PERGAMON

Energy Conversion and Management 43 (2002) 1301–1310

ENERGY
CONVERSION &
MANAGEMENT

www.elsevier.com/locate/enconman

Evaluation of supercritical water gasification and biomethanation for wet biomass utilization in Japan

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Abstract

Two wet biomass gasification processes, supercritical water gasification and biomethanation, were evaluated from energy, environmental, and economic aspects. Gasification of 1 dry-t/d of water hyacinth was taken as a model case. Assumptions were made that system should be energetically independent, that no environmentally harmful material should be released, and that carbon dioxide should be removed from the product gas. Energy efficiency, carbon dioxide payback time, and price of the product gas were chosen as indices for energy, environmental, and economic evaluation, respectively. Under the conditions assumed here, supercritical water gasification is evaluated to be more advantageous over biomethanation, but the cost of the product gas is still 1.86 times more expensive than city gas in Tokyo. To improve efficiency of supercritical water gasification, improvement of heat exchanger efficiency is effective. Utilization of fermentation sludge will make biomethanation much more advantageous. © 2002 Elsevier Science Ltd. All rights reserved.

Keywords: Wet biomass; Supercritical water; Biomethanation

1. Introduction

Wet biomass grows rapidly and abundantly, showing a potential to be a desirable energy crop, but high moisture content prevents it from being practical energy resources using conventional energy technologies such as combustion. Water hyacinth, for example, yields 150 dry-t/ha/yr under a good condition [1], but its moisture content is higher than 95%. When moisture content is high, heat of combustion of usual biomass gets smaller than the heat of evaporation of water, and thus cannot be used as a combustion fuel. Gasification technology proposed for the dry material such as fluidized bed gasification and down-draft gasifier technology for wood or straw is not

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PII: S0196-8904(02)00016-X

applicable, either. Pretreatment of the feedstock requires a large amount of heat for drying, which makes whole process unpractical.

To circumvent this problem, gasification in supercritical water was proposed and investigated by Xu et al. [2], and analysis from energy efficiency of the system including carbon dioxide removal was conducted [3]. Supercritical water, which is water at a temperature higher than its critical temperature (647 K) and a pressure higher than its critical pressure (22.1 MPa), shows characteristics between water and steam. Values of density, diffusivity, viscosity for water under supercritical conditions are between those of water and steam, and dependent on temperature and pressure sensitively. Also it is known that supercritical water mixes with most of the organic compounds, and rapid and homogeneous reactions of organic compounds are possible in supercritical water. Adschiri et al. have shown that cellulose decomposes much more rapidly in supercritical water than in subcritical water [4]. This high reactivity can be used to decompose organic materials into gases without pretreatment of drying feedstock. Yu et al. [5] succeeded in gasification of 0.2 M glucose in supercritical water at 600 °C, 34.5 MPa completely. Thus, Supercritical water gasification is a promising technology for gasification of wet biomass since it does not require drying of feedstock beforehand, and after complete gasification, cooling down and depressurization of the process will separate gas and water automatically.

For wet biomass gasification, biomethanation has been employed in the developing countries. This is a cheap process that produces methane from biomass as well as fermentation sludge for fertilizer. However, in countries such as Japan, fertilizer is being oversupplied, and treatment of fermentation sludge is problematic. Compost production from garbage is facing the same problem. Thus, biomethanation may not be a desirable selection in Japan.

To find out the possibility of wet biomass utilization as a renewable energy resource in Japan, comparison of these two technologies is conducted in this paper. Evaluation from energy, environmental, and economical viewpoint is applied.

2. Assumptions and condition for calculation

The following assumptions were made:

1. System should be energetically independent. If electricity or heat supply is needed for the process, it should be supplied by the product gas using proper technologies.
2. No environmentally harmful material should be released. This means all the waste is to be treated inside the process. Fermentation sludge from the biomethanation process is to be treated since fertilizer is oversupplied in Japan, and as a waste, its BOD is too high for releasing to sewage or environment, according to Japanese laws.
3. Carbon dioxide should be removed from the product gas. Utilization of the product gas as city gas is expected here. Inclusion of inert gas will not desirable.
4. For economic evaluation, cost needed for biomass cultivation and transportation as well as for delivery of product gas is not considered.

As a model case for the calculation, gasification of 1 dry-t/d of water hyacinth is considered here. The elementary composition of water hyacinth is as shown in Table 1 [6]. Based on this

Table 1
Ultimate analysis of water hyacinth

C	0.335	P	0.007
H	0.056	S	0.0035
N	0.0315	Mg	0.0025
K	0.0275	Fe	0.0004
Na	0.02	Zn	0.000275
Ca	0.0095	Mn	0.000065

result, its composition was assumed to be $C_6H_{12}O_{6.8}$ for the following calculation. Gas composition of the supercritical water gasification product was assumed to be at equilibrium for the reaction condition, which is 600 °C, 34.5 MPa. Also the following are assumed for biomethanation process:

1. Organic part of biomass contains 10% of lignin, which cannot be fermented.
2. 80% of the part other than this 10% (72%) is converted into methane and CO_2. Methane yield is 14.8%. CO_2 yield is 40.5% The other part ($1 - 0.10 - 0.148 - 0.406 = 0.346$) is dissolved in the liquid phase. This part is converted into a part of active sludge.
3. 30 days are required for fermentation and 10 h for active sludge treatment.
4. Increase in active sludge is dried by a filter press to water content of 75%, and then burnt. Water from the press contains 120 ppm of solid fine particles.

Supercritical water gasification process evaluated here is the one proposed previously in University of Hawaii [3], which is shown in Fig. 1. The feedstock is liquefied first by heating up to 200 °C, and then delivered to the gasification reactor by a high-pressure pump. Heat recovery from the reactor effluent is conducted using a heat exchanger, whose thermal efficiency was put to be 75%. The effluent is cooled down under high pressure and more water is supplied to dissolve carbon dioxide. product gas is available under high pressure. Part of the combustible gas is dissolved in the water phase, which is used to heat the input flow of the reactor. Also, part of the product gas is used to supply needed heat.

Biomethanation process evaluated here is shown in Fig. 2. Product gas is treated with monoethanol amine to remove carbon dioxide. Fermentation sludge is treated with active sludge so that BOD of the effluent is sufficiently low to be released to the environment. Surplus active sludge is treated with filter press and then combusted.

3. Results and discussions

3.1. Supercritical water gasification

Flow composition for supercritical water gasification process is shown in Table 2. The flow numbers in the table corresponds to those in Fig. 1. Flow calculation is based on 1 mol of biomass, which is $C_6H_{12}O_{6.8}$ as is previously assumed. In supercritical water gasification, complete gasification to gas composition at chemical equilibrium state was assumed. This complete

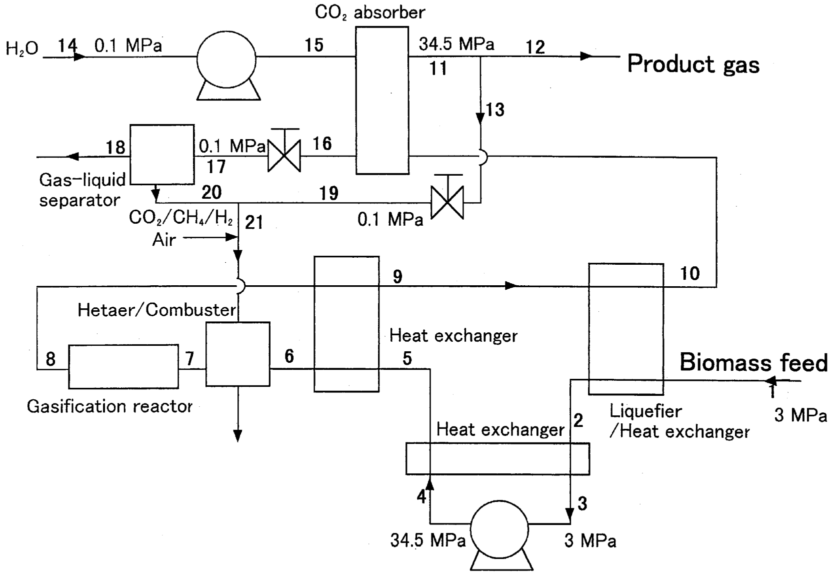

Fig. 1. Flowsheet of supercritical water gasification process.

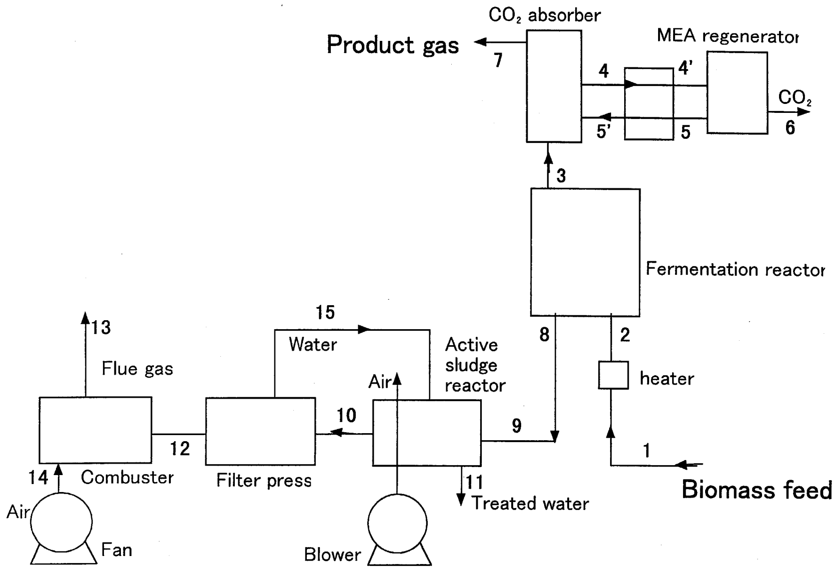

Fig. 2. Flowsheet of biomethanation process.

gasification is one of the advantages of the supercritical water gasification [2]. Conventional gasification processes are not free from production of char or fermentation sludge. Based on this flow composition, temperature, and pressure, enthalpy at each point can be evaluated. Product gas composition is shown in Table 3. Heating value of this gas is calculated to be 20 625 kJ/Nm^3,

Table 2
Flow composition for supercritical water gasification process

Flow #	Flow rate (mol/s)								T (K)	P (MPa)
	Biomass	H_2O	H_2	CH_4	CO	CO_2	N_2	NH_3		
1	1.00	42.84	0.00	0.00	0.00	0.00	0.00	0.00	300	3.0
2	1.00	42.84	0.00	0.00	0.00	0.00	0.00	0.00	462	3.0
3	1.00	42.84	0.00	0.00	0.00	0.00	0.00	0.00	300	3.0
4	1.00	42.84	0.00	0.00	0.00	0.00	0.00	0.00	300	34.5
5	1.00	42.84	0.00	0.00	0.00	0.00	0.00	0.00	462	34.5
6	1.00	42.84	0.00	0.00	0.00	0.00	0.00	0.00	727	34.5
7	1.00	42.84	0.00	0.00	0.00	0.00	0.00	0.00	873	34.5
8	0.00	42.68	2.33	1.97	0.07	3.42	0.21	0.02	873	34.5
9	0.00	42.68	2.33	1.97	0.07	3.42	0.21	0.02	472	34.5
10	0.00	42.68	2.33	1.97	0.07	3.42	0.21	0.02	300	34.5
11	0.00	0.00	2.31	1.97	0.07	0.51	0.19	0.00	300	34.5
12	0.00	0.00	1.76	1.50	0.05	0.39	0.14	0.00	300	34.5
13	0.00	0.00	0.55	0.47	0.02	0.12	0.05	0.00	300	34.5
14	0.00	535.11	0.00	0.00	0.00	0.00	0.00	0.00	300	0.1
15	0.00	535.11	0.00	0.00	0.00	0.00	0.00	0.00	300	34.5
16	0.00	577.79	0.02	0.00	0.00	2.91	0.02	0.02	300	34.5
17	0.00	577.79	0.02	0.00	0.00	2.91	0.02	0.02	300	0.1
18	0.00	577.65	0.00	0.00	0.00	0.18	0.00	0.02	300	0.1
19	0.00	0.00	0.55	0.47	0.02	0.12	0.05	0.00	300	0.1
20	0.00	0.14	0.02	0.00	0.00	2.73	0.02	0.00	300	0.1
21	0.00	0.14	0.57	0.47	0.02	2.85	0.07	0.00	300	0.1

Table 3
Product gas composition for supercritical water gasification

H_2	0.46
CH_4	0.39
CO_2	0.10
N_2	0.04
CO	0.01

which is less than half of city gas of Tokyo (46 047 kJ/Nm^3). Electricity needed for the process is to be produced by a proper technology as shown in assumption. Here, a fuel cell setup, whose thermal efficiency is 0.5, is employed. Heat required at the heat exchanger is 564.8 kJ/mol-biomass and electricity needed for screw feeder is 94.32 kJ/mol-biomass, while produced gas in the reactor is 2337.9 kJ/mol-biomass, and heating value of dry biomass is 2446.2 kJ/mol. Thus, energy efficiency is

$$\frac{2337.9 - 564.8 - 94.3/0.5}{2446.2} = 64.8\% \tag{1}$$

Initial cost of each component is shown in Table 4. Total initial cost is 2.473×10^8 yen, and assuming depreciation period of 30 years, the cost of the product gas is calculated as

Table 4
Initial cost for each component of supercritical water gasification process

Item	Cost (10^6 yen)
Reactor	10.2
Screw feeder	6.1
Conveyer	0.2
Pumps	0.3
Heat exchanger	21.1
Combustor	52.5
CO_2 absorber	3.4
Gas–liquid separator	3.4
Fuel cell	149.7
Total	247.3

$$\frac{2.47 \times 10^8 \text{ yen}}{30 \text{ yr} \times (2.70 \times 10^9 \text{ kJ/yr})} = 3.05 \text{ yen/MJ} \tag{2}$$

which is 1.86 times more expensive than city gas in Tokyo (1.64 yen/MJ). It should be noted that cost for cultivation and product gas delivery is not included in this calculation. Running cost is not needed because all the fuel and electricity needed in supplied by by-product and part of the product gas. Labor cost is not included.

To calculate CO_2 payback time, the conversion factor of 2.26 kg-CO_2 /1000 yen is used. Thus,

$$2.26 \times (2.47 \times 10^8/1000) = 5.59 \times 10^5 \text{ kg-CO}_2 \tag{3}$$

is produced for the construction. While using natural gas for the same heating energy, 1 mol (0.044 kg) of carbon dioxide is emitted per 890.7 kJ. Carbon dioxide should be recovered after energy production of

$$(5.59 \times 10^5/0.044) \times 890.7 = 1.13 \times 10^{10} \text{ kJ} \tag{4}$$

Since this process produces 2.70×10^9 kJ/yr, CO_2 payback time is

$$\frac{1.13 \times 10^{10} \text{ kJ}}{2.70 \times 10^9 \text{ kJ/yr}} = 4.19 \text{ yr} \tag{5}$$

Since the largest heat requirement is at the heat exchanger, heat exchanger efficiency is changed to 90% and the process efficiencies are also evaluated. The results are shown in Table 5, and it is shown that improvement of heat exchanger efficiency is effective to improve the practicality of the process, although the cost of the product gas is still higher than that of city gas.

3.2. Biomethanation

Flow composition for supercritical water gasification process is shown in Table 6. The flow numbers in the table corresponds to those in Fig. 2. Flow calculation is based on 1 dry-t of biomass with the composition of $C_6H_{12}O_{6.8}$. Based on this flow composition, temperature, and

Table 5
Effect of heat exchanger efficiency on supercritical water gasification characteristics

	Heat exchanger efficiency	
	75%	90%
Energy efficiency (–)	0.648	0.786
Cost of product gas (yen/MJ)	3.05	2.52
CO_2 payback time (yr)	4.19	3.46

Table 6
Flow composition for biomethanation process

Flow #	Biomass (t/d)	H_2O (t/d)	CH_4 (t/d)	CO_2 (t/d)	MEA (t/d)	Sludge (t/d)	Diss. org. (t/d)	O_2 (t/d)	N_2 (t/d)	T (K)	P (MPa)
1	1.00	9.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	300	0.1
2	1.00	9.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	318	0.1
3	0.00	0.00	0.15	0.41	0.00	0.00	0.00	0.00	0.00	300	0.1
4	0.00	3.73	0.00	0.41	1.12	0.00	0.00	0.00	0.00	300	0.1
4′	0.00	3.73	0.00	0.41	1.12	0.00	0.00	0.00	0.00	473	0.1
5	0.00	3.73	0.00	0.00	1.12	0.00	0.00	0.00	0.00	473	0.1
5′	0.00	3.73	0.00	0.00	1.12	0.00	0.00	0.00	0.00	300	0.1
6	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	300	0.1
7	0.00	0.00	0.15	0.00	0.00	0.00	0.00	0.00	0.00	300	0.1
8	0.00	9.00	0.00	0.00	0.00	0.10	0.35	0.00	0.00	318	0.1
9	0.00	9.00	0.00	0.00	0.00	0.10	0.35	0.00	0.00	300	0.1
10	0.00	5.94	0.00	0.00	0.00	0.45	0.00	0.00	0.00	300	0.1
11	0.00	7.66	0.00	0.00	0.00	0.00	0.00	0.00	0.00	300	0.1
12	0.00	1.34	0.00	0.00	0.00	0.45	0.00	0.00	0.00	300	0.1
13	0.00	1.34	0.00	0.00	0.00	0.00	0.00	0.79	4.14	1073	0.1
14	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.18	4.14	300	0.1
15	0.00	4.60	0.00	0.00	0.00	0.00	0.00	0.00	0.00	300	0.1

pressure, enthalpy at each point can be evaluated. Product gas composition is assumed to be 100% methane, thus the heating value of product gas is 39763 kJ/Nm^3, which is still less than that of city gas of Tokyo (46047 kJ/Nm^3). Process requirement heat and electricity are shown in Table 7. Considering that produced gas in the reactor is 8.21 GJ/dry-t, and heating value of dry biomass is 11.42 GJ/dry-t, energy efficiency for biomethanation process is calculated as

$$\frac{8.21 - 1.62 - 0.52/0.5}{11.42} = 49.3\% \tag{6}$$

Here again, it is assumed that electricity needed for the process is produced by fuel cell, whose thermal efficiency is 0.5.

Initial cost of each component is shown in Table 8. Total initial cost is 2.28×10^8 yen, and assuming depreciation period of 30 yr, the cost of the product gas is calculated as

$$\frac{2.28 \times 10^8 \text{ yen}}{30 \text{ yr} \times (2.03 \times 10^9 \text{ kJ/yr})} = 3.74 \text{ yen/MJ} \tag{7}$$

Table 7
Heat and electricity requirement for biomethanation process (for 1 dry-t of water hyacinth)

Heat	
Biomass heating for fermentation	0.68 GJ
Evaporation of water in sludge	0.65 GJ
MEA regeneration	0.27 GJ
Heat loss from the reactor	0.02 GJ
Total	1.62 GJ
Electricity	
Screw feeder	0.44 GJ
Aeration	0.08 GJ
Total	0.52 GJ

Table 8
Intial cost for each component of biomethanation process

Item	Cost (10^6 yen)
Reactor	7.7
Screw feeder	6.1
Conveyer	0.2
Heater	18.7
CO_2 absorber	12.4
Heat exchanger	5.2
MEA regenerator	0.7
Active sludge reactor	6.0
Combustor	60.2
Fan	0.8
Fuel cell	110.2
Total	288.2

which is much more expensive than city gas in Tokyo (1.64 yen/MJ). Again, it should be noted that cost for cultivation and product gas delivery, and labor cost are not included in this calculation. Running cost is not needed because all the fuel and electricity needed in supplied by by-product and part of the product gas.

To calculate CO_2 payback time, the conversion factor of 2.26 kg-CO_2/1000 yen is used. Thus,

$$2.26 \times (2.28 \times 10^8/1000) = 5.15 \times 10^5 \text{ kg-CO}_2 \quad (8)$$

is produced for the construction. While using natural gas for the same heating energy, 1 mol (0.044 kg) of carbon dioxide is emitted per 890.7 kJ. Carbon dioxide should be recovered after energy production of

$$(5.15 \times 10^5/0.044) \times 890.7 = 1.04 \times 10^{10} \text{ kJ} \quad (9)$$

Since this process produces 2.06×10^9 kJ/yr, CO_2 payback time is

$$\frac{1.04 \times 10^{10}\ \text{kJ}}{2.06 \times 10^9\ \text{kJ/yr}} = 5.05\ \text{yr} \tag{10}$$

It should be noted that most of the energy requirement is for the treatment of the fermentation sludge. This fact imply that biomethanation will be desirable process if proper utilization of fermentation sludge is possible.

4. Conclusions

Two wet biomass gasification processes, supercritical water gasification and biomethanation, were evaluated from energy, environmental, and economic aspects. Assumptions were made that system should be energetically independent, that no environmentally harmful material should be released, and that carbon dioxide should be removed from the product gas. The following conclusion are obtained:

1. Under the conditions assumed here, supercritical water gasification is evaluated to be more advantageous over biomethanation, but the cost of the product gas is still 1.86 times more expensive than city gas in Tokyo.
2. To improve efficiency of supercritical water gasification, improvement of heat exchanger efficiency is effective.
3. Utilization of fermentation sludge will make biomethanation much more advantageous.
4. Carbon dioxide payback time is less than 5 years and both supercritical water gasification and biomethanation is a practical process for decreasing carbon dioxide emission.

Acknowledgements

This research was conducted as an AGS project (the Alliance for Global Sustainability, an International Partnership between Massachusetts Institute of Technology, the Swess Federal Institutes of Technology, and the University of Tokyo), and funded by Sogo Kenkyu Shoreikai. Part of this calculation is based on the activity conducted in process design course at Dept. of Chem. System Eng., Univ. of Tokyo. The author would like to appreciate Mr.'s Y. Fukushima, S. Muramatsu, H. Ohkawa, and Y. Yamada for their considerable work. The author also would like to thank Dr. T. Minowa in National Institute for Resources and Environment, MITI, Japan for useful advice.

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