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Utilizing heat sinks for further energy efficiency improvement in multiple heat integrated five-column methanol distillation scheme

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ABSTRACT

Although the potential of energy efficiency improvement of methanol distillation is largely reduced, heats are still in lack of recovery for discharging along with liquid products at embarrassing temperatures. Instead of routinely elevating certain stream temperatures to make a heat source at the cost of other energies. This work suggests an opposite strategy to utilize heat sinks to obtain temperature differences enough for heat recovery. In our former publication, compositions of lower boiling points are observed at the medium pressure column and the atmospheric column, whence make heat sinks available. This facilitates process adjustments for higher heat efficiency: (1) transit the medium column into a preceding atmospheric column, (2) pressured column top vapor distributes heat for thermal integration between bottoms of the light ends column and the preceding atmospheric column, (3) steam condensate from all the reboilers take over 90% heat supply to the former atmospheric column. Compared with the prototype, these changes knock down 31.85% specific stream consumption from 0.919 to 0.697 kg (steam)/kg (methanol). Exemplified by the evolution of five-column methanol distillations, the heat sinks strategy adds another train of thought to create heat transfer drive when utilizing low temperature heat for thermal coupling within chemical plant installations.

1. Introduction

Methanol is well-known as important and popular industrial raw material for the production of many chemical feedstock [1–3] and energy resources [4,5]. The year of 2016 saw its global demand hits 95 million tons, as a result of year-over-year growth, with China contributing 80% of it over the past five years [5]. Despite of the efforts for higher purity from the field of methanol synthesis through catalyst development [6,7], distillation is always the first choice to meet strict requirement like US federal specification O-M–232 K Grade "AA" [8]. Currently, the majority of Chinese coal based methanol units [9] consumes a specific energy of 1.07 kg (steam)/kg (methanol) in their popular four-column methanol distillation scheme [10]. Our published five-column scheme [11], the prototype of this work, moved forward greatly by a reduction of 23.41% to 0.919 kg (steam)/kg (methanol). This scheme was adopted by one of the Northern China methanol manufacturers for its undergoing unit revamp. Whereas, the huge volume in need, national or worldwide, still makes remarkable any improvements, even though tiny, in energy efficiency.

Thinking of further improvement, thermal integration [12–14] and process optimization [15,16] will be remembered at once. Following this thought train, double/multi-effect [17–21] is one of the handiest methods that can generally save energy by 20–40% or more, which has been extensively and repeatedly plowed through with vast academic works and industrial practice accumulation. In the prototype scheme, coexistent light split forward/reverse heat coupling achieves attracting specific heat requirement datum, together with other optimization measures, like:

1) Using methanol condensate from the pressured column (PC) to heat light ends column (LEC) bottom and simultaneously lower reflux temperature 5 ~ 10 °C below bubble point. This facilitates:

- ethanol (the key impurity) content control at lower reflux ratio
- lower the heat load of the pressured column
- reduce the risk of cavitation

2) Using fine methanol (from PC top) and steam condensate in feed

Abbreviations: AC, atmospheric column; FPDED, forward parallel double-effect distillation; HPC, high-pressure column; LEC, light ends column; LPC, low-pressure column; MPC, medium pressure column; MPDED, mixed parallel double-effect distillation; PAC, preceding atmospheric column; PC, pressured column; RPDED, reverse parallel double-effect distillation; SAC, succeeding atmospheric column; WC, water column

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pre-heating train.
3) Elevating LEC reflux temperature lowered by injection of extraction water for removal of methanol soluble impurities in its reflux drum.

Although fully developed, further improvement opportunities can survive when investigation in depth is performed into the prototype for some obvious defects:

1) The highest operating pressure keeps unchanged. Higher pressure leads to decreased relative volatility between key components and lower bottom temperature difference with that of certain heating medium, all negative to energy efficiency;
2) Consequently, heat source grade requirement has to be high for adequate heat transfer drive. Steam pressure may touch 1.1 MPa in most units;
3) A large amount of low temperature heat not only does not work well for further heat integration, but requires cooling for safety. This means five-column scheme still leaves potential to cut down energy consumption, perhaps significant ones.

Retrospecting the development of the prototype, the efforts are methodologically focused on creating temperature difference (installation of medium pressure column, or MPC) or heat transfer drive through elevating temperatures of potential heat source streams. What if utilizing low temperature heat sinks to set up similar temperature difference? The success will undoubtedly lead the entire process towards lower energy consumption. It can utilize surplus heat within process fluid and used heat medium at lower pressure for enough temperature difference to thermally drive distillation columns. Although rarely reported, heat sinks can be located or obtained in the scheme by finding existing ones. In the prototype, compositions of lower boiling points are observed at the medium pressure column and the atmospheric column, whence make heat sinks available. Lowering the boiling points of mixtures under separation through reducing the operation pressure or changing/adjusting the compositions. Normal boiling points are around 80–90 °C at LEC and MPC bottom as well as most theoretical stages of atmospheric column exhaustion section, all sound low-temperature heat sinks.

With feasibility and tool in hand, this study is devoted to suggest a more optimized alternative to the prototype based on heat sinks strategy. Parallel or distributive double-effect heat integration is suggested for higher energy efficiency, instead of the multi-effect option with a decreasing energy saving effect with more stages at the cost of surplus investment and complexity. Specifically, when replacing MPC with a proceeding atmospheric column (PAC), a heat sink at bottom appears for composition of low normal boiling point due to reducing the operating pressure receiving heat from the following PC top. This measure permits a lower PC pressure than its counterpart in the prototype and consequently lower temperature and pressure of heating steam. Sharply changing composition profile in the former atmospheric column exhaustion section makes another low temperature heat sink. This second one named as succeeding atmospheric column (SAC) can use heats from PC overhead vapor or steam condensate with a steam bottom reboiler compensating the remaining requirement. These two ways of arrangement give variations of new schemes providing another perspective for low-temperature heat utilization in distillation trains.

2. Parallel or distributive double-effect distillation

Parallel or distributive double-effect distillation (PDED) is a heat supply manner that a high-pressure column (HPC) supplies heat among several low-pressure columns (LPCs) simultaneously [22,23]. It falls in to three variations, namely forward (FPDED), reverse (RPDED) and mixed PDED (MPDED). In FPDED configuration (Fig. 1a), a preceding HPC heats succeeding LPCs which is suitable for most processes with high content of light component in the feed or low relative volatility between the light component and the other components, different from in RPDED (Fig. 1b) proceeding LPCs receiving heat from a HPC at the last of the column train and in MPDED (Fig. 1c) intermediate HPC drives its LPC neighbors before and after in the column train. The MPDED configuration is implemented mostly to the processes with high content of light intermediate component in the feed or low relative volatility between the light and heavy intermediate components. The above mentioned evolutions of five-column methanol distillation are achieved from another angle of viewpoint, namely, the construction of RPDED for the processes with low relative volatility between heavy intermediate component and heavy component or high contents of them in the feed integrated with steam condensate heat recovery.

3. Simulative establishment of the modified five-column schemes

3.1. Description of the prototype

In the prototype [11] (shown in Fig. 2), crude methanol is purified via LEC C1′, MPC C2′, PC C3′, AC C4′ and water column (WC) C5′. Before sending into C1′, the crude methanol is heated to 87.5 °C by background process streams. C1′ is to facilitate tail gas exhaustion. The overhead condensates of C2′, C3′ and C4′ mix together as methanol products. The top and bottom products of C5′ are fusel oil and wastewater. The overhead vapor of C2′ is thermally integrated with the reboiler of C1′. The overhead vapor of C3′ heats C4′ and saturated steam C2′, C3′ and C5′. A side-reboiler which is integrated with background process streams is attached to C4′ exhaustion section.

3.2. Description of the modified five-column schemes

The modified five-column schemes are designed in place of the two sets of heat coupling configurations. Two variations are prepared on purpose of comparison. In RPDED option, C3 (in Fig. 3) with the notably highest top temperature serves as PC in the schemes. The overhead vapor of PAC C2 no longer provides heat for the reboiler of the LEC C1, keeping SAC C4 and WC C5 same as in prototype. This variation features heat distribution among LEC and PAC reboilers as well as SAC side reboiler, different from the prototype whence AC bottom reboiler receives the heat. In this case steam condensate totally used for preheating. PC top pressure is reduced to 0.4 MPa along with the corresponding top temperature 104 °C, about 20 °C higher than the heat sinks and 30 °C lower than it was in prototype. The reboilers of C3 and C4 are heated by saturated steam. This scheme is named as modified scheme 1.

In another modified scheme 2 in Fig. 4, LEC C6, PAC C7, PC C8, SAC C9 and WC C10 are arranged in same train as in Fig. 3. The differences are C8 top heating the C6 and C7 at the bottom reboilers and steam condensate heating C9 side-reboiler.

3.3. Simulative case study of these schemes

The flow rate of crude methanol, with its composition in Table 1, is 239, 234 kg/h at 40 °C and 100 kPa as same as the prototype. The number of theoretical trays and the feed position are the same in all schemes. The purity demand of the purified methanol product is 99.99 wt% and the methanol recoveries is to be more than 99.32% in these schemes. Therefore, the methanol content of the feed to WC is controlled to be less than 0.016 wt%.

Rigorous simulations are then carried on with commercial process simulator Pro/II with Alcohol Package [24] as thermodynamic model for columns other than LEC, for which UNIFAC is selected. Reboilers are all thermosiphon without baffles and the condenser type is subcooled. Saturated steam at 0.6 MPa is selected as hot utility and cooling water as cold utility with inlet and outlet temperatures of 30 °C and 40 °C.