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Study on constraints for heat removal duties of the main fractionator in delayed coking units

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HIGHLIGHTS

- A novel method defines the heat removal constraints of the main fractionator.
- Fractionating precision diagram and column grand composite curve are combined.
- The results are the inequality constraints in a simultaneous optimization model.

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ABSTRACT

A novel method is presented in this paper to quantitatively define the heat removal of the main fractionator in delayed coking units on the basis of a fractionating precision diagram (Houghland diagram) and column grand composite curve (CGCC). By referring to the CGCC method, several envelopes are illustrated at draw trays including the top pumparound draw, diesel draw, intermediate pumparound draw and gas oil draw, the energy and material balances are then calculated. Assuming practical near-minimum thermodynamic condition (PNMTC), the minimum liquid reflux flow is zero in the envelope for pumparound trays without product draw and the minimum liquid reflux flow is defined by Houghland diagram for pumparound trays with product draw. The PNMTC-CGCC is constructed by calculating the enthalpy-flow deficit to quantitatively define the heat removal constraints in each envelope. Meanwhile, the corresponding practical heat removal curve is constructed. A case study shows that the high temperature heat removal ratio within the main fractionator increased by 8%. The proposed method offers heat removal inequality constraints for the model to optimize the heat integration between the main fractionator and the heat exchanger network.

1. Introduction

Energy consumption of delayed coking units (DCUs) has attracted widespread concern in refineries [1]. Clearly, the coking furnace consumes a large amount of fuel. Moreover, the feed preheating temperature affects the heat duty of the furnace and the energy consumption of the whole unit. In several studies, various methods have been proposed to identify opportunities for heat integration with other units or to optimize the feed preheating temperature by an integrated optimization between the fractionator and the heat exchanger network [2,3]. Considering that the main fractionator in the DCU is a complex fractionator with multiple side draws and pumparounds (PAs), the amount of cooling in fact plays an important role in energy-use optimization of the DCU.

Currently, optimization for the heat removal of complex fractionators mainly focuses on increasing, as much as possible, the removal heat duty at a high temperature without affecting the product yield and quality [4]. Generally, the heat removal from a complex fractionator is optimized through an iterative approach using PRO/II simulation system combined with experience or heuristic rules [5]. However, this method is greatly limited to practical applications due to the absence of quantitative guidance for adjusting the heat removal duties. The amount of heat removal of the complex fractionator is often kept constant and the optimal design for the heat exchanger network (HEN) was the major concern [6–8]. Few studies have aimed at optimizing quantitatively the heat removal for the main fractionator of DCUs. For the

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optimization of fractionating processes, many researchers focused on the integration of different columns [9–13]. Obviously, optimization of the heat distribution in a complex fractionator should be better realized by imposing a quantitative optimization to the heat removal for retrofit of the whole fractionating system.

To identify the heat distribution in a complex fractionator, column grand composite curve (CGCC) is widely used. The construction of CGCC presented by Dhole and Linnhoff [14] was based on practical near-minimum thermodynamic condition (PNMTC), in which infinite numbers of intermediate heat exchangers (reboilers and condensers) and trays needed to be set up to achieve the assumption that the operating line is infinitely close to the equilibrium line. As shown in Fig. 1, the points in the CGCC represent the maximum heat duty for setting the intermediate heat exchanger in the corresponding tray. Furthermore, this method considers the irreversible thermodynamic conditions such as multi-component sharp separation, pressure drop and so on. If the CGCC is constructed accurately for a complex fractionator, the amount of PA heat removal can be determined for achieving the ultimate energy target.

Meanwhile, many studies concentrate on CGCC construction and optimization strategies for simple fractionating columns (binary system). The CGCC of a simple binary fractionator can now be generated using a commercial software such as the column targeting tool ASPEN PLUS. However, it is relatively difficult to construct the CGCC by the method used in the simple binary fractionating system for complex fractionators such as the main fractionators of fluid catalytic cracking units (FCCUs) and DCUs being due to the multiple feeds/discharges and several PA heat removals in existence.

Regarding the solution of complex fractionating systems, Sharma et al. [15] pointed out that it is reasonable only to calculate enthalpy-flow deficit at the draw trays to avoid calculating enthalpy-flow deficit at every tray. Packie's method for designing crude distillation columns is used to define the heat removal [16]. However, Packie's diagram is only available for crude distillation columns and based on practical data. Its application and accuracy are limited to other similar columns, such as the main fractionators for FCCUs and DCUs. The Houghland diagram is good enough to replace the Packie diagram by applying it to these main fractionators [17]. Moreover, Ji et al. [18] established a non-linear fitting mathematical model to represent the Houghland diagram.

Considering the characteristics of the main fractionator in the DCUs, a minimum reflux flow ($V_{\min}$ and $L_{\min}$) is calculated by means of the concept of CGCC in this paper. In addition, the heat distribution is presented by dividing the main fractionator into several envelopes. This method can establish the inequality constraints for optimization models in heat removal constraints. Firstly, the practical heat removal curve is constructed by material and enthalpy balances in envelopes. Secondly, the PNMTC-CGCC is constructed to present the ideal condition in which a new approach is used for calculating the minimum reflux flow ($V_{\min}$ and $L_{\min}$). In the assumption of PNMTC, the minimum liquid reflux flow is zero in the envelope for PA trays without product draws and the minimum liquid reflux flow ($L_{\min}$) is defined by the Houghland diagram models for PA trays with product draws. The method presented in this paper can define the ideal heat removal distribution and is finally illustrated through a practical fractionator.

2. Problem statement for the heat removal of the main fractionator

For oil refineries, complex fractionators are often used for material separation, and corresponding heat exchange processes are also designed for heat recovery, such as in crude distillation units (CDUs), FCCUs, DCUs. For the complex fractionator, heat removals at intermediate points can be attained by withdrawing internal liquid streams from the fractionator, cooling and returning them to the fractionator. The cooling medium is usually the feed which is preheated before entering the furnace. Therefore, a dual benefit is realized. Furthermore, several product streams are also drawn out from the complex fractionator.

The sketch of the main fractionator for DCUs is shown in Fig. 2. A mass and heat transfer process takes place between the reaction vapours and the upper feed in the de-superheating section, which is at the bottom of the main fractionator. The lighter petroleum fractions ascend to the upper part of the main fractionator. The heavier petroleum fractions are condensed and then mixed with the feed into the coking furnace as the recycle oil. The separation and energy degradation process of the high temperature reaction vapours is completed in the upper part of the main fractionator.

Hence, the main fractionator is divided into two sections. One is the rectifying section, which is similar to the conventional rectifying distillation in the upper part of the main fractionator and contains multi-stage equilibriums. The other one is the de-superheating section in the lower part of the main fractionator, which is the non-equilibrium stage. The fractionating process is simulated by the simulation method and strategy proposed by Lei et al. [19].

In studying the heat removal constraints of the main fractionator, the main research object is envelope I as shown in Fig. 2, namely the rectifying section of the fractionator.

In the rectifying section of the main fractionator, there are usually four PA heat removals, including the top PA, diesel PA, intermediate PA and gas oil PA. According to the second law of thermodynamics, it is reasonable to increase the heat removal with higher temperature levels, such as intermediate PA and gas oil PA. Meanwhile, the heat removal with a lower temperature level is decreased correspondingly to decrease the process exergy destructions for the fractionating process.

Actually, PAs duties in the complex fractionator have significant effects on heat recovery performance under the same separation specifications. Duties of PAs are the key link between the operation of the complex fractionator and the performance of the HEN. Therefore, the conditions for heat removal distribution can be taken as an important opportunity to retrofit HEN through optimization

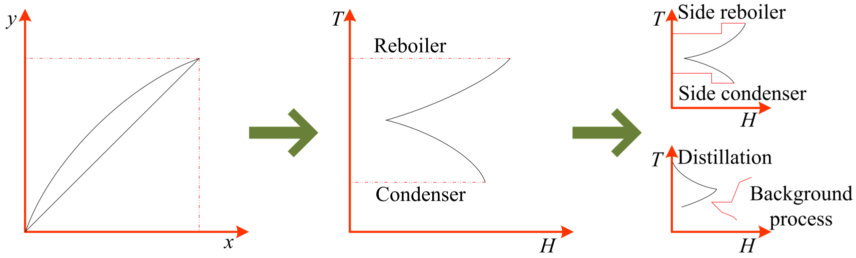

Fig. 1. Column grand composite curve (CGCC) and its application.