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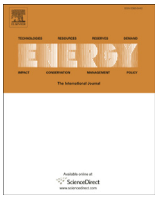

Heat integration of fractionating systems in para-xylene plants based on column optimization

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ABSTRACT

In this paper, the optimization of xylene fractionation and disproportionation units in a para-xylene plant is performed through a new method for systematic design based on GCC (grand composite curve) and CGCC (column grand composite curve). The distillation columns are retrofitted by CGCC firstly. Heat Integration between the columns and the background xylene separation process are then explored by GCC. We found that potential retrofits for columns suggested by CGCC provide better possibilities for further Heat Integration. The effectiveness of the retrofits is finally evaluated by means of thermodynamics and economic analysis. The results show that energy consumption of the retrofitted fractionating columns decreases by 7.13 MW. With the improved thermodynamic efficiencies, all columns operate with less energy requirements. Coupled with Heat Integration, the energy input of the para-xylene plant is reduced by 30.90 MW, and the energy outputs are increased by 17 MW and 58 MW for generation of the 3.5 MPa and 2.5 MPa steams. The energy requirement after the Heat Integration is reduced by 12% compared to the original unit. The retrofits required a fixed capital cost of 6268.91 × 10^3 $ and saved about 24790.74 × 10^3 $/year worth of steam. The payback time is approximately 0.26 year for the retrofits.

1. Introduction

The production of PX (para-xylene) with a maximum yield from naphtha in a para-xylene plant undergoes a series of reactions and separations with a broad range of temperatures and pressures. All units involved in the PX plant, such as catalytic reforming, disproportionation and trans-alkylation, isomerization, adsorption, extraction, xylene fractionation, etc., are connected in a complicated material and energy supply relationship, as shown in Fig. 1 [1]. The mixed xylenes, produced through toluene disproportionation and trans-alkylation with C_9 aromatics, mainly consist of PX, MX (meta-xylene), OX (ortho-xylene) and EB (ethylbenzene). A large amount of energy is required for distillation separation due to the structural similarities and the close boiling temperatures. Distillation is the most popular separation process in chemical industries. Over 95% of separation processes utilize distillation units, but distillation is still one of the lowest energy efficient processes (5–20%) [2]. Optimization of distillation columns for better energy-use is a complex task. The large number of possibilities for column configuration, including the number of stages, reflux ratio, the location of feed stage, the use of side reboilers and side condensers renders the design a combinatorial problem [3]. As a result, methods are required urgently in both distillation analysis and optimization to enable an efficient and economic approach for saving energy.

Thermodynamic analysis is an effective approach for distillation analysis and optimization through identifying the thermodynamic losses due to heat and mass transfer, pressure drop and mixing in an existing design and operation, etc. [4–8]. It can be carried out through a CGCC (column grand composite curve) [9], an IRS (invariant rectifying-stripping) Curve [10], an exergy loss profile [11] or a minimum driving force profile [3]. The exergy analysis for the distillation systems were conducted to determine the distribution of exergy losses inside the column and the optimal distribution of heat to be transferred inside the column [12,13]. Agrawal and Herron [14] proposed a way that can quickly tell a process engineer if an intermediate reboiler or condenser is going to be effective in improving the efficiency and, of the two options, which one would be more effective in a binary distillation. The IRS curves were presented to set quantitative targets such as minimum energy requirement (minimum condenser and reboiler duties), appropriate feed location, proper feed preconditioning, scope for

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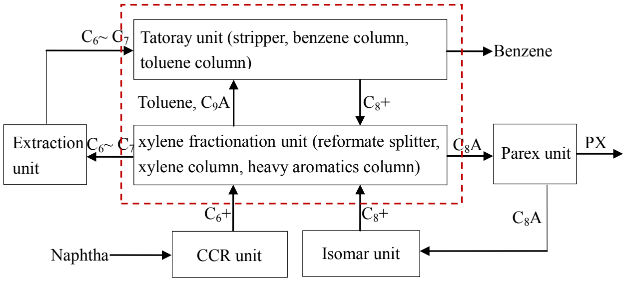

Fig. 1. A simplified flowsheet of a PX plant.

side-condensers/reboilers, as well as thermo-economic optimization of distillation column [10,15]. Koeijer and Rivero [16] described the entropy production rate in one adiabatic and one diabatic experimental water/ethanol rectifying column by applying the theory of irreversible thermodynamics. This analysis showed that the diabatic column looses 39% less exergy than the adiabatic column. Heat and mass transfer on the trays and in the heat exchangers determined the entropy production rate, and neither pressure drop nor mixing effects played a large role in these columns. Demirel et al. [17,18] introduced the theory of nonequilibrium thermodynamics and its use in simultaneously occurring transport processes and chemical reactions of physical, chemical, and biological systems. It also explored the unifying role of thermodynamics in natural phenomena. In general, CGCC is found useful to quantify the energy-saving potential for possible stand-alone modifications and integration with the background process [19]. Dhole and Linnhoff et al. [9] reported procedures for generating the CGCC from simulation of a base-case distillation column, which is constructed using the data of the column internal stream mass flows and enthalpies at PNMTC (practical near minimum thermodynamic condition). The mechanism of the inevitable feed loss, pressure loss and sharp-separation loss are explained in great detail. CGCC depends on operating reflux, feed location and feed condition in the column, and thus it can be used as a tool to optimize columns. Subsequently, researchers develop new methods for generating CGCC. CGCC is also applicable for multi-component, complex distillation column operations, such as crude oil distillation [20–23]. As a graphical tool, it is easily implemented for specification of distillation problems and suitable for rigorous calculations since process simulation is used [24]. For design and retrofit purposes, CGCC identifies the targets for restructuring, modification, and proposes retrofits for operating parameters and configurations involving feed condition, feed splitting and reflux adjustments [25].

Another effective way to reduce energy consumption of distillation columns is Heat Integration. Heat Integration refers to a collection of systematic methods for combining the heating and cooling demands in a process to minimize the use of hot and cold utilities through maximizing the heat recovery [26–28]. The distillation system involves streams to be cooled down or heated up alternatively. So the total energy requirements can be reduced through Heat Integration. The popular tool of Heat Integration is Pinch Technology, which is established on the first and second laws of thermodynamics [29]. Klemes et al. [26,30] summarized the techniques derived from Pinch Analysis to improve the energy efficiency with focus on continuous processes. Pinch Technology is first introduced by Linnhoff and Hindmarsh [31] and now represents a set of thermodynamic methods that evaluate minimum utility demands in the design of Heat Exchanger Networks [32]. It has been employed to analyze and retrofit HENs (Heat Exchanger Networks), entire chemical plants, petrochemical companies, or even complete sites [33,34]. As is known, GCC shows the process heat sink above the pinch and the process heat source below the pinch. It specifies the regions where the process streams may satisfy their own need. GCC is the graphical representation of the Heat Cascade, which is obtained by plotting the values of the temperature boundaries versus the heat flows across the boundaries. It is a useful tool for studying the interface between the process and the utility system and for evaluating Heat Integration of special equipment such as distillation columns, evaporators, heat pumps and heat engines [26]. A distillation column can be plotted as a box in temperature-enthalpy (T-H) diagrams (CGCC), where temperature profile and duty are plotted for the condenser and the reboiler. If placement of a distillation column in the process crosses the pinch at heat transfer, e.g. the reboiler receives heat at a temperature above the process pinch point while rejecting heat from its condenser at a temperature below the process pinch point, which leads to no net energy saving. When the column is located totally above or below the pinch, integration of a reboiler or condenser with the process saves a net energy up to the amount that was integrated. Thus integrating the column totally above or below a process pinch point is more energy efficient [35].

CGCC and Heat Integration have been applied to guide the optimization of fractionating systems. Nguyen et al. [25] used CGCCs and exergy loss profiles to assess an existing operation of a biodiesel production plant and carried out retrofits through feed preheating, side reboiling and reflux ratio modification for distillation columns. The results showed that the overall exergy losses for the columns decreased by 50%. The thermodynamic feasibility of implementing the heat pump system and self-heat-recuperation technology into a conventional distillation column was examined by CGCC [36]. It was found that the advanced process with self-heat-recuperation technology reduces the energy requirements significantly by using the heat recovered from the overhead vapour. Heat Integration was also proposed to improve the energy efficiency. The heat and economic comparisons between two- and three-column methanol distillation schemes were investigated by Heat Integration techniques in which GCC is combined with CGCC [37]. This allowed the identification of which distillation scheme has the better possibility for heat integration between the methanol distillation columns and the background methanol synthesis process. A method for a HIDiC (heat-integrated distillation column) to separate a ternary mixture is proposed [38], in which the integration capabilities between the rectifying and stripping sections of the system are established by CGCC. The CGCC was also applied to assess the thermodynamic feasibility of implementing the heat pump system into dividing-wall columns [39]. The operating cost was reduced by 83% through novel combinations of internal and external heat integration: top dividing wall columns using a top vapour recompression heat pump. And a compact integrating TCS (trichlorosilane) purification process purification process was additionally proposed. Gao et al. conducted an energy and exergy analysis of a five-column methanol distillation scheme using the CGCC [40]. Compared to the typical four-column scheme, the energy consumption was reduced by 15.23%.

From literature review above, we know that previous researches are mainly focused on answering the questions: how to retrofit of distillation columns in a process based on CGCC, and how to implement Heat Integration in a process. There is less report on combining process optimization with Heat Integration in a process. Because the operating conditions of the distillation are varied, then not only is the design of the distillation column itself changed, but also its Heat Integration characteristics. So in an industrial retrofit design process, interesting questions must be considered: how the operation of distillation column impacts the heat demand and supply of the process, and how the operation of distillation column