An Innovative Dimethyl Ether (DME) Production Using Self-Heat Recuperation

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Dimethyl ether (DME) has been categorized as a green energy source, and the demand of the DME continue increasing. In this research, we investigated the feasibility of applying self-heat recuperation technology to DME production process using indirect method and developed an innovative process for DME production process from the energy saving point of view. By installing the self-heat recuperation technology to the DME production process, the energy consumption of the thermal and separation processes can be greatly reduced.

1. Introduction

The demand for dimethyl ether (DME) will continue increasing, since DME is categorized as a green fuel. In fact, DME contains 34.8 % oxygenates and has higher heat value than natural gas. Moreover, it is less toxic to human beings and can be stored as a liquid fuel with pressurising or cooling.

DME is commonly produced by two methods; indirect and direct DME synthesis methods (Papari et al. 2013). In the indirect method called double stage method, methanol is produced and then converted to DME. On the other hand, in direct method called single stage method, DME is synthesised from syngas. A series of reactions was represented by the followings;

Methanol Synthesis

$$CO + 2H_2 \leftrightarrow CH_3OH \tag{1}$$

Methanol dehydration

$$2CH_3OH \leftrightarrow CH_3OCH_3 + H_2O \tag{2}$$

Water gas-shift

$$CO + H_2O \leftrightarrow CO_2 + H_2 \tag{3}$$

Methanol Synthesis from CO_2

$$CO_2 + 3H_2 \leftrightarrow CH_3OH + H_2O \tag{4}$$

Although the direct method is applied, methanol synthesis reaction takes place in the reactor according to the above mentioned equations. The main advantage of direct method is reported that the CO transformation rate is higher than the indirect method. Thus, many investigators try to find or create new catalysts for direct method. However, this CO high transformation phenomenon occurs due to series reactions taking place in the reactor, leading to shifting the reaction equilibrium to the product side. Thus, we can achieve the same CO high transformation rate in the indirect method to that in the direct method, if we get rid of the product methanol as shown in Eq.1 from the reaction field simultaneously.

So, as well as other chemical processes, many DME production processes in the indirect method have reactant recycle system with product separation in order to increasing the overall conversion ratio in the reactor. Distillation processes have often been used for this product separation from reactant recycle

stream in industry due to the large throughput. However, the distillation processes are well known as energy consuming processes since the large latent heat (vaporization and condensation heat) has to be provided to reach at the gas-liquid equilibrium in the column. Thus, many chemical engineers and investigators have been managing to produce a catalyst which achieves high conversion from reactant to production in the reactor for whole process optimization (Dai et al. 2011) or have been developed the reactive distillation process for DME production (An et al. 2004).

Recently, authors have developed a self-heat recuperation technology based on exergy destruction minimization to reduce the energy consumption of chemical processes. Applying the self-heat recuperation technology to chemical processes, not only the latent heat but also the sensible heat of the process stream can be circulated into the processes without any heat addition (Kansha et al. 2009). As a result, the energy consumption and exergy destruction of a process can be greatly reduced in the steady state (Kansha et al. 2013a). In fact, this technology has been applied to several chemical processes as case studies and shows large energy saving potentials in these processes. From these previous studies, it found that thermal and separation processes are suitable processes for self-heat recuperation technology.

In this research, we investigated the feasibility of applying self-heat recuperation technology to DME production process using indirect method and developed an innovative process for DME production process from the energy saving point of view.

2. Self-heat recuperation technology

The most importance of the self-heat recuperation technology (Kansha et al. 2009) is recirculation of a whole process heat which composes from not only latent heat but also sensible heat in a process, leading to significant reduction of the energy consumption of the process (Matsuda et al. 2010). This technology composes from the following main tasks; that a process unit is divided on the basis of functions to balance the heating and cooling loads by performing energy and exergy analysis and that the cooling load is recuperated by compressors and exchanged with the heating load.
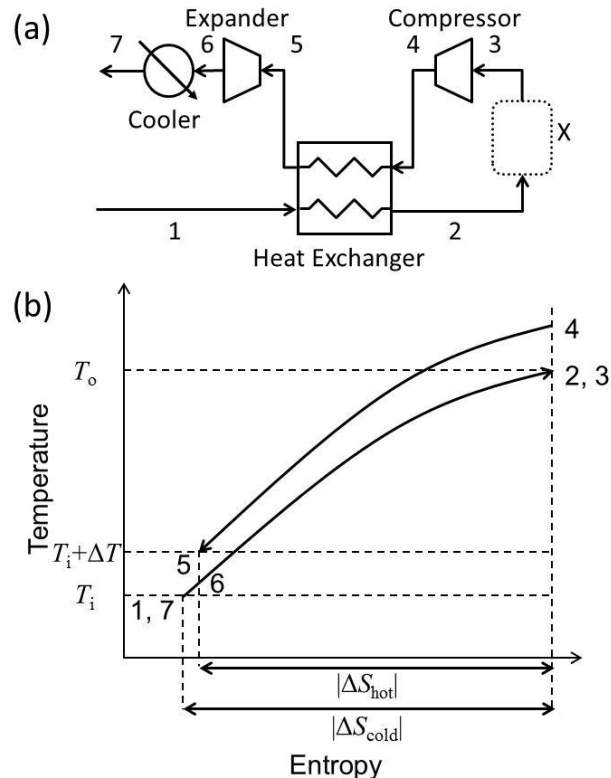

Figure 1: A self-heat recuperative thermal process in the case of a gas fluid: a) flow diagram b) temperature-entropy diagram (Kansha et al. 2013a)

Kansha et al. (2013a) reported that that this process is inherently designed by accounting for the exergy loss minimization of the process due to the heat transfer. Thus, the process based on self-heat

recuperation can be operated with similar amount of energy to the amount of the minimum exergy loss during heat transfer when infinite numbers of compressors and heat exchangers are used alternatively and the compressors work adiabatically as shown in Figure 1.

Expanding the self-heat recuperative thermal process to separation processes such as distillation for benzene-toluene mixture (Kansha et al. 2010), industrial benzene-toluene separation plant (Matsuda et al. 2010b), and for crude oil distillation, a system including not only the separation process itself but also the preheating/cooling section, can be divided on the basis of functions in which the heating and cooling loads are balanced. The enthalpy of inlet stream is equal to the sum of the outlet streams enthalpies in each module. The cooling load in each module is then recuperated by compressors and exchanged by using compression work by following the above mentioned self-heat recuperation technology. Moreover, Kansha et al. (2013b) reported that self-heat recuperation technology can greatly reduce the energy consumption of methanol production process. This result significantly affects the DME synthesis process since methanol is the reactant of the DME synthesis.

3. DME synthesis process

The flow diagram of DME synthesis process is shown in Figure 2. This process is considered as the indirect method. Thus, process feed is provided by the pure methanol. Then, this feed flow is mixed with the recycle stream. This feed flow is fed into the reactor, fixed bed (Farsi et al. 2011). In this reactor, methanol dehydration reaction represented by Eq.2 is taken place. This methanol dehydration as Eq.2 is exthothermic reaction and the reaction heat amount is represented by ΔH^ρ_{298} = -23.40 kJ/mol. Thus, the outlet stream from the reactor contains methanol, water and DME. As well as other many chemical processes, this DME synthesis process equips reactant recycle system with product separation. For this product separation from reactant recycle stream, the product mixture from reactor is fed through a distillation column 1 as shown in Figure 2. This distillation column 1 separates the product DME from the reactor outlet mixture by top of the column. Simultaneously, water and methanol mixture is striped from the bottom of the column. After that this water and methanol mixture is fed into the distillation column 2 with depressurising by valve. By this distillation column 2, the pure methanol is distilled for the reactant recycling and this provides the high reaction conversion.

4. Simulation

To investigate the feasibility of the application of the self-heat recuperation technology to the DME synthesis process, the energy consumption of the DME production process as compared with the bench mark process was examined by commercial process simulator (PRO/II Ver. 9.0, Invensys). The stage numbers of distillation column, the reflux ratios of the distillation columns 1 and 2 are 1.2 and 5.0, and feed and product conditions were referred from the previous work (Lei et al. 2011). The Soave-Redlich-Kwong (SRK) was used as the state equation and the equilibrium for liquid phase mixture was estimated by
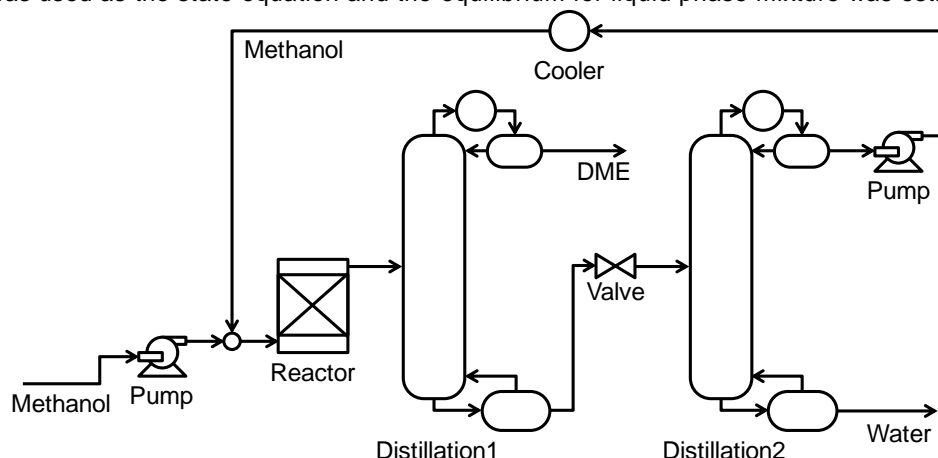

Figure 2: Flow diagram of DME synthesis process

universal functional activity coefficient (UNIFAC). We used the Gibbs reactor module as the reactor. The minimum temperature difference in the heat exchanger was assumed to be 10 K. The adiabatic efficiency of the compressor was 100 %.

Flow rate and stream conditions for the simulations are summarised by the followings;

1) The process feed was provided by the pure methanol (9.0 kmol/h) at 25 °C and 2.0 MPa
2) The feed flow was mixed with the recycle stream (1.0 kmol/h) at 25 °C and 2.0 MPa.
3) The methanol dehydration reaction represented by Eq.2 was assumed to be only taken place at 130 °C by Gibbs reactor.
4) The product DME was 4.2 kmol/h and 99.9 mol%.
5) The pressure of the distillation column 2 was 0.1 MPa.

4.1 The conventional DME production process

By using the commercial process simulator (SimSci PRO/II, 2014) and the above mentioned assumptions, the energy and exergy analysis of the conventional DME production process was conducted. The energy required of this process is only heat for reboilers of distillation column 1 and 2. These amounts are 65.5 kW and 44.6 kW as shown in Figure 3.

4.2 The proposed DME production process

In this paper, we applied the self-heat recuperation technology to the distillation column 2 surrounded by gray dash line in Figure 3 for examining the feasibility and energy saving potential of recycling part at the first step. Figure 4 shows the detailed flow and result of the application of self-heat recuperation to the distillation column 2 of the DME production process and the energy required for the compressor to exergy recuperation. By installing the self-heat recuperation technology to the distillation column 2, the feed condition was changed for balancing the enthalpies of inlet stream and the enthalpies of the outlet streams in this module. Then, all of the condenser duty at the top of column can be circulated into the reboiler duty at the bottom of column by using the compressor and heat exchangers. Finally, only 1.4 kW work was required for introducing heat circulation.
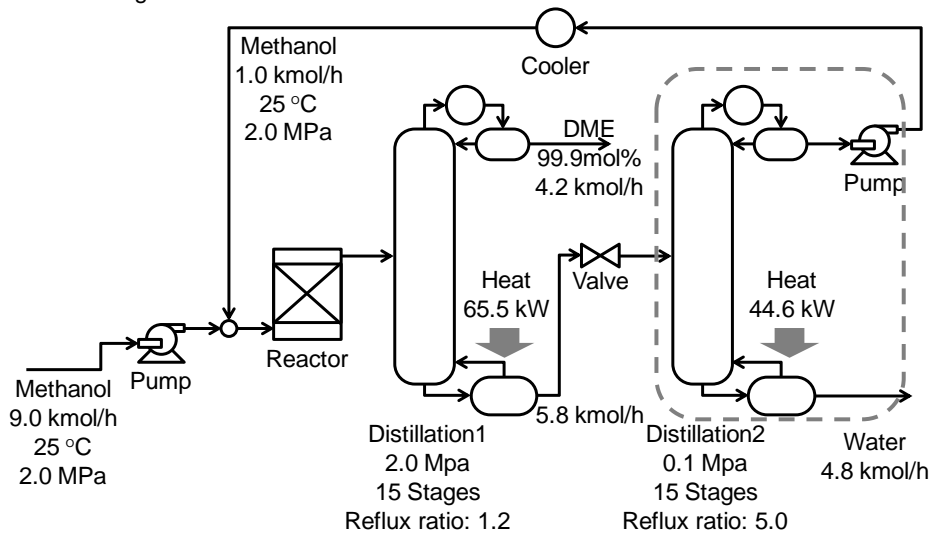

Figure 3:Energy amount of the conventional process and stream conditions

5. Comparison and Discussion

By installing the self-heat recuperation technology to the DME production process using indirect method, the energy consumption of the thermal and separation processes can be greatly reduced. In this paper, we only applied this technology to the distillation column 2 at the first step for this research. In fact that the energy required for the reboiler heat duty 44.6 kW was amazingly reduced to the work 1.4 kW as summarized in Table 1. At the same time, we have been applying this technology to the distillation column 1 and thermal processes around reactor. Then we have achieved the drastic energy saving with some temperature and pressure condition changes due to optimal settings for self-heat recuperation. This means that DME production rate can be increased by increasing recycling rate since we can separate the product and recycling stream by small amount of energy. Thus, it can be said that installation of self-heat recuperation technology is the other option of process design method to achieve high conversion in the reactor. In addition, if we will extend the installation of self-heat recuperation to the methanol synthesis process referred to the results of Kansha et al. (2013b) and will integrate the proposed DME production

process based on self-heat recuperation with the methanol production process based on self-heat recuperation as the series of processes from syngas to DME, this series of processes has great potential instead of current direct DME production method from syngas. Furthermore, it is necessary to apply the self-heat recuperation technology to the DME production process using direct method for comparison purpose.
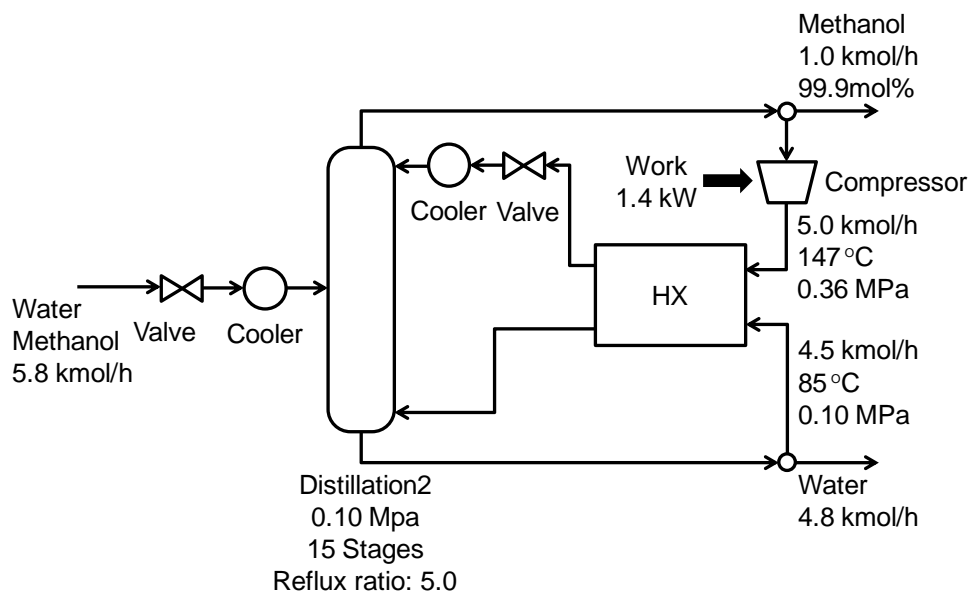

Figure 4: Detailed flow of the distillation column 2 by using self-heat recuperation and stream conditions

Table 1: Energy Comparison

	Distillation 2
Conventional Process	44.6 kW
Proposed Process by SHR	1.4 kW*

* Adiabatic efficiency of the compressor: 100 %

6. Conclusion

In this research, we investigated the feasibility of applying self-heat recuperation technology to DME production process using indirect method and developed an innovative process for DME production process. By installing the self-heat recuperation technology to the DME production process, the energy consumption of the thermal and separation processes can be greatly reduced. This process has a great potential to produce green fuel, DME with low energy consumption.

Acknowledgments

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