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A New Design Methodology of Azeotropic Distillation Processes Based on Self-Heat Recuperation

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In this paper, an innovative design methodology of azeotropic distillation processes by using a self-heat recuperation technology has been proposed to reduce the energy consumption. In this process, the heat of the distillate and condenser of the distillation column are recuperated by compressors and exchanged with the heat of the feed and reboiler of the distillation column, leading to the reduction in the heat energy to the process. The process simulation results show that the proposed methodology achieves the large amount of energy reduction as compared with the conventional azeotropic distillation process

1. Introduction

Recently, bioethanol has rapidly become in great demand all over the world in substitution for petroleum. To produce the bioethanol, it is necessary to separate ethanol from ethanol-water mixture after fermentation of alcohol. In practical, the distillation is widely used for this separation of this mixture. However, this distillation process is a well-known process as an energy–consuming process because ethanol and water form an azeotropic mixture. As a matter of fact, it is reported that about 50% of heat value of bioethanol is required to distill the ethanol from the mixture. To reduce the energy consumption of this process, many researchers proposed membrane separation techniques (Gomez *et al.* 2007, Vane and Alvarez 2008) or pressure swing adsorption (PSA) techniques (Modla and Lang 2008), instead of azeotropic distillation. Most of the researchers have succeeded in developing appropriate membranes and sorbents for these technologies to achieve the efficient distillation. However, they have paid less attention to the scheme of the process itself. As a result, the minimum energy requirement of the process has not been reduced. On the other hand, many innovative distillation columns have been developed, such as vapor recompression distillation column (VRC, Brousse *et al.* 1985, Annakou *et al.* 1995, Gros and Brignole, 1998) and heat integrated distillation column (HIDiC, Huang *et al.* 1996a, b, Nakaiwa *et al.*, 2000, Olujic *et al.*, 2003, Huang *et al.*, 2006a, b) to reduce the energy consumption of the distillation column. However, these heat integration methods still have problems to complicate the designs and operations of distillation columns. Additionally, although almost all of these design methods are focused on the heating by reboiler in the distillation column,

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they are not interested in the heating of feed stream to the distillation. Therefore, the energy balance of the heating duty and cooling duty are not well considered. Recently, by incorporating compressors and heat exchangers, the authors have developed another attractive technology to reduce the energy consumption (Sato *et al.*, 2007, Tsuru *et al.*, 2008, Kansha *et al.*, 2008). In this technology, a process unit is divided into functions and the external heating and cooling load is minimized by using a self-heat recuperation technology. As a result, the energy consumption of a process can be greatly reduced. Following this technology, an innovative design methodology of distillation processes for azeotrope has been proposed in this paper. The simulation results demonstrate that the energy consumption for distillation processes of azeotropic mixtures with self-heat recuperation is drastically decreased as compared with a conventional process which uses external heat source.

2. System Configuration

Figure 1 shows the structure of the proposed integrated process module which consists of three modules, the first and second distillation modules (M1, M3) and heat circulation module (M2) in the case of ethanol-water mixture. In this integrated process module, stream 1 represents the azeotropic mixture feed stream and stream 2 represents the entrainer (benzene) feed stream. These streams are fed into the first distillation column (DC1). The vapor stream from the distillation column is compressed adiabatically by a compressor (C1) ($4 \rightarrow 5$). Successively, stream 5 is cooled by a heat exchanger (HX1) ($5 \rightarrow 6$) and the pressure and temperature of stream 6 are adjusted by valve (V1) and cooler (L1) ($6 \rightarrow 7 \rightarrow 8$). The liquid stream 8 is divided into two streams (9, 10) in the decanter (D). The stream 9 is mainly consisted of benzene and recycled with the feed benzene (3). The bottoms of DC1 are divided into two streams (12, 14). The stream 14 becomes the product (pure ethanol). The stream 12 is heated by the heat exchanger (HX1) and fed into DC1. In the heat circulated module (M2), the effluent stream (10) from M1 is heated by heat exchanger (HX2) and is fed to the second distillation column (DC2). At the same time, the recycled stream, which is distillate stream of DC2, is adiabatically compressed by compressor (C3) ($18 \rightarrow 27$), cooled by exchanging the heat in HX2 ($27 \rightarrow 28$). The pressure and temperature of the stream 28 are adjusted by the valve and cooler (V2, L2) ($28 \rightarrow 29 \rightarrow 30$) and the stream 30 is fed into DC1 as the recycled stream. Next, in the second distillation module (M3), the feed stream 15 is separated into distillate (16) and bottoms (17) by the distillation column (DC2). The vapor distillate 16 is divided into two streams (18, 19) by separator. The stream 18 becomes recycle stream and returned to M2. The stream 19 is adiabatically compressed ($19 \rightarrow 20$) and exchanged the heat in the heat exchanger (HX3) ($20 \rightarrow 21$). The temperature and pressure of the stream 21 are adjusted by valve (V3) and cooler (L3) ($21 \rightarrow 22 \rightarrow 23$) and then the effluent stream is fed into DC2. Successively, the bottoms 17 from DC2 are divided into two streams (24, 25). The stream 25 is the product water. The other stream 24 is vaporized by HX3 and fed into DC2 ($24 \rightarrow 26$).

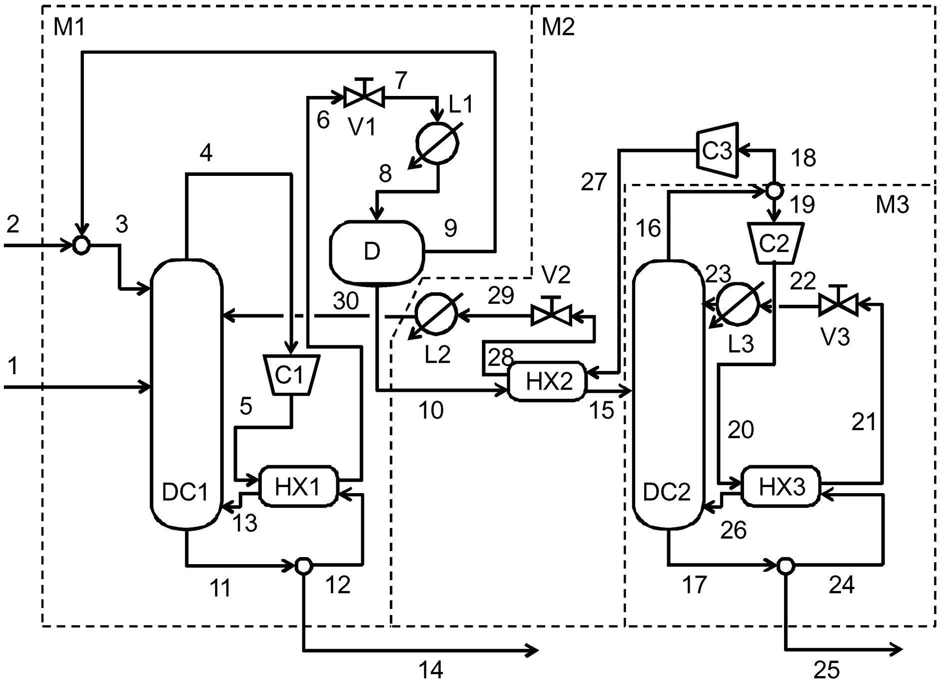

Figure 1 The proposed integrated process module for azeotropic distillation column

3. Simulation Results

We calculated energy consumption for the proposed integrated process module for azeotropic distillation column and compared with energy consumption for a benchmark azeotropic distillation column in an ethanol-water mixture. The process simulation was conducted using the commercial simulator PRO/II^{TM} Ver. 8.1(Invensys).

Considering a distillation process which separates ethanol from the mixture of ethanol (80mol%) and water (20mol%) at standard temperature (77 ^{o}C) and pressure (1 kg/cm^{2}), we assumed that the flow rate was 10 kg-mol/hr and that the composition of benzene was less than 1.0×10^{-4} in the product ethanol from the first distillation column (DC1) and the composition of ethanol was less than 1.0×10^{-3} in the product water from the second distillation column (DC2). The energy consumption of the proposed integrated process module was elucidated by comparing of that of a conventional azeotropic distillation system. Other conditions of the distillation column are shown in Table 1.

In all heat exchange systems, the minimum temperature difference was kept to be constant at 10 K. The Non Random Two-Liquid (NRTL) was applied in liquid. We assumed that the adiabatic efficiency in the compressor was 100%. The work required for changing pressure (W_C) is expressed as follows;

$$W_C = H_{out} - H_{in} \qquad (1)$$

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

In the proposed system, the net work (W_{net}) is represented as the following equation;

$$W_{\text{net}} = W_{\text{C}} \tag{2}$$

where W_{C} represents the work of the compressor.

The distillates from the distillation columns were condensed and exchanged the latent heat to the bottoms and feed as shown in Fig. 2. The self-heat exchange duty is increased to 453.2 kW. It can be seen that the total heating duty is covered by self-heat recuperation results in considerable reduction of energy consumption. The total work of the proposed module with self-heat recuperation can be reduced (57.4 kW(=28.9+3.3+25.2 kW), Fig. 2) comparing with the external heating load of the benchmark flash distillation (395.0 kW(=282.4+112.6 kW), Fig. 3). Thus, the proposed system drastically reduces the total energy consumption.

From this simulation study, it was demonstrated that the proposed integrated process module contribute effectively to the reduction of energy consumption, indicating the proposed module is very promising technology for distillation process

4. Conclusion

The innovative modularity based on self-heat recuperation for distillation process of azeotropic mixtures is proposed in this paper. This module only requires the energy to drive heat circulation, results in the reduction in the total amount of energy consumption. The simulation studies which assume the feeds are the mixture of ethanol (80mol%) and water (20mol%) show that the proposed modules can reduce the external heating load for azeotropic distillation to 14.5% compared with the benchmark distillation systems.

5. Acknowledgement

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Table 1 Conditions for the distillation column

First Distillation Column (DC1)		Second Distillation Column (DC2)	
Number of Stages	20	Number of Stages	10
Pressure	1 kg/cm^2	Pressure	1 kg/cm^2
Feed Stage of Azeotropic Mixture	4	Feed Stage	5
Feed Stage of Benzene	1	Reflux Ratio	2
Feed Stage of Recycled EtOH	4		

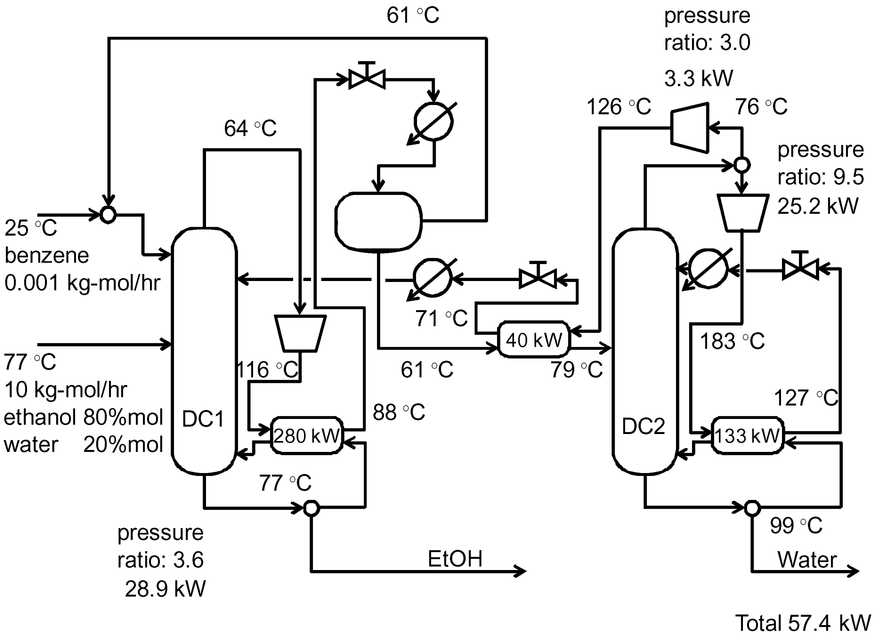

Figure 2 Simulation Results of the proposed integrated process module for azeotropic distillation column

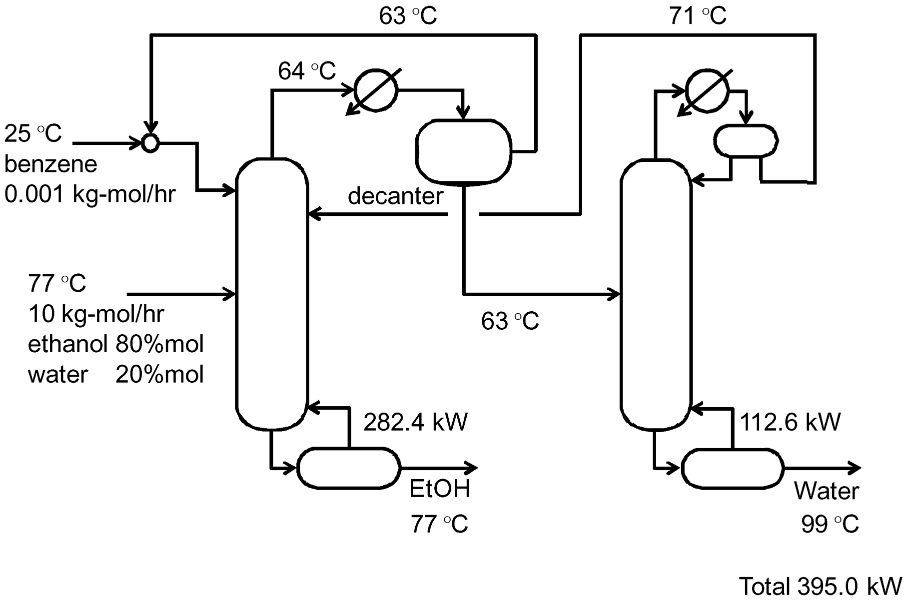

Figure 3 Simulation Results of the conventional azeotropic distillation column

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