Journal of Environment and Engineering
Vol. 5, No. 3, 2010

Effect of Ambient Temperature on the Energy Balance of Anaerobic Digestion Plants*

Firdaus BASRAWI**, Takanobu YAMADA** and Kimio NAKANISHI**
** Kitami Institute of Technology, Department of Mechanical Engineering,
165, Koen-Cho, Kitami City, Hokkaido 090-8507, Japan
E-mail: yama@mail.kitami-it.ac.jp

Abstract
In recent years, production of biogas by an anaerobic digestion method has been reconsidered as an alternative means for producing clean fuel. Thus, research on various aspects of biogas production by anaerobic digestion has become important for its widespread utilization. One of the important aspects is energy balance of the process. The energy balance is affected by a heat demand, whereas the heat demand is affected by ambient temperature. In the present study, in order to clarify the effect of ambient temperature on the energy balance of anaerobic digestion, typical municipal sewage sludge anaerobic digestion in an actual wastewater treatment plant was adopted as analysis model and was studied under various temperature conditions. It was found that the heat demand for heating the sludge was temperature-dependent and that 26~39% of the total amount of heat demand was heat losses from digester tanks. From the energy balance, it was found that net energy can be produced by the anaerobic digestion in any region and season in Japan, and this shown that it has a possiblity to be a new energy resource. It was also shown that, when ambient temperature became closer to the digestion temperature, more efficient anaerobic digestion can be obtained. These results were confirmed by indexes of energy balance that were defined in this study, with notable proportional relations being found between indexes and ambient temperature. Ratio of energy of heat demand to biogas produced had an inverse proportional relation with ambient temperature, whereas ratio of energy of net energy to biogas produced had a proportional relation, and ranges of these values in all of Japan were 0.13~0.44 and 0.45~0.84, respectively.

Key words: Biomass, Biogas, Anaerobic Digestion, Ambient Temperature, Energy Balance, Net Energy

1. Introduction

In general, there are two methods for producing biogas, thermal gasification and biological gasification. The biological gasification method usually refers to anaerobic digestion method and this method has always been produced biogas for decades. However, since cheap fuel has been available, production of fuel by the anaerobic digestion has not been widely used. Thus, the application of anaerobic digestion has been limited as a method for degradation and stabilization of waste, especially in wastewater treatment centers[(1)(2)]. However, the world is now facing twin energy-related threats, that of not having adequate and secure supplies of energy and that of environmental disruption caused by consuming too much fossil fuel[(3)]. Since biogas is a carbon neutral, renewable, and can also prevent environmental pollution because waste is also treated for producing it[(4)-(6)], production of biogas by an anaerobic digestion is reconsidered again. The "Biomass Nippon Strategy" was established in Japan in December 2002 with the objectives of preventing global warming,

*Received 3 Aug., 2010 (No. 10-0334)
[DOI: 10.1299/jee.5.526]

establishing a recycling-oriented society, promoting new strategic biomass-related industries, and promoting the development of agriculture, forestry, fisheries and rural communities(7). There has been a focus on anaerobic digestion as a method for converting biomass with high water content into energy. Thus, studies on various aspects of anaerobic digestion are needed for widespread utilization of anaerobic digestion. One important aspect is the energy balance that includes net energy that can be produced from the anaerobic digestion process. In anaerobic digestion, beside of small electrical power is consumed for the process, inevitably some of the biogas produced is consumed for heating and maintaining sludge temperature under optimum temperature condition. Thus, heat demand of the anaerobic digestion is an important parameter because it directly affects the energy balance of an anaerobic digestion plant, and it should be noted that this heat demand is an ambient temperature-dependant parameter. Although anaerobic digestion technology has been applied for decades and its energy balance has already been reported in some studies, it has only been reported in order to evaluate that anaerobic digestion is efficient system for producing net energy(6),(8)-(16), and no results of the effect of ambient temperature condition on energy balance of an anaerobic digestion plant have been reported.

In the present study, in order to investigate the effect of ambient temperature on the energy balance of anaerobic digestion, typical municipal sewage sludge anaerobic digestion in an actual wastewater treatment plant was used as a model plant and was studied under various ambient temperatures by considering temperature conditions throughout Japan. Energy balance of the model plant was studied on the basis of biogas production energy, heat and electrical demand, boiler and power plant losses, and net energy. Furthermore, four dimensionless indexes of energy balance were defined herein, and their relation with ambient temperature was also been investigated and compared with results of other studies.

Nomenclature

A	Heat transfer area, m^2
c_p	Specific heat, kJ/kgK
E	Energy, kW
K	Overall heat transfer coefficiency, kW/m^{2}K
M	Influent rate of sludge, m^3/s
m	Biogas production rate, m^3/s
Q	Heat, kW
r	Ratio, -
t	Temperature, ℃
TS	Total solid concentration of sludge, -
ρ	Density, kg/m^3
η	Efficiency, -

Subcript

a.d	Anaerobic digestion
amb	Ambient
b.p	Biogas production
b	Boiler
b.l	Boiler losses
h.d	Heat demand
LHV	Lower heating value
m.d	Mechanical energy demand
mech	Mechanical
net1	Net energy 1 (Mechanical energy is not subtracted)

net2	Net energy 2 (Mechanical energy is subtracted)
p.p	Power plant
p.p.l	Power plant losses
s	Sludge
s.h	Sludge heating
s,i	Influent of sludge
t.l	Losses from digester tanks

2. Temperature conditions

2.1 Ambient temperature conditions in Japan

In order to determine appropriate temperature conditions for the analysis process, ambient temperature conditions for every region in Japan were investigated. Average ambient temperature changes for every region in Japan from Hokkaido to Okinawa area are shown in Fig. 1(17). As shown in the figure, Hokkaido temperature data obtained from East Hokkaido had the lowest ambient temperature and Okinawa temperature data obtained from Naha had the highest ambient temperature. Moreover, it was found that ambient temperature gradually increased when area changes from Tohoku (north part of Japan) to Kyushu (south part of Japan). However, for Tokyo and areas located south of Tokyo, similar ambient temperatures were found. Thus, ambient temperature conditions for all of Japan can be represented by ambient temperatures in East Hokkaido, Tokyo and Naha. In this paper, ambient temperatures in those areas are denoted as *low*, *middle* and *high temperature conditions*, respectively.

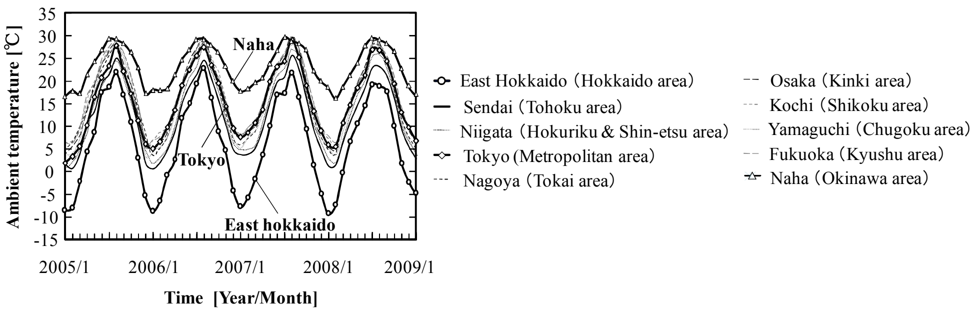

Fig. 1. Ambient temperatures for every region of Japan.

2.2 Temperature conditions for analysis

As also shown in Fig. 1, ambient temperature in all regions fluctuates throughout the year. Thus, influence of season is also important. The above-stated temperature conditions were additionally divided into four seasons: winter (December to February), spring (March to May), summer (June to August) and autumn (September to November). The period from

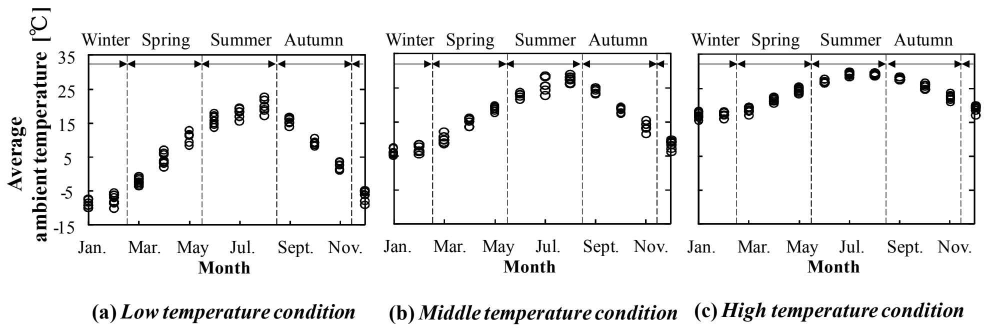

Fig. 2. Monthly average temperatures for each temperature condition in the analysis period.

April 2001 to March 2008 was used as the analysis period. Average monthly ambient temperature conditions for the seven-year analysis period are shown in Fig. 2[17]. Monthly average temperatures for the *low*, *middle* and *high temperature conditions* are shown in Fig. 2 (a), (b) and (c), respectively.

As shown in the figure, average ambient temperatures for all temperature conditions were not dependent on the year; approximately consistent temperatures were found for all years. Average values were calculated from monthly average ambient temperatures for all seven years of the analysis period and the calculated values were used as temperature conditions for analysis. The temperature conditions used for analysis are shown in Table 1.

Table 1. Details of temperature conditions.

		Average ambient temperature [℃]		
		Average	**Maximum**	**Minimum**
Low	Annual	6.4	22.8	-9.5
	Winter	-6.9	-4.1	-9.5
	Spring	4.9	13.1	-3.0
	Summer	18.0	22.8	13.9
	Autumn	9.4	17.0	1.4
Middle	Annual	16.6	29.0	5.1
	Winter	7.3	9.9	5.1
	Spring	14.7	19.8	8.7
	Summer	25.5	29.0	25.3
	Autumn	18.8	25.2	11.6
High	Annual	23.3	29.9	15.7
	Winter	18.0	20.2	15.7
	Spring	21.6	25.5	17.2
	Summer	28.4	29.9	26.6
	Autumn	25.3	28.5	21.1

3. Materials and methods

3.1 Analysis model of anaerobic digestion plant

Biogas production by the anaerobic digestion method is generally used for sludge that has high water content. Sludge with high water content includes municipal sewage sludge, livestock waste, food waste, wastewater from food processing factories and crops. Theoretically, anaerobic digestion is a process in which microorganisms break down high-molecular-weight organic compounds to low-molecular-weight organic compounds and finally convert them to biogas in the absence of oxygen. Anaerobic digestion is a complex process carried out by a consortium of very different microorganisms and is affected by various factors including the type of organic compound, total solid concentration of sludge (TS), organic compound concentration, digestion temperature and pH value. A two-stage digestion system operating under mesophilic conditions with a digestion period of 30 days is generally used in wastewater treatment centers in Japan[6][18]. Since an actual municipal sewage sludge anaerobic digestion system was adopted as an analysis model, this typical digestion system was analyzed in this study. Design parameters of the analysis model of an anaerobic digestion plant are shown in Table 2. This plant is equipped with two cylindrical digester tanks of different sizes to process municipal sewage sludge from a population of 100 000 that produce influent sludge with average values of 4.0% TS, 80.8% organic concentrations and pH 5.6. This plant can produce approximately 130 000m^3/month of biogas with a digestion coefficient of 62%.

Table 2. Design parameters of the model anaerobic digestion plant.

Population covered	[people]	100000		
Digester tank total volume				
Tank A (2units)	[m^3]	6438		
Tank B (2units)	[m^3]	3650		
		Minimum	Maximum	Average
Wastewater amount	[m^3/month]	1163000	2254000	1564000
Digestion coefficient	[%]	47	83	62
Biogas production	[m^3/month]	102400	151400	129500
Influent sludge				
Sludge amount	[m^3/month]	5731	9794	7461
Solid concentration	[%]	3.1	5.4	4.0
Organic contents	[%]	74.5	88.5	80.8
pH	[-]	5.2	6.1	5.6
Effluent sludge				
Sludge amount	[m^3/month]	3267	7278	5821
Solid concentration	[%]	1.41	3.8	2.0
Organic contents	[%]	53.3	67.8	61.0
pH	[-]	7.0	7.5	7.3

3.2 Heat demand of the anaerobic digestion plant

Temperature is one of the most important factors affecting microbial activity and therefore sludge temperature must be maintained under an optimum condition to prevent failure of the process. A large amount of heat is required for mantaining an optimum digestion temperature. The amount of heat required for anaerobic digestion $Q_{h.d}$ can be divided as the amount of heat required for sludge heating $Q_{s.h}$ and the amount of heat required to cover losses of heat to the environment from the digestion tanks $Q_{t.l}$. It can be expressed as the following equation:

$$Q_{h.d} = Q_{s.h} + Q_{t.l}. \tag{1}$$

Important parameters that have been used to calculate these heat demands are shown in Table 3. $Q_{s.h}$ can be expressed as the following equation:

$$Q_{s.h} = m_s c_{p,s} \rho_s \left(t_{a.d} - t_{s,i}\right), \tag{2}$$

where m_s is the amount of influent sludge [m^3/s], $c_{p,s}$ is the specific heat of sludge [kJ/kgK], ρ_s is the density of sludge [kg/m^3], $t_{a.d}$ is the anaerobic digestion temperature [℃], and $t_{s,i}$ is the temperature of influent sludge [℃].

Since water concentration of the sludge is high, values of specific heat and density were assumed to be equivalent to those of water(19). In addition, temperature of influent sludge for every temperature condition was assumed to be equal to wastewater temperature(20)-(22). In order to achieve optimum digestion under mesophilic condition, digestion temperature must be maintained in the range of 30 to 37℃ (18)(23). Thus, in the calculation, temperature of sludge in the digester tank was assumed to be constant at 37℃. In order to calculate heat losses from the digestion tanks $Q_{t.l}$, if heat losses from radiation can be neglected, $Q_{t.l}$ can be expressed as the following equation:

$$Q_{t.l} = KA\left(t_{a.d} - t_{amb}\right), \tag{3}$$

where A is the heat transfer area [m^2], K is the overall heat transfer coefficient of the digester tanks [kW/m^{2}K], and t_{amb} is the ambient temperature [℃]. The values of A and K were obtained from actual material and measurement of the model plant. It should be noted that since $t_{s,i}$ is also indirectly ambient temperature-dependent, both $Q_{s.h}$ and $Q_{t.l}$ are ambient temperature-dependent equations.

Table 3. Important parameters used for calculating heat demand of the model plant.

Digester tank				
Tank A				
Overall wall area	[m ^{2}]	1041		
Heat transfer coe.	[W/(m ^{2}K)]	2.76		
Tank B				
Overall wall area	[m ^{2}]	675		
Heat transfer coe.	[W/(m ^{2}K)]	2.44		
Digestion temperature	[℃]	37		
		Minimum	Maximum	Average
Temperature of influent sludge				
Low temperature condition	[℃]	9.3	18.6	14.2
Middle temperature condition	[℃]	17.1	27.6	21.7
High temperature condition	[℃]	23.2	29.8	26.8

3.3 Energy balance and net energy

A block diagram of energy balance in the anaerobic digestion plant is shown in Fig. 3. As shown in the figure, some of the produced biogas is consumed as fuel to cover the heat demand of the anaerobic digestion. A small amount of electrical power is also used to cover electrical demand for the process. Thus, the remaining biogas that is not used by the boiler and power plant can be considered as net energy produced from the process. The heat energy of biogas produced $Q_{b.p}$ can be expressed as equation (4):

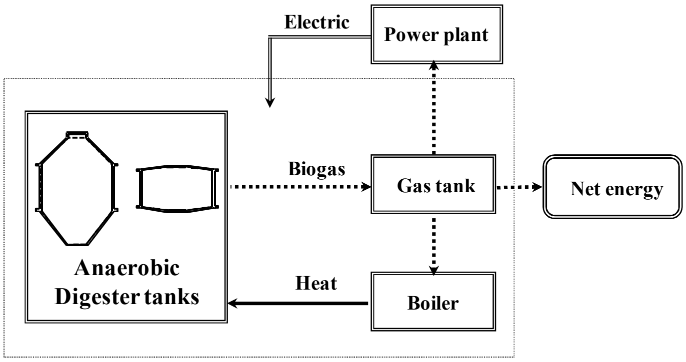

Fig. 3. Block diagram of energy balance in the anaerobic digestion plant.

$$Q_{b.p} = m_{b.p} Q_{LHV} , \tag{4}$$

where $m_{b.p}$ is the biogas production rate [m^3/s], Q_{LHV} is the lower heating value of the biogas [kJ/m^3]. After traces such as water and hydrogen sulfide had been eliminated from the bulk biogas, the bulk biogas was finally composed of approximately 60%-v methane and 40%-v carbon dioxide and therefore Q_{LHV} was assumed to be 21 500kJ/m^3. The net energy that only heat demand is considered E_{net1} can be expressed as equation (5):

$$E_{net1} = Q_{b.p} - \left(Q_{h.d} + Q_{b.l}\right), \tag{5}$$

where $Q_{b.l}$ is the boiler loss [kW]. It should be noted that the sum of $Q_{h.d}$ and $Q_{b.l}$ is also equal to the biogas energy that supplied to the boiler. If the boiler efficiency η_b can be expressed as equation (6), E_{net1} can be rewritten as shown in equation (7):

$$\eta_b = \frac{Q_{h.d}}{Q_{h.d} + Q_{b.l}}, \tag{6}$$

$$E_{net1} = Q_{b.p} - \frac{Q_{h.d}}{\eta_b}. \tag{7}$$

The boiler efficiency η_b herein, was assumed to be equal to 80%[24].

Details of the actual electrical power demand for the anaerobic digestion process are shown in Fig. 4. It should be noted that these values are average values of electrical power for March 2007 to March 2010. As shown in Fig. 4, electrical power is mainly required for pumping sludge to the digester tank (influent sludge pump), thickening the sludge (sludge thickener), stirring the sludge (sludge stirrer), blowing air and biogas to the boiler (air and gas blower), and recirculating hot water and sludge for heat exchange purpose (sludge and hot water circulating pump). Electrical power is not required for pumping out digestered sludge (effluent sludge) from the digester tank, a process that is achieved by gravitational force. As shown in the figure, electrical power demand for anaerobic digestion was not temperature-dependant and was approximately constant throughout the year with only a small difference between summer and winter for the sludge and hot water circulating pump. Since the difference is not more than 7.5% of the total elecrical power demand, electrical power is assumed to be constant at 62.5kW in any temperature condition.

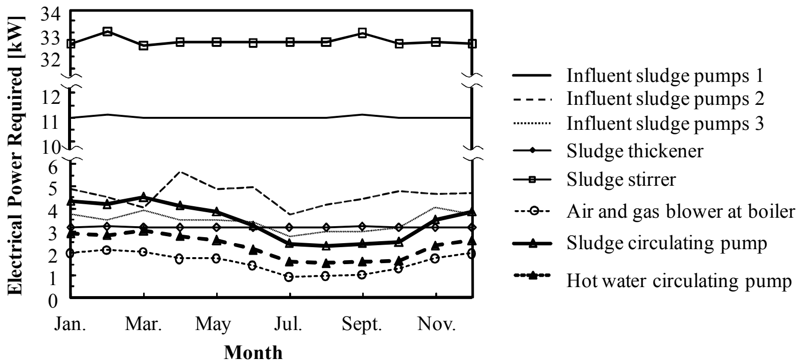

Fig. 4. Details of actual electrical power required for the anaerobic digestion process.

In previous studies, electrical power demand E_{mech} was not considered in the calculation of energy balance due to the neglible percentages of E_{mech} to total energy required[8][12]. However, even though the percentage of electrical power demand to total energy demand is low, if heat demand is also low, percentage of electrical power demand will be significant. Moreover, since energy conversion efficiency from primary energy to electrical power is usually lower than that from primary energy to heat, a significant amount of primary energy is required for electrical power production. Thus, net energy evaluation with consideration of electrical power is also important, and hence net energy for both calculation methods has been considered in the present study. The net energy that considered both electrical power and heat demand E_{net2} can be expressed as the following equation (8) :

$$E_{net2} = Q_{b.p} - \left(Q_{h.d} + Q_{b.l} + E_{mech} + Q_{p.p.l}\right), \tag{8}$$

where $Q_{p.p.l}$ is the power plant loss [kW]. It should be noted that the sum of E_{mech} and $Q_{p.p.l}$ is also equal with biogas energy supplied to the power plant. If the power plant efficiency $\eta_{p.p}$ can be expressed as equation (9), E_{net2} can be rewritten as shown in equation (10):

$$\eta_{p.p} = \frac{E_{mech}}{E_{mech} + Q_{p.p.l}}, \tag{9}$$

$$E_{net2} = Q_{b.p} - \left(\frac{Q_{h.d}}{\eta_b} + \frac{E_{mech}}{\eta_{p.p}} \right). \tag{10}$$

The power plant efficiency $\eta_{p.p}$ herein, was assumed to be equal to 37%[24].

Furthermore, in order to evaluate and compare the energy balance of one anaerobic digestion plant with another plant without considering the scale of the plant, the following four dimensionless indexes of energy balance were defined: ratio of heat demand to heat energy of biogas produced, $r_{h.d/b.p}$; ratio of heat and electrical power demand to heat energy of biogas produced, $r_{h.d\&m.d/b.p}$; and ratios of net energy to heat energy of biogas produced, $r_{net1/b.p}$ and $r_{net2/b.p}$. These ratios can be expressed as the following equations:

$$r_{h.d/b.p} = \frac{Q_{h.d}}{Q_{b.p}}, \tag{11}$$

$$r_{h.d\&m.d/b.p} = \frac{Q_{h.d} + E_{mech}}{Q_{b.p}}, \tag{12}$$

$$r_{net1/b.p} = \frac{E_{net1}}{Q_{b.p}}, \tag{13}$$

$$r_{net2/b.p} = \frac{E_{net2}}{Q_{b.p}}. \tag{14}$$

It should be noted that E_{net1} was calculated from $Q_{h.d}$ and that E_{net2} was calculated from $Q_{h.d}$ and E_{mech}. These defined indexes can provide an overall picture of the energy balance and efficiency of the anaerobic digestion plant. A plant that has low $r_{h.d/b.p}$ and $r_{h.d\&m.d/b.p}$ ratios or high $r_{net1/b.p}$ and $r_{net2/b.p}$ ratios can be considered as an efficient plant. Conversely, an $r_{h.d/b.p}$ ratio higher than 1.0 or an $r_{net/b.p}$ ratio that shows a negative value indicates that more energy is consumed than that produced from the plant, and hence it is not an efficient plant.

4. Results and discussion

4.1 Heat demand and ambient temperature

Heat demand of the model plant for all temperature conditions in a one-year period are shown in Fig. 5. Results for (a) *low*, (b) *middle* and (c) *high temperature conditions* are shown from the left to right sides.

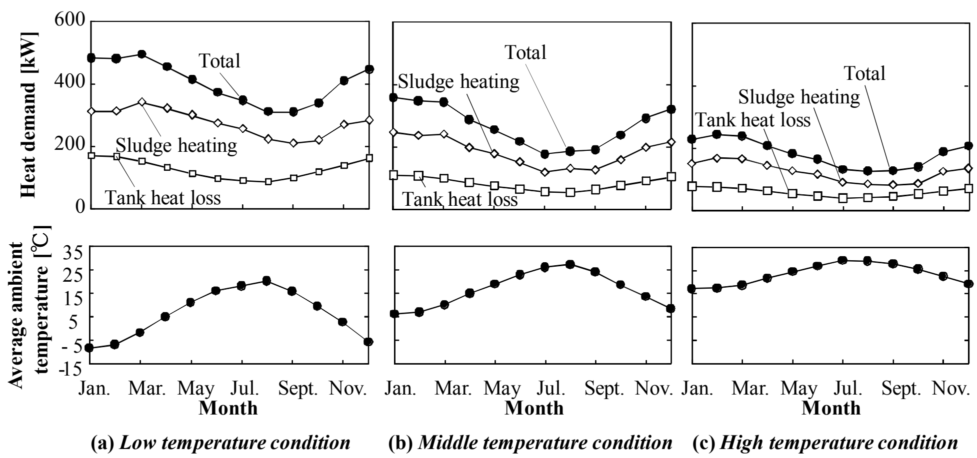

Fig. 5. Details of heat demand for all temperature conditions.

As shown in the figure, when temperature increased from *low* to *high temperature conditions*, heat demand generally decreased. Heat demand was highest in the *low temperature condition* and lowest in the *high temperature condition*. Furthermore, heat demand was higher when temperature was low in January and it was lower when temperature became higher and reached a peak in August. Thus, heat demand of the anaerobic digestion plant is affected by the ambient temperature condition. It was also found that percentages of heat losses from the digester tanks in all temperature conditions were being about 26~39% of the total heat demand.

4.2 Details of energy balance for all temperature conditions and seasons

Annual energy balance for all temperature conditions are shown in Fig. 6 and details of energy balance in the model plant for all temperature conditions and seasons are shown in Table 4. It should be noted that the ratio of all amounts to the biogas production energy are also shown in the Table 4. In general, in a higher temperature condition, heat demand was lower and net energy was higher. Furthermore, even in the same temperature condition, since ambient temperature fluctuated with seasons, different energy balance conditions were obtained for all seasons. The highest net energy E_{net1} value of 935kW, which was 84% of the total energy from biogas produced, was found in summer of the *high temperature condition*. On the other hand, even in the lowest temperature condition, i.e., winter of the *low temperature condition*, E_{net1} was 474kW, which was 45% of the total energy from biogas produced. The results clearly indicate that anaerobic digestion is an effective method for producing biogas in any season and in any region of Japan and that more net energy can be produced under a higher temperature condition.

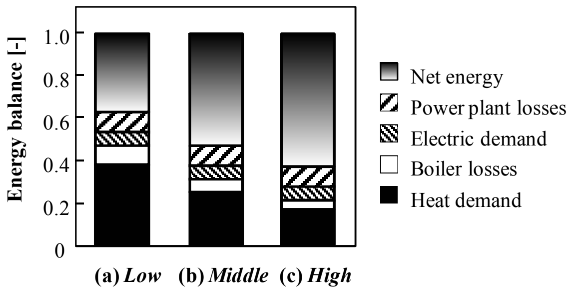

Fig. 6. Annual energy balance for all temperature conditions.

Table 4. Details of the energy balance for all temperature conditions.

		Biogas Production, $Q_{b,p}$ [kW]	Heat Demand, $Q_{h,d}$ [kW]	[-]	Boiler Losses, $Q_{b,l}$ [kW]	[-]	Electrical Demand, E_{mech} [kW]	[-]	Power plant Losses, $Q_{p,p,l}$ [kW]	[-]	Net energy1 E_{net1} [kW]	[-]	Net energy2 E_{net2} [kW]	[-]
Low temperature condition	Annual	1071	406	0.379	101	0.095	63	0.058	107	0.099	564	0.526	395	0.369
	Winter	1062	470	0.443	118	0.111	63	0.059	107	0.100	474	0.446	305	0.287
	Spring	1058	455	0.430	114	0.108	63	0.059	107	0.101	489	0.462	320	0.302
	Summer	1111	344	0.310	86	0.077	63	0.056	107	0.096	681	0.613	512	0.460
	Autumn	1055	354	0.335	88	0.084	63	0.059	107	0.101	613	0.581	443	0.420
Middle temperature condition	Annual	1071	269	0.251	67	0.063	63	0.058	107	0.099	735	0.686	566	0.529
	Winter	1062	343	0.323	86	0.081	63	0.059	107	0.100	633	0.596	463	0.437
	Spring	1058	296	0.280	74	0.070	63	0.059	107	0.101	688	0.650	518	0.490
	Summer	1111	195	0.175	49	0.044	63	0.056	107	0.096	868	0.781	699	0.629
	Autumn	1055	241	0.228	60	0.057	63	0.059	107	0.101	754	0.714	584	0.554
High temperature condition	Annual	1071	183	0.171	46	0.043	63	0.058	107	0.099	843	0.787	674	0.629
	Winter	1062	227	0.214	57	0.054	63	0.059	107	0.100	777	0.732	608	0.573
	Spring	1058	210	0.198	52	0.050	63	0.059	107	0.101	796	0.752	626	0.592
	Summer	1111	141	0.127	35	0.032	63	0.056	107	0.096	935	0.841	765	0.689
	Autumn	1055	153	0.145	38	0.036	63	0.059	107	0.101	864	0.819	695	0.659

As a method for utilizing this net energy, if there are facilites near the anaerobic digestion plant that require heat and electrical power, net energy produced from the anaerobic digestion can be utilized efficiently by application of a cogeneration system. If there are no nearby facilities, biogas produced can also be purified and utilized as a fuel for natural gas vehicles[(25)(26)] or supplied to a grid gas[(26)(27)]. In the case of wastewater treatment facilities, less than 30 of 300 facilities that are equipped with an anaerobic digester currently utilize biogas with a cogeneration system, and the remaining facilities incinerated the surplus of biogas[(2)(28)]. In the current situation, heat rejected from the incinerated biogas can alternatively be recovered and supplied to facilities via thermal energy storage transportation.

4.3 Relations of ambient temperature to indexes of energy balance

Relations of ambient temperature to indexes of energy balance are shown in Fig. 7. The ratio of heat demand to biogas production energy $r_{h.d/b.p}$, the ratio of heat and electrical demand to biogas production energy $r_{h.d\&m.d/b.p}$, and the ratios of net energy to biogas production energy $r_{net1/b.p}$, $r_{net2/b.p}$ are shown in Fig. 7(a), (b), (c) and (d) respectively.

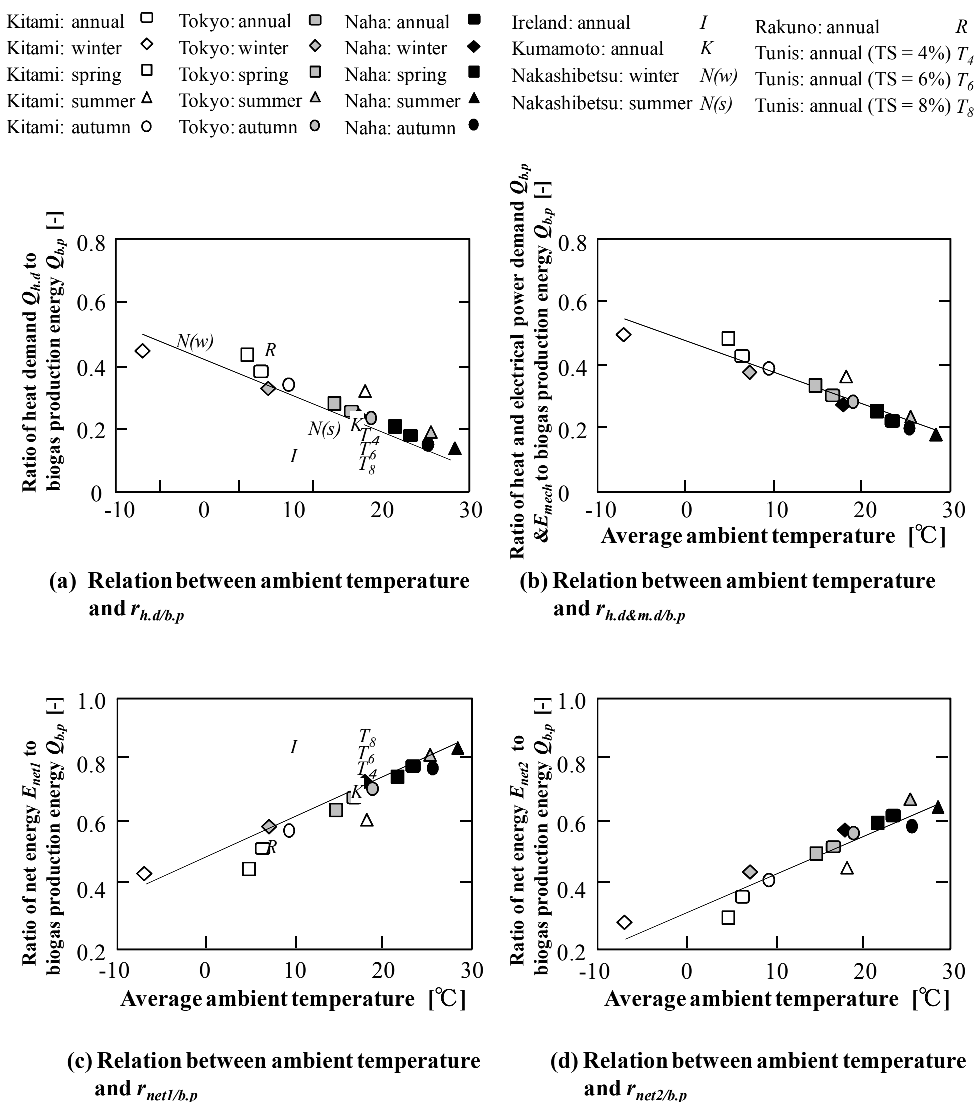

Fig. 7. Relations of ambient temperature to indexes of energy balance.

Results obtained in this study were compared with results of other studies in which mesophilic digestion was used. Results for anaerobic digestion of livestock manure in Nakashibetsu, Hokkaido (*N*)[(6)] and Rakuno University, Hokkaido (*R*)[(9)], anaerobic digestion of fruit and vegetable waste in Tunisia (*T*)[(8)], anaerobic digestion of municipal sewage sludge in Chubu wastewater treatment plant, Kumamoto (*K*)[(10)], and anaerobic digestion of grass in Ireland (*I*)[(11)] are also shown in Fig. 7. It should be noted that all results of other studies are annual results except for the results obtained in Nakashibetsu, which are shown for summer (*N(s)*) and winter (*N(w)*). Furthermore, results for anaerobic digestion in Tunisia were for sludges with different total solid concentration (TS) values and therefore results with TS values of 4% (T_4), 6% (T_6) and 8% (T_8) are shown in the figure.

As shown in the figure, all ratios had notable proportional relations to ambient temperature. $r_{h.d/b.p}$ and $r_{h.d\&m.d/b.p}$ had an inverse proportional relation with ambient temperature, whereas $r_{net1/b.p}$ and $r_{net2/b.p}$ had a proportional relation with ambient temperature. Ranges of $r_{h.d/b.p}$ and $r_{h.d\&m.d/b.p}$ ratios in all of Japan were approximately 0.13~0.44 and 0.18~0.50, respectively, whereas ranges of $r_{net1/b.p}$ and $r_{net2/b.p}$ ratios were approximately 0.45~0.84 and 0.29~0.68, respectively. The highest $r_{h.d/b.p}$ and $r_{h.d\&m.d/b.p}$ ratios and the lowest $r_{net1/b.p}$ and $r_{net2/b.p}$ ratios were in winter in the *low temperature condition*, whereas the lowest $r_{h.d/b.p}$ and $r_{h.d\&m.d/b.p}$ ratios and the highest $r_{net/b.p\,p}$ and $r_{net2/b.p}$ ratios were in summer in the *high temperature condition.*

Moreover, results for $r_{h.d/b.p}$ and $r_{net1/b.p}$ ratios obtained in this study were approximately consistent with results of other studies except for T_6, T_8 and *I*. This was because TS values for those cases were higher than sludge with 4% TS that was considered in this study, with T_6 of 6%, T_8 of 8% and *I* of 10%. A higher TS value means that more organics are contained in the sludge and hence more biogas can be produced. Thus, compared to the results obtained in the present study, those values had lower $r_{h.d/b.p}$ and $r_{h.d\&m.d/b.p}$ ratios and higher $r_{net1/b.p}$ and $r_{net2/b.p}$ ratios. In addition, a digester tank with insulation material of high performance was used for case *I*. It was reported that tank heat loss was only 12.8% of the total heat demand, which was approximately 2~3(26~39%)-times lower than the result obtained in this study.

These results clearly shown that significant amount of energy can be produced by the anaerobic digestion in all region and season. Energy balance in the anaerobic digestion plant was directly affected by ambient temperature with more efficient system can be obtained when ambient temperature became closer to the digestion temperature. Besides that an assumption of energy balance of the anaerobic digestion can also be made if ambient temperature is known. Under lower temperature condition, an insulation material of a higher efficiency can also be used in order to increase the efficiency of the anaerobic digestion.

5. Conclusions

The effect of ambient temperature on the energy balance of an anaerobic digestion plant was investigated and the following results were obtained:

1. The anaerobic digestion plant was affected by ambient temperature conditions with heat demand was highest in the low temperature condition and lowest in the high temperature condition. The amount of tank heat losses of a typical cylindrical digester tank in wastewater treatment centre in all temperature condition were approximately 26~39% of the total heat demand.
2. In the highest ambient temperature condition, which was in summer in the *high temperature condition*, net energy was 84% of the total energy from biogas produced. Whereas, in the lowest temperature condition, which was in winter in the *low temperature condition* net energy was 45% of the total energy from biogas produced. These results

clearly net energy can be produced by the anaerobic digestion in any region and any season in Japan, and this shown that it has a possiblity to be a new energy resource. It was also clearly shown that more net energy can be obtained in a region that has a higher ambient temperature condition.

3. The energy balance indexes ($r_{h.d/b.p}$, $r_{h.d\&m.d/b.p}$, $r_{net1/b.p}$, $r_{net2/b.p}$) also showed notable proportional relations to the ambient temperature, with more efficient system can be obtained when ambient temperature became closer to the digestion temperature. $r_{h.d/b.p}$ and $r_{h.d\&m.d/b.p}$ had an inverse proportional relation with ambient temperature, whereas $r_{net1/b.p}$ and $r_{net2/b.p}$ had a proportional relation with ambient temperature. The ranges of $r_{h.d/b.p}$ and $r_{h.d\&m.d/b.p}$ ratios for studied anaerobic digestion in the whole of Japan were approximately 0.13~0.44 and 0.18~0.50, respectively, and $r_{net1/b.p}$ and $r_{net2/b.p}$ ratios were approximately 0.45~0.84 and 0.29~0.68, respectively. Results obtained in this paper were also found to be consistent with an energy balances in other studies in which mesophilic digestion were also used.

References

(1) Y. Chen, J. J. Cheng, K. S. Creamer, Inhibition of anaerobic digestion process: A review, *Bioresource Technology*, 99, (2008), pp. 4044-4064.

(2) T. Kenichiro, T. Yagishita, S. Sawayama, Current status of biogas plants in Japan, *Journal of the Japan Institute of Energy*, 84, (2005), pp. 537-543. [in Japanese]

(3) International Energy Agency, World energy outlook, (2006), pp. 37.

(4) J. B. Holm-Nielsen, T. A. Seadi, P. Oleskowicz-Popiel, The future of anaerobic digestion and biogas utilization, *Bioresource Technology*, 100, (2009), pp. 5478-5484.

(5) A. J. Ward, P. J. Hobbs, P. J. Holliman, D. L. Jones, Optimisation of the anaerobic digestion of agricultural resources, *Bioresource Technology*, 99, (2008), pp. 7928-7940.

(6) NTS Co., Ltd., Gaseous fuel fabrication from biomass and its energy utilization, (2007), pp. 3-4, 170, 290-291. [in Japanese]

(7) Y. Kuzuhara, Biomass nippon strategy - why “biomass nippon” now?, *Biomass and Bioenergy*, 29, (2005), pp. 331-335.

(8) H. Bouallagui, O. Haouari, Y. Touhami, R. B. Cheikh, L. Marouani, M. Hamdi, Effect of temperature on the performance of an anaerobic tubular reactor treating fruit and vegetable waste, *Process Biochemistry*, 39, (2004), pp. 2143-2148.

(9) Material from Livestock Industry's Environmental Improvement Organization (LEIO) webpage. < www.leio.or.jp/pdf/119/tokus1_36f.pdf >. [in Japanese]

(10) Material from Kumamoto City webpage. <http://www.city.kumamoto.kumamoto.jp/Content/Web/Upload/file/Bun_3598_228%8F%CD-2.pdf >. [in Japanese]

(11) B. M. Smyth, J. D. Murphy, C. M. O'Brien, What is the energy balance of grass biomethane in Ireland and other temperate northern European climates, *Renewable and Sustainable Energy Reviews*, 13, 2009, pp. 2349-2360.

(12) M. Lubken, M. Wichern, M. Schlattmann, A. Gronauer, H. Horn, Modelling the energy balance of an anaerobic digester fed with cattle manure and renewable energy crops, *Water Research*, 41, (2007), pp. 4085-4096.

(13) I. Bohn, L. Bjornsson, B. Mattiasson, The energy balance in farm scale anaerobic digestion of crop residues at 11-37℃, *Process Biochemistry*, 42, (2007), pp. 57-64.

(14) G. D. Zupancic, N. Uranjek-Zevart, M. Ros, Full-scale anaerobic co-digestion of organic waste and municipal sludge, *Biomass & Bioenergy*, 32, (2008), pp. 162-167.

(15) S. Osumi, J. Tsubota, Estimation of improved energy balance of anaerobic digestion plant by hyper thermal hydrolysis, *Journal of the Japan Institute of Energy*, 89, (2010), pp. 167-171. [in Japanese]

(16) Y. Arai, K. Takahashi, N. Wada, Feasibility study of biogas plant system from animal manure, *Proceedings of the Japan Institute of Energy Conference*, 13, (2004), pp. 132-133. [in Japanese]
(17) Japan Meteorology Agency. Information of weather satistics, (http://www.jma.go.jp/jma/menu/report.html). [in Japanese]
(18) M. Hiraoka, Z. Yoshino, Sludge treatment engineering: process planning and design, Kodansha, (1983), p. 191. [in Japanese]
(19) Metcalf & Eddy, Inc, Wastewater engineering: Treatment and reuse, Fourth edition, McGraw-Hill, (2003), p. 1525.
(20) Kitami City Sewerage Management Office, Annual report of sewer maintenance, (2001-2008). [in Japanese]
(21) Y. Nakayama, M. Kanda, T. Kinouchi, Research regarding water and heat transfer in urban sewage system based on water temperature observation in the sewage treatment facility, *Journal of Japan Society of Hydrology and Water Resources*, 1, (2007), pp. 25-33.
(22) Okinawa Prefecture Sewerage Management Office, Annual report of sewer maintenance, (2007). [in Japanese]
(23) Environmental Technology Society, Guide book for treatment of sewage, industrial liquid waste & sludge, (1979), p. 500. [in Japanese]
(24) S. Naing, T. Yamada, K. Nakanishi, Applied performance research of a cogeneration arrangement with proposed efficiency well-balance method, *Journal of Power and Energy Systems*, 1, (2007), pp. 199-210.
(25) Japan Gas Association, Biomass energy utilization. (http://www.gas.or.jp/default.html). [in Japanese]
(26) European Biomass Association, A biogas roadmap for Europe, pp. 8-9.
(27) Kanazawa Water and Energy Center, Effective utilization of biogas. (http://www2.city.kanazawa.ishikawa.jp/). [in Japanese]
(28) The Way of Source Committee, Utilization of sewage sludge, Current situation and challenges of utilizing sewage sludge sources, Japan Ministry of Land, Infrastructure, Transport and Tourism, (2006), (http://www.mlit.go.jp/). [in Japanese]