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Energy-saving columns: Design and control of a Kaibel and a multi-sidestream column for separating hydrocarbon mixture

Xiaohong Wang*, Xinshuai Yu, Li Xie, Minggao Li, Yuanpeng Zhang

College of Chemical Engineering, Qingdao University of Science and Technology, Qingdao, 266042, China

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ABSTRACT

Due to the conventional sequence has a disadvantage of high energy consumption, this paper proposes the optimal design and control of the Kaibel and multi-sidestream column for separating five-component hydrocarbon mixture. First, three processes are simulated by steady-state simulation. The three distillation structures are designed by minimizing the total annual cost (TAC) and the results show that the multi-sidestream column is the most energy-efficient configuration, with savings of 29.5% to the conventional sequence, and 12.2% to the Kaibel dividing wall column (KDWC). Second, the suitable control of three processes are designed. The temperature controller is used in multi-sidestream column and the component controller is used in KDWC. The results show that the response time towards disturbance of the KDWC is longer and the purity of the multi-sidestream column is not up to the requirement. Finally, aiming at the problem above, the control structures of KDWC and multi-sidestream column are optimized. Temperature controller is added in the KDWC instead of the component controller. Under the control of temperature, it can return to stable in a short time. A double temperature controller is added in multi-sidestream column based on defects of basic control structure. Its product purity can attain above the designed value. Compared to the multi-sidestream column process, the control structure of KDWC can handle feed disturbance more effectively, and the purity is closer to the design value.

1. Introduction

Distillation is an important and widely used separation unit in the chemical industries. It is simplicity and flexibility but still exists energy-intensive problem. Therefore, the process intensification technology is essential to reduce both energy and cost. DWC, which has been successfully implemented in industry, provides a promising direction for process intensification technologies. DWC, which has been successfully implemented in industry, provides a promising direction for process intensification technologies. DWC has been successfully implemented in industries, reported by the German company BASF [1]. Mutalib and Smith [2] investigated free degrees in the three-product DWC. Halvorsen and Skogestad [3] studied steady optimal steady-state operation of a three-component DWC. Wang and Wong [4] introduced a DWC for separating ethanol. Researchers have investigated various control structures to face different DWC configurations. Skogestad [5,6] studied the control of three-component DWC. Kiss and Rewagad [7] provided traditional PID control and advanced MPC of three-component DWC. Xia [8] studied the different control structures for extractive DWC.

Although some researchers have investigated control structures for the different DWC configurations, relatively few studies have been devoted to the four-component KDWC. The KDWC was introduced by Gerd Kaibel at BASF in 1987 [9]. The KDWC is a heat and mass integrated separation process, with potential for large savings in capital cost, energy requirement and plot space compared to the conventional sequence for multicomponent separations. Niggemann [10] conducted simulation and experimental studies for separation of a mixture of fatty alcohols mixtures into three high-purity components. A systematic procedure for the synthesis and intensification of column configurations for five-component mixtures distillation is presented by Caballero and Reyes-Labarta [11], showing that it is possible reduce until just two columns with internal walls the sharp separation of a five-component mixture that usually requires four columns. Esparza-Hernández [12] investigated the control of several four-component separation sequences including the KDWC. Qian [13] analyzed the control of a KDWC for an alcohols mixture in a multi-loop framework. Guoliang Fan [14] demonstrates that traditional single-loop PID control is inserted into the four-component KDWC to handle disturbances. Detailed analysis of optimal operation of Kaibel Columns is provided by Maryam Ghadrdan [15]. Its aim is to study the Kaibel distillation column from an operability point of view.

The synthesis of sidestream distillation system is a problem of multi-

* Corresponding author
E-mail address: wxhlee@sohu.com (X. Wang).

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Nomenclature

TAC	Total annual cost 10^6\$/year
KDWC	Kaibel dividing wall column -
DWC	Dividing wall column -
Q_C	Condenser duty MW
Q_R	Reboiler duty MW
RR	Reflux ratio -
N_F	Feed stage(s) -
Q_R/F	Reboiler duty/feed flow rate -
S1	Sidestream flow rate kmol/h
$T_{T3,\ 10}$	The temperature on stage 31 of the T3 column K

hierarchy combinatorial optimization. The out layer of this problem is to find the optimal distillation sequence, the middle layer is to identify the heat integration strategy and the inside layer is to confirm the optimal operation parameters for every unit included in the flowsheet.

The dynamic controls for many kinds of distillation processes are widely studied in recent years, but there is relatively little research for the control study of the sidestream distillation with multiple rectifiers. A systematic procedure was presented by Giridhar [16], which can synthesize all feasible basic configurations using N-1 distillation columns with each column having only a condenser at the top and a boiler at the bottom. A method for the systematic synthesis of all the distillation systems with less than N-1columns is presented by Errico et al. [17] showing that distillation systems with less than N-1 columns have the potential to save both energy and capital costs compared to the conventional simple column configurations where N-1 columns are employed. It also generates all feasible thermally coupled schemes with classical two-way liquid and vapor communication between the distillation columns. Caballero and Grossmann [18–21] have presented a systematic approach for generating all the thermodynamic equivalent structures for a given sequence, then, this method could be integrated in the framework of Disjunctive Programming to exact the best solution for a given objective function. Caballero and Grossmann [22] improved a superstructure approach for synthesizing heat-integrated thermally coupled distillation sequences, which was based on a state-task approach instead of an equipment-based system. Zou et al. [23] designed the sidestream distillation system with thermal coupling by using the superstructure, the equipment and operating costs of the system are effectively reduced. Tapp M et al. [24] Described the process of the expansion of operating leaves in distillation column sections by distributed feed addition and sidestream withdrawal. Nasser MZ [25] studied that design and control a single side stream distillation column to separate acetone-ethanol-*n*-butanol using model predictive. Zhang Z et al. [26] tudied the teady-state simulation and dynamic control of DME/Methanol/Water liquid sidestream distillation column. Rong, Bettoni A et al. [27] deal with the advanced control of a side-stream distillation column removing benzene from a reformed gasoline stream. The above works can create a large number of new distillation configurations, which has formulated a large new search space for the optimization work.

William L. Luyben [28] studied the control structure of vapor side stream column with rectifier, and the modified control structure provides stable regulatory control by manipulating the vapor side stream flowrate to control the stage temperature. Zheng et al. [29] using a feed-forward controller to maintain the product purities of reactive dividing-wall column very good. Li et al. [30] studied the control of a complete industrial acetic acid solvent dehydration system in purified terephthalic acid production, the proposed temperature control strategy can overcome the drawback of the PX imbalance and better maintains the stability of the overall solvent dehydration system under a disturbance for the upper-zone feed streams.

This paper proposes the KDWC and the multi-sidestream column to separate the five-component hydrocarbon mixture. Firstly, the optimal design of the steady-state simulation is carried out with TAC. Then for the dynamic study, the control structure of the KDWC uses the component control. In addition, the multi-sidestream column with the R/F and Q_R/F feed flowrate control are used to handle the feed flowrate and feed composition disturbance so as to assess the control behavior. Finally, KDWC and multi-sidestream columns are optimized by adding temperature controller and double temperature controller. It is of great significant that the dynamic performance of the KDWC and the multi-sidestream column is enhanced using temperature controllers and double temperature controllers.

2. Design of the flowsheet

The three distillation flowsheets aim at separating a mixture of 10 mol% n-pentane, 10 mol% n-hexane, 20 mol% n-heptane, 30 mol% n-octane and 30 mol% n-nonane. The feed flowrate is fixed as 100 kmol/h. The operating conditions for all flowsheets are as follows: feed temperature is 25 °C, feed pressure is 1 atm, vapor fraction is 0, and set 99% mol as minimum target purities for all products. The three distillation flowsheets are simulated by Aspen Plus 7.3. The PENG-ROB equation with built-in binary interaction parameters is selected as a property method in calculation.

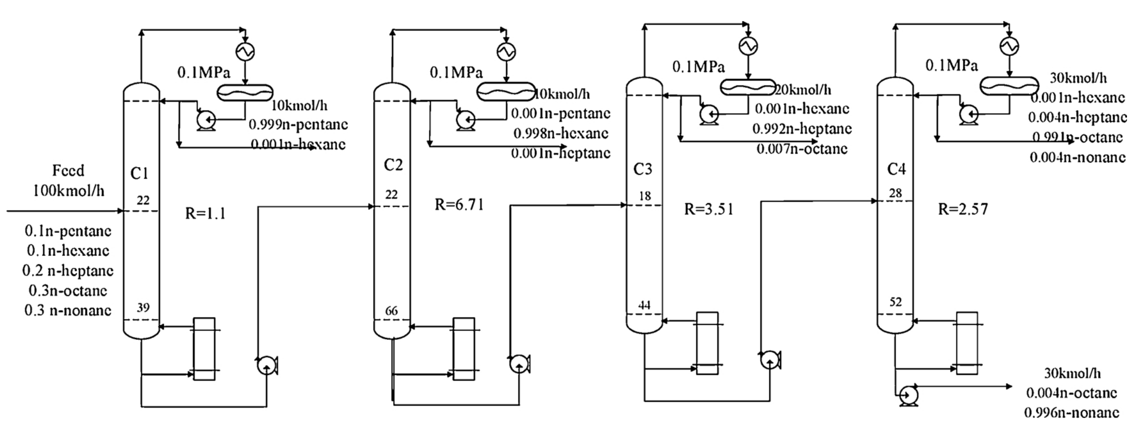

Fig. 1. The flowsheet of the conventional sequence.