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Simulation of Fuel Ethanol Production from Lignocellulosic Biomass

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Abstract: Models for hydrolysis, fermentation and concentration process, production and utilization of biogas as well as lignin gasification are developed to calculate the heat demand of ethanol production process and the amounts of heat and power generated from residues and wastewater of the process. For the energy analysis, all relevant information about the process streams, physical properties, and mass and energy balances are considered. Energy integration is investigated for establishing a network of facilities for heat and power generation from wastewater and residues treatment aiming at the increase of energy efficiency. Feeding the lignin to an IGCC process, the electric efficiency is increased by 4.4% compared with combustion, which leads to an overall energy efficiency of 53.8%. A detailed sensitivity analysis on energy efficiency is also carried out.

Key words: lignocellulosic biomass; fuel ethanol; energy integration

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1 INTRODUCTION

There is an increasing interest in many countries in the use of fuel ethanol which is produced from renewable biomass as a replacement of fossil fuels for the consideration of environment and energy security[1,2]. Lignocellulosic biomass is considered one of most promising feedstocks for production of fuel ethanol due to its global availability and environmental benefits of its use[3,4]. Consequently wide varieties of processes for the production of ethanol from lignocellulosic biomass are studied and are currently under development[5−8].

One of the main challenges for cost-effective production from lignocellulosic biomass is high energy consumption. So, process design integration is needed and more efficient use of energy is necessary. Furthermore, to reduce operating costs, energy integration is very important to meet the heat and electricity consumption for the whole process. The process integration was also proposed in Ref.[9]. However, in their case, the utility streams and combined heat and power production were not considered and only the energy consumption was targeted based on enzymatic hydrolysis. The purpose of this work is to increase the energy efficiency for the production process of ethanol based on double acid hydrolysis and cogeneration systems to produce heat and electricity aiming at the surplus electricity generation increase.

Process modeling for ethanol production from lignocellulosic biomass including all the major processing steps was dealt with in this work. It was based on experimental data from the Center for Biomass Energy Technology, East China University of Science and Technology, which allowed for both evaluation of the process at its present state of development and optimization of the overall process design.

2 MATERIALS AND METHODS

2.1 Methods

Thermodynamic model for the whole process was developed in consideration of mass and energy balances as well as physical properties of all process streams using commercial flowsheet calculation software Belsim–Vali[10]. The data from this model were then used in the energy integration software Easy2 for targeting the minimum energy requirements and calculating the optimal utility system with regard to minimal operating cost[11]. The information transfer between different models was managed by OSMOSE framework, a software developed at the Laboratory of Industrial Energy Systems (LENI)[12].

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2.2 Feedstocks

For the base case simulation, the materials used were assumed that the cellulose content be 35%, hemicellulose 25%, lignin 25% and moisture 15%, and the LHV (low heating value) of feedstock was about 16.95 MJ/kg.

2.3 Process Description

Production of fuel ethanol from lignocellulosic biomass includes six major steps: hydrolysis of hemicellulose and cellulose to sugar, fermentation of sugar to ethanol, recovery of ethanol from the fermentation broth, mixing of ethanol and gasoline to production of fuel ethanol, and treatment of lignin and wastewater for energy recovery and environmental protection purposes. The process flow chart is shown in Fig.1, and the conditions used in simulation are listed in Table 1.

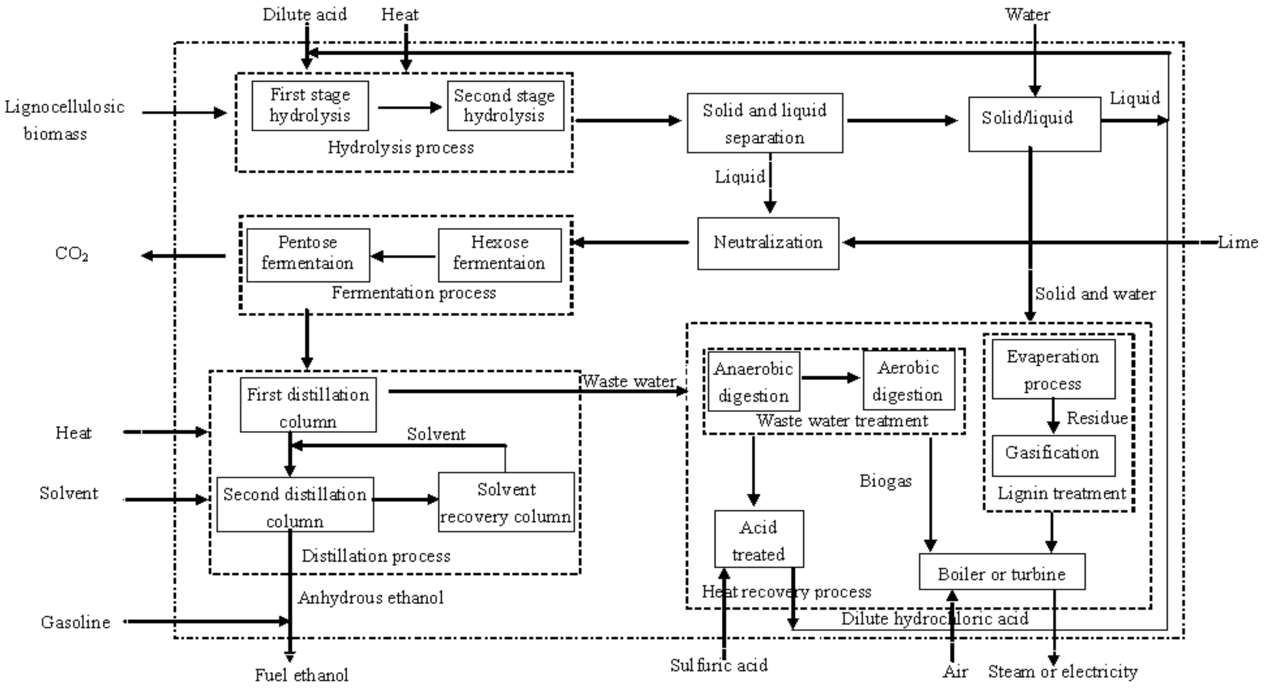

Fig.1 Production process of fuel ethanol from lignocellulosic biomass

Table 1 Conditions of process simulation

Parameter	Value	Parameter	Value
Acid concentration (%)	1	Conversion rate of cellulose to glucose (%)	70
Ratio of liquid to solid (L/kg)	8	Fermentation temperature (℃)	38
First stage temperature (℃)	165	Glucose conversion rate (%)	95
Second stage temperature (℃)	120	Xylose conversion rate (%)	60
First stage residence time (min)	25	Residence time (h)	72
Second stage residence time (min)	15	Anaerobic digestion conversion rate (%)	90%
Hemicellulose conversion rate (%)	80[1)]	Evaporation effects	3

Note: 1) Conversion rate of hemicellulose to fermentable sugar is 80%, while the sugar degradation rate 10%.

(1) Hydrolysis

In this stimulation, dilute acid hydrolysis is used. For reducing energy consumption, hydrochloric acid is used as catalyst, and the reaction temperature can be much lower than that of sulfuric acid hydrolysis. To reduce the degradation and increase the sugar concentration, two-stage hydrolysis is used for increasing monosaccharide concentration to more than 6%(ω) in hydrolysate. Conversion rates of hemicellulose and cellulose are 80% and 70%, respectively.

(2) Fermentation

Glucose is first fermented to produce ethanol with 95% conversion rate, then, the fermentation of xylose is kept at a slower rate with a lower yield of 60%.

(3) Distillation

In this simulation, the first part is distillation of fermentation broth to separate ethanol from water with the ethanol concentration of 95%, and the cyclohexane is used as entrainer to concentrate ethanol content up to 99.5% (mass balance).

(4) Wastewater treatment

Wastewater can be treated by anaerobic digestion and aerobic digestion methods. Anaerobic digestion produces a biogas stream rich in methane, so it is fed to the combustor for energy recovery. With anaerobic digestion, 90% of whole organic component is converted to methane and carbon dioxide.

This part also includes an acid recovery step. Hydrochloric acid is recovered by treating the wastewater using sulfuric acid. As stated above, the energy consumption for hydrochloric acid hydrolysis is less than that of sulfuric acid hydrolysis.

(5) Lignin treatment

Lignin (10%~25%) is present in all lignocellulosic biomass and can not be hydrolyzed. Therefore, any ethanol production process will have lignin as a residue. In this process, the residue is evaporated by 3 effects evaporator to reach a targeted moisture content of about 35%. In the present study, all residues (lignin, non-converted hemicellulose and cellulose) are assumed to produce heat and electricity by integrated gasification combined cycle (IGCC).

(6) Energy system

The biogas and residues are used to produce steam and electricity to satisfy thermal and electricity needs for the ethanol production, and surplus electricity generated is considered available for sale to the grid.

3 RESULTS AND DISCUSSION

3.1 Sensitivity Analysis of Heat Consumption

Distillation is a high energy consumption process[13]. Ethanol concentration is the major energy consumption factor, which heavily depends on the ratio of liquid to solid in hydrolysis process. The ratio not only influences heat consumption of hydrolysis process, but also distillation process. In general, the ratio of liquid to solid can not be too low, because it will result in lower hydrolysis conversion. In this simulation, the ratio of liquid to solid from 8 to 10 L/kg is examined, under the assumption of the same hydrolysis conversion. The effect of ratio on heat consumption is shown in Fig.2. With decreasing the ratio from 10 to 8 L/kg, about 10% energy recovery rate can be obtained.

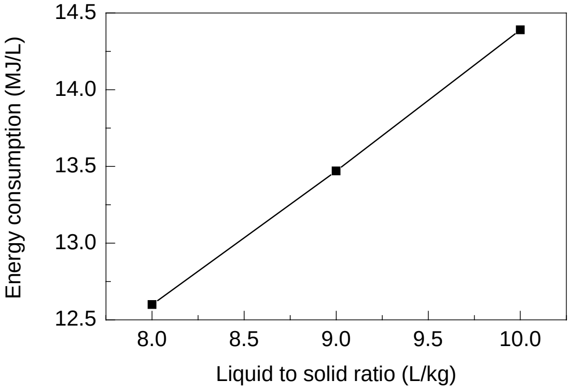

Fig.2 Effect of ratio of liquid to solid on hydrolysis energy consumption

3.2 Effects of Conversion Rate on Ethanol Efficiency

In this simulation, the overall ethanol yield is not so high. One of main reasons is that the conversion rate of biomass to fermentable sugar is only 70% for avoiding possible release of inhibitors. Another reason is the conversion of xylose to ethanol is only 60%. If the conversion rate can be increased with technical progress, the overall ethanol yield can be increased. The effects of cellulose and xylose conversion rates on ethanol yield are shown in Fig.3. With the increase of cellulose conversion rate from 70% to 90%, ethanol yield can be increased by 11%, and when xylose conversion rate increases from 60% to 90%, ethanol yield can be increased by 10%.

3.3 Energy Integration

For the gasification simulation, an earlier developed model is used. The feedstock is first gasified and the producer gas is directly burnt in a close-coupled

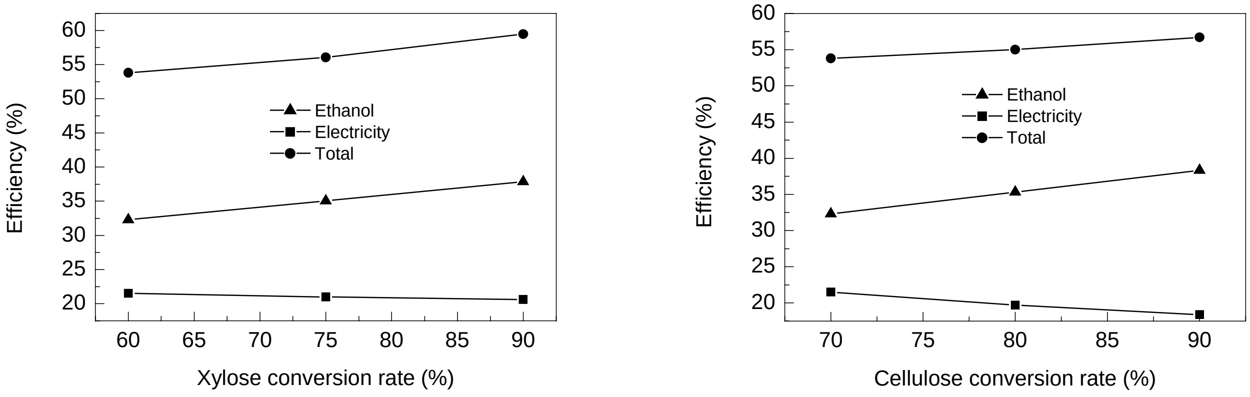

Fig.3 Effects of xylose and cellulose conversion rates on efficiencies

gas turbine. The excess heat from the gas turbine exhausts is further recovered by a steam cycle, which, as before, also satisfies the heat requirements of process. The composite profile of whole process is shown in Fig.4. The line 1 is the power needed for the whole process, and the line 2 the power provided by the energy system, and the rest of energy is used to produce electricity (line 3). The energy efficiency is shown in Table 2. It is shown that the electricity production can be increased by 4.4% using IGCC instead of combustion.

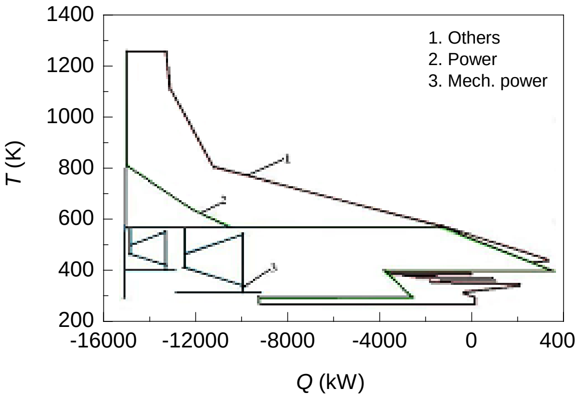

Fig.4 Integrated composite profile of IGCC for the whole process

Table 2 Energy efficiency analysis

Biomass input[1)	57.55 MW[2)	
Output	Combustion	IGCC
Ethanol	18.57 MW	18.57 MW
Electricity	9.84 MW	12.37 MW
Total	28.41 MW	30.94 MW
η_{ethanol}	32.3%	32.3%
$\eta_{\text{electricity}}$	17.1%	21.5%
η_{total1}	49.4%	53.8%

Note 1) Energy input of raw material; 2) High heating value.

3.4 Influence of Raw Material

Sawdust, rice husk and corn stalk are the major potential lignocellulosic biomass feedstocks for ethanol production in China. In this work, these three materials are selected to investigate the influences of feedstock. Based on the compositions of raw materials in Table 3 and the modeled conversion rates outlined in Table1, the respective ethanol and electricity yields per mass unit of the material are shown in Fig.5. As expected, it can be seen that the higher the content of cellulose and hemicellulose is, the more ethanol is produced. The ethanol concentration in the fermentation broth is also increased, thus less energy is consumed in the distillation process. On the other hand, increasing lignin content results in the increase of electricity production.

Table 3 Typical compositions of lignocellulosic feed materials

Lignocellulosic biomass	Water (%)	Hemicellulose (%)	Cellulose (%)	Lignin (%)	Ash and others (%)
Sawdust	15	21.09	36.61	26.48	0.82
Rice husk	15	27.22	24.30	12.59	20.89
Corn stalk	15	24.87	34.51	14	11.62

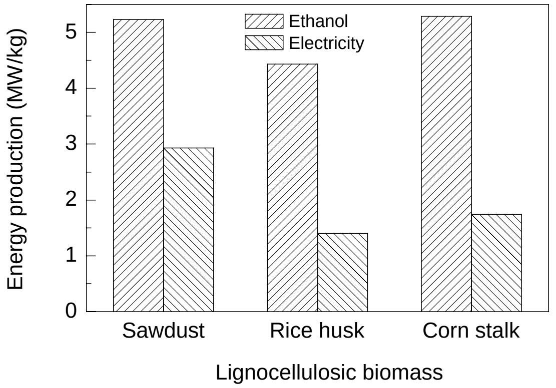

Fig.5 Energy production from different kinds of biomass

4 CONCLUSIONS

(1) With increasing conversion rate of cellulose from 70% to 90%, ethanol yield can be increased by 11%, and when conversion rate of xylose increases from 60% to 90%, ethanol yield can be increased by 10%.

(2) To increase the energy efficiency, IGCC process is used instead of combustion for cogeneration of heat and power, the total energy efficiency is 53.8%, and the electricity production can be increased by 4.4% using IGCC instead of combustion.

(3) The influence of raw materials on energy efficiency is also investigated. The higher the content of cellulose and hemicellulose is, the more ethanol yield can be obtained and less energy is thus consumed in the distillation process. On the other hand, increasing lignin content results in the increase of electricity production.

REFERENCES:

[1] Yu S R, Tao J. Life Cycle Simulation-based Economic and Risk Assessment of Biomass-based Fuel Ethanol (BFE) Projects in Different Feedstock Planting Areas [J]. Energy, 2008, 33: 375–384.

[2] Quintero J A, Montoya M I, Sanchez O J, et al. Fuel Ethanol Production from Sugarcane and Corn: Comparative Analysis for a Colombian Case [J]. Energy, 2008, 33: 385–399.

[3] Farrell A E, Plevin R J, Turner B T, et al. Ethanol Can Contribute to Energy and Environmental Goals [J]. Science, 2006, 311(5760): 506–508.

[4] Knauf M, Moniruzzaman M. Lignocellulosic Biomass Processing: A Perspective [J]. International Sugar Journal, 2004, 106(1263): 147–150.

[5] Sun Y, Cheng J Y. Hydrolysis of Lignocellulosic Materials for Ethanol Production: A Review [J]. Bioresour. Technol., 2002, 83: 1−11.

[6] Zhang S P, Yan Y J, Ren Z W, et al. Fuel Ethanol Production from Lignocellulosic Biomass [J]. Progress in Chemistry, 2007, (7): 1129−1133.

[7] Jeffries T W. Engineering Yeasts for Xylose Metabolism [J]. Curr. Opin. Biotechnol., 2006, 17: 320−326.

[8] Sanchez O J, Cardona A C. Trends in Biotechnological Production of Fuel Ethanol from Different Feedstocks [J]. Bioresour. Technol., 2008, 99: 5270−5295.

[9] Cardona A C, Sanchez O J. Energy Consumption Analysis of Integrated Flowsheets for Production of Fuel Ethanol from Lignocellulosic Biomass [J]. Energy, 2006, 31: 2447−2459.

[10] Belsim S A. Optimization [DB/OL]. http://www.belsim.com, 2009−01−06.

[11] Gassner M, Marechal F. Thermo−Economic Optimisation of the Integration of Electrolysis in Synthetic Natural Gas Production from Wood [J]. Energy, 2008, 33: 189−198.

[12] François Maréchal. Energy Integration and Sustainable Energy System Analysis [DB/OL]. http://leniwww.epfl.ch, 2007−11−07.

[13] Linnhoff B, Dunford H, Smith R. Heat Integration of Distillation Columns into Overall Processes [J]. Chem. Eng. Sci., 1983, 38(8): 1175−1188.