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Production planning optimization of an ethylene plant considering process operation and energy utilization

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ABSTRACT

A novel short-term planning model of the ethylene plant that incorporates the operating variables and energy utilization in both the thermal cracking and the down-stream process is proposed to explore the potential for increasing the production margin and reducing the energy losses. A multi-period mixed-integer nonlinear programming (MINLP) model is formulated to attain the scheduling of parallel furnaces and the energy distribution of the overall plant, along with the determination of the key process operation involving the coil outlet temperature (COT) and coke deposition. The behavior of the product yields and coke formation in terms of varying COT profiles is investigated to enhance the profitability of the whole plant. A real industrial example is investigated to exploit the performance of the proposed model. The results show that the integrated approach attains an improvement in overall profit and achieves significant enhancement in energy savings, compared with the original optimization approach.

1. Introduction

New markets for chemical products are emerging in developing countries with increasing modernization and urbanization. Therefore there is an extending demand for ethylene production, which is the most valuable and fundamental material in petrochemical industry. Ethylene plants are large-scale factories employing multiple cracking furnaces that can process a variety of raw materials ranging from gasses (e.g., ethane) to naphtha, and gas oils. Operational optimization for either parallel furnaces system or entire real-world chemical plants is becoming a subject of growing interest in chemical industry (Al-Qahtani and Elkamel, 2011). Many studies have been carried out on process synthesis regarding optimizing the flow-sheet and suggesting modifications. A mixed integer mathematical model for the operational planning of an ethylene plant was presented, and a procedure was introduced in an earlier work based on combination of the nonlinear optimization and process simulation (Diaz and Bandoni, 1996). An MINLP model taking operating condition into account was addressed later for the plant-site scheduling, focusing on the feedstock management in terms of vessels arrivals and storage tanks (Tjoa et al., 1997). Moreover, nonlinear operational planning models for ethylene production were proposed considering the operating condition (Gubitoso and Pinto, 2007). Both cyclic scheduling with consideration of secondary ethane (Zhao et al., 2010) and dynamic scheduling (Zhao et al., 2011) were investigated for the cracking furnace system in the real process condition. The optimal reaction conditions for the steam cracking of ethane were studied based on kinetics to improve the ethylene yield (van Goethem et al., 2013). The optimal sequencing process for olefins separation was determined in the proposed methodology regarding the economic optimization of the distillation-based system for ethylene production (Khor et al., 2014).

These studies have provided a better insight into the process at design and operation stages. The planning and scheduling for the entire ethylene plant has also been studied with significant economical and operational benefits by preceding research. Especially in the parallel cracking furnaces system, it is worth noting that many considerations for process operating condition (e.g., coke formation) have been addressed in the furnace system design and operation. Cyclic scheduling policy of continuous parallel furnaces has been studied to improve the operational optimization regarding the decaying performance (Jain and Grossmann, 1998; Lim et al., 2006). Fuzzy programming method was applied for optimizing the ethane pyrolysis considering its conversion, steam/hydrocarbon ratio, and inlet temperature and pressure (Riverol and Pilipovik, 2007). The scheduling problem for the maintenance policy of parallel cracking furnaces was addressed for an ethylene plant, taking

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Nomenclature

Sets

- C set of commodities
- CF set of fuel products
- CR set of raw material: nap (naphtha), ago (atmosphere gas oil), hvgo (hydrocracking vent gas oil), etha (ethane)
- CP set of final product: hy (hydrogen), fg (including mthane and propane), mtha (methane), prop (propane), etha (ethane), ethy (ethylene), prol (propylene), but (butadiene), ben (benzene), c4 (C4 products), c5 (C5 products), cgaso (cracked gasoline), cfo (cracked fuel oil)s
- $CPI_{u,c}$ set of input commodities of compressor u
- CS set of different pressure steam: super pressure steam (SS) and medium pressure steam (MS)
- CV set of intermediate products: hy, fg, mtha, prop, etha, ethy, prol, but, ben, c4, c5, cgaso, cfo
- $FI_{f,c}$ set of input material c of furnace f
- $FO_{f,c}$ set of output products c of furnace f
- $M_{f,u}$ set of units association between cracking furnace and compressor
- $Mb_{uc,ut}$ set of units association between compressor and turbine
- $SI_{u,c}$ set of input material c of separation unit u
- $SO_{u,c}$ set of output products c of separation unit u
- T set of time periods
- U set of units
- UB set of boilers
- UC set of compressors
- UCL set of cooling units
- UF set of cracking furnaces: ba101-115
- UFB set of cracking furnaces and boilers
- US set of separation unit: mes, ets, etys, pros, prols,c4s, c5s (demethanizer, deethanizer, ethane-ethylene splitter, depropanizer, propane-propylene splitter, debutanizer, depentanizer)
- UT set of turbines

Indices

- c commodities
- f cracking furnaces (subset of u)
- i segment of compressor
- lo lower bound
- r raw material (subset of c)
- t time period
- u units (cracking furnaces/separation units/ compressors/turbines/cooling unit)
- up upper bound

Parameters

- $Ac_{r,f,c}$ pre-exponential factor for impact of coking deposition on product yields
- $Acc_{f,r}$ linearized coke factor
- $Af_{f,r}$ pre-linear coefficient for fuel consumption of cracking furnace f related to unit throughout when cracking material r
- $Ar_{f,r}$ pre-linear factor coking reaction
- $As_{f,r}$ pre-linear coefficient for steam generation of cracking furnace f related to unit throughout when cracking material r
- Asc_u pre-linear coefficient of unit load on dilution steam
- Ast_u pre-linear factor for impact of extracted steam on steam consumption
- Aw_u power consumption coefficient of compressor u related to unit load
- Awg_u pre-linear factor for impact of extracted steam on power generation
- $Bc_{r,f,c}$ pre-linearized factor for impact of COT on product yields
- $Bf_{f,r}$ pre-linear coefficient for fuel consumption of cracking furnace f related to coil outlet temperature
- $Bs_{f,r}$ pre-linear coefficient for steam generation of cracking furnace f related to coil outlet temperature
- Bsi_u pre-linear coefficient of inlet material temperature on dilution steam
- $Bsti_u$ pre-linear factor for impact of inlet steam temperature on steam consumption
- $Bsto_u$ pre-linear factor for impact of outlet steam temperature on steam consumption
- Bso_u pre-linear coefficient of outlet material temperature on dilution steam
- $Bw_{u,i}$ power consumption coefficient of compressor u related to inlet material temperature of segment i
- $Bwgi_u$ pre-linear factor for impact of inlet steam temperature on power generation
- $Bwgo_u$ pre-linear factor for impact of outlet steam temperature on power generation
- Ced_u pre-linear factor for impact of unit top pressure on steam consumption
- $Cf_{f,r}$ pre-linear coefficient for fuel consumption of cracking furnace f related to dilution steam
- $Cfp_{u,c}$ pre-linear coefficient of separation unit top pressure on product yield
- $Cs_{f,r}$ pre-linear coefficient for steam generation of cracking furnace f related to dilution steam
- $Csti_u$ pre-linear factor for impact of inlet steam pressure on steam consumption
- $Csto_u$ pre-linear factor for impact of outlet steam pressure on steam consumption
- $Cw_{u,i}$ power consumption coefficient of compressor u related to inlet pressure of segment i
- $Cwgi_u$ pre-linear factor for impact of inlet steam pressure on power generation
- $Cwgo_u$ pre-linear factor for impact of outlet steam pressure on power generation
- $Dfc_{f,r}$ constant value for aggregated model of fuel consumption of cracking furnace f when cracking material r
- $DP_{c,t}$ market demand of final product c of period t
- $DR_{f,r}$ dilution steam ratio of the furnace f when consuming material r
- $Dsc_{f,r}$ constant value for aggregated model of steam generation of cracking furnace f when cracking material r
- Ec activation energy of coking reaction
- Fcd_f constant factor of energy consumption of furnace f
- $Fs_{u,c}$ separation factor of unit u for product c
- H_c the enthalpy values of fuel c
- H_{stm} the enthalpy values of saturated steam
- H_{wat} the enthalpy values of water
- IC_c inventory cost of commodity c
- MIU_u inventory capacity of commodities c
- MIS_c safety inventory level of commodity c
- Mp_r molar concentration of propylene
- pri_c price of commodity c
- SEC_f material switching cost coefficient for cracking furnace f