Chemical Engineering & Processing: Process Intensification 123 (2018) 1–11

Contents lists available at ScienceDirect

Chemical Engineering & Processing: Process Intensification

journal homepage: www.elsevier.com/locate/cep

Enhanced product quality in lubricant type vacuum distillation unit by implementing dividing wall column

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ARTICLE INFO

Keywords:
Lubricant type vacuum distillation unit
Overlap
Enhanced product quality
Process simulation
Thermally coupled configuration
Dividing wall column

ABSTRACT

Lubricants are highly value-add petroleum refinery products fabricated from lube base oils, the side cuts from lube-type vacuum towers of crude distillation units. In such a popular lubricant type vacuum distillation unit (LTVDU), the 4th lube side cut, nearby the feeding stage, is normally designed to control the 3rd lube cut end boiling point and the bitumen residue flash point temperature. With useless wider boiling point range than the other lube side cuts, its fate is to discharge as fuel or circulate back to the vacuum furnace for limited higher yield at the cost of more energy. This situation triggered our work to reduce boiling point overlap between the 3rd and 4th lube cuts by implementing dividing wall column (DWC) into LTVDU. This novel design is verified to benefit through an industrial case study. Namely, the 4th lube cut boiling point range is so dramatically narrowed as to be a new lube product, without adding extra heat loads. This way the lube base oil product yield can be greatly improved. Industrially, this DWC designed at LTVDU washing zone can deliver excellent hydraulics and carbon residual controlling performance for larger specific liquid flow by section crossing off for DWC.

1. Introduction

Petroleum refining continues to be a major contributor in the production of transportation fuels and various chemicals. The crude distillation unit (CDU) is the first processing unit in a refinery to separate crude oil into a series of oil products for deep processing. This unit features both the largest equipment and the greatest energy consumer (approximately 35% to 45% of the total energy consumption) in a refinery [1]. So basically, heightening performance or yield efficiency of CDU greatly benefits the entire refinery and continuously rivets interests and efforts to make improvement.

A conventional CDU consists of a pre-distillation unit (PDU), an atmospheric distillation unit (ADU), and a vacuum distillation unit (VDU), along with a number of stripping columns to control initial boiling points (IBPs) of side draw oil products [2,3]. Pump-around circuits are used to recuperate heat at different temperature levels from the column and provide intermediate reflux as well as sound inner column hydraulics [4,5]. Together with oil products, these pump-around streams are typically used to preheat crude feedstock through the preheat train (PHT) to recover energy [6,7].

The implementation of PDU is widely applied in industry to remove vaporized light ends (i.e. methane, ethane, propane, butane and light-naphtha) from the crude oil before the atmospheric furnace [8–12]. ADU mainly splits the crude into heavy-naphtha, kerosene, diesel and atmospheric gas oil (AGO), leaving additional gas oil, or atmospheric residue (AR), to VDU.

There are two major types of VDUs – feedstock preparation and lubricant production [13–23]. Many researchers and engineers focused on improving the energy efficiency of the CDU through the use of various energy saving techniques [1–5]. For example, Cui and Sun [7] proposed a coupling design of several CDU PHTs based on pinch analysis [24]. Simulative trials found that an extra 9.58% energy consumption was reduced through the coupling design. Waheed and Oni [3] combined application of exergy analysis with other traditional retrofit methods to improve the performance of CDU. The process improvement carried out resulted in an increase in the overall CDU energy and exergy efficiency by 4.0% and 1.6%, respectively. Kansha et al. [25] investigated the energy saving potential of a self-heat recuperation technology (SHRT) for an ADU. They observed that the whole-process heat can be recirculated within the process without additional heat input. However, the proposed SHRT required several compressors which can cope with high temperature, heavy vapor oil and a relatively high compression ratio. It is still not ascertained the feasibility of using SHRT on CDU.

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http://dx.doi.org/10.1016/j.cep.2017.10.020
Received 2 August 2017; Received in revised form 25 September 2017; Accepted 25 October 2017
0255-2701/

Nomenclature

ADU	Atmospheric distillation unit
AGO	Atmospheric gas oil
AR	Atmospheric residue
BDC	Basic distillation configuration
CDU	Crude distillation unit
DWC	Dividingwall column
EBP	End boiling point
IBP	Initial boiling point
LTVDU	Lubricant type vacuum distillation unit
MINLP	Mixed-integer nonlinear programming
PDU	Pre-distillation unit
PHT	Preheat train
SHRT	Self-heat recuperation technology
SSC	Side stream column
TCC	Thermally coupled configuration
TEC	Thermodynamically equivalent configuration
VDU	Vacuum distillation unit
VLE	Vapor-liquid equilibrium
VR	Vacuum residue

These options coincidentally applied promising energy efficient techniques under the premise of unchanged product quality specifications or even yield. What will be fruited by following another logic of improving product quality and yield efficiency? This study reversely focuses on these two aspects that suffer most conventional lubricant type vacuum distillation units (LTVDUs) without extra energy request.

A conventional lubricant type CDU, demonstrated in Fig. 1, differs from feedstock preparation CDU with only its VDU. LTVDU separates AR into side cuts as lube base oils with desirable viscosity, flash point, carbon residue and other properties [17], as well as diesel and vacuum residue (VR) as fuel and bitumen [7,13]. In order to narrow boiling point ranges and overlaps between each other of 1st, 2nd and 3rd lube oil cuts, side strippers are allocated to control IBPs. Notably, a 4th lube side cut is designed to be sacrificed to control the end boiling point (EBP) of the 3rd lube cut and the flash point temperature of the bitumen residue. However, because the boiling range of a side stream is strongly restricted by thermodynamics and by the nature of distillation operation [26], the 4th lube cut seriously overlaps with adjacent lube cut and residue, resulting in inferior product quality. Normally, a high-purity side stream usually requires a large reflux ratio and a large number of stages, as well as larger associated energy consumption, which is not economical overall [27]. On the other hand, dividing wall column (DWC) can produce three purified products within only one column shell [28–33]. It is therefore easily induced that with the same energy input, a DWC might achieve better separation performance than a side stream column (SSC). For this reason, DWC has potential to overcome the excessive overlap between adjacent fractions.

As one of the most important advanced distillation technologies, DWC has been widely used for ternary separations [28–37]. It appeals chemical process industry by reducing up to 30% investment costs and up to 40% energy savings over conventional direct and indirect distillation sequences [34–37]. Recently, DWC has shown great potential when retrofitted from conventional two-column system [38] and SSC [26,39]. An optimal design of a DWC requires adequate mathematical models and computer-based simulations. However, commercial process simulators (e.g. Aspen Plus, Aspen HYSYS, Pro/II etc.) do not include such particular subroutines for DWC. To facilitate rigorous simulation study on computer, Triantafyllou and Smith [40] suggested decomposing a complex distillation column into a sequence of simple columns. The basic idea of this decomposition method fully utilizes the concept of thermodynamically equivalent configurations (TECs) evolved from thermally coupled configurations (TCCs) [41–44].

In this study, the decomposition method helps elaborate integration of DWC into the conventional LTVDU to enhance product quality. To the best of our knowledge, few studies exist on the novel application of DWC together with a conventional LTVDU. Here, we investigate the feasibility of potential use of DWC. Before configuring the novel LTVDU with DWC, a systematic synthesis procedure for synthesizing SSCs and DWCs from basic distillation configurations (BDCs) proposed by Errico et al. [42] and Rong [43] is reviewed to provide basic knowledge for better understanding. Then, the decomposition method debuts to rearrange the conventional LTVDU and makes the bottom section a SSC. Finally, a design of the LTVDU SSC to novel DWC configurations is presented.

2. The systematic procedure for synthesizing SSCs and DWCs from BDCs

The systematic procedure is illustrated stepwise in Fig. 2. Different from the original papers [42,43] where all distillation column configurations were based on four-component zeotropic mixtures, a ternary system herein is sufficient for illustrating the novel LTVDU DWC design. In this procedure, the volatilities of components decrease in alphabetical order. Therefore, *A* is the most volatile component followed by *B*

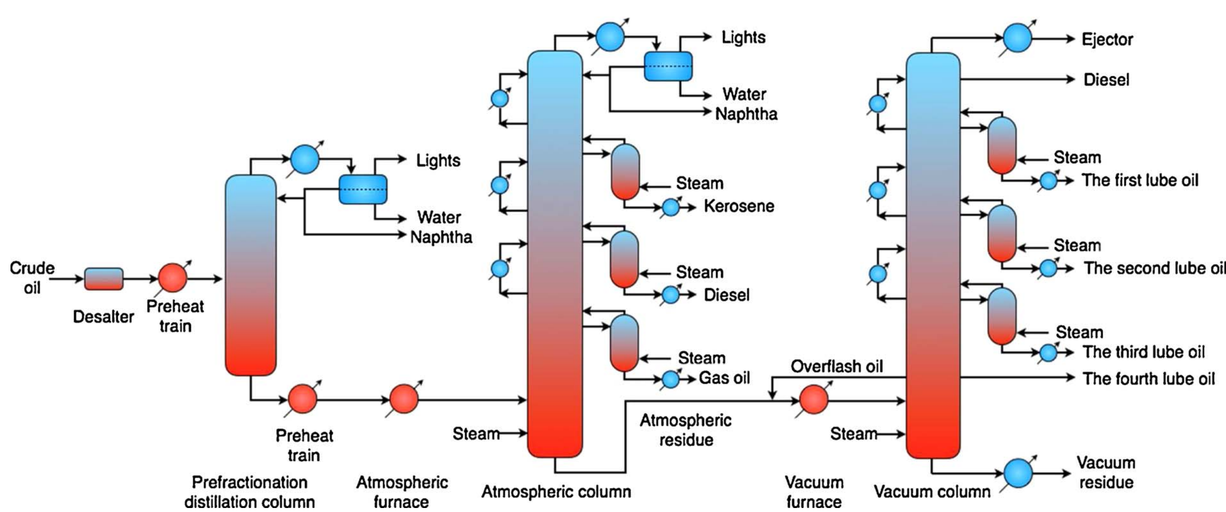

Fig. 1. Schematic diagram of a conventional lubricant type CDU.