Development of a Biomass Gasifier which uses the Superheated Steam and its Application to Micro Co-Generation System

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ABSTRACT Micro scale gasifier of biomass, which are refuse derived fuel and wood pellets, using the superheated steam has been developed and the feasibility of the generation pyrolysis gas as a fuel for micro co-generation was verified. The thermal cracking experiments were conducted at the superheated steam temperature from 500 to 700 degree C. The quantitative analysis of pyrolysis gases were carried out and residue amounts of char and tar were determined. Moisture and tar in the pyrolysis gas were removed by a cooling device which was kept at 0 degree C. The calorific values of the pyrolysis gases were about 14 to 19 MJ/Nm³, and were 1/3 to 1/2 than that of town gas(13A). Then, the refined gas was supplied to a micro gas engine of 1 kW output as a fuel. The experiments were conducted repeatedly by changing the mixture ratio of pyrolysis gas and town gas. As a result, it turned out that the mixture of 13% of pyrolysis gas to the town gas is possible under keeping constant power output.

Keywords: Biomass gasification, Superheated steam, Refuse derived fuel, Wood pellet, Packed bed Gas engine, Micro co-generation

1. INTRODUCTION

Our humans' life depends on the fossil fuels that the drying up such as coal or oil is expected now. And, the conventional society system, which was premised on mass production, mass consumption and mass disposal, surpassed the natural purification ability and caused various environmental problems such as global warming or a waste problem. In such situation, biomass energy attracts attention from the viewpoint of carbon neutral tints. And a study of the gasification generation that used biomass for raw materials is developing rapidly.

On the other hand, RDF and wood pellet are known as a kind of the biomass. However, the use as the fuel of these biomass does not spread out. If a gasification of the biomass is made, the use as the fuel spreads, and the application to the gas engine is enabled.

Therefore, in this study, we carried out the development of the pyrolysis gasification facility which uses superheated steam as heating medium. And we examined those pyrolysis gases' feasibility as fuels for small gas engines of the co-generation.

At first we examined a pyrolysis characteristic of the RDF in the superheated steam atmosphere experimentally and got fundamental knowledge for gasification facility development. Next, we built a simple calculation model in order to predict quantity of gas generation in the pyrolysis gasification process of the biomass. And we run the simulation and predicted quantity of pyrolysis generation gas from both the heat balance and the mass balance. In addition, in a pyrolysis process, we measured the temperature change of the sample, RDF and an ingredient of the pyrolysis generation gas and examined utility as the gas fuel of the RDF from an experiment and the theoretical both sides. Furthermore, we performed a proof experiment to use refined gas for as gas engine fuel.

2. GASIFICATION EXPERIMENT
2.1 Experiment Setup
(a) Pyrolysis characteristics experiment facility

Figure 1 shows the outline of the pyrolysis experimental setup which examines basic properties of
matter and a pyrolysis characteristic of the RDF experimentally. A single pellet of the RDF to show in figure 2 was inserted in test sections in the figure, and the mass change of the pellet was measured by an electronic balance. In addition, the basic properties of the RDF are shown in table 1.

![Fig. 2 Photo of RDF pellet](image)

Table 1 Basic properties of RDF test pellet

<table>
<thead>
<tr>
<th>Higher heating Value MJ/kg</th>
<th>19.34</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lower heating Value MJ/kg</td>
<td>17.74</td>
</tr>
</tbody>
</table>

Proximate Analysis wtv:  
- Moisture: 5.83
- Volatile: 80.9

Ultimate Analysis wt%:  
- C: 42.50
- H: 6.00
- N: 0.96
- O: 30.11
- S: 0.05
- Cl: 0.50

The experimental facility consists of a boiler, a blower, a superheater and a test section. The generated saturation steam is heated by superheater 1, and flow rate is measured with a flowmeter. It is heated with superheater 2 and 3, and the saturation steam becomes the superheated steam and flows in in a test section afterwards. A thermocouple is set up in a test section, and pyrolysis temperature is set in the targeted value by the temperature adjustment. The temperature of the superheated steam is coordinated between 373K - 1073K voluntarily. RDF hung from an electronic balance by a wire and cotton yarn is installed in the test section, and a mass change of the RDF is measured. Superheated steam is supplied at velocity of 1m/s in a test section.

(b) Gasification experiment facility

Figure 3 shows the outline of the RDF gasification facility.

The RDF gasification device consists of a boiler, a superheater, a heater for thermal insulation, RDF filling part, the condensation part, cooling part, a filter and a multiplication flowmeter. The generated saturation steam is adjusted to arbitrary temperature, flow quantity by a boiler. It is heated by a superheater and becomes the superheated steam and flows in a test section afterwards. The RDF filled up a test section is heated by superheated steam, and pyrolysis gas is generated.

Table 2 shows temperature of the superheated steam in the experiment and flow quantity and quantity of filling of the RDF. In addition, table 3 shows physical properties of the RDF (Omuta RDF power plant’s data).

![Fig. 3 Outline of experimental setup for biomass gasifier with superheated steam](image)

The RFD gasification device consists of a boiler, a superheater, a heater for thermal insulation, RDF filling part, the condensation part, cooling part, a filter and a multiplication flowmeter. The generated saturation steam is adjusted to arbitrary temperature, flow quantity by a boiler. It is heated by a superheater and becomes the superheated steam and flows in a test section afterwards. The RDF filled up a test section is heated by superheated steam, and pyrolysis gas is generated.

Table 2: Experiment condition of RDF gasification

<table>
<thead>
<tr>
<th>Flow Rate $G_{steam}$ kg/h</th>
<th>Flow Temperature $T_{steam}$ K</th>
<th>Mass of RDF $M$ kg</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>15</td>
<td>823</td>
</tr>
<tr>
<td>2</td>
<td>13</td>
<td>823</td>
</tr>
</tbody>
</table>

Table 3: Physical properties of RDF

<table>
<thead>
<tr>
<th>Density $\rho$, kg/m$^3$</th>
<th>Thermal Conductivity $\lambda$, W/(m·K)</th>
<th>Specific Heat $c_p$, J/(kg·K)</th>
<th>Porosity $\varepsilon$</th>
</tr>
</thead>
<tbody>
<tr>
<td>RDF</td>
<td>1154</td>
<td>0.29</td>
<td>1097*(3.44*10$^{-5}$). T</td>
</tr>
</tbody>
</table>

2.2 Results

(a) Pyrolysis characteristic of the RDF

Figure 4 and figure 5 show the result of the pyrolysis experiment. Figure 4 shows temperature of the superheated steam and the relations of the mass decrement of the RDF.

![Fig. 4 Fraction of residue of RDF pellet by different flow Temperature](image)

The mass decrement of the RDF $(1-X)$ is defined in the next expression from reaction rate $X(t)$. In addition, reaction rate $r(t)$ is given by a time change of reactant mass $W(t)$ shown in the equation 2.

$$X(t) = \frac{W_{\text{initial}} - W(t)}{W_{\text{initial}}}$$  \hspace{1cm} (1)

$$r(t) = \frac{1}{A} \frac{dW}{dt} = \frac{1}{A} \frac{W(t) - W(t+1)}{dt}$$  \hspace{1cm} (2)

As temperature of the superheated steam rises with 673K, 773K from 573K, mass decrease speed of the RDF
suddenly grew higher. In addition, the mass of the RDF was in inverse proportion to a temperature rise of the superheated steam and suddenly decreased.

Figure 5 shows mass decrement of the RDF by the pyrolysis and the relations of the reaction velocity. The reaction rate suddenly increased with mass decrement (1 - X) decreasing from 1 to 0.9 first. The reaction rate increased slowly afterwards till mass decrement (1 - X) decreased to around 0.5. Furthermore, if a mass decrement of the RDF (1 - X) became smaller than 0.5, reaction rate r suddenly deteriorated and became approximately 0 with around 0.3.

![Graph showing mass decrement of the RDF and reaction velocity](image)

**Fig. 5** Mass decrement of the RDF and the relations of the pyrolysis reaction rate

(b) Gasification experiment of the RDF and wood pellet

Figure 6 shows an example of the measurement result of the quantity of pyrolysis gasification. The quantity of RDF filling of this time is 4.5kg.

![Graph showing gasification rate of pyrolysis gas](image)

**Fig. 6** Gasification rate of the pyrolysis gas

0 seconds of the horizontal axis means the time when saturation steam heating was started by the super heater. Ingredient analysis of the pyrolysis gas was performed at the time of 1200, 2100 and 3000 seconds from an experiment start. In time to be shown in the figure, the quantity of pyrolysis gasification was not influenced most of the current of air temperature and showed the same tendency. And the quantity of greatest outbreak became 18 liters after a heating start in 1500 seconds.

In addition, the ingredient analysis of pyrolysis gas stored up in a tank after an experiment start by 3000s from 900s was performed. Ingredient analysis in superheated steam temperature 973K (700 degrees Celsius) is shown in table 4. The lower heating value of pyrolysis gas stored up in a tank was 13.69 MJ/Nm³. The values at 1200, 2100 and 3000 second mean instantaneous value.

Table 4  Calorific properties of pyrolysis gas

<table>
<thead>
<tr>
<th></th>
<th>Unit</th>
<th>1200s</th>
<th>2100s</th>
<th>3000s</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Higher Heating</td>
<td>MJ/Nm³</td>
<td>13.28</td>
<td>30.72</td>
<td>31.94</td>
<td>14.90</td>
</tr>
<tr>
<td>Lower Heating</td>
<td>MJ/Nm³</td>
<td>12.32</td>
<td>27.93</td>
<td>28.96</td>
<td>13.69</td>
</tr>
<tr>
<td>Density</td>
<td>kg/Nm³</td>
<td>1.66</td>
<td>1.06</td>
<td>1.04</td>
<td>1.44</td>
</tr>
<tr>
<td>Burning Velocity</td>
<td>cm/s</td>
<td>15.93</td>
<td>39.92</td>
<td>40.91</td>
<td>19.36</td>
</tr>
<tr>
<td>Wobbe Index</td>
<td>kJ/Nm³</td>
<td>11.70</td>
<td>33.63</td>
<td>35.61</td>
<td>14.11</td>
</tr>
</tbody>
</table>

Temperature distribution of the test section inside and quantity of per one minute gas generation are shown in figure 7. The temperature of the superheated steam of this time is 823K, and the flow rate is 15kg/h. Three points of thermometry positions are distance from the upper end of test section part ( RDF filling part) of figure 3. In addition, in the figure, ingredient analysis of the pyrolysis gas at the time of 1200, 2100 and 3000 seconds from an experiment start are shown.

![Graph showing temperature and gasification rate change](image)

**Fig. 7** Temperatures in the test section and Gasification rate change with time (Ts=823 K, Flow rate=15 kg/h)

The temperatures at 150, 300, and 450 mm finally exceeded pyrolysis temperature (780K) of the RDF, too. In addition, the pyrolysis of the RDF occurred to two phases across 630K. Carbon dioxide occurred to a large quantity (about 60%) by the first phase reaction, and most of the methane and the hydrogen were not had in generation gas. On the other hand, the gas which included methane and hydrogen abundantly was provided by the second phase reaction from one phase of end game, and the ingredient ratio of the hydrogen was greatest, and it increased to 27%. The ingredient ratio of the carbon dioxide was equal to or less than 20% then.

Furthermore, the ingredient ratio of the hydrocarbon fell so that RDF filling part temperature became the high temperature, and the generation gas which was hydrogen rich was provided.

3. SIMULATION

3.1 Physical Model and Basic Equations

Figure 8 shows the simple analysis model of the
pyrolysis gasification in the RDF filling part. The superheated steam flows into the gasification furnace in temperature $T_F$ and passes through $n$ layer from one level, and it is discharged from a gasification furnace to the outside (the lower part).

![Diagram of pyrolysis gasification](image)

Fig. 8 Simple analysis model of the pyrolysis gasification in the RDF filling part

In calculation, the test section was divided into $n$ pieces, $\Delta L$, along the direction of a flow of an air current. And the quantity of heat transfer while superheated steam passes distance $\Delta L$ was calculated. Then heat transfer occurs in the RDF by conduction, convection, and radiation. In addition, each layer was decided so that the Bio number became smaller than 0.1(-). And lumped heat capacity method was applied to the solid part of RDF.

(a) Heat balance equations;

Because it is thought that the temperature of the RDF is different from the superheated steam which is a heating medium, it is handled as two phase. The unsteady heat balances about both superheated steam and the RDF are shown to equations 3 and 4[1]. $Q_r$ of the equations are heat transfer term by the radiation to show to equation 5.

$$\rho c_{pF}\frac{\partial T_F}{\partial t} + (u \cdot V_T) = (\nabla \cdot \lambda_T \nabla T_F) + ha(T_S - T_F) - Q_r + H$$

$$(1 - \varepsilon) \rho c_{ps}\frac{\partial T_S}{\partial t} = (\nabla \cdot \lambda_S \nabla T_S) - \rho a(T_S - T_F) + Q_r - W$$

$$Q_r = \phi \sigma(T_F^4 - T_S^4)$$

(b) Mass balance equations

Equation 6 is a material income and expenditure expression of the RDF. In addition, equation 7 is a gasification reaction rate expression. Furthermore, the pyrolysis reaction is assumed first order reaction and gave it with equation 8.

$$\rho f_i \frac{\partial x}{\partial t} = R(x, T)$$

$$R(x, T) = \rho f_i A_i \exp\left[-\frac{E_i}{RT}\right](1-x)$$

$$x = \frac{W_{x0} - W_x}{W_{x0}}$$

3.2 Results

(a) Prediction of the quantity of pyrolysis gas

Temperature changes in each position of the RDF filling part by an experiment and the calculation are shown in figure 9. The temperature change by the calculation result showed a monotonous upward trend. On the other hand, the experiment result showed a temperature change divided into two steps. Here, we try to think about the difference of a calculation result and the experiment result. It is known for the temperature level of the neighborhood of 600K to have reaction an equation (9) and shift reaction, methane shown in the equation (10) frequently[2][3].These reaction is endothermic reaction. And the calorific value is approximately equal with heat of combustion of the hydrogen, and it is about 200kJ/mol. In other words about 0.31kW endotherm happens in the vicinity of 600K, and it is thought that temperature deteriorated.

$$CO + H_2O \rightarrow CO_2 + H_2 \quad (\Delta H_{298} = -41.2kJ/mol)$$

$$CO + 3H_2 \rightarrow CH_4 + H_2O \quad (\Delta H_{298} = -206.1kJ/mol)$$

$$C_nH_m + 2nH_2O \rightarrow \left(2n + \frac{m}{2}\right)H_2 + nCO_2 \quad (\Delta H_{298} > 0)$$

![Comparison of temperature profiles between calculation and experiment](image)

On the other hand, resolution exothermic reaction of hydrocarbons shown in the equation (10) occurs by the second phase reaction. On this account it is thought that it followed that experimental value exceeds a calculation value.
The comparison of the quantity of gas generation by a calculation and the experiment is shown in figure 10. Quantity of gas generation by the calculation is slower than the experiment result. On the other hand, as for the experiment result, the peak of the quantity of gas generation emerged after an experiment start in the vicinity of 1700 seconds so that pyrolysis of the RDF went in a low temperature domain. On this account the quantity of gas generation showed a tendency to have a point of inflection toward on the way. It is guessed that there is the cause of the difference between both in the pyrolysis characteristic of RDF raw materials.

(b) Comparison of the pyrolysis characteristic of the wood pellet to the RDF

Figure 11 shows the wood pellet. And the basic properties of the wood pellet are shown in table 5.

<table>
<thead>
<tr>
<th>Biomass</th>
<th>wood pellet</th>
</tr>
</thead>
<tbody>
<tr>
<td>Higher heating Value MJ/kg</td>
<td>-</td>
</tr>
<tr>
<td>Lower heating Value MJ/kg</td>
<td>17.14</td>
</tr>
<tr>
<td>Proximate Analysis wt%</td>
<td></td>
</tr>
<tr>
<td>Moisture</td>
<td>7.5</td>
</tr>
<tr>
<td>Volatile</td>
<td>77.8</td>
</tr>
<tr>
<td>Ash</td>
<td>0.3</td>
</tr>
<tr>
<td>Ultimate Analysis wt%</td>
<td></td>
</tr>
<tr>
<td>O</td>
<td>46.5</td>
</tr>
<tr>
<td>H</td>
<td>6.0</td>
</tr>
<tr>
<td>N</td>
<td>0.1</td>
</tr>
<tr>
<td>G</td>
<td>46.4</td>
</tr>
<tr>
<td>S</td>
<td>0.01</td>
</tr>
<tr>
<td>Cl</td>
<td>0.01</td>
</tr>
</tbody>
</table>

Figure 12 shows an example of the measurement results both of the quantity of pyrolysis gasification and multiplication outbreak quantity of gasification. The quantity of wood pellet of this time is 5.8 kg. 0 seconds of the horizontal axis means the time when saturation steam heating was started by the super heater.

The experiment result about the quantity of gasification per one minute considerably exceeded a calculation result and grew big than 2.5 times by the comparison with the quantity of maximum outbreak. On the other hand, the experiment result and the calculation result became approximately equal when they compared it with quantity of multiplication gasification. However, by the comparison of the end time for pyrolysis, the calculation result came to have a long 40% in comparison with the experiment result.

Figure 12 Comparisons between calculation and experiment both of gasification quantity per one minute and multiplication quantity of gasification

Table 6 shows each ratio of quantity of outbreak gas and quantity of tar and the quantity of the char provided by a pyrolysis gasification of a wood pellet and the RDF. At the time of condition of RUN1 that temperature of the superheated steam was the highest than the other cases, the cold gas efficiency became 14.0% at the maximum. In addition, each ratios that a char and tar held to a product then decreased. This is because carbon included in a char and tar was done a gasification of by pyrolysis. In addition, from comparison with the RDF, about 10% ratios of the tar decreased in all experiment conditions in the case of a wood pellet.

| Table 6 Energy balance of wood pellet and RDF |
| RUN1 | RUN2 | RUN3 | RDF |
| gas (%) | 14.0 | 11.8 | 11.6 | 11.2 |
| char (%) | 41.5 | 43.4 | 43.5 | 34.7 |
| tar (%) | 44.5 | 44.8 | 44.9 | 54.1 |

4. FEASIBILITY OF THE PYROLYSIS GAS TO MICRO CO-GENERATION

Application possibility of the pyrolysis gas as the gas engine fuel for co-generation was examined both experimentally and theoretically. The experiment was performed by a method to mix pyrolysis gas to town gas 13A.

Figure 13 shows a change of higher heating value $H_0$ and Wobbe index $WI$ and the combustion speed $SM$ when a
mixture ratio of the pyrolysis gas changed. About 60% carbon dioxide was included in pyrolysis gas. Therefore combustion speed SM became 2.63cm/s and 6.7% of the town gas. Higher heating value \( H_\text{b} \) became 8933 kJ/Nm\(^3\) and became 21.2% of the town gas. When a gas engine was impossible of consecutive movement, ratio \( P_e \) of the pyrolysis gas was 33.3Vol\%, and, as for higher heating value \( H_\text{b} \) of the mixture, as for 35000 kJ/Nm\(^3\), Wobbe index \( W_i \), 37000 kJ/Nm\(^3\), the combustion speed SM were 31cm/s.

About a case used pyrolysis gas for as fuel, prediction simulation of the output performance of the small gas engine was carried out [4]. The specifications of the small gas engine which is necessary for a calculation are shown in table 7. And an example of the prediction result is shown in figure 14.

### Table 7 Specifications of the small gas engine

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crank radius</td>
<td>0.027 m</td>
</tr>
<tr>
<td>Length of the conrod</td>
<td>0.09 m</td>
</tr>
<tr>
<td>Revolution speed</td>
<td>2050 rpm</td>
</tr>
<tr>
<td>Void volume</td>
<td>18.3 cc</td>
</tr>
<tr>
<td>Engine displacement</td>
<td>18.3 cc</td>
</tr>
<tr>
<td>Piston radius</td>
<td>0.031 m</td>
</tr>
<tr>
<td>Initial pressure</td>
<td>0.1 MPa</td>
</tr>
<tr>
<td>Initial temperature</td>
<td>300 K</td>
</tr>
<tr>
<td>Air ratio</td>
<td>1</td>
</tr>
<tr>
<td>Specific heat ratio</td>
<td>1.33</td>
</tr>
<tr>
<td>Compression ratio</td>
<td>11</td>
</tr>
<tr>
<td>Ignition timing</td>
<td>-22 deg</td>
</tr>
</tbody>
</table>

![RDF Pyrolysis gas vs 13A gas](image_url)

**Fig. 14** Prediction of the gas engine power output

Calculation results when RDF pyrolysis gas and town gas 13A were used for fuel were shown in the figure. In the case of the RDF pyrolysis gas, the maximum pressure of the engine deteriorated in 10MPa from 13MPa for the fall of the heating value. In addition, as for the engine output, 20% decreased as a result of this.

**5. CONCLUSION**

(a) In the RDF pyrolysis experiment that used superheated steam for a heating medium, generation gas of 0.47m\(^3\) was provided from raw materials of 4.5kg at the maximum. In addition, the cold gas efficiency became 12.3% then.

(b) By the gasification experiment of woody pellet, the cold gas efficiency became 14.0% at the maximum. In addition, each ratios that a char and tar held to a product then decreased. Furthermore, from the comparison with the RDF, the tar ingredient in the pyrolysis product was decreased about 10% in the case of a wood pellet.

(c) The proposed pyrolysis gas generation prediction model was able to predict temperature distribution and pyrolysis gas generation quantity of the RDF at the test section.

**REFERENCES**


**NOMENCLATURE**

\[ A \] : area [m\(^2\)]
\[ A_i \] : frequency factor [1/s]
\[ a \] : specific surface area [1/m]
\[ c_p \] : specific heat at constant pressure [kJ/kg·K]
\[ E \] : activation energy [kJ/mol]
\[ f \] : volatilization rate [-]
\[ G \] : mass flow rate [kg/h]
\[ H \] : heating value [kJ/Nm\(^3\)]
\[ h \] : heat transfer coefficient [W/m\(^2\)·K]
\[ L \] : quantity of multiplication generation gas [m\(^3\)]
\[ l \] : gasification rate [m\(^3\)]
\[ M \] : mass [kg]
\[ P \] : ingredient of pyrolysis gas [%]
\[ Q \] : heat quantity [kJ]
\[ R \] : gas constant [kJ/K·mol]
\[ \dot{r}(X,t) \] : reaction rate [kg/(m\(^2\)·s)]
\[ T \] : temperature [K]
\[ t \] : time [s]
\[ u \] : velocity [m/s]
\[ w \] : reactant mass [kg]
\[ X \] : reaction rate [-]
\[ \dot{f} \] : mass decrement [-]
\[ x \] : local reaction rate [-]

**Greeks**

\[ \Delta H \] : enthalpy change [kJ/mol]
\[ \Delta L \] : length of calculation element [m]
\[ \varepsilon \] : porosity [-]
\[ \eta \] : efficiency [-]
\[ \lambda \] : thermal conductivity [W/m·K]
\[ \rho \] : density [kg/m\(^3\)]
\[ \sigma \] : stefan-Boltzmann constant [W/m\(^2\)·K\(^4\)]
\[ \phi \] : angle factor [-]