Long-term Operation of a Small-scale Gasification and Power Generation Plant for Chicken Manure

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Abstract

We have developed a new process called as the STAR-MEET system for generating a fuel gas by high-temperature air reforming of the pyrolysis gas produced from chicken manure to drive a dual-fueled diesel engine for production of electric power and thermal energy. We have installed a commercial plant of the STAR-MEET system with the capacity of 2tons/day of dried chicken manure. This plant was successfully operated for 90 days continuous feed of chicken manure and continuous extraction of ash, in May 2007. The heating value of the reformed gas reached at 4MJ/Nm^3 and its value is almost the same level as wood chips. High-temperature air reforming effectively suppressed tar formation, and there was no significant condensation of tar nor dust in the down stream components after this long-term continuous operation. We have also successfully demonstrated 55 days continuous daily operation of the dual-fueled diesel engine generator also.

2. Introduction

For solving energy and environmental problems, development of innovative and realistic technologies for energy conversion systems has been desired. And the fuel resource is required which can reduce the dependence on the fossil fuels. Solid wastes or biomass is classified into new renewable energy in Japan and recommended to be effectively utilized. But as these energy resources have the characteristics of geographical dispersion, distributed small-scale power generation is desirable in terms of efficient utilization of energy.

Under this social background, we have been developing a small-scale power generation system for burnable solid wastes, which is called as the STAR-MEET system [1]. The system utilizes the energy conversion from solid to gas with an air-blown updraft type fixed bed gasification combined with a reformer and power generation with internal combustion engines. To decompose tar in the gasified gas, we use the high temperature air and steam reforming technology. The reformed gas has the following characteristics: 1) low calorific gas, 2) fluctuation of gas heat value and flow rate, 3) inclusion of a small amount of tar. In order to generate electric power from these low-grade fuel gases, we have developed and chosen the use of a dual-fueled diesel engine to generate power [2].

On the other hand, appropriate treatment of chicken manure produced in chicken houses has become more important due to enforcement of regulation against treatment of livestock excretion and possible infection of aviation influenza in Japan. Furthermore, energy demands in chicken farms have been increasing for the lighting and the ventilation in chicken houses, egg washing and chicken manure drying.

To solve these problems, we have been applying the STAR-MEET system in a chicken farm to convert chicken manure into electricity and thermal energy. This system can kill the influenza virus by high temperature treatment and leads cost reduction by using electric power and thermal energy produced from this system in the farm. So, we have developed and installed the gasification and power generation facility next to a chicken house supplying the fuel gas produced from dried chicken manure to a dual-fueled engine diesel generator. In this paper, we will report on the successful long-term continuous operation of the gasification part (90 days) and the dual-fueled diesel engine (55 days).

3. Outline of the Commercial Plant

Figure 1 shows the photograph of the commercial facility. The left side one is the chicken manure drying system utilizing body heat of chickens and the right side one is the gasification and power generation facility.

Figure 1. Commercial facility.

Figure 2 shows the block-flow diagram of the commercial plant. Gasification and reforming unit consist of a fix-bed type up-draft gasifier and a reformer. The dried chicken manure dried in the dryer called “seconov” is supplied from the top of the gasifier by the continuous feeding system and the ash is extracted from the bottom of the gasifier. The gasification agent (air + steam) is preheated up to 200C and is supplied from the bottom of the gasifier. The tar contained in the pylorysis gas is decomposed into inflammable gases without catalyst under the action of high temperature air preheated to 500C in the reformer. The reforming reaction is accelerated in the pebble layer which is composed of packed ceramic balls of 30 mm in diameter and located about 600 mm downstream from the reformer inlet. The remaining dust in the reformed gas is removed by the high temperature dust filter. Then reformed gas is cooled in the gas cooler generating the condensate. The condensate is stored in the drain drum, and sprayed into the combustor. So, this facility doesn’t need a waste water treatment unit. Detrimental gas components in the reformed gas is removed by the activated carbon sucker tower and the reformed gas is supplied through the exhaust gas blower to the dual-fueled diesel engine generator. On the other hand, the excess gas coming out of the gasifier is burned in the combustor and is used to preheat the air for reforming. The condensed water recovered in the reformed gas coolers, is atomized into this combustor to be evaporated. Therefore, no waste water treatment system is required.

Generated electrical power and accompanied hot water are used in a windowless automated chicken house. The chicken manure has been dried by means of the heat released from the chicken with the moisture content down to less than 20%. The hot water produced from the system is utilized to accelerate the drying of the chicken manure. The electric power from the dual-fueled diesel engine generator is used to drive the automated chicken house system.

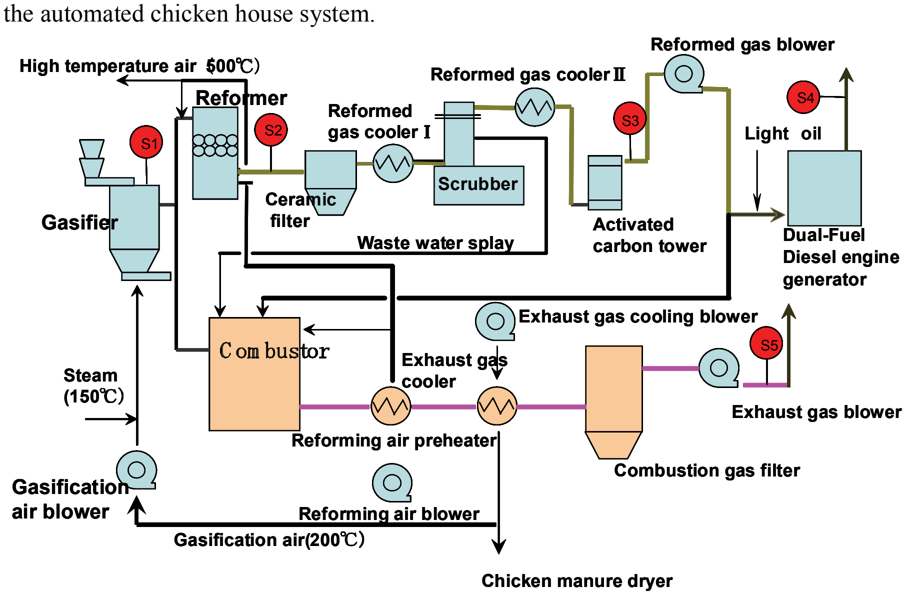

Figure 2. Block-flow diagram of the gasification and power generation system.

4. Characteristic of the Biomass Fuel

In this commercial plant, we used dried chicken manure as the biomass fuels. Table 1 compares the properties of chicken manure and wood chips. Although wood chips are known as an easy fuel for gasification, chicken manure contains high ash components which makes it hard to gasify. Chicken manure has lower heating value than wood chips, so that heating value of the fuel gas produced from chicken manure may be lower than that from wood chips. In addition, chicken manure contains a lot of nitrogen, so we need to concern about the detrimental gases, for example, ammonia and hydrogen cyanide in the fuel gas which may be sources of Fuel-NOx when we burn the fuel gas in an internal combustion engine.

5. Operating Conditions of the Plant

The operating conditions for the continuous 90 days demonstration test are shown in Table 2. The supplied amount of air as a gasification agent and that of steam as a reforming agent were shown by the air ratio and the steam ratio. Their definitions are as follows:

$$\text{Air ratio (mol/mol)} = \frac{\text{Oxygen amount in air}}{\text{Oxygen amount required for complete combustion of the fuel}} \tag{1}$$

$$\text{Steam ratio (mol/mol)} = \frac{\text{Mole of steam supplied into the gasifier}}{\text{Mole of carbon in the fuel supplied into the gasifier}} \tag{2}$$

Regarding the temperature in the combustion zone at the bottom of the gasifier, if it becomes lower than 900C, gasification and thermal decomposition reactions will not be promoted, while if it becomes higher than 1000C, ash will melt and form the clinker. So we have selected the temperature in the combustion zone from 900 to 1000C. Regarding the reforming temperature, it should be higher than 80C for the reforming reaction to be promoted, while if it is higher than 950C, tar contents will change to soot and the dust concentration in the fuel gas will increase, so we have selected the reforming temperature from 800 to 900C. These operating conditions had been determined so that we could maintain the long term stable operation of the plant. Such compromise made us possible to demonstrate continuous 90 days operation.

Table 1. Properties of chicken manure and wood chips.

Items	Unit	Chicken manure	Wood chip
Water content	%	9.1	15.7
Ash	%	22.6	0.5
Combustible	%	77.4	99.5
LHV	MJ/kg	10.3	16.4
C	%	33.5	49.1
H	%	4.2	6.3
N	%	5.1	0.11
O	%	33.8	44.4
S	%	0.3	below 0.1
Cl	%	0.5	below 0.1

Table 2. Operating conditions for continuous 90 days demonstration test.

Items	Unit	Values	Temperature
Gasification Air Ratio	–	0.24～0.39	200℃
Gasification Steam Ratio	–	0.28～0.56	150℃
Reforming Air Ratio	–	0.02～0.05	500℃
Chicken Manure Feed Rate	kg/day	2,000	25℃

6. Gasification Performance in the Continuous 90 Days Operation

Figure 3 shows the results of 90 days continuous operation. From this figure, we confirmed that although the first half of the operation showed some fluctuation, in the latter half of the operation, the heating value of the reformed gas increased and became stable at around our target value of 4MJ/Nm^3. Further, the un-burnt carbon in ash is almost less than 5% during the latter half operation, so it has been confirmed that the chicken manure has successfully been gasified stably. The continuous feeding system and the ash extracting system were trouble free during the continuous operation, and we have not experienced the stoppage due to tar and dust clogging. The residual ash with low carbon content can be sold as a fertilizer due to their rich contents of phosphorous and potassium and recent high rise of prices of these nutrients for chemical fertilizers.

Figure 4 shows the relationship between the gasification air ratio and the temperature in the combustion zone, where the arrow indicates the timing of steam injection. The increase of the gasification air ratio resulted in the increase of the temperature in the combustion zone at the bottom of the gasifier and it reached to 1000C. But by injecting steam, this temperature increase could be suppressed to avoid melting of ash.

Figure 5 shows the relationship between the gasification air ratio and the heating value of the pyrolysis gas. From this figure, it has been confirmed that when the gasification air ratio increases, the heating value of the pyrolysis gas increases too.

Figure 6 shows the relationship between the gasification air ratio and the treatment rate of chicken manure. It is confirmed that the treatment rate of chicken manure can be raised with the increase of the gasification air ratio due to acceleration of combustion of char.

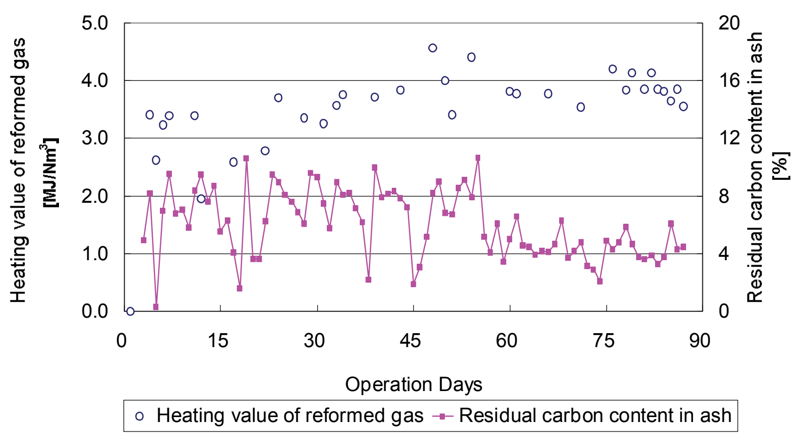

Figure 3. Time change of the heating value of the reformed gas and the residual carbon content in ash.

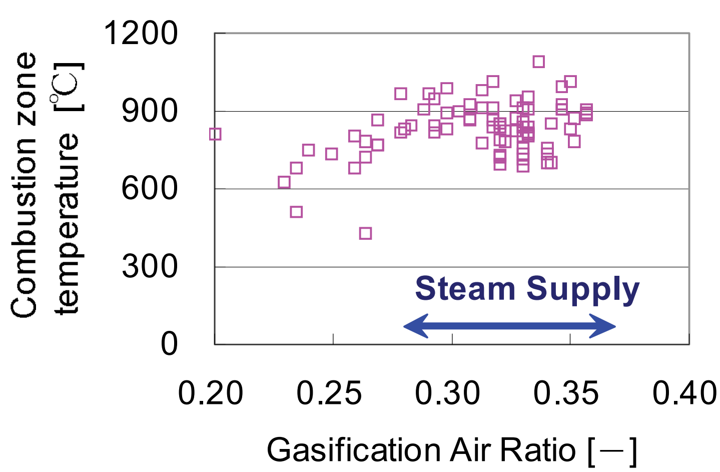

Figure 4. Relationship between the gasification air ratio and the temperature in the combustion zone.

7. Reforming Performance in the Continuous 90 Days Operation

Figure 7 shows the relationship between the reforming air ratio and the heating value of the reformed gas. The heating value of the reformed gas reached the maximum value of 4.5MJ/Nm^3, and it decreased gradually by increasing the reforming air ratio due to progress of partial combustion of burnable components in the pyrolysis gas.

Figure 8 shows the relationship between the reforming air ratio and the maximum temperature in the reformer. This figure clearly shows that the temperature rose with the increase of the reforming air ratio due to progress of the partial combustion. For confirmation of tar reforming performance, we have measured the tar concentration by the method shown in [3] at the exit of the gasifier and the reformer when the reforming air ratio was 0.035. The measurement results are shown in Table 3. The tar decomposition rate has successfully reached to more than 95%.

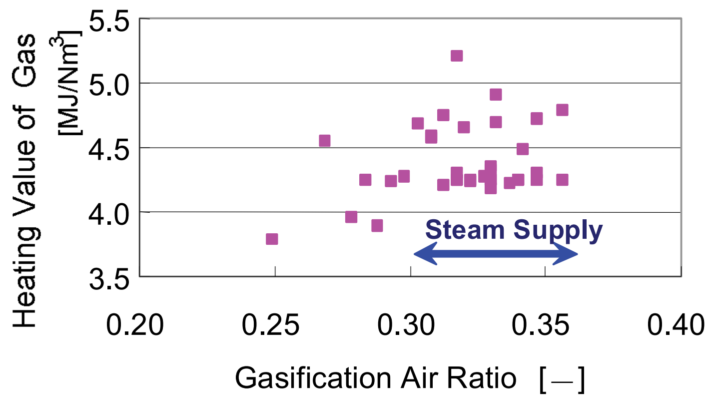

Figure 5. Relationship between the gasification air ratio and the heating value of the pyrolysis gas.

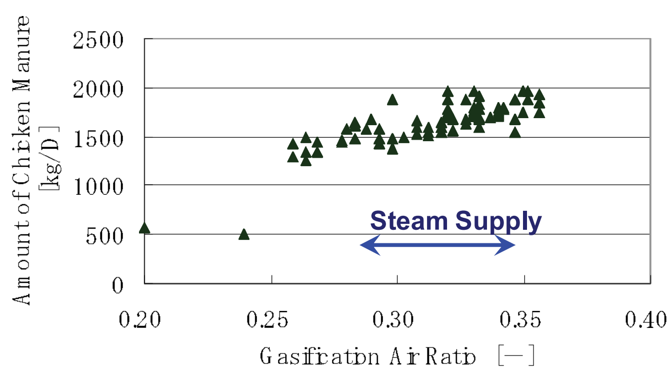

Figure 6. Relationship between the gasification air ratio and the treatment rate of chicken manure.

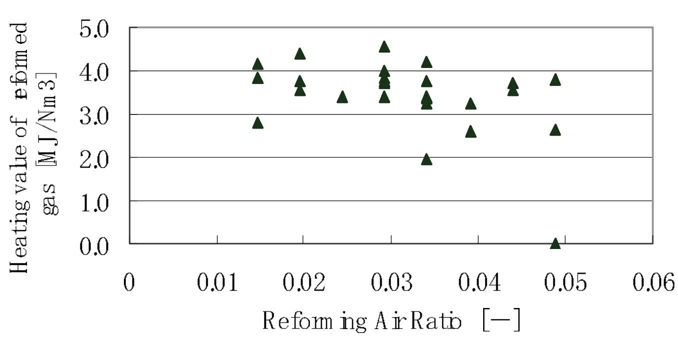

Figure 7. Relationship between the reforming air ratio and the heating value of the reformed gas.

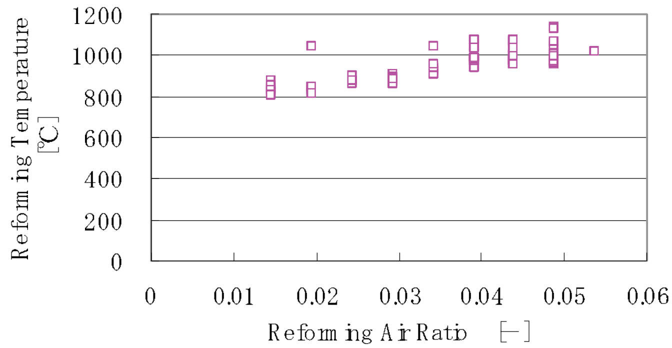

Figure 8. Relationship between the reforming air ratio and the maximum temperature in the reformer.

Table 3. Measurement results of the tar concentration in the produced gas at the exit of the gasifier and the reformer.

	Gasifier	Reformer	Tar Decomposition Rate
	g/Nm^3	g/Nm^3	%
Tar Concentration	4.00	0.18	95.5%

Table 4. Concentration of ammonia, hydrogen cyanide, NOx at the exit of the gasifier, reformer and the combustor.

Items	Unit	Gasifier	Reformer	Combustor
NH_3	ppm	31000	6.2	below2.0
HCN	ppm	4300	0.14	below0.1
NOx	ppm	10	7	220

Chicken manure contains much more nitrogen compared with wood chips. Therefore, we have measured the concentration of ammonia, hydrogen cyanide, and NOx in the pyrolysis gas and the reformed gas. The measurement results are shown in Table 4. We found out that there were significant content of ammonia and hydrogen cyanide in the pyrolysis gas, but they were almost completely decomposed in the reformed and combustion gases. In the combustor where a part of the pyrolysis gas combusted, the fuel NOx should be formed. But NOx concentration in the combustion gas was well below the emission standard.

8. Performance of a Dual-fueled Diesel Engine

Heating value of the gaseous fuel produced in this system is as low as 1/10 of that of natural gas, and there is almost no established energy conversion methods for such low-calorific gases. Therefore, we developed a dual-fueled diesel engine for burning low-calorific gases. At the start of the plant operation, the engine is fueled by diesel oil only. Then the produced low-calorific gas is gradually mixed into the combustion air, and in the steady state operation, 20-30% of the total thermal input is supplied by diesel oil, and 70-80% of the total thermal input is supplied by low-calorific gas. With this method, it is possible to keep the electrical output constant by controlling the amount of diesel oil supply even if the heating value of the gas fluctuates.

Table 5 shows the specification of the dual-fueled diesel engine generator installed. Its rated output is 64kW and it was successfully operated for 55 days during daytime only. No trouble has been observed due to tar contaminant.

Figure 9 shows the combustible components in the fuel gas as a function of the lower heating value (LHV) of the fuel gas. The main combustible components are CO and H_2, whose concentrations were about 15% and 10% respectively at the target value of the heating value of 4MJ/Nm^3.

Table 5. Specification of dual-fueled diesel engine.

Rated output	64kW
Revolutions	1800rpm
Cylinder No.	6
Total displacement	6.373 L
Compression ratio	17
Injection pressure	21.6MPa

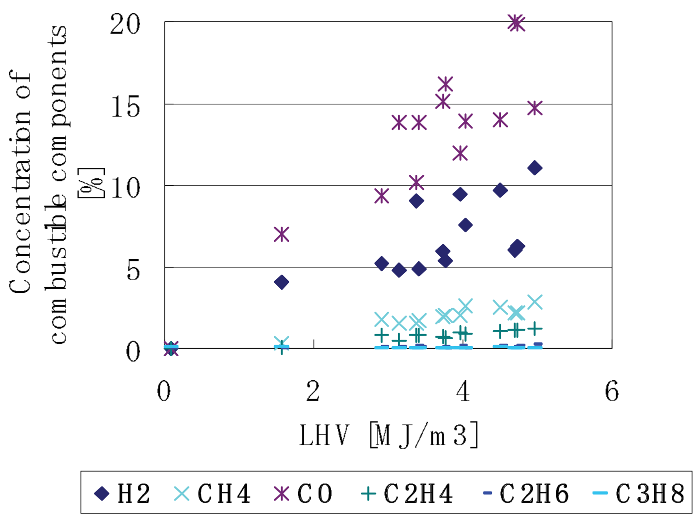

Figure 9. Combustible components of the fuel gas.

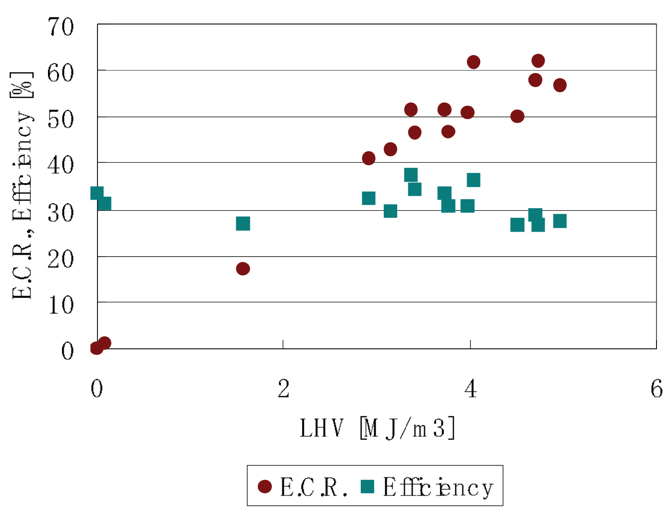

Figure 10. Thermal efficiency and energy contribution ratio.

Figure 10 shows the thermal efficiency (electrical output/ thermal energy of the fuel supplied into the engine) and the energy contribution ratio of the reformed gas (thermal energy input of the reformed gas/thermal energy of the fuel supplied into the engine) as a function of the lower heating value of the reformed gas. From this figure we can see that wide range fluctuation of the heating value of the fuel gas can be accepted by controlling the amount of diesel oil supply, and almost constant thermal efficiency of about 30% can be achievable regardless of the heating value of the fuel gas.

Figure 11 shows the CO and NOx emissions from the engine. Our experimental research results showed that the thermal NOx emission will drastically reduced while the CO emission will increase by increasing the supply of low-calorific fuel gas [2]. The results shown in this figure indicate almost constant NOx emission regardless of the heating value of the fuel gas (energy contribution ratio of the fuel gas), which needs further investigation to clarify the thermal NOx and fuel NOx contributions. We are going to install the catalytic combustor at the exit of the engine to reduce the CO emission.

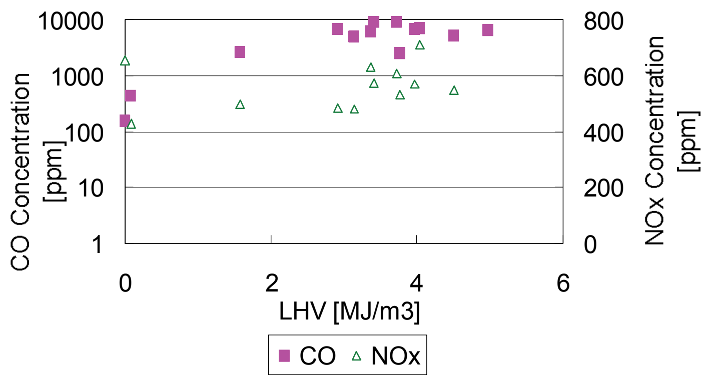

Figure 11. CO and NOx emissions from the dual-fueled diesel engine.

9. Energy Balance of the Commercial Plant

Finally, Table 6 shows the total energy balance of the commercial plant. In this table, the cold gas efficiency = chemical energy of the reformed gas/thermal energy of the chicken manure supplied into the gasifier and the gross thermal efficiency = electrical output of the engine/ thermal energy of the chicken manure supplied into the gasifier. From this table we can confirm that the cold gas efficiency, the carbon conversion efficiency and the gross thermal efficiency of 73.8%, 96.6% and 21.8%, respectively were achieved even though that chicken manure is difficult to be gasified compared with woody biomass due to its lower heating value and higher ash content.

Table 6. Energy balance of the commercial plant.

Items	Units	Values
Chicken Manure LHV	MJ/kg	10.3
Feed Rate of Chicken Manure	kg/h	90.0
Reformed Gas LHV	MJ/Nm^3	4.4
Flow Rate of Reformed gas	Nm^3/h	156
Cold gas efficiency	%	73.8
Carbon conversion efficency	%	96.6
Gross thermal efficiency	%	21.8

10. Conclusions

From the long term continuous operations of the commercial plant of gasification and power generation for chicken manure, we obtained the following conclusions:

i. We have successfully demonstrated continuous 90 days operation of the plant, and there was no stoppage of the plant by the clogging of tar and/or dust.
ii. By supplying steam into the pyrolizer, we have successfully increased the heating value of the pyrolysis gas and the treatment rate of the chicken manure.
iii. It is confirmed that the heating value of the reformed gas was stably at around $4MJ/Nm^3$, and tar and detrimental nitrogen compounds were almost decomposed in the reformer.
iv. The dual-fueled diesel engine generator was maintenance free during 55days continuous daily operation, and even if the heating value of the fuel gas fluctuated, almost constant power output and thermal efficiency could be obtained.
v. Even though that chicken manure is difficult to be gasified, we have successfully achieved the cold gas efficiency exceeding 70%, the carbon conversion efficiency exceeding 95% and the gross thermal efficiency exceeding 20% in this commercial operation of the plant.

11. References

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Author Biographies

Dr. Kunio Yoshikawa is a Professor of the Frontier Research Center, Tokyo Institute of Technology, Japan. He graduated from Tokyo Institute of Technology and obtained Ph.D. in 1986. After graduating from Tokyo Institute of Technology, Prof. Yoshikawa worked for Mitsubishi Heavy Industries for one year, and then returned to his home university as a Research Associate, then Associate Professor and Professor. His major research areas are energy conversion, thermal engineering, combustion, waste treatment technologies, and atmospheric environmental engineering. He has authored more than 200 papers. His main awards are the American Institute of Aeronautics and Astronautics (AIAA) Best Paper Award in 1999, the American Society of Mechanical Engineers (ASME) James Harry Potter Gold Medal in 2001, and the Japanese Society of Mechanical Engineers (JSME) Environmental Technology Achievement Award in 2006.