A new Design Methodology for Heat Integrated Distillation Column Based on Self-Heat Recuperation

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In this paper, a novel design methodology based on self-heat recuperation for heat integrated distillation column (HIDiC) is proposed. In HIDiC, the condensation heat is recovered and exchanged with the vaporization heat in the column for energy saving. By following self-heat recuperation technology, the energy input and output of HIDiC are analyzed and the process heat circulates through the process by using pressure change, leading to further energy saving. The simulation result demonstrates that the energy consumption for HIDiC based on the proposed design methodology by using self-heat recuperation is drastically decreased as compared with benchmark processes which use external heat sources.

1. Introduction

Many innovative energy saving distillation processes have been developed. A vapor recompression (VRC) (Brousse et al., 1985) is one of the most distillation column, in which the top vapor stream is compressed and the heat of the stream is exchanged with the heat of the bottom liquid stream of the column to recover condensation heat to the vaporization heat. Another famous distillation column is a heat integrated distillation column (HIDiC, Nakaiwa et al., 2003). To design this process, the distillation column can be divided into two parts and the condensation heat is exchanged with the vaporization heat between these two parts by using pressure difference. HIDiC has an advantage that the compression work can be smaller than that of VRC due to the temperature difference for heat exchange and a disadvantage that the whole process must be renewed from the conventional process. However, both VRC and HIDiC are generally focused on the heating by reboiler in the distillation column and not designed under consideration of the heating of feed stream to the distillation.

Recently, by incorporating compressors and heat exchangers, authors have developed a self-heat recuperation technology to reduce the energy consumption of the chemical process (Kansha et al., 2009, 2010a, 2010b). In this technology, a process unit is divided into functions to analyze the process required/exhausted heat and all of the self heat of process stream is managed to be recirculated in the process based on exergy

recuperation without heat addition. As a result, the energy consumption of a process can be greatly reduced.

In this paper, the design methodology for HIDiC based on self-heat recuperation technology is proposed, the distillation process with HIDiC by following this design methodology is reconstructed and the energy saving amount of the process is calculated by using commercial process simulator to confirm further reduction of the energy consumption as compared with the other benchmark distillation processes.

2. Process Design and Configuration

Figure 1 shows the desired distillation process with HIDiC based on the proposed design methodology by using self-heat recuperation technology. This process consists of two modules, preheater and HIDiC. The summation of enthalpy of inlet streams is equal to the summation of enthalpy of outlet streams in each module by following self-heat recuperation technology, resulting in that the vaporization heat of rebolier is equal to the condensation heat of condenser in HIDiC module and that the total heating duty is equal to the total cooling duty in preheater module.

A feed stream of the mixture is S1 at standard temperature and pressure and divided into two streams (S2, S3). These streams are heated by heat exchangers (HX1, HX2) (S2→S4, S3→S5) and mixed (S6) to maximized the heat recovery duty in the heat exchangers. The mixed stream is heated by a heat exchanger (HX3) and fed into HIDiC module as S7. Here, the main role of the HX3 is to exchange the latent heat between the feed stream (S6→S7) and the effluent stream (S16→S17). The main roles of the other heat exchangers are to exchange the sensible heat. HIDiC module is designed by following the conventional HIDiC. In HIDiC module, the feed stream (S7) is mixed with the effluent stream (S14) from a higher pressure column (DC2) and fed into a lower pressure column (DC1) (S8). S8 is separated into top vapor stream (S9) and bottom liquid stream (S15) by the DC1. S15 becomes bottom product and returned to preheater module. Simultaneously, S9 is adiabatically compressed by a compressor (C1) and fed into the DC2 as S10. S10 is separated into top vapor stream (S11) and bottom liquid stream (S13). S13 is depressurized by a valve (V1) (S14) and mixed with feed stream S7. Then, S11 is cooled by a cooler (CO1) and returned to preheater module as top product. The cooling duty of the CO1 is same as the compressor duty of the C1. The effluent stream (S12) from HIDiC module is depressurized by an expander (E1) (S16) and cooled by the HX3 and the HX1 (S16→S17→S18). Then pressure is adjusted to the standard pressure and temperature by a valve (V2) and a cooler (CO2) (S18→S19→S20). S20 becomes distilled product. S15 is cooled by the HX2 and a cooler (CO3) and then becomes bottom product (S15→S21→S22). In this figure, the heat exchange between the DC1 and the DC2 is assumed to be well established.

The relationship among conventional distillation preheating duty (Q_F), condenser duty (Q_{Cond}) and reboiler duty (Q_{Reb}) is expressed as follows;

$$Q_F \cong Q_{Reb} - Q_{Cond} \tag{1}$$

By following self-heat recuperation technology, S7 is preheated by the effluent streams through the heat exchangers (HX1, HX2, HX3) in preheater module, because the summation of enthalpy of inlet streams and outlet streams are equal. Therefore, the

additional preheating duty (Q_F) is not required in HIDiC module. Thus, the reboiler duty (Q_{Reb}) is equal to the condenser duty (Q_{Cond}) from Eq. (1). When the heat exchange area is wide enough for heat exchanging between DC1 and DC2, the whole reboiler duty (Q_{Reb}) is exchanged with the whole condenser duty (Q_{Cond}).
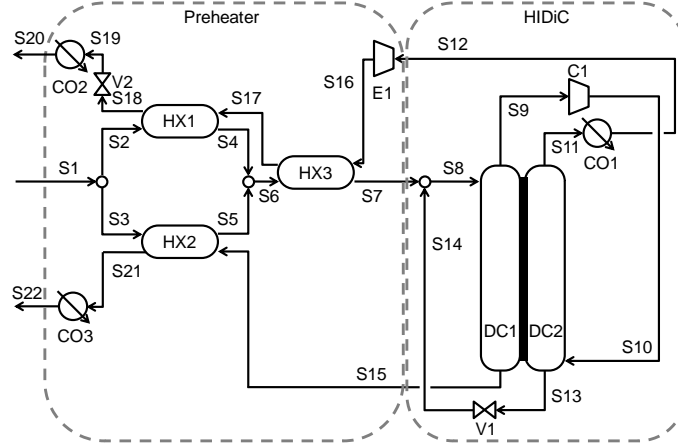

Figure 1: HIDiC process based on self-heat recuperation technology

3. Simulation

We examined the steady state energy consumption of the HIDiC process which designed by self-heat recuperation technology as compared with the conventional distillation process, the HIDiC process, and the heat integrated HIDiC process in a commercial process simulator PRO/II[TM] Ver. 8.1 (Invensys).

Considering a distillation process which separates benzene from the mixture of benzene (50mol%) and toluene (50mol%) at standard temperature (25 ^{O}C) and pressure (1 atm), we assumed that the feed flow rate to the process was 200 kg-mol/hr (F), that the composition of the product from the distillate (D) was 99.5% benzene and 0.5% toluene at 25 ^{O}C and 1 atm, and that the pressure and heat losses of processes are neglected. We made the following assumptions; i) the number of stages of the conventional distillation column was 99, and the numbers of stages in two parts of HIDiC were 50, which did not include reboiler and condenser, ii) the minimum temperature difference was kept to be constant at 10 K in all heat exchangers, iii) the Soave-Redlich-Kwong equation of the state (SRK) was applied to real gas, iv) adiabatic efficiency in the compressor was 80% and v) the pressure ratio of the compression work and heat transfer value (UA) in HIDiC wre kept to 5 and 750 Js^{-1}K. The work required for changing pressure (W_C) is expressed as follows;

$$W_C = H_{out} - H_{in} \tag{2}$$

where the enthalpy of the stream is changed from H_{in} to H_{out} in adiabatic irreversible process.

Figures 2 and 3 show the simulation results of the conventional distillation column and HIDiC with a feed furnace, respectively. The required energy of the conventional

distillation column was 2,531 kW in reboiler. On the other hand, the furnace duty of the feed stream to the boiling point was 535 kW, the reboiler duty of HIDiC was 521 kW and the compressor work was 544 kW in HIDiC. Thus, the total required energy of HIDiC was 1,600 kW. Although the total required energy of HIDiC was 37% reduced as compared with the conventional distillation column, this reduction was not enough because the power for compressor was used in HIDiC instead of the fuel in the furnace. These results show that HIDiC cannot be always have high energy efficiency when the amount of the internal heat circulation of the process was small.
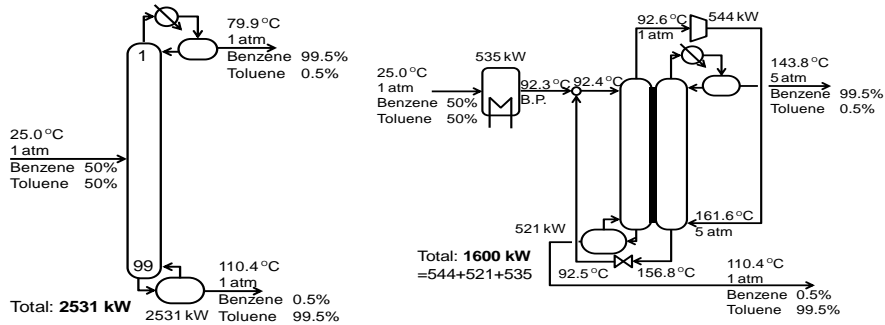

Figure 2: The conventional distillation column   Figure 3: HIDiC (Feed: Boiling point)

Next, to maximize the internal heat circulation of the process, HIDiC process with a feed heat recovery was proposed as shown in Figure 4.
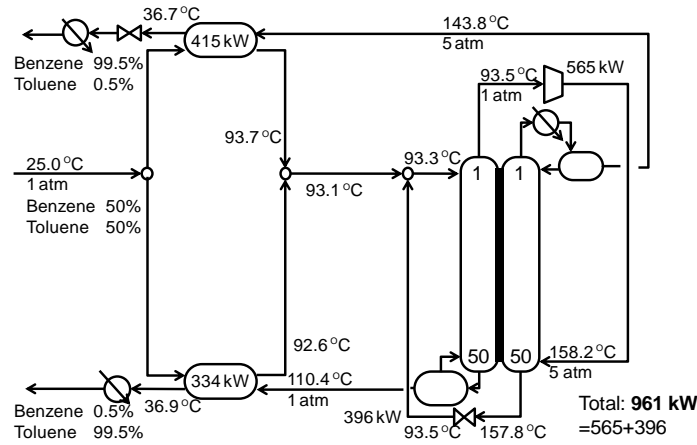

Figure 4: HIDiC process with the feed heat recovery

In this process, the required energy was 396 kW as reboiler duty in HIDiC and 565 kW as compression work. In this simulation, we assumed that the minimum temperature difference was equal to 10 K in the heat exchangers. Simultaneously, we examined the total energy required of HIDiC process based on the proposed design methodology using self-heat recuperation as shown in Figure 5. In this process, the reboiler duty was 20 kW, the compression work was 663 kW and the recovery work from the expander was 20 kW. Thus, the total required energy was 623 kW. Note that the reboiler duty can

be 0 when the heat exchange in HIDiC was well established, as mentioned before. Figure 6 summarizes the required energy of each distillation process. It can be seen that the heat duty of HIDiC process based on the proposed design methodology is drastically decreased instead of slightly increasing of compression work as compared with the other distillation processes, because heat balance of each module was naturally well-established due to self-heat recuperation technology, leading to maximizing the internal heat circulation in the process. Since a distillation process is divided into two parts by enthalpy balance based on self-heat recuperation, the reboiler duty becomes equal to the condenser duty. Then the condensation heat is recovered by HIDiC into the vaporization heat in the reboiler duty and the heat of the effluent streams are recovered to the heat of the feed stream effectively as using the compression work without any heat addition and large exergy loss. Therefore the process based on the proposed design methodology can be maximizing the internal heat circulation and drastically reduce the energy input to the process as compared with the other distillation processes.
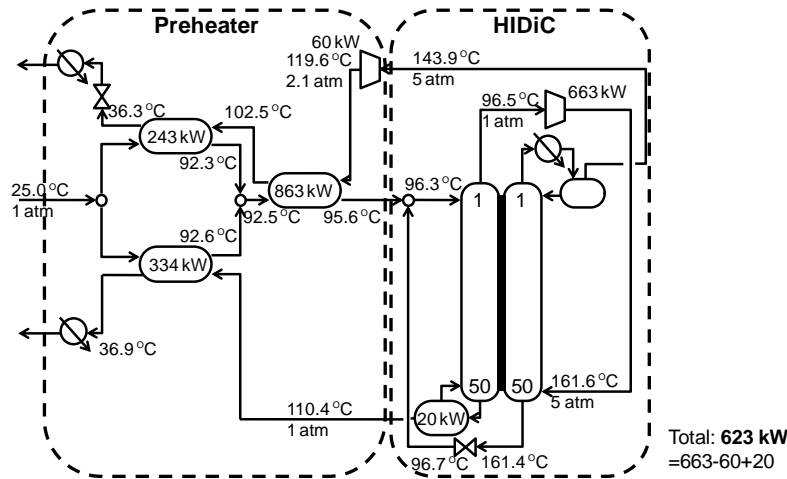

Figure 5: HIDiC process based on self-heat recuperation technology

4. Conclusion

A novel design methodology for heat integrated distillation column (HIDiC) based on self-heat recuperation technology is proposed in this paper. In the conventional HIDiC, vaporization duty is not equal to condensation duty, because it is designed without considering preheating duty. However, by combining self-heat recuperation with HIDiC, not only sensible heat but also latent heat of the preheating duty is exchanged with those of the product cooling duty in preheater module and the vaporization duty is exchanged with the condensation duty in HIDiC module. Therefore, all of the process stream heat is recirculated in the process. Thus, the energy saving performance of HIDiC becomes more effective due to exergy analysis and self-heat recuperation.
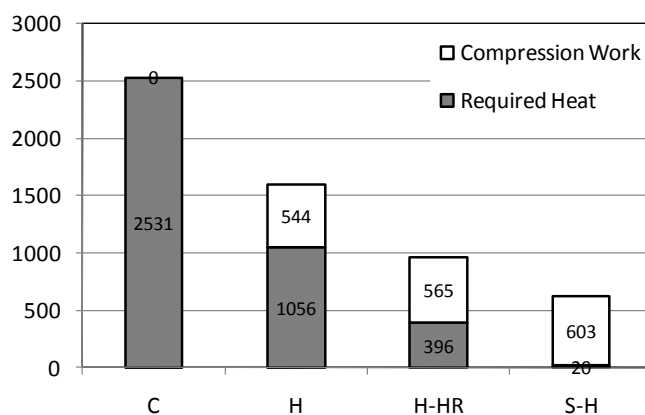
Figure 6: The summary of energy recuirement (C: the conventional distillation process, H: HIDiC process, H-HR: HIDiC with feed heat recovery, S-H: HIDiC based on self-heat recuperation)

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