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Optimization of coal-based methanol distillation scheme using process superstructure method to maximize energy efficiency

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ABSTRACT

Despite the current methanol distillation system (MDS) touching a highly energy-efficient level, there are still opportunities to cut more corners when moving eyesight from heating media to electricity and work efficiency of rotary equipments. To simultaneously optimize this process for higher overall energy efficiency, methodologically an improved substitute pathway is herein proposed of corresponding process superstructure. In detail, it is an all-in-one integration of heat and work exchanger networks (HEN-WEN), exemplified by a 4-column double-effect methanol distillation scheme popular among Chinese coal-based factories. The completion of this work indicates a hope of potential reductions of pump electricity and reboiler steam consumption of the whole unit by further 68.38% and 15.83%, respectively.

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1. Introduction

Methanol (CH_3OH) is not only one of the most important chemical raw/starting materials or solvents, but also a promising environment-friendly fuel [1]. Although approximately 80% of its worldwide production capacity starts from syngas produced from natural gas, more than 90% Chinese yield is from coal, with more impurities than its natural gas counterparts [2–4]. When coal-based crude feeds methanol distillation system (MDS), more measures are necessary for pure product quality, such as extraction water injection into topping column reflux drum to remove alcohol-soluble light impurities, but insoluble to water.

Distillation is an energy intensive unit operation. Heat-integrated distillation processes of more than two columns are presently popular worldwide for energy cutting down by a large margin, expect for those yielding crude from natural gas which use methanol syngas as heating medium to condense it [1]. Furthermore, several heat-integrated distillation operations are proposed for better energy utilization, including double-effect distillation, divided-wall column, Petlyuk column and heat pump assisted distillation [5,9]. Among all these alternatives, double-effect distillation is overwhelmingly adopted in methanol industry [1,6–8]. So far, 3-column double-effect MDS by Lurgi [1,10] has been the most widely used.

Special for coal-based 3-column MDS (Fig. 1; In this figure and throughout the remainder of this work, red lines are used to represent hot process streams or hot utility, and blue lines are used to represent cold process streams or cold utility.) a two-stage condenser is designed for its light ends column (LEC), facilitating light impurities removal with tail gas from the first of higher temperature. Freshwater injection is another different design into reflux drum to extract alcohol-soluble impurities, which are not or less soluble in water and intermittently discharged from near vapor-liquid interface. LEC bottom product is pumped into pressured column (PC) whose bottom stream enters atmospheric column (AC) with PC overhead vapor driving AC rebolier (double-effect). Refined methanol yields from both PC and AC top with wastewater from AC bottom and a side stream drawn from lower than its feed stage to control middle impurities, like ethanol, in top product.

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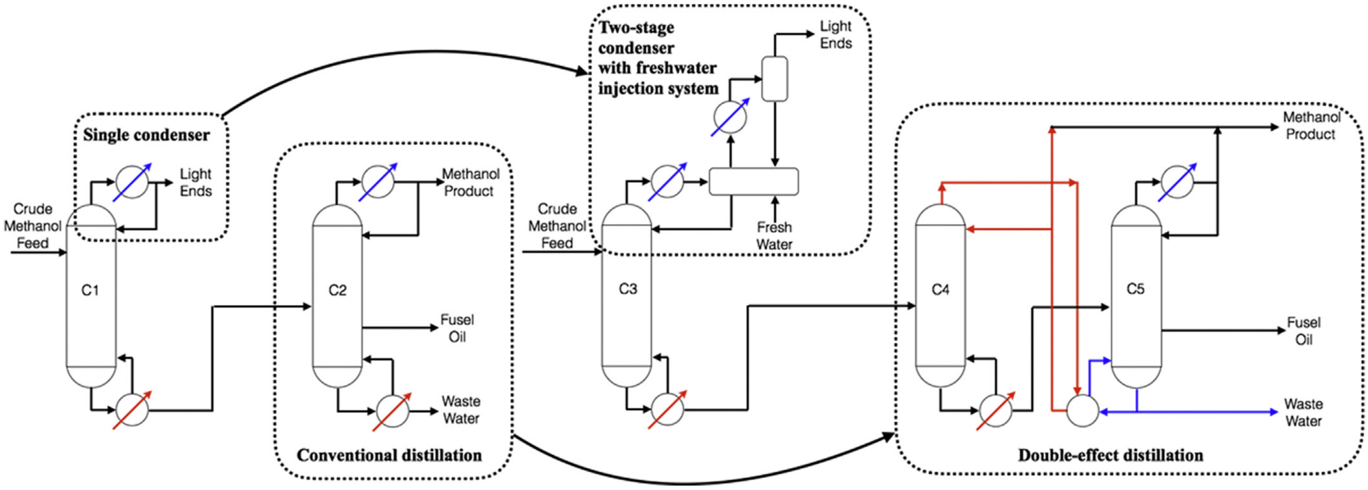

Fig. 1. 2-column and 3-column double-effect methanol distillation schemes. (C1: Topping column; C2: Refining column; C3: Light ends column; C4: Pressured column; C5: Atmospheric column).

After this improvement over 2-column, a water column (WC) is added to 3-column MDS to recover more methanol from side cut or wastewater (approximately 1–3% of total methanol product), giving birth to 4-column MDS [7,8]. So far, this MDS has been the most welcomed and widely used in China. However, it may still be interestingly possible to develop further promising commercial 4-column MDS. To facilitate this purpose, a corresponding process superstructure is developed in this work to screen any other possible alternatives that had not been industrialized before.

Process superstructure is a systematic method for chemical process synthesis [11–13]. It refers to a process network composed by all potentially useful units and all relevant connections [14,15]. These components are then formulated in an optimization model in form of unit operation models, interconnection equations and constraints, such as thermodynamic property calculation equations, composition requirements etc. [11]. It is utilized in this study to develop a novel MDS superstructure of all candidate 4-column MDSs. Heat exchanger network (HEN) and work exchanger network (WEN) of the winner are synthesized into the optimized process simultaneously to maximize its energy efficiency. To reduce calculation scale, only double-effect category is considered for its popularity around methanol industrial community.

In detail, three double-effect configurations are proposed with only the qualified one to be selected for superstructure development. Then industrially popular HPS and LPS are used as basic structures for subsequent superstructure modeling, by which proposed MDS superstructure are analyzed for promising schemes. The decision is made on simultaneous HEN and WEN syntheses performed on SimSci Pro/II™ [16], important process integration for higher efficiency of energy.

2. Double-effect distillation

This important heat-integrated manner saves large amount of energy without adding extra rotating machines powered by electricity, eye-catching for decades [17–21]. Its high-pressure column (HPC) top vapor drives low-pressure column (LPC) reboiler, or uses the LPC reboiler as condenser, saving a condenser or reboiler as well as their heating and cooling utilities. Three different double-effect configurations [22–24] are presented in Fig. 2, of feed splitting (FS), light split forward (LSF) and light split reverse (LSR). Before developing a process superstructure, it is important to select a suitable configuration to reduce calculation space.

The FS feed is split into two parts and pumped into HPC and LPC, respectively. Pressure difference between two columns offers sufficient temperature difference at HPC top and LPC bottom. The other two variations of LSF and LSR share a common feature of entire feed stream sent to one of the two adjacent columns of cascade pressure. In LSF case a pre-positional HPC is first fed yielding half of total light key product at top, with bottom stream separated in LPC for product at the top as well. The mass flow of LSF is in the same direction of heat integration. For LSR, pre-positional LPC is fed before post-positional HPC, where the mass flow and heat integration are in opposite directions.

Different features of these three configurations, varying in operating pressure and temperature, have a great influence on operation difficulty and subsequent popularity in industry. FS is rarely encountered in-situ because full separation of light from heavy key components in both two columns means higher HPC bottom temperature, calling for a higher level of utility. Unlike FS, LSF HPC has a lower bottom temperature and requirement to hot utility, with the other half light components in the bottom. More favorably, coherent mass flow and heat integration make starting up smoother and more easily controllable. These advantages make LSF overwhelmingly popular in industrial methanol plants [1,6–8,10]. LSR benefits from the lowest temperature at LPC bottom due to low-pressure and light components content, as well as subsequent the lowest HPC pressure. Simulative comparisons indicate LSR is the least energy user among the three counterparts [22,23]. However, the drawback undermining its popularity is the relatively complicated starting procedure and longer duration between starting-up and operative stabilization.

From the analyses above, only LSF pattern is utilized to develop process superstructure for industrial rationality.

3. HPS and LPS

Chinese commercial 4-columns LSF MDS falls into two different conceptual flowsheets according to utility difference, especially in steam pressure: high-pressure scheme (HPS) and low-pressure scheme (LPS). HPS (Fig. 3) designates a pressure difference between PC top and AC bottom of over 650 kPa. It features side stream(s), or fusel oil, of AC feeding WC. The majority of purified wastewater discharges from AC bottom, causing higher temperature there for trace methanol content. So PC should operate at a higher pressure than otherwise in LPS case, when heating AC, to

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