		♠
	2. Reactor 2. Bed		♠
	3. Reactor 1. Bed		♠
	3. Reactor 2. Bed		♠

		MV	CV
Max. Skin Temperature	1. Reactor 1. Bed		♠
	1. Reactor 2. Bed		♠
	1. Reactor 3. Bed		♠
	2. Reactor 1. Bed		♠
	2. Reactor 2. Bed		♠
	3. Reactor 1. Bed		♠
	3. Reactor 2. Bed		♠
Bed ΔT	1. Reactor 1. Bed		♠
	1. Reactor 2. Bed		♠
	1. Reactor 3. Bed		♠
	2. Reactor 1. Bed		♠
	2. Reactor 2. Bed		♠
	3. Reactor 1. Bed		♠
	3. Reactor 2. Bed		♠
Conversion			♠

in which 'u' represents inputs, 'y' is used to define outputs and the superscript ˆ denotes the predicted values. Δu is the input variation and r is the reference trajectory of the outputs. In this optimization problem, the first term is used to minimize the error resulting from the difference between predicted outputs and reference trajectory during prediction horizon, P. The second term is the difference of control actions taken at each time step during control horizon, C. Weighting matrices w1 and w2 are positive definite matrices, with different magnitudes for all MV's and CV's. These matrices were used in controller tuning. Increasing w1, CV weights, makes the control tighter. Increasing w2, MV weights, results in smoother moves. The optimal input sequence's only first input is implemented to the system and the calculations are re-executed in the next sampling time [8].

The controller was tuned in offline program with simulations. MPC manipulates 7 temperatures to control 28 controlled variables within their pre-defined limits. As the temperatures are manipulated, output prediction of each controlled variable is estimated according to the correlation matrix of each controlled variable to the manipulated variables.

3.6. Controller commissioning

Reactor controller is designed in SMOCPro, tuned with simulations and then commissioned. Routine operational fluctuations are rejected by control moves, as it anticipates the future trajectory behavior of each variable. Reactor inlet temperatures are manipulated for the desired conversion, regarding the WABT of each bed.

Figure 2 shows the controller performance with simulation results of equalization of WABT's, while conversion is kept constant. Deactivation of catalyst at the same time in all beds to increase the life of unit, is one of the aims of Reactor controller. Controller increases some inlet temperatures while decreasing others. Total ΔT is fluctuated as the inlet temperatures are changed. On the other hand, the dead time between reactor temperatures and conversion decreases the fluctuation effect of ΔT on conversion. Conversion stays constant as seen in Figure 2. All in all reactor inlet temperature manipulation affect all controlled variables while achieving the equalization of WABT.

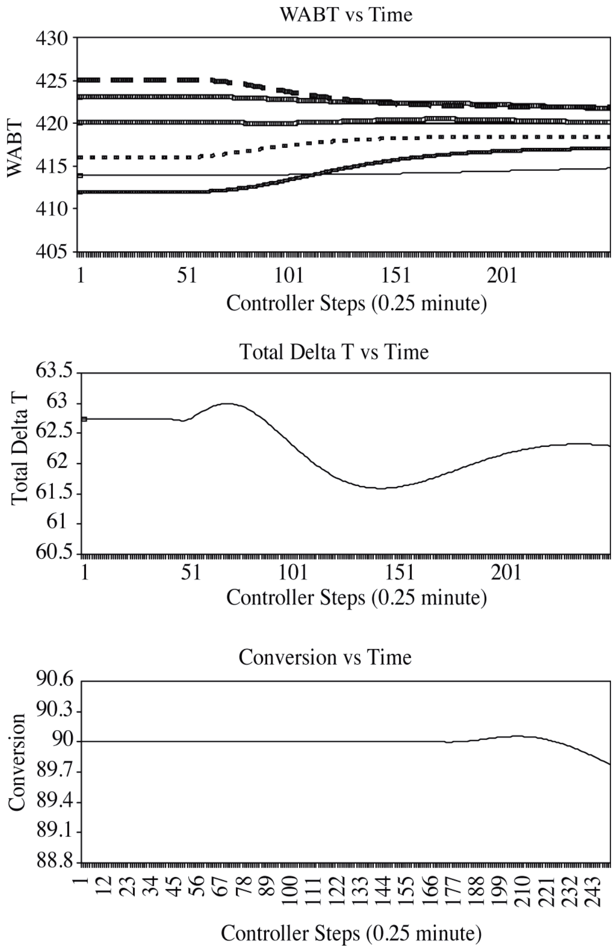

Figure 2. Simulation results of equalization of WABT at constant conversion.

Figure 3 shows the designed controller performance with simulation results of increasing conversion. Reactor inlet temperatures are manipulated to increase conversion regarding the limits of WABT. As the temperatures increase, total ΔT also increases as a sign of reactions in reactor. Production of more valuable products is increased by the increase of cracking heavy vacuum gas oils. Lastly, conversion is increased and simulation aim is attained.

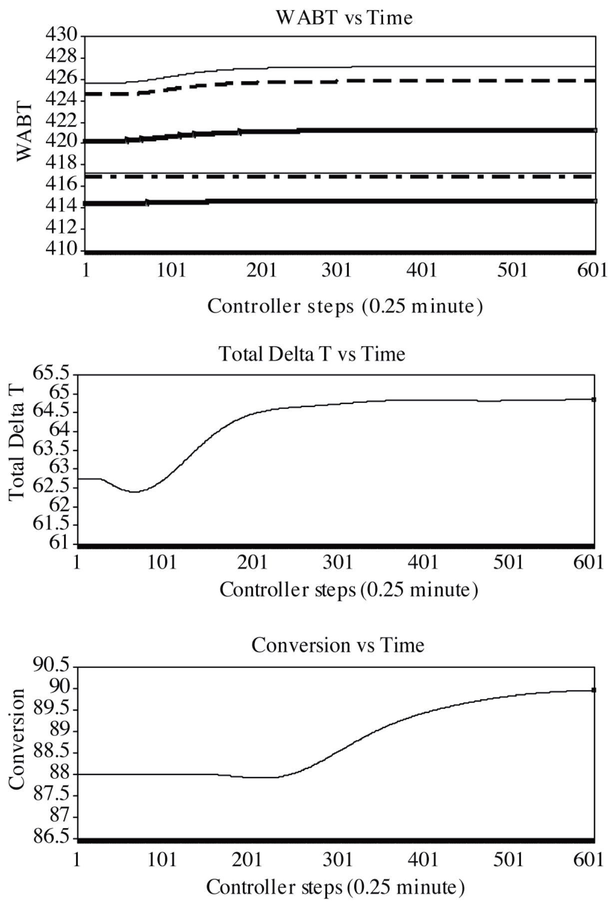

Figure 3. Simulation results of Increasing conversion.

4. Results

Over two and a half month's period of controller running, overall desired conversion amount is attained. Reactor inlet temperatures are manipulated to control conversion, WABT, max. skin temperatures, quench hydrogen flow and bed ΔT's. Predictive controller intervenes before reactor temperatures gets to the critical limits, which made the operation safer. Also standard deviation of conversion is decreased by 1.1%. There is a significant improvement in equalizing the WABT's, while conversion is controlled in the limits.

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