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Interaction Between Process Plant Operation and Cracking Furnaces Maintenance Policy in an Ethylene Plant

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ABSTRACT

This work addresses the problem of the determination of a maintenance policy for cracking furnaces in an ethylene plant, taking into account the interactions between the entire process plant operation and furnace performance. An important recycle stream (ethane from units downstream the furnaces) constitutes part of the feed, so nonlinear models of units from the entire ethylene process have been included in the optimization problem. The resulting model is a mixed integer nonlinear programming problem where integer variables are associated to the number of time cycles that each feed is processed in a furnace.

1. INTRODUCTION

The increasing challenge of international competitiveness in the oil and petrochemical industry at a global level makes no longer possible to define optimal production policies only on operating conditions. Pinto *et al.* (1999) have derived and applied planning and scheduling models to optimal operation in oil refineries. Furthermore, in plants processing different feedstocks and requiring cyclic shut downs for cleaning, as it is the case of ethylene plants, a correct assigning of feeds to units and time cycles is essential to reach global optimal operation. Jain and Grossmann (1998) have studied the scheduling of multiple feeds on parallel units with decaying performance.

In this paper, we formulate and solve the problem of the determination of a maintenance policy for cracking furnaces in an ethylene plant, taking into account the interactions between the entire process plant operation and furnace performance. Thermal cracking of ethane produces depositions of coke on the tubes internal surface, so furnaces performance decay with time and they have to be periodically shut down and cleaned with a certain stopping policy. Downstream process information is obtained through the addition of nonlinear models for the entire process plant (Bandoni *et al.*, 1989; Diaz and Bandoni, 1996) because an important recycle stream (ethane from units downstream the furnaces) constitutes part of the feed. In this way, it is possible to have a more realistic insight of the influence of the main scheduling decisions on the entire plant performance.

Ethylene production process has been modeled with ten parallel furnaces and multiple feeds together with the entire plant model that includes: quenching, hydrogenation reactors, separation train, ethane recycle, ethylene recycle, cracked gas compressor, ethylene and propylene compressors and utility plant. These plant sectors are represented by nonlinear correlations for unit parameters and mass balances.

The resulting model is a mixed integer nonlinear programming problem where integer variables are associated to the number of time cycles that each feed is processed in a furnace. The objective is to maximize profits, calculated as the difference between income (production of ethylene, propylene, propane, butane, gasoline and residual gas) and cost (ethane, natural gas consumption for boilers and furnaces, electricity and cleanup costs for furnaces). The problem has been solved using GAMS (Brooke *et al.*, 1992).

2. ETHYLENE PLANT DESCRIPTION

The ethylene plant under study (Fig. 1) produces 260,000 ton/y of 99.9% pure ethylene. It consists of ten pyrolysis furnaces, a cracked gas compressor, heat recovery network, separation system, refrigeration system and steam generation system. The feed, which has high ethane content, is cracked in the pyrolysis furnaces to produce ethylene and subproducts. Previously, the feed gas at high temperature is diluted with a steam stream to minimize coke deposition in the tubes. Cracked gas is compressed from 0.2 to 30 kg/cm2, and afterwards it is cooled to -100°C. Before to the cooling stage, water is fully removed from the process stream and acetylene, one of the reaction side products, is totally converted to ethylene. Finally, these gases at high pressure and cryogenic temperature enter the separation train; where the first unit is a demethanizer column that produces residual gas (mainly hydrogen and methane) as top product. This residual gas is used as fuel in the plant boilers. Ethane and ethylene are obtained as top products from the deethanizer column and are then separated in a splitter; ethane is recycled to the pyrolysis furnaces and ethylene is obtained as the plant main product. Propane and propylene constitute the top stream in the depropanizer column and are sent to a splitter. Butane and gasoline are separated in a debutanizer column.

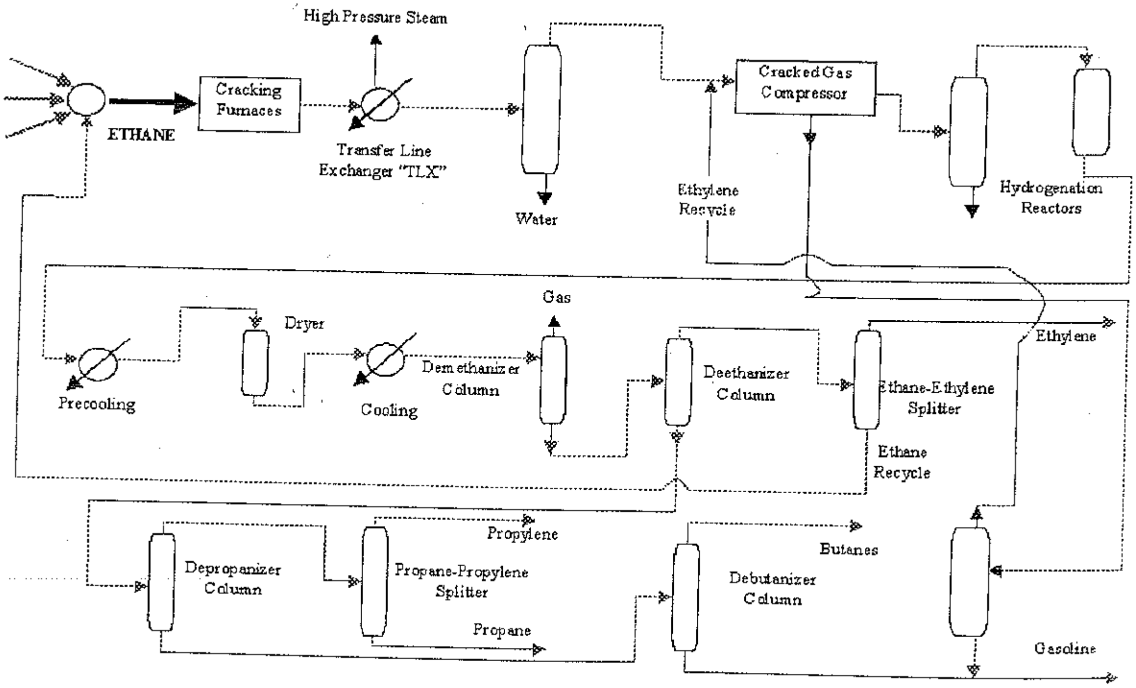

Figure 1: Process plant and alternative gas feeds.

There are two main process recycles in the plant: a) ethane recycle, which is the bottom stream from the ethane-ethylene splitter and is sent to the cracking furnaces after mixing with the ethane fresh feed; b) ethylene recycle, that is recycled from the gasoline stabilization column.

3. CYCLIC ASSIGNMENT OF FEEDS TO CRACKING FURNACES AND MAINTENANCE POLICY

In this plant, ethylene is obtained by thermal cracking of ethane. Ethylene yield and, consequently, net profit are closely related to feed composition. Diaz and Bandoni (1996) have shown optimal profit variations as function of propane content in the feed; mixtures with higher ethane concentration render higher profit.

The coke produced as a byproduct in the thermal cracking of ethane deposits on internal tube surface with two undesirable effects that make ethylene yield decrease. One of them is the insulation of the reacting mixture (a strong negative effect as the reaction is highly endothermic) and the other is the decrease of tubes cross sectional area. Consequently, cracking furnaces must be periodically shut down and cleaned with the associated cost of clean up and loss of production. Therefore, there is a compromise between operating the furnaces for very long periods of time with decreasing plant performance against higher clean up costs with better performance.

In this work, we have addressed the problem of cyclic assignment of ethane mixtures with different ethane content to cracking furnaces and the determination of optimal operating conditions and clean up times. The model takes into account the important ethane recycle stream that is sent back to cracking. The entire plant model comprises correlations to represent furnaces operation and the separation train, together with the utility system and the three main compressors (cracked gas, ethylene and propylene compressors). These correlations (Bandoni *et al.*, 1989) have been obtained from plant data and results of runs with rigorous unit models.

4. MATHEMATICAL MODEL

The cyclic assignment of different feeds to cracking furnaces and determination of operating times, as well as clean up periods, has been formulated as a MINLP problem, as proposed by Jain and Grossmann (1998). These authors formulated the scheduling of multiple feeds to different cracking furnaces as a MINLP problem with linear constraints and a pseudoconcave objective function (maximization problem), which guarantees global optimality. To obtain linear constraints, they have approximated mass balances around mixers as linear equations. The scheduling was performed without a downstream plant model, and consequently, the ethane recycle has not been included in the optimization model.

In this work, the objective function is the maximization of profit, defined as the difference between the sales revenue and the total operating cost. The revenue from products is defined over all products generated in the plant (ethylene, propylene, propane, butane, gasoline, residual gas); the feed costs are mainly associated to ethane feed cost. The model for the optimal assignment of feeds to furnaces, operating times and number of cycles for each feed in the furnaces includes the following equations:

Component Mass Balances at Furnaces Entrance

$$F_{ij} T_{cycle} + R_{ij}\, T_i = D_{ij} T_i \qquad \forall\, i,j \qquad (1)$$

$$F_i = \sum F_{ij} \qquad \forall\, i \qquad (2)$$

Recycle Stream

$$R_{ij} = f(Rug_i, Pdem_i, Rel_i, Fsep_i) \qquad \forall i,j \tag{3}$$

Tube Roughness

$$Rug_i = C1_i + C2_i T_i / n_i \qquad \forall i \tag{4}$$

Furnaces Inlet Pressure

$$Pin_i = f(D_i, Rd_i, Pout_i, Conv_i, Rou_i) \qquad \forall i \tag{5}$$

Furnaces Production

$$Ff_{ij} = f(D_i, Rd_i, Pin_i, Conv_i) \qquad \forall i,j \tag{6}$$

Integrality Constraints for Number of Cycles

$$n_i = \sum k y_{ik} \qquad \forall i \tag{7}$$

$$\sum y_{ik} = 1 \qquad \forall i \tag{8}$$

Total Processing and Clean up Time

$$Dt_i = n_i \tau_i + T_i \qquad \forall i \tag{9}$$

$$\sum Dt_i = T_{cycle} \tag{10}$$

Plant Process Streams

$$Ft_{uij} = f(Pdem_i, Rel_i, fs_{uij}) \qquad \forall i,j,u \tag{11}$$

$$Fb_{uij} = f(Pdem_i, Rel_i, fs_{uij}) \qquad \forall i,j,u \tag{12}$$

Equations (1) and (2) stand for mass balances at the furnaces entrance; the term $R_{ij}\ T_i$ that represents the recycle stream is not taken into account when the entire plant model is not included. Equations (3) to (6) are correlations that determine internal tube roughness and furnaces production as function of operating time, furnace inlet pressure and component molar flowrates. Equations (7) to (10) represent timing and integrality constraints (Jain and Grossmann, 1998). Equations (11) and (12) are product stream flowrate of the different units that constitute the separation train. The model also comprises correlations that evaluate main plant compressors consumption and utility system.

5. NUMERICAL RESULTS

We have analyzed the cyclic assignment of alternative gas feeds to a cracking furnace that represents ten existing furnaces in the plant. The model has been implemented in GAMS (Brooke *et al.*, 1992). A comparison of results has been performed between the optimal maintenance policy with and without the entire plant model. We have studied problems with two and three gas feeds. Feed molar compositions are shown in Table 1, together with clean up times for each one.

Table 1 Feed molar compositions and clean up times

Feed	Methane	Ethane	Propane	τ_i (days)
A	0.40	99.40	0.20	2
B	3.73	90.90	5.37	3
C	0.40	84.80	14.80	2 ½

Conversion is function of internal tube roughness and it is consequently a linear function of processing time. Table 2 shows main timing variables for the studied cases. The same trend has been observed in the assignment of two and three alternative feeds to a furnace when not taking into account the ethane recycle stream (Cases 1 and 3). In these cases, each feed is processed only one time cycle in the furnace, but feed A is the one with longer processing time due to its high ethane content. Additionally, mean conversion is almost the same for all of them. When nonlinear models representing the entire plant are included in the problem (Cases 2 and 4), a different time schedule is obtained and the trend is the same for the processing of two or three feeds. In both cases, numerical results confirm the convenience of processing feed A for a longer time, as it is the one with higher ethane content. Moreover, as it has been associated to lower roughness coefficients, it only requires one shut down for cleaning (n_A = 1). Feeds B and C are processed for shorter times and both of them require two time cycles; i.e., two shut down periods each ($n_B = n_C = 2$). As regards profit, the model that includes the entire plant model predicts higher values because molar ethane flowrates at the furnaces entrance are parameters; i.e., there are fixed feed loads to furnaces. In cases 1 and 3, a higher flowrate of fresh ethane is needed, as there is no recycle.

Table 2 Optimal assignment of feeds and processing times

Case	Feed	Recycle	T (d)	Tcycle	n	Mean Conversion	Fresh Feed (Kmol/h)	Profit (U$S/h)
1	A	No	63	128	1	0.700	970	9463
	B		60		1	0.700	875	
2	A	Yes	86	165	1	0.700	707	10678
	B		71		2	0.698	577	
3	A	No	62	189	1	0.700	675	10359
	B		55		1	0.700	587	
	C		53		1	0.686	522	
4	A	Yes	94	235	1	0.700	544	11044
	B		73		2	0.697	415	
	C		54		2	0.653	278	

The optimal assignment of the three feeds (cases 3 and 4) is shown in Fig. 2, along with processing and clean up times.

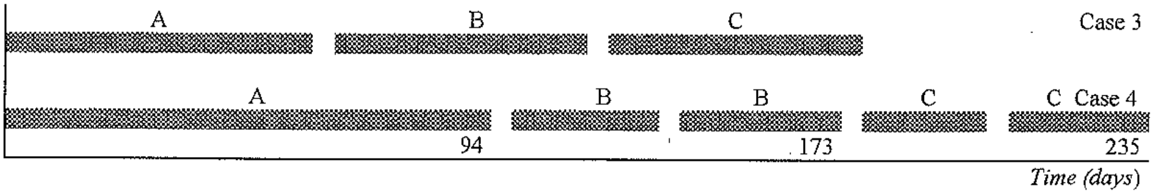

Figure 2. Processing times distribution and optimal assignment of feeds (Cases 3 & 4).

Table 3 Main plant operating variable values for case 4 (three feeds)

Variable	A	B	C
Inlet Furnace Pressure (bar)	3.548	3.393	2.778
Ethane Recycle (Kmol/h)	578.76	529.33	538.44
Roughness	0.007	0.006	0.002
Ethylene Stream (Kmol/h)	1124.36	1077.72	1024.93
Dilution Ratio	0.27	0.27	0.27

Table 3 presents a comparison of main plant operating variables associated to the processing of each alternative feed for case 4. This problem contains 260 equations, 415 continuous variables and 24 binary variables and has been solved with GAMS (using DICOPT++ with CONOPT and OSL) in four major iterations.

6. CONCLUSIONS

This paper has presented a model for the determination of optimal maintenance policy in ethylene plants with multiple feeds with a downstream nonlinear plant model to take into account operating decisions in the ethane recycle to furnaces feed. Different cleaning up and stopping policies are obtained when the entire plant model is added to the scheduling model. These results show that the ethane recycle should not be neglected when determining optimal operating policies.

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Notation

F_{ij}	Fresh feed flowrate of component j in feed i (Kmol/h)
T_{cycle}	Total cycle time (h)
R_{ij}	Flowrate of component j in ethane recycle stream for feed i (Kmol/h)
D_{ij}	Inlet flowrate of component j and feed i to furnaces (Kmol/h)
T_i	Total processing time for feed i (not including clean up)
Rug_i	Internal coil roughness for feed i
$Pdem_i$	Demethanizer column pressure (bar)
Rel_i	Ethylene/Ethane ratio at the entrance of separation train
$Fsep_{uij}$	Separation factor in unit u for feed i
C_{1i}, C_{2i}	Internal coil roughness coefficients
n_i	Number of subcycles of feed i in the furnaces
Pin_i	Furnace inlet pressure for feed i (bar)
Rd_i	Dilution ratio for feed i
$Pout_i$	Furnace outlet pressure for feed i (bar)
$Conv_i$	Ethane conversion for feed i
Ff_{ij}	Molar flowrate of component j and feed i in furnaces product stream (Kmol/h)
y_{ik}	Binary variable ($y_{ik}=1$ if feed i is processed k subcycles in the furnace)
Dt_i	Total processing and clean up time for feed i
τ_i	Clean up time for feed i
Ft_{uij}	Molar flowrate of component j and feed i as top product in unit u (Kmol/h)
Fb_{uij}	Molar flowrate of component j and feed i as bottom product in unit u (Kmol/h)

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