[Review Paper]

Energy Saving Bioethanol Distillation Process with Self-heat Recuperation Technology

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Bioethanol is a renewable liquid fuel that has become established as a viable alternative to gasoline. Bioethanol is produced mainly in the US and Brazil from corn and sugarcane as feedstock, and world-wide production has been expanding. However, a distillation process is essential for refining bioethanol, which requires a large amount of heat, and thus offsets the carbon-neutral value. The energy efficiency of the distillation process with "Self-heat recuperation" technology was studied, which recovers sensible and latent heats by compressing the vapor from the top of the distillation column. In this study, the effect of energy saving in the distillation of bioethanol with self-heat recuperation technology was analyzed in comparison to the conventional counterpart using a temperature-heat diagram, as well as demonstrated on a pilot scale. Further demonstration tests were conducted for enzyme-recovering distillation that is used in the cellulosic ethanol production process from cellulosic biomass as feedstock to study the effect of energy saving using distillation with self-heat recuperation.

Keywords
Bioethanol, Cellulosic biomass, Distillation, Vapor compression, Self-heat recuperation

1. Introduction

Bioethanol is a promising alternative to gasoline, so production is rapidly expanding in response to agricultural policies, global warming countermeasures, sustainable society needs and energy security. In fact, total production worldwide in 2012 amounted to as much as 85 million kL, which is higher than the domestic annual gasoline consumption of 60 million kL in Japan. The main feedstocks for bioethanol production are currently corn and sugarcane containing starch and sugar, which raises the problem of competition with food supply requirements. However, bioethanol production may also use cellulosic feedstocks allowing greater expansion in the near future.

An example of a bioethanol production process from cellulosic feedstock is shown in Fig. 1. The distillation process to separate and refine ethanol derived from the fermentation process is one of the most important unit operations. The distillation process first evaporates and then condenses the liquid mixture, resulting in separation and concentration of the components with different boiling points. The boiling point of ethanol at ordinary pressure is 79 °C and that of water is 100 °C. In the ethanol distillation process, the fermented water mixture containing only a few percent of ethanol is heated and then concentrated until the ethanol concentration is 90 % using the difference in the boiling points of the liquids. The thermodynamic requirements for the distillation process are supply of the latent heat of evaporation to the reboiler at the bottom of the column to vaporize the liquid mixture, and removal of the latent heat of condensation from the vapor by the condenser at the top of the column to condense the vapor into liquid1). Therefore, the distillation process of bioethanol production consumes a large amount of heat energy despite the advantage of easy and stable separation of the ethanol from the fermentation mixture compared to other ethanol separation methods such as membrane filtration or extraction. For example, the energy required for distillation from 10 wt% ethanol to

![Fig. 1 Production of Bioethanol](Image URL)
90 wt%, assuming heat is recovered from the bottom products (liquid discharged from the bottom of the column), is 4.6 MJ/L-ethanol, which accounts for 20 % of the heat energy equivalent of the produced bioethanol, so that the energy conversion efficiency of bioethanol production is reduced by the same amount of energy. Especially in the United States, the heat required for ethanol distillation is obtained from natural gas, resulting in reduction in the carbon neutral value of bioethanol.

Consequently, significant improvements in the energy efficiency of the distillation process of bioethanol production are required in terms of cost reduction as well as greenhouse gas (GHG) emission reduction, and many studies are currently investigating energy efficiency technologies1).

The present study describes energy saving in the distillation of bioethanol production using the bioethanol distillation process with self-heat recuperation technology and gives an overview of demonstration tests.

2. **Effect of Self-heat Recuperation on Energy Saving in Bioethanol Distillation**

Self-heat recuperation is a technology to utilize the internal release of heat as the heat source for both the reboiler and the raw material preheating zones at the bottom of the distillation column, and to recover the heat released by condensation of the vapor at the top of the distillation column, as proposed by Dr. Atsushi Tsutsumi, Project Professor, Institute of Industrial Science, The University of Tokyo, with other researchers in the Collaborative Research Center for Energy Engineering2). Maximum recovery of latent heat and sensible heat can be achieved by pairing the reboiler and the condenser for each distillation column, thus establishing an integrated heat circulation with only the compressor requiring external power, resulting in drastic reduction of energy consumption to one sixth compared to conventional distillation columns.

In the present study, T-Q diagrams (temperature-heat diagrams) demonstrated the effect of energy saving achieved by this innovative self-heat recuperation technology with significant potential for energy saving in the ethanol distillation process. **Figure 2** shows the T-Q diagram of conventional ethanol distillation as a comparison. In the process of conventional ethanol distillation, heat is recovered (1 \(\rightarrow\) 2) by heat exchange between the sensible heat contained in the bottom products discharged from the bottom of the distillation column (4 \(\rightarrow\) 5) and the raw material solution (fermented liquid), resulting in reduction of the required energy for distillation by more than 20 %. However, the latent heat and sensible heat contained in the distillate (concentrated ethanol) at the top of the distillation column is only removed by the condenser (6 \(\rightarrow\) 7) and not recovered, because the temperature of the ethanol vapor 6 at the column top is lower than that of the effluent 4 at the column bottom by more than 21 °C, so that the latent and sensible heat is not suitable anymore for this distillation process. Therefore, the conventional distillation process requires a minimum of 4.6 MJ/L-ethanol supplied from external sources even with recovery of the sensible heat of the bottom products (4 \(\rightarrow\) 5).

The T-Q diagram of the ethanol distillation with self-heat recuperation process is shown in **Figure 3**. A heat exchanger is installed to recover the sensible heat contained in the bottom products discharged from the bottom of the distillation column (6 \(\rightarrow\) 7) as in the conventional distillation process. The concentrated ethanol vapor discharged from the top of the column is adiabatically compressed by the compressor (8 \(\rightarrow\) 9, 11) to raise the temperature of the vapor. Heat is exchanged between the vapor in the recirculation zone 9 and the circulation liquid of the bottom of the distillation column as well as between the vapor in the distillation zone 11 and the raw material solution 1 supplied to the distillation column at the pre-heating zone, thus achieving recovery of the latent heat and sensible heat of the compressed ethanol vapor. In particular, the latent heat that is compressed to a high temperature (11 \(\rightarrow\) 12) is exchanged immediately at the pre-heating zone before the solution 3 is supplied to the distillation column, and the sensible heat of the ethanol condensed from the concentrated ethanol (13 \(\rightarrow\) 14) is exchanged at the heat exchanger located in parallel with the heat exchanger for the bottom products, so that heat exchange between the latent and sensible heats can be maximized, thus optimizing the

![T-Q Diagram of Conventional Distillation](image-url)
energy saving.

The self-heat recuperation technology is expected to achieve a considerable saving of energy by accomplishing the maximum recovery of the latent and sensible heats, and has potential uses in various applications including other types of distillation processes and concentration/drying processes. Ethanol distillation is considered particularly suitable for application of this technology due to the following factors:
(a) Bioethanol production plants are generally located independently in the middle of farmland, so application of heat cascades is not common.
(b) Distillation is relatively a simple operation in which the separation is basically between only two main components, i.e. ethanol and water.
(c) Operating temperature is 150 °C or lower.
(d) Ethanol will not prevent adequate increase of temperature by adiabatic compression (Saturated vapor cannot be condensed by compression).

The present demonstration tests were conducted to evaluate the expected effect of energy saving of the self-heat recuperation technology applied to the bioethanol production process.

3. Experimental

3.1. Overview of Demonstration Tests at the Pilot Plant

Bioethanol distillation with self-heat recuperation is a distillation process with the potential for significant energy saving, but technical engineering issues remain, such as whether ethanol vapor can be compressed by a compressor without mechanical malfunction caused by condensation or other factors, and whether balance control between pressure and heat is possible during start-up and steady operation. Therefore, demonstration tests were undertaken at the pilot plant in Kitakyushu, Fukuoka in 2011, following design of the pilot plant, and erection and installation of the vapor compressor in 2010.

Table 1 shows the equipment specification of the pilot plant used for the demonstration tests of bioethanol distillation with self-heat recuperation. The pilot plant consisted of a normal type of distillation facility that had been used for a NEDO commissioned project called "Experimental Project on the System of Recycling Food Waste by Converting into Ethanol" with the addition of a compressor and a heat exchanger, so that the specification of the distillation facility was unchanged. The ethanol concentration of raw material was set to 10 wt%, according to the target rate of "Development of Innovative and Comprehensive Production System for Cellulosic Ethanol," and the ethanol concentration of the top of the distillation column was set to 90 wt%, which is the designed condition for ethanol distillation before the membrane separation process.

Boiler steam from the gasification melting furnace (incinerator) had been used as the heat source for conventional distillations, whereas the compressed ethanol vapor was the heat source for this distillation process with self-heat recuperation, and a heat exchanger for ethanol vapor was additionally installed. A compressor with tolerance for ethanol vapor usage was employed, and the normal rated power of the electric motor was set to 15 kW.

Figure 4 shows the pilot plant for the demonstration tests. The compressor was installed on the projecting balcony of the fourth floor to immediately compress the ethanol vapor from the top of the distillation column. The rest of the heat exchange equipment was installed adjacent to the existing distillation column on the first floor.

3.2. Results of Demonstration Tests at the Pilot Plant

The demonstration tests were conducted in two stages,
March through to April, and September through to October in 2011. In the first stage, tests confirmed that the compressor could compress ethanol vapor without mechanical malfunctions. However, some problems were identified such as adjustment of the balance of heat exchange and optimization of ethanol vapor processing. Therefore, necessary changes to resolve these problems were made before moving on to the second stage. The results of the second stage of demonstration tests are shown in Fig. 5. The operation method to compress the ethanol vapor discharged from the top of the distillation column with a set pressure was established, and increase of the temperature of the ethanol vapor by adiabatic compression was confirmed, and the actual increased temperature was even higher than the expected calculated temperature. The actual measured adiabatic compression efficiency rate was 58 %, which was higher than the target rate of 50 %.

Table 2 summarizes the effect of energy saving achieved in actual operation of the ethanol distillation with self-heat recuperation pilot plant. Normalizing the steam consumption of 56,200 kcal/h in conventional distillation to 1 as an evaluation reference value, the electric motor power in the distillation with self-heat recuperation was 9.3 kW, which can be converted into 8000 kcal/h of energy consumption or 1/7 of the stem consumption. The electricity cost and steam cost are related as follows:

\[
\text{Electricity cost} = (\text{Steam cost}) \times 3
\]

Therefore, the energy cost was 1/2, which demonstrated that the energy cost for the ethanol distillation with self-heat recuperation could be significantly decreased to 50 % of that for the conventional method. However, this energy cost evaluation was simplified, so the relationship between the local electricity cost and steam cost must be reflected in any study of a commercial plant.

The equipment cost requires a more detailed study, but the compressor, heat exchanger, control equipment, etc. may raise the equipment cost to 1.5 times that for the conventional distillation system. However, the depreciation life of equipment is believed to be within 3 to 5 years because of the energy cost reduction.

3.3. Enzyme-recovering Distillation with Self-heat Recuperation

Bioethanol distillation with self-heat recuperation is expected to be applied to the first generation bioethanol production process of converting corn and sugarcane as feedstock into fermented liquid containing 10 % ethanol before distillation. Investigations of the second generation bioethanol production process using cellulose feedstock has increased in recent years, and may suggest a process of recycling the enzymes used for saccharification and fermentation by recovery from the bottom of the distillation column (solution discharged from the bottom of the column)\(^3\). This process is intended to concentrate, recover and recycle the enzymes in the bottom products from the ethanol production process to convert cellulose-based biomass as feedstock because a large amount of enzymes is required to convert cellulose into glucose in the saccharification process. However, water must be evaporated together with ethanol at the distillation column to separate the water introduced into the system together with the

| Table 2: Effect of Self-heat Recuperation Process |
|-----------------------------------------------|
| **External steam consumption** | **Compressor power** | **Energy consumption** | **Energy cost value** |
| Conventional process | 56,200 kcal/h (4.6 MJ/L-EtOH) | - | 1 | 1 |
| Self-heat recuperation process | - | 9.3 kW (8000 kcal/h) (0.7 MJ/L-EtOH) | 1/7 | 1/2 |

Fig. 4 Pilot Plant in Japan

Fig. 5 Material Balance in the Pilot Plant Test
cellulose-based material. The latent heat of evaporation of water is three times that of ethanol. Therefore, an enormous amount of energy is required for the process of recovering enzymes from the concentrated bottom products, compared to conventional ethanol production from corn or sugarcane as feedstock.

To solve such problems, a demonstration test was conducted at the “Cellulosic Ethanol Plant” in Kure, Hiroshima in 2013 with two distillation columns fitted with the self-heat recuperation technology4). Figure 7 shows a photo of the self-heat recuperation equipment incorporated into the integrated cellulosic ethanol production system. The equipment is indicated by the dotted line, and the concentration column and the rectification column are located behind. Both of the two columns are equipped with a compressor. The performance test with this equipment demonstrated the feasibility of stable operation, except during startup, with a model solution containing 6% ethanol achieving the designated distillation performance without additional vapor formation outside. Table 3 displays the heating values consumed by each column of distillation and rectification, and other values calculated from the result of actual operations. The heating value of 10.2 MJ/L-ethanol in total of the additional vapor previously supplied from outside into both columns (8.0 MJ/L-ethanol for concentration and 2.2 MJ/L-ethanol for rectification) was reduced to 2.9 MJ/L-ethanol in total by the compressor power. The actual adiabatic compression ratios at each of these compressors were low at approx. 30% due to the small scale equipment, whereas.

Fig. 7 Cellulosic Ethanol Plant

Table 3 Energy Saving for Ethanol Distillation with Enzyme Recovery and Self-heat Recuperation

|                      | Conventional distillation | Self-heat recuperation—actual data of demo plant (Kure) | Self-heat recuperation—estimation of a commercial plant |
|----------------------|---------------------------|--------------------------------------------------------|--------------------------------------------------------|
| Concentration column | Heating value of extra steam | 8.0 MJ/L                                                | -                                                      |
|                      | Energy for compressor     | -                                                      | 2.2 MJ/L                                               |
|                      | (heating value)           | -                                                      | 1.0 MJ/L                                               |
|                      | Compression ratio         | -                                                      | 2.5                                                    |
|                      | Adiabatic compression ratio | -                                                      | 29%                                                   |
|                      | Heating value of extra steam | 2.2 MJ/L                                            | -                                                      |
| Rectification column | Energy for compressor     | -                                                      | 0.7 MJ/L                                               |
|                      | (heating value)           | -                                                      | 0.3 MJ/L                                               |
|                      | Compression ratio         | -                                                      | 3                                                      |
|                      | Adiabatic compression ratio | -                                                      | 31%                                                   |
|                      | Total                     | Energy charge ratio 10.2 MJ/L                          | 2.9 MJ/L                                               |
|                      |                           | -                                                      | 1.3 MJ/L                                               |
commercial scale equipment could supposedly achieve as high as 65%, thus reducing the consumption of energy from outside to 1.3 MJ/L-ethanol.

Therefore, our new innovative technology of ethanol distillation with enzyme recovery could secure our achievement of the target value of 2.5 MJ/L-ethanol in the "Biofuel Technology Innovation Plan for Conversion of Cellulosic Biomass to Ethanol" proposed by the Agency for Natural Resources and Energy, Ministry of Economy, Trade and Industry (METI) in 2008.

4. Conclusion

Latent heat recovery technology is believed to have great potential in the quest to develop eagerly anticipated energy saving technologies driven by globally growing demand for energy or viable sustainability. The self-heat recuperation technology has demonstrated high potential for the maximum recovery of both latent and sensible heats. After the successful application of the self-heat recuperation technology to bioethanol distillation in demonstration tests at the pilot plant, we plan to study scaling-up and continue efforts for commercialization.

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要 旨
自己熱再生技術によるバイオエタノール蒸留の省エネルギー化

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バイオエタノールはガソリン代替として利用できる液体燃料であり、主にアメリカやブラジルなどでトウモロコシやサトウキビを原料として生産されており、世界での生産量は拡大を続けている。しかし、バイオエタノールの精製には蒸留プロセスが必要となり、このプロセスに多大な熱量が必要となるため、バイオエタノールはカーボンニュートラルとしての価値を損ねている。そこで本研究では、蒸留塔の塔頂の蒸気を圧縮することによりエクセルギーを再生させ、潜熱と顯熱を最大限に利用する「自己熱再生技術」を用いた蒸留プロセスの省エネルギー化の検討を行った。今回の検討では、湿度、熱量線図から従来のエタノール蒸留に対する省エネルギー効果の検討を行った。また、パイロットプラント規模で実証試験を行い、エタノール蒸留の省エネルギー効果の実証を行った。その他、セルロース系バイオマスからのエタノール製造プロセスを対象とし、酵素回収蒸留においても実証試験を行い、自己熱再生技術による省エネルギー効果の検証を行った。