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Comparative analysis and evaluation of three crude oil vacuum distillation processes for process selection

Wugen Gu^a, Yuqing Huang^a, Kan Wang^a, Bingjian Zhang^a, Qinglin Chen^{a,*},
Chi-Wai Hui^b

^a School of Chemistry and Chemical Engineering/Key Lab of Low-carbon Chemistry & Energy Conservation of Guangdong Province, Sun Yat-Sen University, Guangzhou 510275, China

^b Chemical and Biomolecular Engineering Department, Hong Kong University of Science and Technology, Clear Water Bay, Hong Kong

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ABSTRACT

There exists three practicable crude oil vacuum distillation processes and different processes have a significant impact on material and energy performances, including product yield, economic potential, heat recovery and the efficiencies of recoverable energy and recoverable exergy. Process selection is an important and difficult task for designers with various targets since the material and energy performances of a process do not coordinate with each other. In this work, an approach with simultaneous considerations of material and energy performances is proposed to comparatively analyze and evaluate the three processes, in order to provide insights for designers to screen a suitable process and vacuum furnace outlet temperature. The approach is conducted in three steps. In the first step, a simulation model is rebuilt to obtain basic material and energy data. In the second step, comparative analyses and evaluations are performed to measure the material and energy performances of three process options under the same operating conditions. In the last step, the variations of the material and energy performances are further investigated to determine the vacuum furnace outlet temperature. The results indicate that the cycle process has the highest product yield and best economic potential but the lowest efficiencies of recoverable energy and recoverable exergy, while the drawn process has the highest efficiencies of recoverable energy and recoverable exergy but the worst economic potential. The results also demonstrate that the selection of a vacuum distillation process and the determination of the vacuum furnace outlet temperature play a critical role in designing a crude oil vacuum distillation process.

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1. Introduction

The crude oil distillation unit (CDU) is a major process unit in a refinery for separating crude oil into various product fractions. It not only has the largest capacity, but also is one of the largest energy consumers in the refinery which consumes fuel at the equivalent of 2% of the crude oil processed [1]. Consequently, it is a major CO₂ emitter in the refinery [2,3]. With high-energy costs and regulations on strict greenhouse gas emission, the CDU is required urgently to improve the energy efficiency and economic profit. Generally, a crude oil distillation process contains a preflash column, an atmospheric distillation column and a vacuum distillation column. In a typical vacuum distillation process, an overflash oil is

usually drawn out directly. With the processing requirement, two modified vacuum processes are practically applied in which the overflash oil is either sent into the stripping section of a vacuum distillation column or cycled to a vacuum furnace. Different processes have a significant impact on material and energy performances, including product yield, economic potential, heat recovery and the efficiencies of recoverable energy and recoverable exergy. However, the material and energy performances of a process do not coordinate with each other. Exploring the mutual relations can provide insights for designers to determine a suitable vacuum distillation process and vacuum furnace outlet temperature.

The energy analysis and optimization of crude oil distillation processes have been a hot research topic and widely investigated. The early crude oil distillation process only contained two-distillation columns, an atmospheric distillation column and a vacuum distillation column. Al-Muslim et al. [4–6] implemented an energy and exergy analysis of this two-distillation column

* Corresponding author. Tel.: +86 20 84113659; fax: +86 20 84113731.

E-mail address: chqlin@mail.sysu.edu.cn (Q. Chen).

process and a single atmospheric distillation process, and pointed out that the overall exergy efficiency of the former was 17.5% higher than that of the latter. Bagajewicz and Ji addressed a heat demand-supply diagram and used it as a tool to put forward a rigorous procedure for the design of a vacuum fractionation unit [7]. The column grand composite curve was an effective tool to quantitatively identify the targets for possible column modifications, and widely used to retrofit crude oil distillation columns [8,9], a methanol plant [10], a biodiesel production plant [11,12] and multicomponent separation systems [13]. Subsequently, the pre-distillation device was introduced into the process. Errico et al. [14] and Benali et al. [15,16] employed exergy analysis to better understand the distribution of energy degradations in the distillation column, and their studies showed that both energy consumption and exergy loss were reduced when a flash drum was added. The installation of a preflash vessel was also introduced to revamp a crude distillation unit in Kamel's work [17,18]. Based on the former work, a pre-distillation system for heavy crude oil was considered and a two-preflash drum process was determined as an optimum scheme by thermodynamic analysis [19]. Up to now, the conventional three-column crude oil distillation process, including a pre-flash/pre-distillation column, an atmospheric distillation column and a vacuum distillation column, has been widely applied in refineries. Ricardo et al. presented a method for the calculation of the physical and chemical exergy of crude oil and its fractions [20], and then carried out an exergo-economic analysis of all equipment items in this conventional process to provide improvement potential [21]. Mittal et al. [22] considered that crude oil blending had a significant impact on energy, emission and economic profit (E3), and developed an E3 methodology framework for better operating the crude oil distillation system. Recently, the optimization work of an atmospheric distillation column has been done by Arjmand et al. [23]. The vapor feed was introduced into the upper stages of the atmospheric distillation column, leading to a sizable energy saving. Furthermore, several researchers paid attention to the multi-stage crude oil distillation process in which one or more vacuum distillations were added between a conventional atmospheric and a vacuum distillation column. Gu et al. [24] proposed a general multi-stage distillation energy consumption model to optimize the yield distribution of distillation columns and the flowrates of side-stream products on each distillation column were determined by maximizing the thermal exergy recovery. Li et al. [25] investigated the multi-stage effect on the crude oil distillation unit in thermodynamics and recommended adding more vacuum distillation columns for energy saving. According to the literature mentioned above, it is inferred that the researchers paid more attention to improving energy performance and providing solutions for the pre-distillation column, the atmospheric distillation column and the whole distillation system, but ignored the interactive relationship between different vacuum distillation processes and material and energy performances. It is an important and difficult task for designers to select a suitable vacuum distillation process, and comparative analyses and evaluations of three process options can aid designers in process selection.

Process simulation, as an important aid tool in process design and analysis, provides basic data for the energy analysis and optimization of chemical processes. An equilibrium model or a rate based model is generally used for the simulation of distillation processes. The equilibrium model assumes that vapor–liquid equilibrium is reached at each stage. The departure from the equilibrium is accounted for by tray efficiency for tray columns or the height equivalent of a theoretical plate for packed columns. More et al. [26] used a distillation module based on the equilibrium model in Aspen Plus to address the optimization of the crude oil distillation system with a binary feed. Benali et al. [15,16] employed

a distillation module based on the equilibrium model in PRO/II to design an improved crude oil distillation process and determine optimal parameters. The rate-based model [27–29] assumes that the vapor–liquid equilibrium only occurs at the interface, and the Maxwell–Stefan equation is used to describe the mass transfer between the vapor and liquid phases. Packed reactive distillation columns [30], reactive dividing wall columns [31] and molecular distillation [32] of green coffee oil were simulated with the rate based models. In these studies, a single distillation module from the simulation systems was employed to simulate the practical atmospheric or vacuum distillation column. Actually, the vapor–liquid separation of the feed only occurs in the feed section. Additionally, the bottom of the rectifying section of a vacuum distillation column is a blind tray, and the liquid from the bottom of the rectifying section cannot directly flow into the stripping section. It is inaccurate to represent a vacuum distillation column with a single distillation module. A simulation model for the vacuum distillation column must be properly rebuilt to provide reliable basic data.

This work is focused on providing insights for designers by comparative analyses and evaluations of three crude oil distillation process options. It is organized as follows. In Section 2, three practicable vacuum distillation processes are depicted. An approach for comparative analyses and evaluations of three process options is presented in Section 3. Then, the results of the three process options are discussed in detail by employing the proposed approach in the following section. Finally, the conclusions are given.

2. Process description

A CDU is generally the first process, and is also the largest capacity in a refinery complex. Different fractions are produced depending on the difference in their boiling temperature, and are further processed in the downstream plants for desired products. An actual CDU in China is investigated in this paper, and its flow-sheet is illustrated in Fig. 1. The crude oil, introduced from a storage tank at atmospheric temperature, firstly passes through the pre-heat train 1 which makes use of the heat of side-stream product streams and pump-around circuits from the atmospheric and vacuum distillation columns. The preheated crude oil then enters a desalter to remove the trace salt and water. Afterwards, the desalted crude oil enters the preheat train 2, and is preheated up to about 200 °C. Then it is pumped into a prefractionation distillation column, and the light naphtha is separated. The topped crude oil from the bottom of the prefractionation distillation column goes through the preheat train 3, and then enters into the atmospheric furnace and is heated up to about 365 °C. Finally, the topped crude oil is introduced to the atmospheric distillation column which operates at atmospheric pressure. Superheated steam is introduced from the bottom of the column, which is used to reduce the partial pressure in the column and thus enhance vaporization and separation of the crude oil. Heavy naphtha, kerosene, diesel, and gas oil are drawn from the column. These side-stream products are diverted into side strippers where the initial boiling point of the product is controlled by stripping steams. This atmospheric column is equipped with three pump-around circuits (APA1, APA2 and APA3) to recover heat for the preheat trains. The atmospheric residue (AR) is further heated by a vacuum furnace and then fed to a vacuum distillation column. The AR is overflashed so that the total vapor flowing up to the rectifying section is enough to produce target products. The extra amount of vapor is known as an overflash oil. It is worth noting that the bottom of the rectifying section is a blind tray in the vacuum distillation column. The overflash oil from the rectifying section of the distillation column cannot flow directly into the stripping section inside the column, and it is drawn out at

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