A case study of woody biomass heat supply system for Japanese large-scale mushroom production farm

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Abstract: This paper introduces a woody biomass heat energy system built for heat supply to a large-scale mushroom production farm in Iwate prefecture in Japan. The characteristic feature of this system is to use cheap waste wood bark with high water content as the raw material, supplying hot water and steam from biomass boilers for heating the mushroom cultivation houses. During the period when the heat demand of the cultivation house decreases, it is possible to produce high calorific value dry wood fuel from raw wet biomass utilizing boiler surplus heat. This dry wood fuel is stored on site and can be flexibly used within the plant as needed. It is also possible to deliver the stored dry wood fuel to other local boilers or cogeneration facilities in the surrounding area as fuel. A material-thermal equilibrium simulation model of the plant was established, and various energy performance simulations were conducted. According to the simulation, when supplying the hot water rated heat of 1100 kW, the energy efficiency to the calorific value of the input wet bark fuel (with 55% water content by wet basis) is calculated as 76.8%, where the heat amount of the surplus dry wood fuel is included as effective energy output. Analysis of exergy (maximum useful work obtained from energy theoretically) was also performed for the same case. The effective utilization of exergy of two heats (i.e., hot water and surplus dry fuel) was 45.1% against the exergy of the wet input fuel. This value is considered to be much larger than the exergy evaluation in the case of large-scale biomass power generation.

1. Introduction

Shiitake is a very popular food ingredient in Japan, and the production of shiitake mushrooms in Japan reached about 70,000 tons in 2016, 89% of which were produced by sawdust block bed cultivation in special houses [1]. This house-cultivation method has made the mushroom mass production highly efficient because the process of growing mushrooms from incubation to harvesting can be completed at periodical intervals by artificial temperature and moisture controlling in the air conditioning facility and has made shipping possible regardless of the season. On the other hand, in such house cultivation throughout the year, a large amount of energy is required to keep the proper temperature inside the house. Liquid fuels such as kerosene have been used for this air-conditioning energy in heating, and in many cases, it is covered by electricity for cooling. However, in recent years, attempts have been started to make the most of unused woody biomass resources such as residual scraps from the forest and sawdust waste from sawmills as local energy sources. The use of energy obtained from such biomass resources is also expected to reduce greenhouse gas emissions derived from fossil fuels.

In Japan, the biomass power generation business using the Feed-in Tariff (FIT) system introduced from fiscal 2012 is rapidly spreading. In order to ensure the profitability of woody biomass power generation projects, large generation capacity is required [2]. In fact, considerable numbers of projects which have scales of tens of thousands of kW or more capacity are already running or being planned. Large power capacity requires a large amount of fuel, so there are many cases that depend on the import of large amounts of pellets and PKS (Palm Kernel Shell) from overseas [3,4]. On the other hand, the biomass system that supplies the heat of combustion of woody biomass to local heat demand, rather than the power generation system, may be able to obtain business profitability even with smaller equipment. For example, it is estimated that if the heat energy produced by a biomass heat supply plant is fully utilized, the plant can achieve profitability in under 240 actual operation days annually from a scale of 10 ton or more biomass input per day [5]. The main problem in supplying heat with biomass is that the thermal energy demand generally varies with time, day, or season so that efficient constant heat supply operation is difficult. One possible solution is to produce and store high calorific value dried wood fuel using the surplus heat during the time when the heat demand drops, and surplus heat is generated. This proposal has the potential to compensate for the gap between efficient thermal production and fluctuating thermal demand.
This paper reports a case of a woody biomass heat supply plant for large-scale mushroom cultivation houses built in Iwate Prefecture, Japan, as one of regional biomass energy systems. This biomass plant (from now on 'the target plant') has two biomass boilers, the first boiler supplies the necessary heat to keep the required temperature in the mushroom cultivation houses, and the second supplies steam for sawdust bed block sterilization.

One of the characteristic features of this plant is to use wet waste bark from a sawmill factory as a cheap raw material. The bark is the leftover waste after the processing of Japanese red pine (Pinus densiflora) timber harvested from regional forests. Usually bark material has high ash content and high moisture (water content between 50-70% wet bases), therefore it is normally difficult to use as the boiler fuel directly. Example study reports on general properties and uses of bark are referenced to [6, 7].

Another feature of this plant is that dry wood fuel having a high calorific value can be produced by boiler surplus heat from the input raw material (wet bark) during the time when the cultivation house heat demand (i.e., hot water demand) decreases. The water content of the produced dry wood fuel is designed to be approximately 15%. This water content value meets the European Pellets Standard EN14961-1 M15 [8]. Therefore most biomass boilers and cogeneration facilities are expected to accept wood fuel (pellet or chip) with this dry level.

This dry wood fuel is stored on site and can be used within the plant as needed. It is also possible to deliver the stored dry wood fuel to other local boilers or cogeneration facilities in the surrounding area. The flexibility of such "store and use" of dry wood fuel can compensate for the temporal and distance difference that occurs between heat production and its demand.

2. Methodology

It is highly important to predict in detail the operating performance under various conditions related to the actual heat supply plant, to prevent problems that may occur in the plant, thereby realizing stable operation. For this purpose, the authors established a material-thermal equilibrium simulation model for the above biomass heat supply plant and conducted various energy performance simulations. Moreover, in addition to the energy evaluation using conventional enthalpy, analysis of exergy was also conducted in order to evaluate the possibility of effective energy use in the target plant.

This study was conducted mainly according to the following procedure.

- Detail of heat demand such as hot water and steam required for shiitake mushroom cultivation was surveyed.
- System design for the target plant construction was summarized, and features of the plant were clarified.
- A material-thermal equilibrium simulation model for the target plant was established.
- Plant mass and thermal energy simulation using the established simulation model was conducted to achieve various performance predictions.
- Analysis of exergy (maximum useful work obtained from energy theoretically) was also performed for the representative plant operation case.

For each item, study result and discussion are reported in the following cession.

3. Results and Discussion

3.1. Survey of heat demand required for shiitake mushroom cultivation

Heat capacities of the biomass boilers were decided considering fluctuation of heat demands required for the shiitake mushroom cultivation process as follows.

3.1.1. Heat demand for cultivation house heating

Detailed guidelines on how to grow shiitake mushrooms are disclosed by many agriculture-related organizations ([9] as an example). In the shiitake cultivation process, one cycle period from sawdust block incubation to harvesting takes around one year. During this period, the house temperature must be strictly controlled to appropriate values according to the stage of cultivation. Including future plans, 60 cultivation houses are to be built in total, and each house will be operated having some weeks shifting of the cultivation cycle schedule in order to facilitate mushroom shipping throughout the year. The layout of each cultivation house is shown in figure 1, and a view of the cultivation houses is shown in figure 2.
In each house, sawdust bed blocks are arranged in a line on multiple shelves, and the cultivation process is proceeded by controlling the temperature at between about 10-20 °C corresponding to the cultivation stage. About 15,000 blocks are cultivated in one house. The inside of the house is shown in figure 3.

Although each house has a heat insulating structure, the inside temperature is significantly influenced by the outside air temperature by day and season. Considering these conditions, it is necessary to calculate the maximum and the minimum heat supply necessary for air conditioning in the houses. In Iwate Prefecture, located in the northern part of the Japanese Archipelago, the average temperature in January and February is about -1 °C due to the cold climate. On the other hand, the average temperature in August is around 23 °C. Therefore, the heat demand for cultivation houses is the largest in January, and heat supply from the external heat source in summer is unnecessary because of the seasonal fluctuation in heat demand as shown in figure 4.
On a typical day in January, when the demand for heat is the maximum, a change in the energy demand for heating in the whole 60 cultivation houses due to the influence of the outside temperature is predicted to be as shown in figure 5. At the peak time, there is a heat demand of 1100 [kW]. If the boiler operation is constantly maintained at this output, there will be excess heat generated than is necessary for most hours and days.

![Figure 5. Typical heat demand trend during 24 hours of a winter day.](image)

The heat demand required for the cultivation houses is planned to be supplied by hot water of 80 °C from a biomass boiler. Based on heat demand characteristics in figure 5, 1200 kW was selected as the combustion heat capacity of the boiler. However, as described above, in order to maintain stable operation of the boiler for 24 hours, excessive heat generated by the boiler should be efficiently utilized somehow.

### 3.1.2. Steam requirement for sawdust bed block sterilization

Before entering the cultivation process, sawdust bed blocks must be sterilized. The sterilization process requires high-temperature steam in a 5-hour cycle for every 1000 blocks in a batch, and it is planned to sterilize 4 batches a day at maximum production. To meet this, the maximum amount of steam required to the steam boiler is calculated to be 700 [kg/h]. Unlike the case of hot water supply for heating, the amount of steam necessary for sterilization does not change with the season, but it depends on the production amount of the sawdust bed block. Therefore, excess heat of the steam boiler occurs depending on the time. As one method to utilize the excess steam, future plans include installing steam driven chillers to supply cold water in summer to the cultivation houses for temperature conditioning.

### 3.2. Construction design and features of the target plant

The target plant is a biomass heat supply system which is designed to cover the heat demands in the shiitake mushroom cultivation process as described in section 3.1. This system is designed and constructed with the following features.

1) The plant has a hot water boiler, and a steam boiler, each of them operates independently.
2) In order to satisfy the winter season peak heating demand of 60 mushrooms cultivation houses, the hot water boiler has an output heat capacity of 1200 kW.
3) The steam boiler can supply a maximum steam amount of 700 [kg/h] to the sterilization process.
4) As the main part of input biomass material to the plant, waste wet bark (Japanese red pine) supplied by a sawmill factory is used. The bark material has a high-water content between 50-70% (wet basis). The representative low heating value of this bark material is measured as 19.0 [MJ/kg-dry basis].
5) Other woody biomass materials can also be supplied as input to the target plant, such as wood tips, waste sawdust bed blocks, and their mixed material with bark.
6) Since standard wood boilers are used in the plant, boiler input fuel is requested to be dried to achieve less than approximately 15% water content. To achieve this condition, this plant is designed to have combustion exhaust gas from the boilers returned to the dryers in order to heat the input wet fuel and to decrease the water content to about 15%.
7) As described in (6) dry wood fuel is obtained at the exit of the dryers and fed to the boilers. After being fed to the boilers, if surplus dry fuel remains, it is to be stored in the storage silo. This stored dry fuel can be used as necessary in the plant or transported to other local boilers in the vicinity area as their fuel.
Figure 6. Flow diagram of woody biomass heat supply system for mushroom cultivation houses.

Construction of the target plant was conducted by Toshiba Corporation according to the above-mentioned characteristics. The plant construction was completed in 2016. The system flow diagram of the target plant built is shown in figure 6. The view of the plant is shown in figure 7. Figure 8 is a plan view of the entire facility showing the arrangement of the target plant and the cultivation house group.

Figure 7. View of biomass heat supply system.

Figure 8. Plan view of the entire facility.

3.3. Material-thermal equilibrium simulation model for the target plant

The authors established a material-thermal equilibrium simulation model of the target plant and conducted energy performance predictions using the simulation model. The model was made using Excel. In the first step, a software module of each plant component was created one by one based on general definition formulas or theoretical expressions reflecting characteristics at the rated value given in the component catalog and specification documents. The mass flow rate and enthalpy were calculated as an index of material balance and energy balance at input and output of each component module. Regarding material balance, the mass balance of each elemental component (C, H, O, N, and S) in solids, liquids and gases, was calculated. Regarding energy balance, specific enthalpy was calculated for each substance (wood, air, water, steam, gas components). The specific enthalpy calculation formulas used in the simulation model are listed in table 1.
Table 1. Specific enthalpy calculation formulas used in the model

<table>
<thead>
<tr>
<th>Component</th>
<th>Specific enthalpy calculation formula</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Wood</strong></td>
<td>Specific heat of dry wood $[\text{kcal/kg} \cdot ^\circ \text{C}] = 0.266 + 0.00116 \cdot t$</td>
</tr>
<tr>
<td></td>
<td>$h [\text{kcal/kg}] = \int_0^{T(\circ \text{C})} (0.266 + 0.00116 \cdot t)dt$</td>
</tr>
<tr>
<td><strong>Air</strong></td>
<td>$h [\text{kcal/kg}] = \text{dry air enthalpy} + \text{steam enthalpy}$</td>
</tr>
<tr>
<td></td>
<td>$= 4.186 \times {0.240 \cdot t + (597.3 + 0.441 \cdot t) \cdot X}$</td>
</tr>
<tr>
<td></td>
<td>$t[^\circ \text{C}]: \text{dry bulb temperature}, X[\text{kg/kg}]: \text{absolute humidity}$</td>
</tr>
<tr>
<td><strong>Water</strong></td>
<td>$h [\text{kcal/kg}] = \sum_{i=0}^{\gamma} E_i T_i$ $\quad (E_i: \text{specific coefficients})$</td>
</tr>
<tr>
<td><strong>Saturated Steam</strong></td>
<td>$h [\text{kcal/kg}] = \sum_{i=0}^{\gamma} F_i T_i$ $\quad (F_i: \text{specific coefficients})$</td>
</tr>
<tr>
<td><strong>Gas Components</strong></td>
<td>$h [\text{kcal/Nm}^3] = \int_{273.15}^{T(\circ \text{C})} \frac{Cp \cdot dT}{\text{22.4}} = \left[\left(a \cdot T + b \cdot \frac{T^2}{2} + c \cdot \frac{T^3}{3}\right)\right]_{273.15}^{T(\circ \text{K})} \div 22.4$ $\quad (a, b, c: \text{specific coefficients for each gas component})$</td>
</tr>
</tbody>
</table>

In the second step, the characteristic model modules created as above were connected according to the actual plant flows, and a whole integrated model was established. Repeat calculations were performed for this whole model until the balance of mass and enthalpy was achieved while adjusting the flow rate of each part under the substance inputs at the rated level.

In the third step, simulations in accordance with the actual operating conditions of the system were carried out under different conditions and collation of the measured temperature data group and supplied heat amount with the simulated result was carried out. As a result, the model which can almost reproduce the operating condition of the actual system was completed.

3.4. **Plant performance predictions using a simulation model**

Simulation analysis of the target plant was carried out by using the material-thermal equilibrium simulation model prepared in the previous section, and various performance predictions on energy balance were evaluated. In this section, representative study results are described for each of the hot water supply system and the steam supply system.

3.4.1. **Energy balance prediction on the hot water system**

The plant operating condition for this energy balance simulation was assumed as follows. The input wet wood fuel (bark material) has a water content of 55% (wet basis) as of the actual measured value, and the input fuel amount is 800 [kg/h] which is the maximum rating for the dryer. The hot water temperature supplied from the boiler to the cultivation houses is 80 °C. The result of the simulation is shown as the energy flow chart shown in figure 9. According to this energy flow chart, this operating condition enables surplus production of dry fuel of 371 kW (equivalent to 70 [kg/h] in absolute dry weight), in addition to the 1100kW hot water supply, which matches with the winter’s peak demand described in subsection 2.1.

In figure 9, the energy efficiency of the hot water heat supplied with respect to the heating value of input wet bark fuel is calculated to be 57.6%. This value is much higher than around 25% of efficiency in large-scale biomass power generation. Also, if the heat amount of the surplus dry wood fuel produced is also added as effective energy output, the energy efficiency will be as high as 76.8%. It is understood that this plant system can efficiently use the energy of the wet bark material which is otherwise difficult to use effectively.
3.4.2. Energy balance prediction on the steam supply system

Another example of energy balance simulation result with the steam production is shown in figure 10. This material-thermal equilibrium corresponds to the plant operating condition where the steam with a maximum capacity of 700[kg/h] (equivalent to 517kW) at the temperature of 158 °C is supplied from the steam boiler to the sterilizing facility. The 603[kg/h] of the wet wood fuel (bark with water content 55% wet basis) having a heating value of 1447kW is supplied as the raw material to the dryer, and no surplus dry fuel is obtained in this case. The energy efficiency of the steam supplied with respect to the heating value of input wet bark fuel is calculated to be 37.5%.

By additional simulation of various steam supply cases, the relationship between the water content and the input amount of the wet fuel to the dryer is summarized as follows.

- In the case where the wet fuel water content is 55%, surplus dry wood fuel can be obtained when the wet fuel input amount is in the range over 600[kg/h] up to the operating limit 800[kg/h] of the dryer.
- In the case where the water content is 60%, the surplus dry wood fuel can be obtained only at a wet fuel input of 800[kg/h].
- In the case where the water content exceeds 65%, the surplus dry wood fuel cannot be obtained for all range from 600[kg/h] to 800[kg/h]. In this case, the steam supply from the steam boiler falls below the rated amount.
3.5. Exergy analysis

Exergy is defined as the maximum useful work that can theoretically be taken out from the system on the premise of environmental temperature, and therefore it can be used as an indicator of “effective availability of energy”. In general, as energy to be produced from woody biomass, there are different energy forms such as electricity, thermal heat, and chemical energy. Therefore, it is considered to be practical and effective to use exergy as the indicator of “effective availability of energy” to evaluate the real values of different energy forms. In the following, the exergy was calculated and evaluated based on the material-thermal balance in the hot water supply operation of the target plant shown in figure 9.

Exergy is expressed as $E_x$ in the below calculations. Formula (1) is used for exergy calculation of wood fuel [10], and formula (2) is used otherwise.

$$E_x = Q_w + \gamma \omega$$  \hspace{1cm} (1)

Where,

$Q_w$: The low calorific value of wood (wet basis) [kJ/h]

$\gamma$: Latent heat of water under ambient temperature [kJ/h]

$\omega$: Water content (weight ratio)

$$E_x = Q \times \left(1 - \frac{T_0}{T_2}\right)$$  \hspace{1cm} (2)

Where,

$Q$: Enthalpy [kJ/h]

$T_0$: Ambient temperature [K] (293.15 in this study)

$T_2$: Temperature at the energy use [K]

As for thermal energy transfer flow in this system, there are three major energy losses besides the amount of heat applied to the surplus dry wood fuel and the hot water supplied to the load. Calculation of exergies for each of them was conducted, and the result is shown in figure 11.

![Figure 11. Exergies in the steam supply case](image)

According to figure 11, the exergy of the surplus dry wood fuel (chemical heat value) was as large as the exergy of the hot water supplied from the boiler. The effective utilization of exergy of two heats (i.e., hot water and surplus dry fuel) was in total 45.1% against the exergy of the input wet fuel. This number is smaller than the energy efficiency of the plant mentioned in 5.1, but it is still much larger than the value of 25% of the energy efficiency (equivalent to exergy efficiency for electricity) in large-scale biomass power generation (6000-8000kW class [2]). It is considered more appropriate to use exergy efficiency rather than energy efficiency when the biomass heat supplied is compared with biomass power generation.

4. Conclusions

- A woody biomass heat energy system built for heat supply to shiitake mushroom production farm in Japan was introduced. Daily and seasonal heat demand for cultivation houses were evaluated and used as design base of the biomass heat supply plant.
A material-thermal equilibrium simulation model of the target plant was established, and various energy performance simulations were conducted. The material-thermal equilibrium simulation model is a very useful tool to predict system performance and to avoid troubles before the actual operation of the plant.

According to the simulation, when supplying the hot water rated heat of 1100 kW, the energy efficiency to the calorific value of the input wet bark fuel (with 55% water content by wet basis) is calculated as 76.8%, where the heat amount of the surplus dry wood fuel is included as effective energy output.

Analysis of exergy (maximum useful work obtained from energy theoretically) was also performed for the same case. The effective utilization of exergy of two heats (i.e., hot water and surplus dry fuel) was 45.1% against the exergy of the input wet fuel. This value is considered to be much larger than the exergy evaluation in the case of large-scale biomass power generation.

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[9] Okinawa Prefecture Agriculture, Forestry and Fisheries Department 2016 Guidelines for shiitake cultivation