

A Novel Close-loop Strategy for Integrating Process Operations of Fluidized Catalytic Cracking Unit with Production Planning Optimization

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Abstract Production planning models generated by common modeling systems do not involve constraints for process operations, and a solution optimized by these models is called a quasi-optimal plan. The quasi-optimal plan cannot be executed in practice some time for no corresponding operating conditions. In order to determine a practically feasible optimal plan and corresponding operating conditions of fluidized catalytic cracking unit (FCCU), a novel close-loop integrated strategy, including determination of a quasi-optimal plan, search of operating conditions of FCCU and revision of the production planning model, was proposed in this article. In the strategy, a generalized genetic algorithm (GA) coupled with a sequential process simulator of FCCU was applied to search operating conditions implementing the quasi-optimal plan of FCCU and output the optimal individual in the GA search as a final genetic individual. When no corresponding operating conditions were found, the final genetic individual based correction (FGIC) method was presented to revise the production planning model, and then a new quasi-optimal production plan was determined. The above steps were repeated until a practically feasible optimal plan and corresponding operating conditions of FCCU were obtained. The close-loop integrated strategy was validated by two cases, and it was indicated that the strategy was efficient in determining a practically executed optimal plan and corresponding operating conditions of FCCU.

Keywords production planning, process operations, fluidized catalytic cracking unit, integrated strategy

1 INTRODUCTION

Production planning is one important component of production management in petrochemical enterprises. The decision level for production plans determines the economic profitability of an enterprise. The objective of production planning optimization is to improve the profitability of an enterprise, by optimum distribution of materials and energy across the total enterprise. Therefore, production planning optimization is the cost-effective technology for a petrochemical enterprise, which does not need investment for new process and equipments. Since 1950s, the potential benefits of optimization of production planning have long been observed, with application of linear programming (LP) in material balance and production operation planning [1]. As LP applied technologies such as branch and bound method [2] for mixed-integer programming and Dantzig-Wolfe decomposition [3] was studied and developed, LP technology succeeded in enterprise wide optimization of production planning. By the application of Swing-cut technology for distillation units and Delta-base model for secondary processing units, world-class LP planning models appeared. The availability of LP-based commercial software for refinery production planning, such as PIMS (Process Industry Modeling System), RPMS (Refinery and Petrochemical Modeling System), GRTMPS (Generalized Refining Transportation Marketing Planning System), and GIOPIMS (Graphic I/O Petrochemical Industry Modeling System) [4], has allowed the development of general production planning models of the total enterprise.

However, a production plan optimized by above

production planning software is a quasi-optimal plan because operating constraints are not involved in planning models generated by these software, and it is uncertain whether the plan in mathematical meaning is feasible in practice. In order to ensure that the plan is practically feasible, process operating constraints are required to be added to the linear production planning model. Because these constraints are complex implicit correlations of operating parameters and product yield and have highly nonlinear characteristics, a nonlinear programming (NLP) model is induced, which is hard to handle. In order to improve the operability and avoid NLP problems, some methods were proposed to implement production planning optimization with process operations. Linear relations were applied to denote effect of operating conditions on products yield rates by Neiro and Pinto [5], and the NLP model was simplified to a LP model. A production management close-loop system of petrochemical enterprises was proposed by Chen *et al.* [6], where production management of petrochemical enterprises was regarded as a close-loop system with information feedback route-way. In the system, determination of optimal plans were integrated with their execution, and an optimal plan can be determined at given operating conditions. However, how to determine operating conditions of units implementing the optimal plan was not considered, and practically feasible optimal plans and corresponding operating conditions cannot be obtained in the operating range of units. An optimal production planning system based on refinery process simulation was developed by Ding *et al.* [7], and a hierarchy method of sustainable production planning of continuous process industries was proposed by Zhou [8].

Optimal plans were revised by process simulation results, and the operability was improved by their methods. However, corresponding operating conditions to the optimal plan cannot be obtained and correction methods have not been studied.

In this article, a novel close-loop integrated strategy was proposed for integrating process operations and production planning optimization and applied to fluidized catalytic cracking unit (FCCU). The solution procedure, where the plan was ensured feasible in practice and operating conditions implementing the plan were determined, was decomposed into two parts: determining a quasi-optimal plan by linear planning software and searching corresponding operating parameters to the plan by unit simulators. First, a quasi-optimal production plan was determined with GIOPIMS, and then the plan of FCCU was assigned to the unit. Second, a FCCU sequential simulator was established and coupled into a generalized genetic algorithm (GA) to search operating conditions implementing the FCCU plan and output a final genetic individual. When no corresponding operating conditions were obtained in allowable ranges, a final genetic individual based correction (FGIC) method was presented to revise the planning model. Optimal integration of production planning and FCCU process operations can be implemented through determination, search, revision, and redetermination, which is a closed-loop process.

2 DETERMINATION OF A QUASI-OPTIMAL PLAN

Linear programming model is widely applied in production planning systems including GIOPIMS to determine an optimal plan due to its simple pattern, mature solution algorithm, solid mathematical researches and versatile solvers. In this study, GIOPIMS was used as a modeling and optimization platform for production planning of a petrochemical enterprise. Mathematical formulations of the LP production planning model generated by GIOPIMS were given as follows:

$$\max J = \sum_{m \in M} P_m x_m - \sum_{n \in N} P_n x_n - \sum_{u \in U} Q_u \sum_{i \in \tilde{U}_{IL,u}} x_i - \sum_{t \in \tilde{T}} H_t z_t - C \quad (1)$$

$$\text{s.t. } (1 - \eta_u) \sum_{i \in \tilde{U}_{IL,u}} x_i = \sum_{j \in \tilde{U}_{OL,u}} x_j, \forall u \in \tilde{U} \quad (2)$$

$$y_u F_u^L \leq \sum_{i \in \tilde{U}_{IL,u}} x_i \leq y_u F_u^U, \forall u \in \tilde{U} \quad (3)$$

$$\lambda_i^L \sum_{i \in \tilde{U}_{IL,u}} x_i \leq x_i \leq \lambda_i^U \sum_{i \in \tilde{U}_{IL,u}} x_i, \forall i \in \tilde{U}_{IL,u}, \forall u \in \tilde{U} \quad (4)$$

$$\varphi_j^L \cdot \sum_{j \in \tilde{U}_{OL,u}} x_j \leq x_j \leq \varphi_j^U \cdot \sum_{j \in \tilde{U}_{OL,u}} x_j, \forall j \in \tilde{U}_{OL,u}, \forall u \in \tilde{U} \quad (5)$$

$$D_m^L \leq x_m \leq D_m^U, \forall m \in \tilde{M} \quad (6)$$

$$R_n^L \leq x_n \leq R_n^U, \forall n \in \tilde{N} \quad (7)$$

$$I_t + \sum_{i \in \tilde{T}_{IL,t}} x_i = z_t + \sum_{j \in \tilde{T}_{OL,t}} x_j, \forall t \in \tilde{T} \quad (8)$$

$$W_t^L \leq z_t \leq W_t^U, t \in \tilde{T} \quad (9)$$

$$\theta_{n,h} \sum_{i \in \tilde{L}_{BL,n}} x_i \geq (\leq) \sum_{i \in \tilde{L}_{BL,n}} \theta_{i,h} x_i, \forall h \in \tilde{L}_{IX,n}, \forall n \in \tilde{L} \quad (10)$$

$$x \geq 0, y \in [0,1], z \geq 0 \quad (11)$$

The objective of production planning optimization is to maximize the gross profit of a petrochemical enterprise. Constraints comprise material balance, processing capacity, proportion limit of inflows, yield limit of outflows, demand limit of products, supply limit of raw materials, inventory balance, inventory capacity, and quality index limit of outflows. Eq. (5) denotes yield limit of outflows of production units, where the lower and upper yield limit of products are given. The equation can denote multiplan production options without binary variables. The values of the lower limit and upper limit are determined by empirical data, which strongly affect the optimal plan. This kind of constraint is usually applied in the LP production planning model, such as in the model proposed by Li *et al* [9].

Optimized results by GIOPIMS are an optimal production plan of the whole enterprise, which is composed of maximum gross profit (J^*), production tasks of units (X^*), working status (Y^*), and final inventories (Z^*). Because the planning model does not consider constraints for process operations, the plan cannot be ensured practically feasible in allowable ranges of operating conditions of production units and is called a quasi-optimal plan. The quasi-optimal plan of a production unit is required to be validated whether it can be practically executed or not by searching corresponding operating conditions to the plan.

3 SEARCH OF FCCU OPERATING CONDITIONS WITH GA

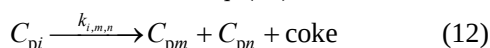
After the quasi-optimal production plan of FCCU was obtained, its feasibility in practice needs to be determined, namely whether corresponding operating conditions of FCCU implementing the plan can be found out or not in allowable ranges of operating conditions. At first, a FCCU simulator was developed to judge whether a set of operating conditions could implement a production plan. Then, a GA coupled with the simulator was applied to search FCCU operating conditions corresponding to the plan.

3.1 Developing a FCCU simulator

In this article, the reactor, main fractionator, and absorption-stabilization system were modeled together because yield data of products denoted the flow rate of outflows from separate section of FCCU. The main fractionator and absorption-stabilization system are separation units and can be modeled in common process simulation systems [10, 11]. However, the FCC reactor model composed of the riser reactor and disengaging-stripping section was not included in

common process simulation systems, which was required to be established manually and combined with the models of other sections conveniently. The flow-sheet of modeling part of FCCU can be seen in Fig. 1.

For modeling the FCC reactor, a large number of papers have been published [12–17]. Using lumps generation method in form of narrow boiling pseudocomponents, pseudoreaction mechanism, and reaction rate correlation based on normal probability distribution proposed by Gupta *et al.* [17], the kinetic model was established for the riser. In the model, feedstock and products were denoted as 56 pseudocomponents. In the cracking process, it is assumed that one mole of a pseudocomponent on cracking gives one mole each of two other smaller pseudocomponents and some amount of coke as Eq. (12).



where C_p denotes pseudocomponents, i, m, n are pseudocomponents' numbers, coke is the amount of coke formed when one kmol i th pseudocomponent cracks to produce one kmol each of m th and n th pseudocomponents. The correlation of reaction rate constant ($k_{i,m,n}$) was given by Eq. (13):

$$k_{\max,i} = k_0 W_i^\mu e^{-\frac{E_0 W_i^\nu}{RT}}, \quad i = 1, \dots, 30$$

$$k_{\max,i} = k_0^D W_i^\mu e^{-\frac{E_0 W_i^\nu}{RT}}, \quad i = 31, \dots, 46$$

$$k_{\max,i} = k_0^S W_i^\mu e^{-\frac{E_0 W_i^\nu}{RT}}, \quad i = 47, \dots, 56$$

$$k_{i,m,n} = \left\{ k_{\max,i} e^{-\tau_1 [(W_m - W_n) k_{\max,i}]^2} \right\} \times \left\{ \frac{e^{-[W_i - (W_m + W_n)]/\tau_2} - e^{-W_i}}{1 - e^{-W_i}} \right\}, \quad i = 1, \dots, 56 \quad (13)$$

In Eq. (13), W denotes molecular weight, $k_{\max,i}$ is the maximum cracking rate of i th pseudocomponent, parameters to be estimated by plant data are k_0 , k_0^D , k_0^S , μ , E_0 , ν , τ_1 , and τ_2 . k_0 is the frequency factor of the reaction rate constant for pseudocomponents C_{p1} – C_{p30} , k_0^D is the frequency factor for pseudocomponents C_{p31} – C_{p46} , and k_0^S is the frequency factor for pseudocomponents C_{p47} – C_{p56} . μ is correlating frequency factor in terms of molecular weight of pseudocomponents, E_0 is the activation energy, ν correlates activation energy of individual pseudocomponent in terms of its molecular weight, τ_1 denotes the coke forming tendency of the feed, and τ_2 indicates cracking tendency of pseudocomponents. Mathematical formulations for material balance, heat balance, and hydrodynamics in the riser reactor proposed by Gupta *et al.* [17] were applied here. Disengaging-stripping section was modeled as a perfectly mixed continuous tank referring the model presented by Han and Chuang [15, 16].

Combining the above kinetic model of the reactor based on the pseudocomponent approach with the models of the main fractionator and adsorption-stabilization system, a sequential FCCU simulator was completed. Input parameters of the simulator comprise: (1) equipment parameters (α), such as tray profiles, feed position, and discharging position. Equipment parameters are given and fixed in the simulation; (2)

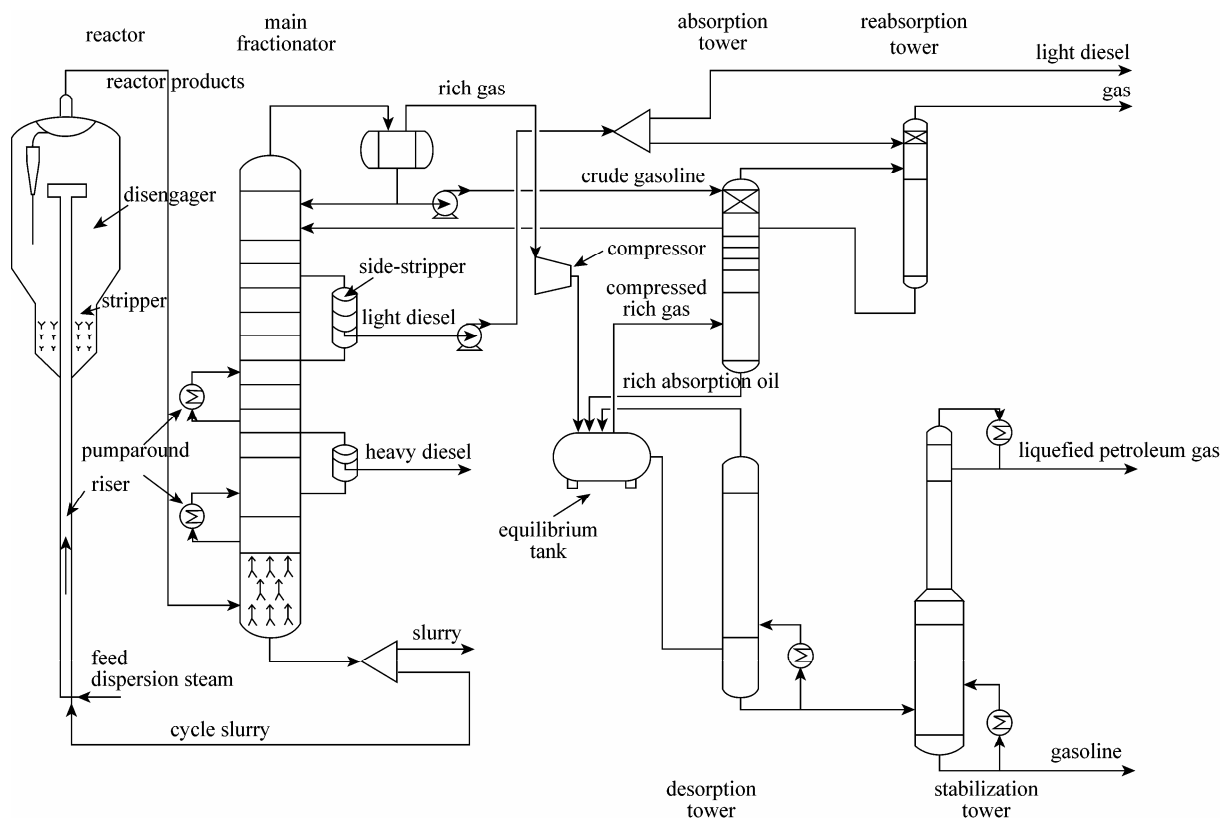


Figure 1 Flowsheet of modeling parts of FCCU

process operating conditions (β), including operating conditions of the reactor (ratio of catalyst to oil, pre-heating temperature of FCC feed, dispersion steam flow rate in the rise reactor, stripper steam flow rate in the disengaging-stripping section), main fractionator operating conditions (mid pumparound flow rate, return temperature of mid pumparound, bottom pumparound flow rate, return temperature of bottom pumparound, stripper steam flow rate of the first side line, stripper steam flow rate of the second side line, top condensed temperature), and operating conditions of absorption-stabilization system (molar reflux ratio of stabilization tower). These parameters are postulated during simulating the process; (3) production tasks (X), comprising yield of dry gas, liquefied petroleum gas (LPG), gasoline, diesel, slurry, and coke. Production tasks are assumed in the simulation. If assumed operating conditions can implement given production tasks, convergent information will be output; otherwise divergent information will be output.

3.2 GA search of FCCU operating conditions

A generalized genetic algorithm (GA) [18] was applied to search FCCU operating conditions, which can implement the quasi-optimal plan of FCCU, X_{FCC}^* . In the algorithm, a real code was chosen to design a chromosome representation of solutions of the problem with genetic operators. An individual was composed of a set of FCCU operating conditions and a production plan of FCCU, namely $V = (\beta, X)$. An initial population of individuals, V , was obtained by stochastic search in the basis of operating range. Only individuals whose simulated results were convergent

were added to the initial population. The fitness of an individual was given by Eq. (14):

$$f(V_i) = \sqrt{\sum_{j \in U_{\text{OL}, \text{FCC}}} (x_{i,j} - x_j^*)^2} / \sqrt{\sum_{j \in U_{\text{OL}, \text{FCC}}} (x_j^*)^2}, \quad i = 1, 2, \dots, N \quad (14)$$

where f was the fitness of an individual, V_i denoted the i th individual, $x_{i,j}$ was the yield of j th product in i th individual, and x_j^* was the yield of j th FCCU product in the quasi-optimal plan. The fitness of an individual denoted the deviation of product yield of FCCU in the individual and the quasi-optimal plan of FCCU. Ordinal-based evaluation function given by Eq. (15), where $a = 0.1$, was applied to evaluate individuals.

$$\text{eval}(V_i) = a(1-a)^{i-1}, \quad i = 1, 2, \dots, N. \quad (15)$$

Parameters on which a GA depended were the population size (N), probability of crossover (P_c), probability of mutation (P_m), and maximum number of generation (K). In the algorithm, these parameters took the following values: $N = 50$, $P_c = 0.8$, $P_m = 0.1$, $K = 30$.

The GA search procedure is shown in Fig. 2, where k denoted the number of evolutionary generation. If the fitness of the optimal individual (V_{OPT}^k) in the k th generation was lesser than ε after a few numbers of generations, operating conditions in V_{OPT}^k (β_{OPT}^k) can implement X_{FCC}^* and the search finished. V_{OPT}^k was output as the final searched individual, V_{FNL} . Otherwise, the search terminated at K generation and corresponding operating conditions to X_{FCC}^* was not found, which indicated that X_{FCC}^* was infeasible in practice. The optimal individual in the last generation (V_{OPT}^K) was considered as V_{FNL} .

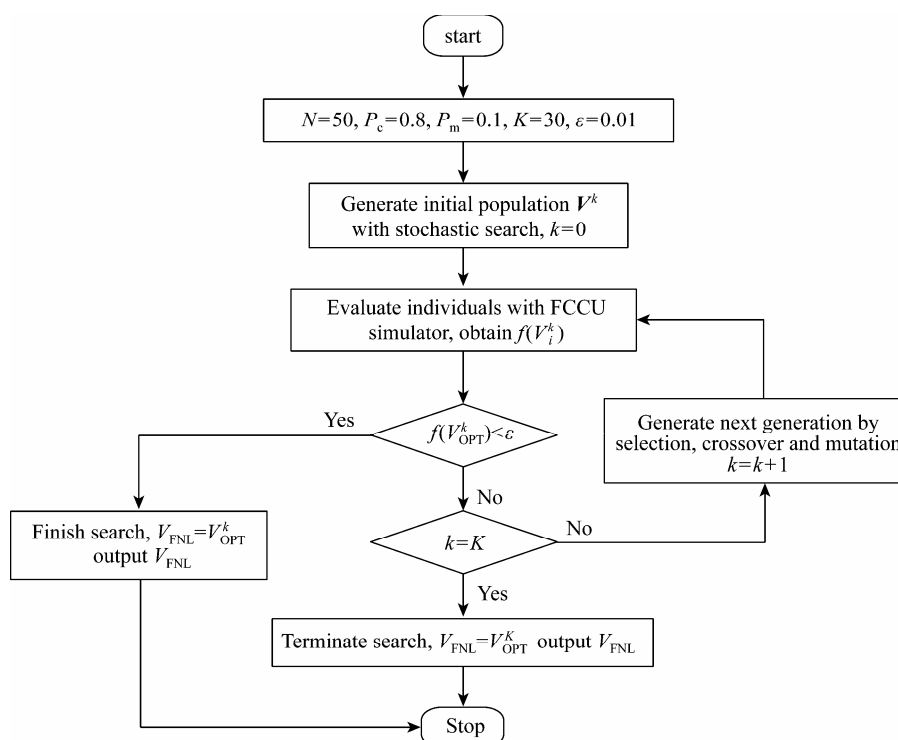


Figure 2 Flowchart of GA Search of FCCU operating conditions

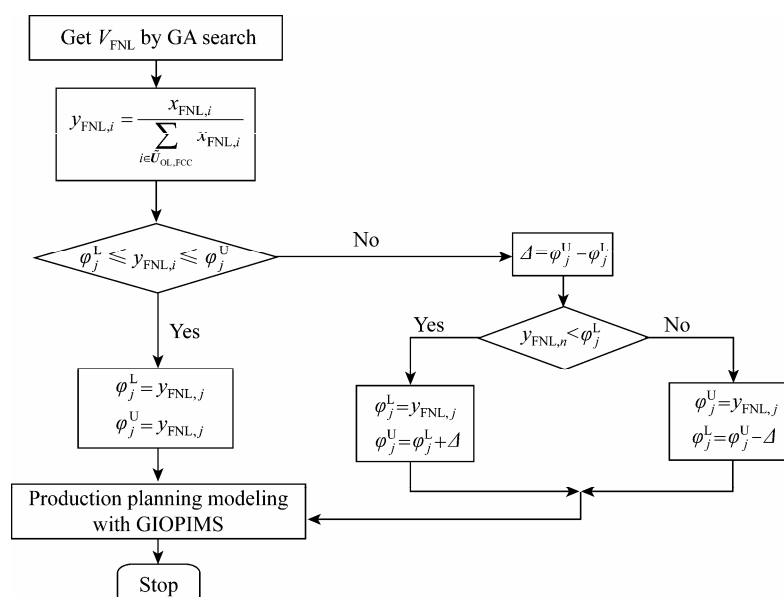


Figure 3 Flowchart of optimal integration of production planning and process operations of FCCU

4 REVISION OF THE PLANNING MODEL

When the quasi-optimal plan of FCCU was practically infeasible, the planning model should be revised to determine a new quasi-optimal by GIOPIMS. A final genetic individual based correction (FGIC) method was proposed to revise the planning model. The method can be seen in Fig. 3 and was described as follows:

(1) If the yield rate of FCCU products in V_{FNL} ($y_{FNL,j}, y_{FNL,j} = x_{FNL,j} / \sum_{j \in U_{OL,FCC}} x_{FNL,j}$) was within the

range of products yield rates in the planning model ($[\phi_j^L, \phi_j^U]$), production tasks in V_{FNL} (X_{FNL}) was the practically optimal plan and β_{FNL} was corresponding FCC operating conditions to X_{FNL} . Because the optimal plan of FCCU has been changed to X_{FNL} , the planning model was revised by setting the lower and upper yield limit of the j th FCC product in the Eq. (5) to equal to $y_{FNL,j}$ and the optimal plan of the whole enterprise was redetermined.

(2) If $y_{FNL,j}$ outranged $[\phi_j^L, \phi_j^U]$, it was indicated that the range of yield rate of the j th FCC product in the planning model was unreasonable and needs to be adjusted. The range was defined as Δ , and then $\Delta = \phi_j^U - \phi_j^L$. If $y_{FNL,j} < \phi_j^L$, $\phi_j^L = y_{FNL,j}$ and $\phi_j^U = \phi_j^L + \Delta$; Otherwise, $\phi_j^U = y_{FNL,j}$ and $\phi_j^L = \phi_j^U - \Delta$. A new quasi-optimal plan was obtained by optimization of the revised planning model, and corresponding operating conditions to the new quasi-optimal plan of FCCU was searched with the GA again.

Based on above works, a close-loop strategy for integration of production planning and FCCU process operations was proposed. The integrated strategy includes determination of a quasi-optimal plan by GIOPIMS, searching corresponding operating conditions

to the quasi-optimal plan of FCCU by a GA coupled with a sequential FCCU simulator, and revision of the planning model in GIOPIMS.

5 CASE STUDY

Two integrated cases of production planning and FCC process operations were studied to demonstrate the proposed close-loop strategy. Before case study, the kinetic parameters of FCC reactor model were estimated with plant data.

5.1 Parameter estimation for FCC reactor model

Rate constant parameters were estimated by industrial FCC plant data. There were eight parameters to be regressed by adjusting the parameters in such a way that the deviation in predicted and actual data was minimum. To achieve this, these parameters (k_0 , k_0^D , k_0^S , μ , E_0 , v , τ_1 , and τ_2) were determined by stochastic search method. Comparison of calculated results and plant data can be seen in Table 1. From the table, yield rates of main products of FCCU were consistent with plant data. The values of eight variables obtained by parameter estimation were given below: $k_0 = 0.0186$, $k_0^D = 0.0079$, $k_0^S = 0.0234$, $\mu = 0$, $E_0 = 191.9737$, $v = 0.43$, $\tau_1 = 0$, $\tau_2 = 19.1178$, which were used for case study.

Table 1 Comparison of simulation results with plant data

FCCU product	Yield rate/% (by mass)		Relative deviation/%
	Plant data	Model predictions	
dry gas	3.5477	4.5641	28.65
LPG	15.6895	14.5241	-7.43
gasoline	42.8905	42.2986	-1.38
diesel	23.0532	23.2827	1.00

5.2 Two integrated cases of FCCU

Case I was a demonstrator where no corresponding operating conditions to the quasi-optimal plan of FCCU was found but the yield rate of a FCCU product in V_{FNL} searched by GA was within the range of yield rate of corresponding FCC products in the planning model. In this case, the production plan of FCCU in V_{FNL} was the final feasible plan. The lower and upper limits of yield rate of FCCU products in the planning model, the quasi-optimal and final feasible plan were given in Table 2. The quasi-optimal plan was taken as a reference plan, the gross profit of the final plan decreased 854.52×10^4 CNY in the basis of the reference plan. However, a practically feasible production plan of FCCU with corresponding operating condition and can be executed.

Model parameters and the quasi-optimal and feasible plans in case II were given in Table 3. Corresponding operating conditions to the first quasi-optimal plan of FCCU was not found and the yield rate of some FCCU products in $V_{\text{FNL}}^{(0)}$ searched by GA out-ranged the range of yield rate of corresponding FCC products in the planning model. The LP planning model was revised based on $V_{\text{FNL}}^{(0)}$, a new quasi-optimal plan was determined with GIOPIMS. Corresponding operating conditions to the second quasi-optimal plan of FCCU were not found by GA. However the FCCU plan in $V_{\text{FLN}}^{(1)}$ was in the new range of yield rate of products, and it was the final feasible plan. The first quasi-optimal plan was taken

as a reference plan, in basis of which the gross profit of the second quasi-optimal plan and the final feasible plan decreased to 653.94×10^4 CNY and 992.77×10^4 CNY, respectively.

6 CONCLUSIONS

A quasi-optimal production plan for the whole enterprise was obtained by GIOPIMS, and its feasibility was validated by searching corresponding operating conditions to the quasi-optimal plan of FCCU. A kinetic model for the FCC reactor was established and model parameters were estimated by plant data. Then, the reactor model was combined with models for the main fractionator and absorption-stabilization system established in common process simulation systems to develop a sequential FCCU simulator. A generalized genetic algorithm coupled with the simulator was applied to search operating conditions implementing the quasi-optimal plan of FCCU, and a final individual comprising a feasible FCCU plan and corresponding operating conditions was found. When the production plan in the final individual deviated from the quasi-optimal plan of FCCU, FGIC method was presented to revise the planning model in GIOPIMS. Based on above works, a novel close-loop strategy for integration of FCCU process operations and production planning was proposed. Two cases were studied to demonstrate the integrated strategy, and it was indicated that the strategy was effective in determining a

Table 2 Model parameters of the planning model and the production plan in Case I

		Processing load/ kg·h ⁻¹	Yield rate/% (by mass)						Profit change×10 ⁻⁴ / CNY
			Dry gas	LPG	Gasoline	Diesel	Slurry	Coke	
model parameter	lower limit	0	3.2858	10.3566	33.9215	22.9061	13.0434	10.9260	
	upper limit	368055.56	3.6316	11.4468	37.4922	25.3173	14.4164	12.0761	
FCC production plan	quasi-optimal plan ^①	368055.56	12093.06	42130.56	130588.89	93181.94	48006.94	40213.89	
	final feasible plan	368055.56	12117.00	39855.08	129874.57	91698.49	49419.31	42712.38	-854.52 ^②

① denotes reference plan. ② denotes profit change in basis of the reference plan.

Table 3 Model parameters of planning model and the plans in Case II

			Processing load/kg·h ⁻¹	Yield rate/% (by mass)						Profit change×10 ⁻⁴ / CNY
				Dry gas	LPG	Gasoline	Diesel	Slurry	Coke	
primal integration	model parameter	lower limit	0	3.3000	10.8316	34.3965	23.3811	11.6184	10.9973	
		upper limit	368055.56	3.6473	11.9718	38.0172	25.8423	12.8414	12.1550	
	FCC production plan	quasi-optimal plan ^①	368055.56	12145.83	44062.50	131654.17	95113.89	42762.50	40476.39	
		final feasible plan								
secondary integration	model parameter	lower limit	0	3.3000	10.8316	34.3965	23.3811	13.2999	10.9973	
		upper limit	368055.56	3.6473	11.9718	38.0172	25.8423	14.6999	12.1550	
	FCC production plan	quasi-optimal plan ^①	368055.56	12145.83	44062.50	126598.61	93980.56	48951.39	40476.39	-653.94 ^②
		final feasible plan	368055.56	12457.24	42916.75	127705.68	92376.79	49768.43	40990.38	-992.77 ^②

① denotes reference plan. ② denotes profit change in basis of the reference plan.

practically feasible optimal production plan and corresponding operating conditions of FCCU. Integration of FCC process operations and production planning can guide FCC production and operations, and contribute to play a more role of production planning optimization in petrochemical enterprises.

NOMENCLATURE

C	fixed cost of the enterprise, CNY
D	demand amount of products, kg
F	processing capacity of units, kg
H	inventory cost, CNY·kg ⁻¹
I	initial storage amount of inventories, kg
J	gross profit of the enterprise, CNY
$\tilde{L}$	products to be blended
$\tilde{L}_{BL}$	blending components
$\tilde{L}_{IX}$	quality indices
$\tilde{M}$	products
$\tilde{N}$	raw materials
P	price of materials or products, CNY·kg ⁻¹
Q	processing cost of production units, CNY·kg ⁻¹
R	supply amount of materials, kg
$\tilde{T}$	inventories
$\tilde{U}$	units
$\tilde{U}_{IL}$	inlet streams
$\tilde{U}_{OL}$	outlet streams
$\tilde{U}_{OL,FCC}$	outlet streams of FCCU
W	capacity of inventories, kg
x	flow rate of streams, kg
y	0-1 variable to denote if unit u is working
z	final inventory, kg
α	equipment parameters
β	operating conditions
ε	convergence accuracy
η	lost rate of processing units
θ	quality index of products
λ	flow rate ratio of one feed to that of all inlet streams
φ	yield rate of outlet streams

Superscripts

*	quasi-optimal
L	lower limit
U	upper limit

Subscripts

FCC	fluidized catalytic cracking
FNL	final
IL	inlet streams

OL	outlet streams
OPT	optimal

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