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Techno-economic analysis of petrochemical complex retrofitted with simulated moving-bed for olefins and aromatics production

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ABSTRACT

This article presents a preliminary result on deciding whether to use simulated moving-bed (SMB) technology in a conventional petrochemical complex (cPCC) to increase olefins and aromatics production. A process model including an SMB unit, naphtha hydro-treating (NHT), naphtha thermal cracking (NTC), and naphtha catalytic reforming (NCR) was constructed to evaluate the economic feasibility of the retrofit petrochemical complex (rPCC) with the SMB unit for 2500 kt/yr naphtha treatment. The chemical reaction kinetics of NTC and NCR were used to estimate the increase of olefins and aromatics production. The incremental total capital investment for the SMB and additional NHT areas, estimated by the factorial method, was 97.5 $M. The incremental total production cost concerning utility and fixed costs was 25 $M/yr. It was found that the rPCC has economic benefits, because the return on investment (ROI) after tax, payback period (PBP), and internal rate of return (IRR) are 18%, 3.7 yr, and 20%, respectively. The SMB recovery of *n*-paraffins was most influenced on ROI and IRR in sensitivity analysis.

1. Introduction

Basic petrochemicals such as ethylene, propylene, butadiene, and aromatics (arene) such as benzene, toluene, and xylene (BTX) are the main products of the petrochemical industry (Ren et al., 2009; Xiang et al., 2014). Currently, most of these are produced via conventional routes such as reforming and cracking of naphtha, which are vital processes in petrochemical refineries (Ren et al., 2009). The significance of these industrial processes has induced researchers to investigate different aspects of both naphtha cracking and reforming intensively (Rahimpour et al., 2013).

Naphtha is a fraction of petroleum that typically constitutes 15–30 wt% of crude oil and boils at between 30 °C

Abbreviations: BTX, benzene toluene and xylene; cPCC, conventional petrochemical complex; H-HC, heavy hydrocarbons; IRR, internal rate of return, %; L-HC, light hydrocarbons; NCR, naphtha catalytic reforming; NHT, naphtha hydro-treating; NPV, net present value, $; NTC, naphtha thermal cracking; *n*-paraffins, normal paraffins (normal alkanes); Non *n*-paraffins, isoparaffins (isoalkanes) naphthenes (cycloalkanes) and aromatics (arenes); *i*-paraffins, isoparaffins; PBP, payback period, yr; PCC, petrochemical complex; PFD, process flow diagram; PoS, plot of sensitivity; PX, *para*-xylene; ROI, return on investment after tax, %; rPCC, retrofit petrochemical complex with simulated moving-bed unit; SMB, simulated moving-bed.

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Nomenclature

A	capacity (kt/yr)
a	installed cost factor
b	indirect cost factor
c	project contingency factor
C_A	annualized total cost ($/yr)
C_{dep}	depreciation cost ($/yr)
C_{DI}	total direct and indirect costs ($)
C_E	purchased equipment costs ($)
C_F	fixed capital investment ($)
C_I	total installed cost ($)
C_{ID}	indirect cost ($)
C_P	project contingency ($)
C_T	total capital investment ($)
C_{TP}	total production cost ($/yr)
C_{TU}	total utility cost ($/yr)
C_W	working capital ($)
d	working capital factor or diameter (m)
D	distillate flow rate (t/h)
E_a	activation energy (kJ/mol)
f_k	mass flow rate of product k (kt/yr)
i	component index or interest rate (%)
j	reaction index
k_0	pre-exponential factor (kmol/(m^3 s Pa$^{\Sigma\alpha_i}$))
N	number of reactants
N_s	number of theoretical stage
p	partial pressure (Pa)
P_{ASR}	annual sales revenue ($/yr)
P_{butane}	n-butane purity (wt%)
P_{cash}	cash flow ($/yr)
P_G	gross profit ($/yr)
P_N	net profit ($/yr)
p_k	market price of product k ($/t)
R	gas constant, J/(mol K) or molar reflux ratio
R_c	relative change (%)
r	reaction rate (kmol/(m^3 s))
T	temperature (K)
α_i	exponent of ith reactant
η	tray efficiency
φ	corporation income tax rate (%)

and 200 °C. This complex mixture consists of hydrocarbon molecules with 5–12 carbon atoms, and mainly includes paraffins (alkanes), olefins (alkenes), naphthenes (cycloalkanes), and aromatics (Rahimpour et al., 2013). Naphtha thermal cracking (NTC) of hydrocarbons is the most important source for the production of olefins, which are the main feedstock of the polymer industries (Karimzadeh et al., 2009). The naphtha catalytic reforming (NCR) unit has key roles in refineries for obtaining high-octane gasoline and BTX components (Gyngazova et al., 2011; Iranshahi et al., 2014; Rahimpour et al., 2013; Rodríguez and Ancheyta, 2011). The process performance and product yield depend on the composition and the carbon numbers of normal paraffins (n-paraffins), iso-paraffins (i-paraffins), naphthenes, and aromatics in naphtha (Liu et al., 2009). Under typical NTC reaction conditions, n-paraffins in naphtha contribute most to ethylene in the products, whereas i-paraffins are the main sources of propylene. Naphthenes mainly produce butadiene, and aromatics produce hardly any olefins (Liu et al., 2009). The NCR is accomplished mainly by converting n-paraffins and naphthenes in naphtha to i-paraffins and aromatics over bifunctional catalysts (Iranshahi et al., 2014; Rodríguez and Ancheyta, 2011).

The simulated moving-bed (SMB) process has been successfully used in petrochemical separations such as p-xylene separation from its C_8 isomers, n-paraffins separation from branched and cyclic hydrocarbons, and olefins fractionation from paraffins (Sá Gomes et al., 2009). The MaxEne process, which has been used to separate n-paraffins from naphtha, was developed by UOP (USA) to integrate refining and petrochemical facilities (UOP). MaxEne enables an increase in ethylene productivity using existing naphtha cracking units, without making major changes. n-Paraffins are preferably fed into the naphtha cracker to raise the yield of light olefins (ethylene and propylene). The catalytic reforming yield increases significantly when n-paraffins are removed from the feed. Therefore, the separated n- and non n-paraffins (mostly iso-paraffins, naphthenes, and aromatics) can be effectively used as raw materials for olefins and aromatics production, respectively (Chang et al., 2005; Liu et al., 2009).

In our previous study (Do et al., 2015), the effects of naphtha separation into n-paraffins and non n-paraffins by using the SMB process on the NTC and NCR reaction kinetics were investigated for industrial production of olefins and aromatics. Two chemical reaction models of NTC and NCR were proposed and validated with typical plant data obtained from a petrochemical complex (PCC). The olefins and aromatics production rates increased by 14 wt% and 11 wt%, respectively, in the retrofit petrochemical plant (rPCC), since n-paraffins are cracked more in NTC and non n-paraffins produce more aromatics in NCR.

Although more olefins and aromatics were produced in the rPCC, the energy consumption rose because of the SMB unit. Not only does the energy consumption increase, but one also pay the capital investment costs of integrating the SMB and naphtha hydro-treating (NHT) areas into an existing plant. It is therefore necessary to evaluate the technical feasibility and economic profitability of the integration of the SMB unit into an existing petrochemical plant.

The objective of this study is to evaluate the economic feasibility of a rPCC with the SMB unit by developing a process model of the SMB, NHT, NTC, and NCR. The simplified reaction kinetic models of NTC and NCR are used to predict the rPCC product compositions. The product rates and energy consumption of the rPCC are estimated and compared with those of a conventional petrochemical complex (cPCC). The economic feasibility of the rPCC is analyzed in terms of the return on investment (ROI) after tax, payback period (PBP), and internal rate of return (IRR). A sensitivity analysis is performed for the rPCC to identify the key variables that have a strong impact on the ROI and IRR.

2. Process description

Fig. 1 shows the conceptual flow diagram of two PCC configurations: cPCC (conventional petrochemical complex) and rPCC (retrofit petrochemical complex with SMB). As shown in Fig. 1a, the cPCC with a total capacity of 3800 kt/yr of crude naphtha includes two distillation columns to separate light hydrocarbons (L-HC) and heavy hydrocarbons (H-HC), a naphtha hydro-treating (NHT) area, naphtha thermal cracking (NTC) and catalytic reforming (NCR) reactors, and olefins and aromatics separations areas. The inlets of the NTC reactor are light hydrocarbons consisting of a mixture of 1150 kt/yr leaving the distillation column 1 (Distill 1), 40 kt/yr from the