EMISSION CONSTRAINED CYCLIC SCHEDULING OF ETHYLENE CRACKING FURNACE SYSTEMS

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Abstract

Cracking furnace system is the starting and the most critical sector of an ethylene plant where heavier components are cracked into lighter products, such as ethylene, propylene, and etc. During the production, coking can adversely affect the manufacturing performance, such that furnaces have to be decoked for some controlled time. The cracking and decoking processes both influence the plant profit, as well as the emissions from the furnace operations. Nowadays, the profit enhancement is never the sole target for an ethylene plant; emission reduction is becoming a hot concern. How to schedule the decoking operation among multiple cracking furnaces with emission reduction consideration presents a new optimization problem. In this paper, an MINLP (mixed-integer nonlinear programming) model has been developed to optimize the cyclic operation of cracking furnace system with consideration of various emissions. The efficacy of the proposed methodology is demonstrated by a case study with in-depth analysis.

Keywords

Cyclic scheduling, Emission reduction, Optimization, MINLP, Decoking policy, Ethylene cracking furnace

Introduction

Ethylene is the most widely produced organic compound in the world and is essential for daily life. Its production in 2007 reached about 115 million metric tons and is expected to increase by 4.4% per year from 2007 to 2012 (SRI Consulting, 2009). Nowadays, most ethylene plants employ multiple cracking furnaces to process different types of feed and produce various products. The scheduling for the entire furnace system has been demonstrated to have significant economic and operational benefits. It is worth noting that the industrial sustainability has drawn significant interests from the entire chemical engineering society in recent years. Many sustainability considerations have been taken into account during the chemical process design and operation. A critical thought driven by the industrial sustainability is that the scheduling for a cracking furnace system shall help enhance the profitability of a plant with the least carbon footprint.

Optimal scheduling for the cracking furnace system can be obtained through modeling and optimization. Jain and Grossmann (1998) developed an MINLP model for the cyclic scheduling of multiple feeds cracked on parallel ethylene furnaces with exponential decay performance. The solving algorithm for global optimality is also exploited and demonstrated. However, the MINLP model does not consider secondary ethane cracking and non-simultaneous cleanups. In 2000, Schulz et al. developed a discrete-time based MINLP model to study cyclic optimal furnace shutdowns and downstream separation train system. It employs a time-dependent empirical variable of coil internal roughness as the indicator for furnace shutdown operation. Lim et al. (2006) scheduled a neural-network based cracking simulation, which employed

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dynamic data on ethylene and propylene yields, coil skin temperature, and pressure drop information to support the scheduling decisions. To further consider the unexpected uncertainties, they developed a proactive scheduling for the naphtha cracking furnace system (Lim et al. 2009). In this MINLP model, scheduling is not in a cyclic but dynamic scheme, the rescheduling is triggered when the gap between the model prediction and the measurement exceeds a chosen threshold value. Later on, to save the manpower and decoking facilities in plant, also to prevent the significant upset to downstream flowrate, Liu et al. (2010) developed a cyclic scheduling model by considering non-simultaneous cleanup constraints. After that, Zhao et al. (2010) developed an MINLP model to obtain cyclic scheduling strategies for a cracking furnace system with the consideration of secondary ethane cracking. It can simultaneously identify the allocation of feeds with their quantity, time, and sequence information for each cracking furnace. Very recently, Zhao et al. (2011) developed a new MINLP-based reactive scheduling strategy, which can generate new schedules at any time based on the new feed deliveries, the leftover feeds, and the updated furnace operating conditions.

In previous works, how to schedule the cracking furnace system for the best profit has been broadly studied. However, environmental concerns in cracking furnace scheduling, such as the emission controls are almost exclusively neglected. Obviously, during cracking operations, tremendous CO_2 is released from fuel combustion; meanwhile, additional CO_2, CO, and dust are also generated through the decoking operation. For the sake of environmental quality, many ethylene plants in the U.S. have enforced a limit on the decoking time during a fixed time period. Considerably, the profit maximization and the emission restriction are best considered simultaneously for the scheduling of the cracking furnace system.

In this paper, an MINLP model has been developed to optimize the cyclic operation of cracking furnace system with emission reduction consideration. The efficacy of the proposed methodology is demonstrated by a case study with in-depth analysis.

Problem Statement

Scheduling for a cracking furnace system will provide the quantitative answers to the following questions: i) how to allocate different feeds into different furnaces for cracking? ii) what is the processing sequence if two or more feeds are allocated to the same cracking furnace? iii) what is the run length of a cracking operation before its decoking operation (cleanup)? iv) what is the best decoking sequence among multiple furnaces when non-simultaneous cleanups are required? v) what is the average emission rate under such scheduling? Answers to these questions need to optimally coordinate the information elements of feed, furnace, time, quantity, and sequence. For easy understanding of the developed scheduling model, the following terminologies are introduced in advance.

Batch processing time. Batch processing time is the time duration for a furnace starting to crack a feed to the shutdown for decoking. It usually takes 20~90 days, depending on furnace types, feed characteristics, and the cracking severity.

Cleanup time. Cleanup time is the time duration for decoking a furnace, which is also the down time interval between two adjacent processing batches.

Cycle time. Cycle time is the time span of a schedule for each of the cracking furnace, during which, multiple batches and their associated cleanups are performed.

Non-simultaneous cleanup. Non-simultaneous cleanup means the cleanup time of different cracking furnaces cannot be overlapped.

Decay performance. During the batch processing time, the production yields of the products will change dynamically because of the coking and pyrolysis reaction kinetics.

Secondary ethane cracking. Ethane contained in the cracked gas will be fully recovered and reused as the cracking feed again.

Permitted decoking time. For air quality consideration, an ethylene plant is restricted by a limit of the total decoking time during a fixed operational period.

Average emission rate. For cyclic scheduling, average emission rate is the total amount of emission during one cycle divided by the cycle time.

General Methodology

In this section, the cyclic scheduling problem is formulated as an MINLP model. Suppose the furnaces can process M feeds and let $I = \{1, 2, \cdots, M\}$. Feed M is the recycled ethane. The cracking furnace system has N furnaces, i.e. $J = \{1, 2, \cdots, N\}$. Furnace N is the ethane furnace. In one cycle of the schedule, the furnace will process A batches, i.e. $K = \{1, 2, \cdots, A\}$. B products will be generated through cracking each feed, i.e. $L = \{1, 2, \cdots, B\}$. Product B is the ethane which will be recycled for the secondary cracking. A binary variable $y_{i,j,k}$ is introduced to determine a batch process ($y_{i,j,k}$ is 1 if the feed i is processed in the k-th batch in furnace j; otherwise, it is 0). The MINLP model is summarized below:

$$\max J = \frac{\sum_{i=1}^{M}\sum_{j=1}^{N}\sum_{k=1}^{A}\left\{Sa_{i,j,k} - (Cr_i + Cv_{i,j})D_{i,j}\, t_{i,j,k} - Cs_{i,j}\, y_{i,j,k}\right\}}{T} \quad (1)$$

In this model, the objective is to maximize the average net profit per day as shown in Eq. (1), where the net profit in one batch comes from the product sale income $Sa_{i,j,k}$, subtracting the material and operational costs

$(Cr_i + Cv_{i,j})D_{i,j}\,t_{i,j,k}$, as well as the cleanup cost $Cs_{i,j}\,y_{i,j,k}$. The optimization problem should satisfy the constraints (2) through (28).

$$Sa_{i,j,k} = \sum_{l=1}^{B} P_l\left(\int_0^{t_{i,j,k}} D_{i,j}\,(c_{i,j,l} + a_{i,j,l}e^{b_{i,j,l}\,t})\,dt\right), \quad \forall i \in I; \forall j \in J; \forall k \in K \tag{2}$$

Equation (2) indicates how to calculate $Sa_{i,j,k}$, where $D_{i,j}$ is the batch feed flow rate, P_l is the unit price of product *l*, and $c_{i,j,l} + a_{i,j,l}e^{b_{i,j,l}t}$ describes the dynamic change of product *l*'s yield with respect to time. Normally, ethylene yield would decrease during the batch processing time due to decay performance, but propylene yield would increase, until a cleanup is carried out and the production yield will be restored. During the processing, for each feed, the total amount used by all cracking furnaces should be under the plant supply capability.

$$Flo_i\,T + G_i = \sum_{j}^{N}\left(D_{i,j}\sum_{k}^{A} t_{i,j,k}\right), \quad \forall i \in I \tag{3}$$

$$G_i \le \left(Fup_i - Flo_i\right)T, \quad \forall i \in I \tag{4}$$

Equations (3) and (4) are borrowed from Jain and Grossmann (1998), where G_i is the amount of feed flow rate above the lower bound of Flo_i.

$$\sum_{j=1}^{N}\sum_{k=1}^{A} y_{i,j,k} \ge 1, \quad \forall i \in I \tag{5}$$

$$\sum_{i=1}^{M} y_{i,j,1} = 1, \quad \forall j \in J \tag{6}$$

$$\sum_{i=1}^{M} y_{i,j,k} \le 1, \quad \forall j \in J; \forall k \in K \tag{7}$$

Equations (5) through (7) are constraints for the binary variable $y_{i,j,k}$. Equation (5) suggests all the feeds should be processed during one cycle operation. Equation (6) indicates that, for each furnace, the first-batch slot should always be used for cracking a feed. Equation (7) means one batch slot could only be utilized for cracking one feed at most.

$$y_{i,N,k} = 0, \quad \forall i \in I, i \ne M; \forall k \in K \tag{8}$$

$$y_{M,j,k} = 0, \quad \forall j \in J,\ j \ne N; \forall k \in K \tag{9}$$

With the consideration of secondary ethane cracking, Eqs. (8) and (9) are employed to restrict the allocation of feeds; make sure only the ethane furnace can exclusively process recycled ethane.

$$tlo_{i,j}\,y_{i,j,k} \le t_{i,j,k} \le tup_{i,j}\,y_{i,j,k}, \quad \forall i \in I; \forall j \in J; \forall k \in K \tag{10}$$

$$-z_j T^{up} \le E_{j,1} - S_{j,1} \le \left(1 - z_j\right)T^{up}, \quad \forall j \in J \tag{11}$$

$$T^{lo}\left(1 - z_j\right) \le T - h_j \le T^{up}\left(1 - z_j\right), \quad \forall j \in J \tag{12}$$

$$T^{lo} z_j \le h_j \le T^{up} z_j, \quad \forall j \in J \tag{13}$$

$$\sum_{i=1}^{M}\sum_{k=1}^{A}\left(t_{i,j,k} + \tau_{i,j}y_{i,j,k}\right) = T, \quad \forall j \in J \tag{14}$$

$$S_{j,1} = E_{j,A} + \sum_{i=1}^{M}\tau_{i,j}\,y_{i,j,A} - T + h_j, \quad \forall j \in J \tag{15}$$

$$S_{j,k} = E_{j,k-1} + \sum_{i=1}^{M}\tau_{i,j}\,y_{i,j,k-1}, \forall j \in J; \forall k \in K, k \ne 1 \tag{16}$$

$$E_{j,1} = S_{j,1} + \sum_{i=1}^{M} t_{i,j,1} - h_j, \quad \forall j \in J \tag{17}$$

$$E_{j,k} = S_{j,k} + \sum_{i=1}^{M} t_{i,j,k}, \quad \forall j \in J; \forall k \in K, k \ne 1 \tag{18}$$

$$S_{j,1} \le T, \quad \forall j \in J \tag{19}$$

Equations (10) to (19) are timing constraints for batch processing time $t_{i,j,k}$, cycle time *T*, batch starting time $S_{j,k}$, and batch ending time $E_{j,k}$. Equation (10) gives the range of a batch processing time, which can be designated by furnace operational characteristics or industrial experience. Equation (11) defines another binary variable z_j. Because the cyclic scheduling problem is a round-table problem, the first batch may start from the previous cycle or from current cycle, z_j is 1 if the starting time of the first batch in the *j*-th furnace is larger than its ending time; otherwise, it is 0. Equations (12) and (13) are used to replace the nonlinear term Tz_j by h_j for algebraic benefit. Equation (14) indicates that the cycle time at each furnace is the same, which is equal to the summation of all the batch processing time and their cleanup time. The starting and ending time of each batch are characterized by Eqs. (15) through (18). Equation (19) suggests the starting time of the first batch should be less than or equal to the total cycle time. Note that the starting and ending time of a batch are arranged in such a way that if the *k*-th batch is not actually utilized, its starting and ending time will be the exactly same.

$$(x_{j,k,j',k'} - 1)T^{up} \le E_{j,k} - S_{j',k'+1} \le x_{j,k,j',k'}T^{up}, \quad \forall j, j' \in J,\ j < j'; \forall k, k' \in K \tag{20}$$

$$-x_{j,k,j',k'}T^{up} \le E_{j',k'} - S_{j,k+1} \le (1 - x_{j,k,j',k'})T^{up}, \quad \forall j, j' \in J,\ j < j'; \forall k, k' \in K \tag{21}$$

Equations (20) and (21) are non-simultaneous cleanup constraints, where another binary variable $x_{j,k,j',k'}$ is introduced, which is designated as 1 if the *k*-th cleanup in furnace *j* is no overlap behind the *k*'-th cleanup in furnace *j*'; otherwise, it is 0.

$$\sum_{i=1}^{M} y_{i,j,k} \ge \sum_{i=1}^{M} y_{i,j,k''}, \forall j \in J; \forall k, k'' \in K, k < k'' \tag{22}$$

$$x_{j,k,j',k'} \le x_{j,k'',j',k'}, \quad \forall j, j' \in J,\ j < j'; \forall k, k', k'' \in K, k < k'' \tag{23}$$

$$x_{j,k,j',k'} \ge x_{j,k,j',k''}, \quad \forall j, j' \in J,\ j < j'; \forall k, k', k'' \in K, k' < k'' \tag{24}$$

$$\sum_{i=1}^{M} y_{i,j',k'+1} \geq x_{j,k,j',k'} - x_{j,k,j',k'+1}, \quad (25)$$
$$\forall\, j, j' \in J,\ j < j';\ \forall\, k, k' \in K,\ k' \neq A$$

$$\sum_{i=1}^{M} y_{i,j,k+1} \geq x_{j,k+1,j',k'} - x_{j,k,j',k'}, \quad (26)$$
$$\forall\, j, j' \in J,\ j < j';\ \forall\, k, k' \in K,\ k \neq A$$

Equations (22) through (26) are some additional logic constraints for the batch process. Equation (22) shows that if one batch slot of a furnace is not utilized, the following batches of that furnace should neither be utilized. Equations (23) and (24) show that if the k-th cleanup in the furnace j is after the k' -th cleanup in the furnace j', then the k''-th cleanup in the furnace j should also be after the k'-th cleanup in the furnace j' ($k'' > k$); and vice versa. Equations (25) and (26) represent the logic relations characterized by binary variables of x and y.

$$\sum_{i=1}^{M}\sum_{j=1}^{N}\sum_{k=1}^{A} \tau_{i,j} y_{i,j,k} = t^{d} \quad (27)$$

$$t^{d} \leq R^{L} T \quad (28)$$

Equations (27) and (28) are the constraints for the total decoking time from one cycle operation. Usually, the emission compositions are different from normal processing and decoking; more CO and dust will be released during decoking. Thus, most of the plants have a limit of the total decoking time per year. Equation (27) calculates the total decoking time during one cycle operation. Equation (28) ensures the decoking time be within the limited range.

Based on the above equations and explanations, the developed cyclic scheduling model is described by the objective function of Eq. (1), which is to maximize the average net profit while subject to the process constraints and specifications described from Eqs. (2) through (28).

Case Study

A case study derived from Zhao et al. (2010) is presented in this paper. It is a cyclic scheduling problem for a cracking furnace system with six furnaces (N is 6), processing four types of feeds (M is 4). The feeds include gas, naphtha, light diesel, and ethane represented by *Fa*, *Fb*, *Fc*, and *Fpd*, respectively. After cracking, each feed would generate four types of products (B is 4), which are ethylene, propylene, ethane, and the left products represented by *Pa*, *Pb*, *Pd*, and *Pc*, respectively. The cracking furnace system includes one specific ethane furnace for processing recycled ethane, and five ordinary furnaces for processing the other feeds. For emission reduction consideration in this case study, the annual permitted decoking time for the cracking furnace system is 80 day/yr.

Based on the developed methodology, the MINLP model is developed with GAMS version 23.3 and is solved by the solver DICOPT, which employs CPLEX and CONOPT to handle the MIP and NLP problems respectively. The MINLP problem involves 12,266 equations, 1,746 integer variables, and 2,119 continuous variables. The average solving time with an 8-Core Xeon 3.2GHz Dell server for the case studies is within 1 hour. The optimal scheduling solution and its ethylene yield under permitted decoking time is shown in Figure 1, which gives a total cycle time of 305 days and an average net profit of $177,405/day, about $64.75 million/yr. The decoking time in one cycle operation is 67 days, about 80 days/yr, which meets the upper limit of permitted decoking time. As shown in Figure 1, there are six batches in Furnaces 1, 2 and 4, five batches in Furnaces 3 and 5, and three batches in Furnace 6 during one cycle. The feed allocation and processing sequence is marked for every batch. Note that *Fpd* (recycled ethane) has the highest conversion to ethylene, and *Fc* (light diesel) has the lowest; the ethylene yield drops during the batch processing time. Under such permitted decoking time, the estimated CO_2 emission from the schedule is 498.31 ton/day, about 181.88 kt/yr. Suppose all the CO and dust emissions are from the decoking operation, the estimated releasing rate is 1.82 kg/day and 4.38 ton/day.

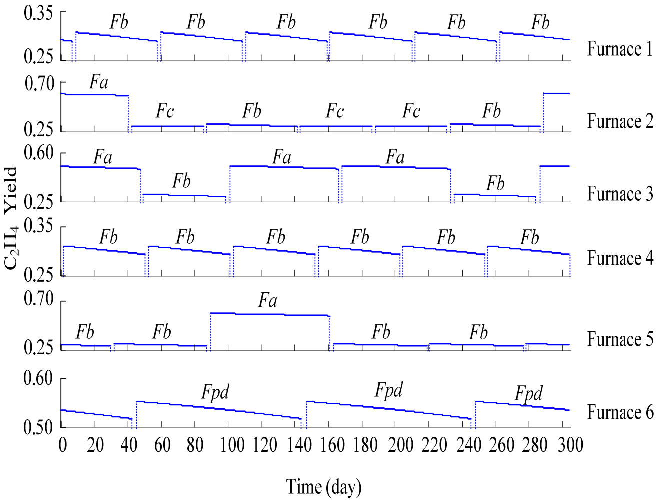

Figure 1. Optimal scheduling result under permitted decoking time

To compare with the optimal scheduling result under permitted decoking time, the scheduling results without decoking time restriction is borrowed from Zhao et al. (2010). In this case, the scheduling is optimized for the maximal profit and the decoking time is unlimited. Figure 2 shows the scheduling result: the scheduling has a cycle time of 208 days and an average net profit of $180,744/day. The decoking time in one cycle operation is 49 days, about 86 days/yr, which is above the assumed limit of permitted decoking time. The estimated CO_2 emission amount from the schedule is 507.84 ton/day; the estimated CO and dust emission amounts are 1.96 kg/day and 4.71 ton/day, respectively.

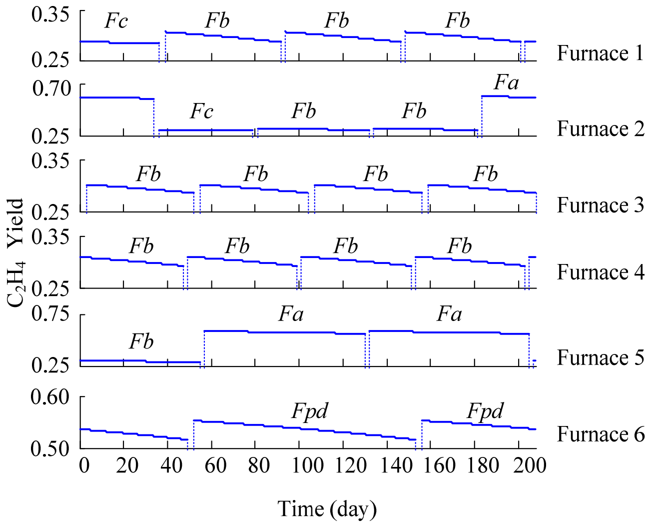

Figure 2. Optimal scheduling result without decoking time restriction (Zhao et al., 2010)

The detailed comparison is summarized in Table 1. The profit from the scheduling under the permitted decoking time is $177,405/day, which is less than $180,744/day from the scheduling without the decoking time limitation, reduced by about 1.85%. The profit drop mainly caused by the decrease of the average ethylene product yield. However, in the case with the decoking time limitation, the average emission rate has been reduced, i.e., CO_2, CO and dust emission has been decreased by 1.88%, 7.14%, and 7.01%. Overall, the emission considered optimization can be regarded as a trade-off between plant profitability and the environmental responsibility, i.e., sacrificing small part of profit to help emission reductions during the production. The developed methodology also for the first time introduces quantitative emission impact analysis during the cracking furnace system scheduling.

Table 1. Case study results comparison

Cases	**With decoking time limitation**	**Without decoking time limitation**
Profit ($/day)	177,405	180,744
Cycle time (day)	305	208
Average ethylene yield	0.380	0.388
Average feed flowrate (ton/day)	1179	1177
Total decoking time in a cycle (day)	67	49
Annual decoking time (day)	80	86
Average CO_2 emission rate (ton/day)	498.31	507.84
Average CO emission rate (kg/day)	1.82	1.96
Average dust emission rate (ton/day)	4.38	4.71

Conclusions

How to schedule the decoking operation for multiple cracking furnaces with emission restriction consideration presents a new optimization problem. In this paper, an MINLP model is developed to optimize the operation of the cracking furnace system with emission consideration as constraints. For the first time, it has also introduced quantitative emission impact analysis during the operational scheduling of cracking furnace systems.

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Nomenclature

Parameters:

$a_{i,j,l}$	pre-exponential factor of product *l*'s yield formula for the feed *i* cracked in the furnace *j*
$b_{i,j,l}$	power factor of product *l*'s yield formula for the feed *i* cracked in the furnace *j*
$c_{i,j,l}$	constant coefficient of product *l*'s yield formula for the feed *i* cracked in the furnace *j*
Cr_i	raw material cost for the feed *i*
$Cs_{i,j}$	one cleanup cost for the feed *i* cracked in the furnace *j*
$Cv_{i,j}$	batch operation cost for the feed *i* cracked in the furnace *j*
$D_{i,j}$	flow rate of the feed *i* cracked in the furnace *j*
Flo_i	lower bound of the total average flow rate for the feed *i*
Fup_i	upper bound of the total average flow rate for the feed *i*
P_l	market price for the product *l*
R^L	the ratio of permitted decoking time
$tlo_{i,j}$	lower bound of batch processing time for the feed *i* cracked in the furnace *j*
$tup_{i,j}$	upper bound of batch processing time for the feed *i* cracked in the furnace *j*
T^{lo}	lower bound of total cycle time
T^{up}	upper bound of total cycle time
$\tau_{i,j}$	cleanup time used after the feed *i* cracked in the furnace *j*

Variables:

$E_{j,k}$	ending time point of the *k*-th batch in the furnace *j*
G_i	extra amount of flow rate for feed *i* that is processed above Flo_i
h_j	a variable to replace the nonlinear term Tz_j
$S_{j,k}$	starting time point of the *k*-th batch in the furnace *j*
$Sa_{i,j,k}$	product sale income of processing feed *i* in the *k*-th batch of the furnace *j*
$t_{i,j,k}$	processing time for the feed *i* cracked in the *k*-th batch of the furnace *j*
t^d	the total decoking time during one cycle operation
T	total cycle time of the scheduling problem
$x_{j,k,j',k'}$	binary variable which is 1 if the *k*-th cleanup in the furnace *j* is no-overlap behind the *k'*-th cleanup in the furnace *j'*; otherwise, if the *k*-th cleanup in the furnace *j* is no-overlap ahead of the *k'*-th cleanup in the furnace *j'*, it is 0.
$y_{i,j,k}$	binary variable which is 1 if the feed *i* is processed in the *k*-th batch of the furnace *j*; otherwise, it is 0.
z_j	binary variable which is 1 if the starting time of the first batch in the furnace *j* is larger than its ending time; otherwise, it is 0.

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