www.rericjournal.ait.ac.th

Development of an Economic Simulator for Bioethanol Production from Lignocellulosic Biomass using Non-Sulfuric Acid Saccharification

Shinji Fujimoto, Takashi Yanagida, Kiyotaka Saga, Bespyatko Lyudmyla and Tomoaki Minowa*

Abstract – *Bioethanol is becoming attractive from the viewpoint of mitigating global warming. Here, it is proposed that bioethanol be produced from woody biomass using non-sulfuric acid saccharification. To estimate the economy and cost of ethanol production, an economic simulator was constructed. First, data such as experimental results and cost data were gathered and classified to construct the simulator. This simulator was used for sensitivity analysis, and factors that affect the economy were examined. Increasing plant capacity decreased the cost of ethanol production. Onsite enzyme cultivation drastically decreased the cost. Increasing feedstock cost increased the cost of ethanol at a ratio of 2.91 to 3.56 JPY/L per 1000JPY. Decreasing the cost of the enzyme drastically decreased the ethanol cost, and decreasing enzyme loading decreased the ethanol cost. In particular, the cost of bioethanol production was sensitive to enzyme cost.*

Keywords – Bioethanol, biomass, economic evaluation, non-sulfuric acid saccharification, system simulation.

1. INTRODUCTION

Bioethanol is becoming an attractive fuel from the viewpoint of mitigating global warming. At present, because bioethanol is generally produced from sugar (*e.g.*, sugarcane) or starch (*e.g.*, corn), there is concern about competition between sources for bioethanol production and food. In fact, the price of grains such as wheat has increased because farmers have begun to cultivate corn to meet the future demand for corn. It is not desirable that sources for bioethanol production compete with food crops. Therefore, bioethanol should be produced from feedstock that is not in competition with food crops. Lignocellulose is not suitable for food consumption, and therefore it has potential for bioethanol production.

In the production of bioethanol from lignocellulose, a pre-treatment step that involves the saccharification (hydrolysis) of cellulose and/or hemicellulose is required for fermentation. Saccharification is described by the following chemical equation, where $C_6H_{10}O_5$, $C_5H_8O_4$, $C_6H_{12}O_6$ and $C_5H_{10}O_5$ are cellulose, hemicellulose, hexose and pentose, respectively.

$$C_6H_{10}O_5 + H_2O = C_6H_{12}O_6 \quad (1)$$

$$C_5H_8O_4 + H_2O = C_5H_{10}O_5 \quad (2)$$

Saccharification can be achieved by using acid or enzymes. At present, some plants that use sulfuric acid saccharification for bioethanol production have been constructed and are being verified in Japan. However, in the process of sulfuric acid saccharification, over-decomposition of the produced sugar occurs during saccharification. This over-decomposition hinders ethanol fermentation and, consequently, decreases the ethanol yield [1], [2]. The sulfuric acid used in sulfuric acid saccharification is harmful for the environment. Thus, treatment with sulfuric acid is problematic and costly.

For these reasons, this study is for investigating the production of bioethanol from woody biomass by using enzyme saccharification (non-sulfuric acid saccharification) as a bioethanol production process with a low impact on the environment [2]. The use of hydrothermal treatment and/or mechanochemical treatment for the pre-treatment steps in saccharification is being investigated. By using this process, it is expected that the sugar yield will increase because over-decomposition of sugar will not occur.

In this study, the following objectives were examined in the bioethanol production process from lignocellulose biomass using enzyme saccharification. First, in order to clarify the potential application of our process and to evaluate the economy, experimental results and cost data were gathered and classified. A process simulator was then constructed. Next, this simulator was used for sensitivity analysis to determine the effect of the process on the economy; that is, factors that sensitively affect the economy were examined.

2. PROCESS FLOW AND SYSTEM COMPONENTS

Figure 1 shows a diagram of the bioethanol production process. The process consists of pre-cutting, hydrothermal treatment, mechanochemical treatment, enzyme saccharification, ethanol fermentation, distillation, and onsite cultivation of the enzyme.

2.1 Pre-cutting

*Biomass Technology Research Center, National Institute of Advanced Industrial Science and Technology (AIST), 3-11-32 Kagayima, Higashihirosima, Hiroshima 739-0046 Japan.

[1]Corresponding author; Tel: + 81 823 72 1955, Fax: + 81 823 72 1955.
E-mail: minowa.tom@aist.go.jp.

Wood chips is supplied to plant as feedstock. In the pre-cutting stage, the chips are cut to a suitable size for pre-treatment, *i.e.* hydrothermal treatment and mechanochemical treatment.

2.2 Hydrothermal Treatment and Mechanochemical Treatment

Hydrothermal treatment and mechanochemical treatment have been proposed as alternatives to sulfuric acid pretreatment. When hydrothermal treatment was prolonged, the generated sugar was subsequently degraded [1], [2]. Mechanochemical treatment requires much more energy, and is therefore not good for economical or environment friendly.

However, treatment time can be decreased by combining hydrothermal and mechanochemical treatment, resulting in a decrease in energy consumption [2]. In this case, the treatment time was decreased to 1/3. In this study, both hydrothermal treatment and/or mechanochemical treatment were considered.

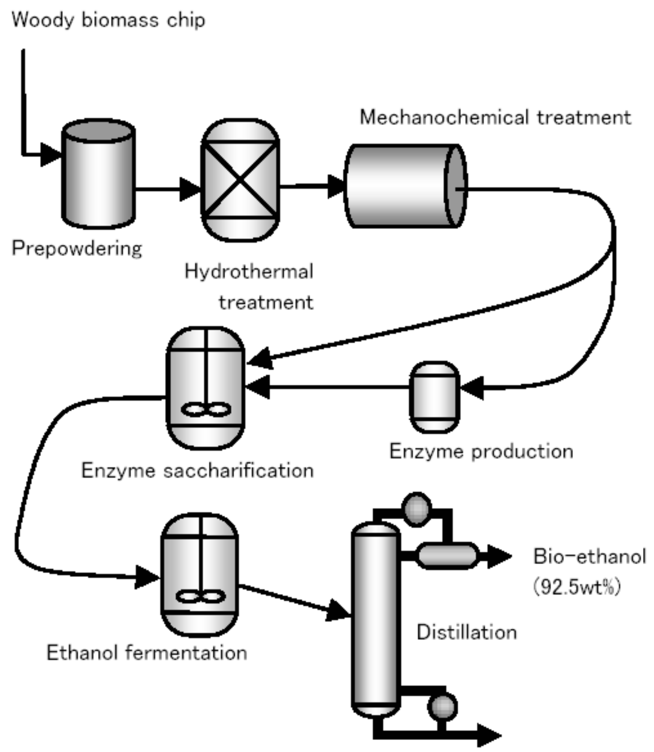

Fig. 1 Ethanol production from woody biomass with non-sulfuric acid pre-treatment.

2.3 Enzyme Saccharification

The saccharification reactions that are indicated in Equations 1 and 2 are achieved by enzyme in our process to avoid over-decomposition by sulfuric acid. There are two methods by which to acquire the enzyme: purchase and onsite cultivation. Purchasing the enzyme would increases the cost of ethanol because the enzyme is expensive. On the other hand, when the enzyme is cultivated onsite, the yield of ethanol decreases because part of its biomass is consumed as nourishment during enzyme cultivation. However, the economy might improve if the cost of enzyme production could be reduced by onsite cultivation.

2.4 Ethanol Fermentation

This study is investigating the fermentation of not only hexose but also pentose, and this fact must be considered in the process design and simulation. The fermentation of pentose and hexose are shown by the following equations:

$$C_6H_{12}O_6 = 2C_2H_5OH + 2CO_2 \quad (3)$$

$$3C_5H_{10}O_5 = 5C_2H_5OH + 5CO_2 \quad (4)$$

2.5 Distillation

Removal of water from ethanol is essential for its use as transportation fuel. Iwasaki *et al.* [3] investigated the efficient removal from the viewpoint of economy by system simulation. They proposed an optimum hybrid system that consists of distillation and a membrane filter and reported that the combination of distillation to 92.5 wt% and membrane filtration to 99.5 wt% was optimum. Therefore, in this study, it was assumed that ethanol was concentrated to 92.5 wt% by the distillation column.

3. SIMULATOR CONSTRUCTION

A simulator can be constructed on the basis of the indicated flow. To estimate the economy, the amount of energy, energy cost, equipment cost, and running cost were estimated.

3.1 Feedstock and Pre-cutting

First, the feedstock cost was estimated. The input terms were the unit cost of feedstock and the daily amount of feedstock. The feedstock cost can be estimated from the unit cost of feedstock and the entered daily amount of feedstock.

The required energy for pre-cutting changes depending on the cut size, and the energy required increases with decreasing cut size. The relation between cut size and energy consumption was obtained from the report of NEDO (New Energy and Industrial Techonology Development Organization) [4]. For example, for pre-cutting under 2 mm, a power of 58.1 kWh/wet-t was required. A power of 21.4 kWh/wet-t was also required by the blower during pre-cutting. The maximum capacity of pre-cutting was estimated to be 160 kW from the cost handbook [5]. From these data, the required power, equipment cost, and equipment number could be estimated.

3.2 Hydrothermal Treatment and Mechanochemical Treatment

In this simulator, the temperature and pressure of the hydrothermal treatment are input terms. The batch operation was assumed. Under these conditions, the heat balance of the hydrothermal treatment process was calculated. It was found that the heat of 2.96 GJ/t was required in the process. The heat of 59.8% could be recovered as steam of 143°C and hot water of 80°C.

By use of previous studies [2], it was estimated that the energy in the mechanochemical treatment was 1154 kWh/t-dry. When hydrothermal and mechanochemical treatments were combined, it was reported that the energy in the mechanochemical treatment decreases to one-third. [2]. The energy data could be used for estimation of the required energy. The maximum capacity of mechanochemical treatment was estimated to be 160 kW from the cost handbook [5]. From these data, equipment cost, and equipment number were estimated.

3.3 Enzyme Supply

In this simulator, the purchase and onsite cultivation of the enzyme are considered. The cost of the enzyme supply is calculated from the purchase price of the enzyme and the amount of enzyme loading that is required in enzyme saccharification. FPU (Filter Paper Unit) is used as the unit of enzyme loading. In the case of onsite cultivation, it is assumed that the there is no enzyme cost. However, part of the biomass is consumed in the cultivation of the enzyme. Therefore, the ethanol yield decreases depending on the amount of enzyme loading. The cost of the equipment for enzyme cultivation is also added.

In advance, a process simulation for the onsite enzyme cultivation was carried out, taking into consideration the results of enzyme cultivation in the laboratory. The obtained material balance is shown in Table 1. The enzyme cultivation costs, such as material cost, can be estimated from the results. Here, the equipment cost for enzyme cultivation can be also estimated and it is included in the cost of the equipment but not in the cost of enzyme supply.

Table 1. Estimated material balance (per kilogram of ethanol) during the enzyme production process.

Input			Output	
Water	1.019 m^3	Cultivation (5 days)	Top layer	0.917 m^3
Glucose	72.078 kg		(protein	14.113 kg)
S: $(NH_4)_2SO_4$	8.939 kg		(other	8.546 kg)
N: NH_3	0.975 kg			
			Residue	0.102 m^3
Air	230.649 m^3		(solution	0.102 m^3)
			(protein	1.568 kg)
			(fungi	13.246 kg)
			(other	0.950 kg)

3.4 Enzyme Saccharification

The input terms are saccharification temperature, saccharification time, and saccharification conversion. The energy required for saccharification can be estimated from the saccharification temperature, amount converted during saccharification, and saccharification time based on thermodynamics. The size of the saccharification tank and number of the tanks are calculated on the basis of the obtained mass flow rate and mass balance. Here, the maximum tank size was fixed at 5000 m^3.

3.5 Ethanol Fermentation

The input terms are fermentation temperature, fermentation time, and fermentation conversion. The required energy for the fermentation reaction can be estimated from the fermentation temperature, fermentation conversion, and fermentation time based on thermodynamics. The size of the fermentation tank and number of the tanks are calculated by use of the obtained mass flow rate and mass balance. Here, the maximum tank size was also fixed at 5000 m^3.

3.6 Distillation

To perform a detailed process simulation, an optimum distillation column should be designed for each case. However, in this study, complicated simulation was avoided because the main goal was to estimate the economy of the process using simple input terms.

Therefore, the tray number in the column was fixed at 30. It was assumed that the recovery rate of the produced ethanol was 99% and that the concentration of the ethanol was 83 mol% (92.5 wt %). The relation between the supplied ethanol concentration and the energy required for distillation under these conditions (Figure 5) was estimated by a priori process simulation using a process simulator (PRO/II; Invensys Systems Japan Inc.). That is, by use of the obtained mass balance date, the required energy for distillation can be automatically estimated. The distillation column cost can also be estimated from the obtained mass balance date.

3.7 Fixed Cost

Each equipment size can be estimated from the obtained mass balance. In this study, the equipment sizes were estimated to be 1.3 times including the margin. The major equipment costs were calculated on the basis of the equipment cost basic data obtained from the AIST Biomass Technology Research Center as in a previous study [6]. In the literature [7], the fixed costs (of instrumentation, buildings, and piping) has been estimated to be about 3.6 times the major equipment cost. The fixed cost was changed at 3.0 times the major equipment cost by use of the experimental rule that considers recent trends.

3.8 Operational Cost

The operational costs are divided into direct operating costs (personnel expenses), fixed property tax/insurance, and general administrative costs.

In a previous study [8], it was reported that the total personnel cost could be calculated by use of the following equation:

$$C_{tp} = n_{staff} * C_{up} * f_{p\text{-}ex} / E \quad (5)$$

In this equation, C_{tp}, n_{staff}, C_{up}, $f_{p\text{-}ex}$, and E represent total personnel cost, staff number, unit personnel cost, expense factor, amount of produced ethanol, respectively. The staff number can be calculated by use of the following equation:

$$n_{staff2} = n_{staff1} *(E_2/E_1)^X \quad (6)$$

Here, the plant factor, X, was 0.27. In the literature, the staff number was estimated to be 23 for a capacity of 20,000 kL [9].

As with other costs, the maintenance cost is 1% of fixed costs, and the test and inspection costs are 20% of the plant operation costs. Fixed property tax and insurance costs are 1.5% and 0.4% of the fixed costs, and the general administrative cost is 25% of the personnel expenses.

A summary of the input terms used in each step is shown in Table 2.

Table 2. Input terms in each step.

Step	Input Term
Feedstock	Daily amount of biomass, moisture content, composition, biomass cost
Pre-cutting	Cutting size, maximum capacity of unit
Hydrothermal treatment	Operation temperature and pressure, solid/water ratio, heat recovery temperature, maximum capacity of the unit
Mechanochemical treatment	Energy consumption rate, maximum capacity of the unit
Enzyme supply	Enzyme load, maximum capacity of the unit
Enzyme saccharification	Enzyme cost, operation temperature, time, conversion, maximum capacity of the unit
Ethanol fermentation	Operation temperature, time, conversion, maximum capacity of the unit
Whole process	Margin, fixed cost
Operation	Daily operation time, no. of days of operation annually, durability, personnel

expenses, tax, maintenance cost, testing and inspection costs, insurance cost, administrative cost, heat and electricity costs

4. RESULTS AND DISCUSSION

4.1 Construction of the Simulator and Economic Estimation of a Base Case

An economic estimation of a base case was performed using the conditions shown in Table 3. Although the constructed simulator can be used to estimate the absolute cost value, it includes irregular information such as variable conditions such as social situation, different location and energy cost. That is, the absolute cost value might change by the variable conditions. In this study, it is not important because sensitivity analysis can be performed without the absolute cost value. Because sensitivity analysis can be performed with the relative value, in this paper, the relative value is used for sensitivity analysis. Figure 2 shows the costs of ethanol production. As observed in this figure, the enzyme cost makes up a greater part of total costs in the base case. The construction and feedstock costs are also relatively large.

Although this ratio in the total cost varies according to the preconditions, the enzyme cost, construction cost, and the feedstock cost were greater in the precondition of the base case. Improvement of these costs would strongly affect the cost of ethanol production. Therefore, sensitivity analysis of these costs was performed. As an economic indicator, a difference of ethanol production cost from that of the base case was used.

Table 3. Condition of the base case.

Step	Input Term	Value
Feedstock	Daily amount of biomass	100 dry-t
	Moisture content	30 wt%
	Composition	Cellulose: 50% Hemicelluloses: 20% Lignin: 29% Ash: 1%
	Biomass cost	10,000 JPY/kg
Pre-cutting	Cutting size	2 mm
	Maximum capacity	160 kW
Hydrothermal treatment	Operation temperature	160°C
	Operation pressure	2 MPa
	Solid/water ratio	0.05
	Heat recovery temperature	
	Maximum capacity	
Mechanochemical treatment	Solid/water ratio	0.05
	Energy consumption rate	1154 kWh/dry-t
	Maximum capacity	160 kW
Enzyme supply	Enzyme load	20 FPU/g-substance
	Maximum capacity	5000 m^3
Enzyme saccharification	Enzyme cost	1,000 JPY/kg
	Operation temperature	45°C
	Time	2 d
	Conversion	C5: 0.8, C6: 0.8
	Maximum capacity	5000 m^3
Ethanol fermentation	Operation temperature	30°C
	Time	3 d
	Conversion	C5: 0.25, C6: 0.9
	Maximum capacity	5000 m^3
Whole process	Margin	1.3
	Fixed cost	3 times the cost of all units
Operation	Daily operation time	24 h
	Annual operation day	300 d
	Durability	9 y
	Annual personnel expenses	4,580,000 JPY/person
	Tax	1.5% of fixed cost
	Maintenance cost	1% the cost of all units

Test and inspection costs	20% of personnel expenses
Insurance cost	0.4% of the fixed cost
Administrative cost	25% of personnel expenses
Heat cost	2 JPY/Mcal
Electricity	4.5 JPY/kWh

*JPY: Japanese Yen

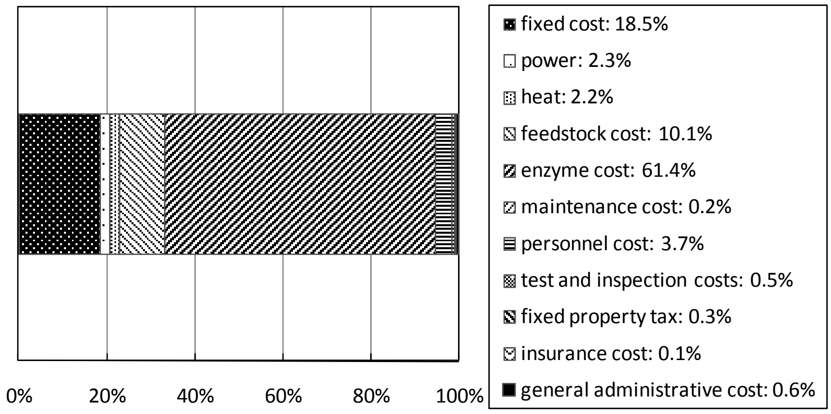

Fig. 2 Ethanol production costs in the base case.

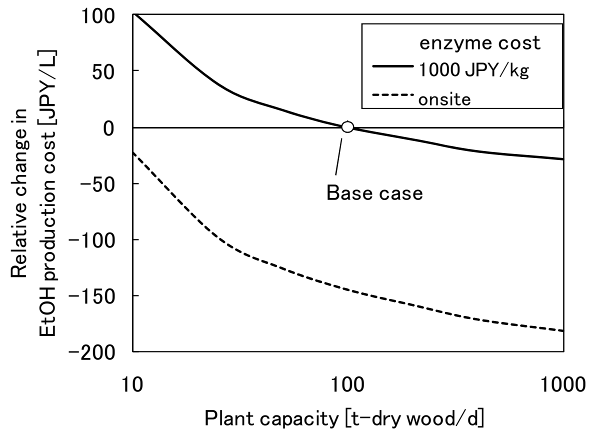

Fig. 3 The effect of plant capacity on the cost of ethanol production.

4.2 Sensitivity Analysis - Plant Capacity and Enzyme Supply

The effect of plant capacity on the costs of ethanol production is shown in Figure 3. From this figure, it can be seen that the ethanol production costs increase with decreasing plant capacity. In particular, the cost in plants with a small capacity drastically increases.

In the case of onsite enzyme production, the construction costs for the equipment for enzyme cultivation are added. Additionally, the yield of ethanol decreases because the sugar, which can be converted into ethanol, is consumed in the enzyme cultivation. These are negative factors in the ethanol production cost. However, the costs decrease if onsite enzyme production is used, because the cost of the enzyme supply is not required. Consequently, the ethanol production cost drastically decreases compared with the case of 1000 JPY/kg. In the capacity of 100 t/d, the difference in ethanol production costs was 145.2 JPY/L. This difference increased with an increasing capacity, and it reached 153.7 JPY/L with a capacity of 1000 t/d. Thus, onsite enzyme production is a big factor in decreasing the cost of ethanol production.

4.3 SensitivityAnalysis — Feedstock Cost

Figure 4 shows the relation between the cost of feedstock and the cost of ethanol production. The ethanol production cost linearly increases with an increasing feedstock cost. The slope in the case of 1000 JPY/kg enzyme was 2.91 JPY/L per 1000 JPY and was 3.56 JPY/L per 1000 JPY in the case of onsite enzyme production. It was found that onsite enzyme production has a higher sensitivity than feedstock cost for the ethanol production cost. In Japan, the cost that is lower than 5000 JPY/t-wood corresponds to building waste wood. Sawmill residue costs 5000–10000 JPY/t-wood.

For use of logging residue and thinned wood, more than 10,000 JPY/t-wood must be considered.

4.4 Sensitivity Analysis — Enzyme Cost

The effect of enzyme cost on the ethanol production cost is shown in Figure 5. The enzyme cost makes up about 60% of the production cost. Therefore, the enzyme cost directly and strongly affects the ethanol production cost. The ethanol production cost changes at a ratio of 17.6 JPY/L per10 JPY enzyme cost.

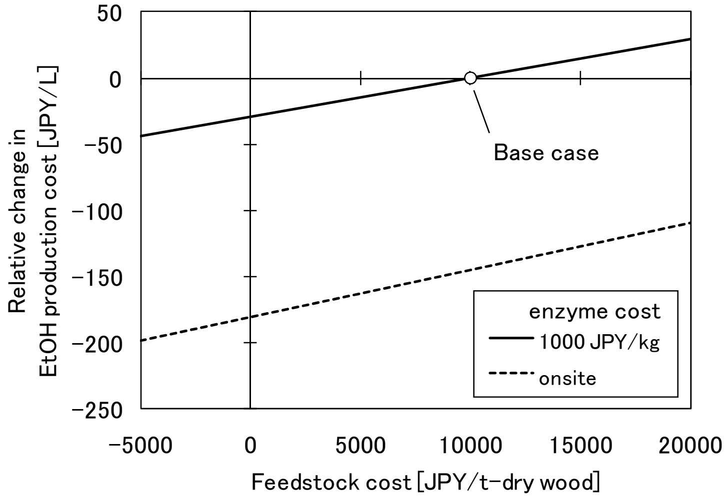

Fig. 4 The effect of feedstock cost on the ethanol production cost.

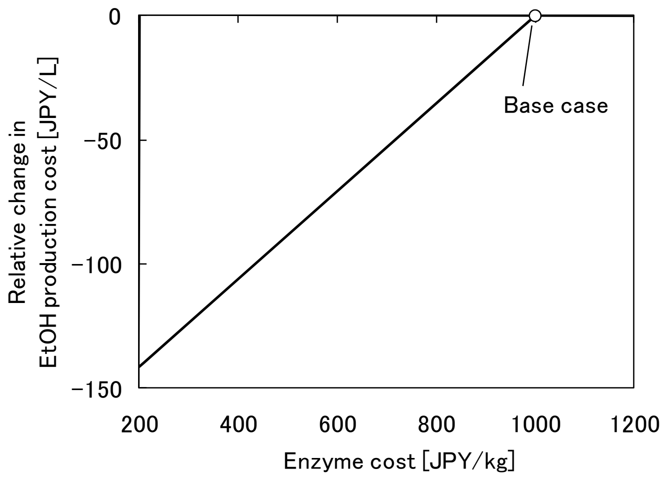

Fig. 5 The effect of enzyme cost on the cost of ethanol production.

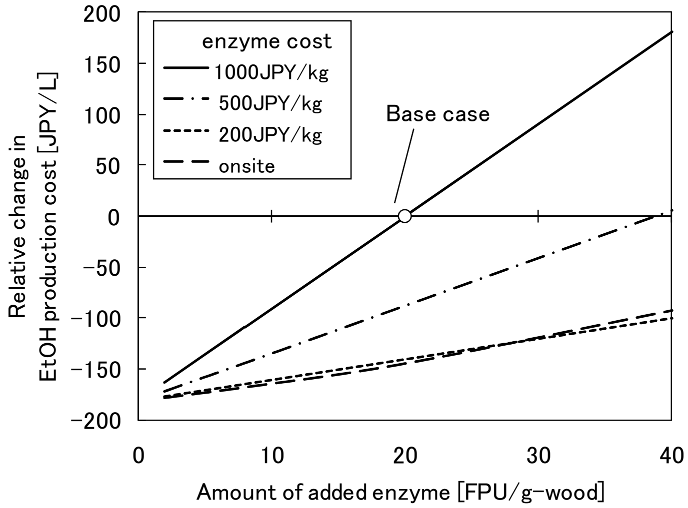

Fig. 6 The effect of enzyme loading on the ethanol production cost.

4.5 Sensitivity Analysis —Enzyme Loading

Figure 6 shows the effect of enzyme loading on the cost of ethanol production. When the saccharification conversion and time do not change and only the enzyme loading changes, the ethanol production cost also changes. That is, if the enzyme loading increases for the same saccharification conversion and time, the ethanol production cost increases. Thus, enzyme cost strongly affects the ethanol production cost.

5. CONCLUSIONS

This study gathered and classified the experimental results and cost data for the production of bioethanol from woody biomass using a non-sulfuric acid saccharification method that was proposed in our research center. Then, a simulator to estimate the economy of the process was constructed. This simulator was used for sensitivity analysis, and factors that sensitively affect the economy were examined. Increasing plant capacity decreased the cost of ethanol production. Onsite enzyme cultivation drastically reduced the cost. Increasing the feedstock cost increased the ethanol cost at a ratio of 2.91 to 3.56 JPY/L per 1000 JPY. Reduced enzyme cost drastically decreased the ethanol cost. Decreasing enzyme loading decreased the cost of ethanol production. The results of this analysis indicated that the cost on ethanol production was particularly sensitive to enzyme cost.

REFERENCES

[1] Hayashi, N., Fujita, S., Irie, G., Sakaki, T. and Shibata, M., 2004. Reaction kinetics of cellulose decomposition in hot-compressed-water. *Journal of the Japan Institute of Energy* 83: 805–814

[2] Fujimoto, S., Inoue, S., Yano, S., Sakaki, T., Minowa, T., Endo, T., Sawayama, S. and Sakanishi, K., 2008. Bioethanol production from lignocellulosic biomass requiring no sulfuric acid: mechanochemical pretreatment and enzymic saccharification. *Journal of the Japan Petroleum Institute* 51: 264–273.

[3] Iwasaki, H., Nonaka, H., Matsumura, Y. and Yamada, K., 2005. Improvement of the refinement process for bioethanol. *Journal of the Japan Institute of Energy* 84: 852–860

[4] Fujimoto, S. and Minowa, T., 2006. Study on wood mill energy. In *Proceedings of The 12th SCEJ Symposium on Fluidization & Particle Processing*. 190–193

[5] Saito, Y., 2000. Cost Estimation Handbook for Chemical Engineers, 3rd edition. Tokyo, Japan: Kogyo Chosakai Publishing Co., Ltd.

[6] Fujimoto, S., Fukuda, T., Kuroda, M., Sasaki, Y., Sakanishi, K., Minowa, T. and Yabe, A., 2006. System efficiency and economical analysis of system for producing energy material from wooden biomass. *International Energy Journal* 7: 289–298

[7] Takaoka, S., 1996. Our energy. Pp.96. Tokyo, Japan: Baifukan Co., Ltd.

[8] Asano, K. and Minowa, T., 2007. Cost analysis of production and CO_2 mitigation for bioethanol production in Japan. AIST/BTRC discussion paper http://unit.aist.go.jp/btrc/ci/research_result/documents/DISCUSSIONPAPER.pdf

[9] Yamada, T., Saiki, T., Saito, Y., Hon-nami, K. and Yokoo, H., 2006. Development and evaluation of ethanol production process from cellulosic biomass based on the highly efficient ethanol fermentation. Proceedings of 1st Biomass kagaku kaigi. 28–29