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Process Intensification in Distillation Systems: Main Trends for Improving Petrochemical Process Performance

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Mini Review

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Abstract

Economic and environmental considerations have encouraged studies on distillation processes, which play an outstanding role among other thermal separation processes in the petrochemical industry, focused on process-intensification-based innovative engineering solutions. Various techniques, such as dividing wall columns, reactive distillation, internal heat-integrated distillation, HiGee distillation column, and cyclic column have been studied and reported. This mini review highlights the current status of these techniques, their applicability, main limitations and challenges and perspectives in the field of petrochemical engineering.

Keywords: Dividing wall column; Energy efficiency; Innovative technology; Process intensification; Separation process; Reactive distillation.

Introduction

Distillation is the most widely applied separation method and will continue to be regarded as an important process in the future. Nevertheless, as an energy-intensive separation process, distillation is under permanent pressure of increasing energy costs, and further developments are necessary to preserve its pre-eminent position in the field of separation technology [1]. Thus, process intensification (PI) in distillation systems, which can achieve significant improvements, such as higher energy efficiency, capital reduction, low environmental impact, and improved capacity and output has received increasing attention [2]. In particular, integrating multiple columns into one unit forming a dividing wall column (DWC), embedding reaction and distillation into a single unit forming a reactive distillation (RD) column, utilizing the heat from the rectifying section to boil the stripping part of the column constituting an internally heat-integrated distillation column (HIDiC), use of alternative energy sources, such as centrifugal fields forming a Higee distillation column, or utilizing separate phase movement to maximize the driving force between gas and liquid phase in cyclic distillation are considered as the most radical approaches of PI in distillation processes [3-7].

Intensified Distillation Processes

Dividing Wall Column

DWC is one of the best PI technologies, and it is the most widely applied technology on an industrial scale with more than 125 commercial operations [8]. They have been received most concern among many PI technologies.

It has some application limitations, such as the only one operating pressure, a large temperature difference between the reboiler and condenser. In most existing DWCs, the operator can only simply adjust the liquid split ratio by using an active liquid splitter, while vapor splitting is fixed during column operation.

Most recently, the use of a novel active vapor distributor (AVD) was proposed to address the need for vapor split control during DWC design and operation [9]. In the proposed AVD, vapor splitting was implemented using a modified chimney tray with a specially designed cap. The liquid level of the chimney tray on each end side of the dividing wall section was adjusted to control the vapor flow split. Thus, the conventional DWC can constitute a standard column that is used in separation and purification steps without any critical issues. The applications of DWC are expected to increase over the next 50 years to establish DWC as a standard distillation equipment [10].

Reactive Distillation

RD is another attractive proven configuration of PI, in which reaction and distillation processes occur simultaneously at the same location. Compared to conventional reaction-distillation sequences, the RD process renders higher reactant conversion, product selectivity, as well as lower consumption of energy, water, and solvent, leading to reduced investment and operating costs [11]. RD systems have been implemented on a commercial scale in the petrochemical industry more than 150 times [12]. Normally, RD systems are used for etherification, esterification, hydrolysis, and alkylation on an industrial scale, and the largest number of installations is for the production of methyl tertiary butyl ether which is used in gasoline blending. Other esters are also produced now by RD, such as ethyl tert-butyl ether, tert-amyl methyl ether, or fatty acid methyl esters.

In recent years, considering the green opportunities, RDs have gained considerable academic and industrial interest although they still have many limitations, such as incompatibility of process conditions for reaction and separation, or relative volatility constraints for reactants and products in the reaction zone of the distillation column, or the long residence time is required or catalyst contamination is a problem [13]. Furthermore, when solid is present in the feed or when the reaction occurs in the gas phase, or when the use of enzymes as catalysts is required, the use of reactive distillation can cause many practical problems.

Cyclic Distillation

Cyclic distillation is another important configuration that has attracted increasing attention. Cyclic distillation, which is based on separate phase movement, enhances the separation efficiency, thereby reducing energy requirements substantially [7]. Besides being applied at the grassroots level, cyclic distillation can bring new life to old distillation columns, by simply changing the internals and the operating mode, and provide key benefits, such as increased column throughput, lower energy requirements, as well as better separation performance [14]. Maleta first reported the performance of a pilot-scale distillation column operated in cyclic mode for ethanol-water separation [15]. This technique has been recently integrated with chemical reactions to constitute a new approach of catalytic cyclic distillation, which outperforms classic RD [16].

This technology is promising and is expected to receive more attention in the future, although the petrochemical industry is reluctant to adopt this technology at present due to several limitations and challenges. The application of cyclic operation to vacuum distillation seems rather difficult. It is challengeable to achieve performance enhancement when the column has more than ten trays [14]. Furthermore, the main challenges faced by this PI technology, such as requirement of additional experimental research studies and reliability for modeling, expanding the use of cyclic operation to azeotropic, extractive, and reactive distillation, and development of reliable tray designs and advanced process control techniques, need to be addressed to further develop this technology [14].

Higee Distillation

“HiGee technology”, which is a synonym for high-gravity technology, exploits centrifugal fields to form a rotating packed bed and provides another mechanism for improving separation efficiency [6]. Recently, a novel high gravity device, the rotating zigzag bed (RZB), which has a unique rotor combining the rotational part with a stationary one, was developed to overcome the disadvantages of the rotating bed [17]. In China, approximately 200 units of a RZB have been commercialized [18]. However, the applications of HiGee distillation in industries are limited. The main reason for the slow deployment of this technology in industries is the energy use and the reliability of these rotating machines. The lack of simulation modules in commercial process simulators is another issue that requires attention [19].

Internally Heat-Integrated Distillation Column (HIDIC)

The HIDiC is the most revolutionary approach to the design of heat pumps. Remarkably, up to 70% energy savings can be achieved using a HIDiC system, when compared to conventional distillation columns, by utilizing heat from the rectifying section to boil the stripping part of the column [20]. However, at present, many challenges, such as high investment costs, complex design, and control problems, need to be overcome for commercializing the HIDiC technology. Additionally, the separation of multicomponent mixtures using this technology is still an extremely challenging research issue.

Advanced Intensified Distillation Configuration

The petrochemical industry still seeks more economical ways to improve process performance. Recently, the application of DWCs was extended to azeotropic, extractive, and reactive distillations. Only a very limited number of azeotropic dividing wall columns (ADWCs) and extractive dividing wall columns (EDWCs) are being operated in the chemical industry and published data is also scarce despite their great potential to notably reduce costs. Recently, Lonza AG has successfully developed and implemented an EDWC [21]. In addition, reactive dividing wall columns (RDWC) have huge economic and ecological potentials for certain applications; however, this innovative technology has not found its way into industrial production processes yet. A probable reason for this might be the very limited availability of experimental research studies verifying the prediction capabilities of respective modeling concepts for this type of distillation column. Recently, Ehlers carried out experiments of RDWC and compared the experimental results with simulation results; the difference was found to be small [22].

More integrated hybrid separation configurations, such as systems combining RD or RDWC with other separation technologies, such as membrane, extraction, adsorption, and reactive separation technologies, also have significant potential for future consideration of supplementing the capability of each unit [13]. Furthermore, different PI methods and different driving forces need to be considered for integration in a unique system to achieve synergetic effects in the research and development of PI.

Conclusions

DWC and RD excel as successful examples of PI technologies. While RD still has several limitations, the conventional DWC can constitute a standard column that is used in separation and purification steps without any critical issues. Their applications and numbers are expected to increase for sustainable development. There are few publications describing ADWCs and EDWCs operated in industries, while publications on RDWCs operated on an industrial scale have not been reported. Additional experimental research studies and reliability for modeling are required for exploiting the potential of RDWC. Furthermore, HIDiC, cyclic distillation, and HiGee distillation have not yet been established in the industry; in other words, petrochemical industries are reluctant to implement these novel techniques. Therefore, in order to flourish further, future research on this topic has to address the main challenges faced by these PI technologies and prove their feasibility on the industrial scale. More integrated hybrid separation configurations, such as systems combining RD or RDWC with other separation technologies also have great potential for future consideration of supplementing the capability of each unit. Furthermore, different PI methods and different driving forces need to be considered for integration in a unique system to achieve synergetic effects in the research and development of PI.

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