Feasibility and performance analysis of utilizing spent mushroom substrate as biomass fuel

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Abstract. A novel biomass system has been developed that utilizes spent mushroom substrates (SMS) and combines a pre-drying and drying system. The novel biomass system consists of a boiler and an Organic Rankine Cycle (ORC), which employs Isophexane as the working fluid to enable operation at high temperatures. The high moisture content of the SMS is dried by pre-drying from condensation waste heat of ORC and drying from the flue gas of the boiler to improve the calorific value of SMS. In the present study, the moisture content of the SMS and evaporation temperature of the ORC ranged from 50% to 65% and from 130℃ to 180℃. The results show although the thermal efficiency of ORC increased with an increase in evaporation temperature, the maximal output power is 412.21 kW at an evaporation temperature of 150 ℃. Additionally, when the moisture content of the SMS is 50 %, the thermal efficiency of the entire system approaches the maximal value (58.6%).

1 Introduction

As global finite fossil fuel resources are gradually depleting, the development and research of biomass energy present a solution to mitigate the impacts of climate change. In Taiwan, the annual production of mushrooms amounts to nearly ten billion NTD. For example, "hundreds of millions" of discarded spent mushroom substrates (SMS) every year, with a weight ranging from 150,000 to 200,000 tons [1].

According to trends in the fuel market, the use of bioenergy has become quite popular in recent years [2]. In Taiwan, the proportion of renewable energy generation has also seen a slight increase over the past decade, with bioenergy sources such as biogas and waste materials being utilized [3]. Bioenergy serves not only heating purposes but also presents a viable subject for in-depth research into combustion-based power generation.

In the realm of one-time energy sources contributing to global economic development, fossil fuels account for 81%, nuclear energy for 5%, and renewable energy for 14% (with biomass contributing 70%) [4]. Biomass, obtained through photosynthesis that absorbs carbon dioxide and stores chemical energy, is combusted to generate heat energy, providing fuel for energy production. The carbon dioxide released into the atmosphere during
combustion is subsequently absorbed by plants during growth [5], forming a closed carbon cycle on the Earth's surface, thereby achieving sustainable circulation, as illustrated in Fig 1.

During the cultivation of mushrooms, a substantial amount of spent mushroom substrate (SMS) is generated. Current regulations in Taiwan impose strict requirements for setting up composting facilities, making it challenging for mushroom farmers to properly dispose of SMS on-site. Converting this waste into compost or drying it for biomass fuel presents a significant obstacle. While some recycling operators handle SMS, their processing capacity is often insufficient due to the complex and costly procedures involved. In the past, SMS was even dumped or burned haphazardly. Typically, SMS has a high moisture content, making the process of drying for biomass fuel energy-intensive.

Although studies by Vats et al. [6] demonstrated the potential for recycling used mushroom substrates, and Leong et al. [7] introduced the concept of incorporating SMS into a circular economy, identifying value-added opportunities such as bio-fertilizers, soil amendments, livestock feed alternatives, and raw material for second-generation biomass fuels, the ORC-based biomass-fired combined heat and power (CHP) plants at medium-scale (100–1500 kW) had been successfully demonstrated [8]. There is a significant lack of research on the integration of drying equipment, combustion boilers, and ORC systems for biomass. Additionally, the ORC with nearly 85% of waste heat being discharged through the condenser. To address this, the condensation temperature of the ORC is elevated, and air is used for cooling. The discharged hot air is utilized for pre-drying SMS with higher moisture content. Meanwhile, the boiler exhaust flue gas is employed for drying to enhance energy utilization. Finally, the effect of evaporation temperature on the thermal performance of the biomass system has been investigated.

2 Methodology

The biomass system is primarily composed of two rotary dryers, a biomass boiler, and an ORC. The operational principles of the system are illustrated in Fig. 2. Firstly, moist SMS enters the rotary dryer, which is pre-dried using waste heat from the ORC condenser (from state a to state b) and then dried through boiler flue gas (from state b to state c). The dried SMS is used as biomass fuel in the boiler (from state c to state d). The energy required for
ORC is derived from the heat generated during the combustion of SMS. This heat is exchanged with water through an internal heat exchanger within the boiler. (from state d to state e). The condensation waste heat from the ORC is used for pre-drying the moist SMS (from state f to state a). Finally, the heat generated from burning SMS not only provides energy to the ORC but also the medium temperature flue gas from the boiler is used to dry SMS (from state e to state b).

Fig. 2. Block diagram of biomass system.

The schematic diagram of the system is shown in Fig. 3. The ORC system utilizes Isohexane as the working fluid [9] and NIST REFPROP 9.0 [10] was used to determine the fluid properties. The heat produced by SMS combustion in the biomass boiler is transferred from the heat source circuit to the ORC circuit. When the working fluid finishes the cycle, the cooling circuit utilizes the condensation waste heat from the ORC to warm the air, and direct it to the rotary dryer for pre-drying of the SMS. The pre-dried SMS is dried by the heat from the flue gas of the boiler. The heat required for drying SMS is calculated through both the cooling and flue gas circuits.

Fig. 3. Schematic diagram of a biomass system using SMS as fuel, with drying equipment.

In the present study, the initial moisture content of the SMS is set at 75%. Due to the high humidity during mushroom growing, the moisture content of the SMS ranges from 70% to 80%. By using two rotary dryers in the system, the moisture content of the SMS is reduced to 5%. The boiler's efficiency is calculated based on the flue gas outlet temperature, and it is estimated at 79.77% when assuming a flue gas outlet temperature of 200°C. The thermal system efficiency is examined by altering the initial moisture content for pre-drying, ranging from 50% to 65%, and by adjusting the evaporation temperature of the working fluid within the ORC system. The efficiency correlation is as outlined below:
\[ \eta_{th} = \frac{W_{ele} + Q_{pre\text{-}dry} + Q_{dryer} - W_{fan}}{Q_{boiler}} \]  \hspace{1cm} (1)

where \( \eta_{th} \) represents the biomass system thermal efficiency, \( W_{ele} \) is the system's electrical output power, \( Q_{dryer} \) is the drying heat, \( Q_{pre\text{-}dry} \) is the pre-drying heat and \( W_{fan} \) is the fan power consumption.

The drying efficiency equation for the dryer is as follows:

\[ \eta = \frac{Q_{in}}{Q_{out}} \]  \hspace{1cm} (2)

where \( \eta \) represents the dryer efficiency, \( Q_{in} \) is the heat input from pre-drying and boiler exhaust gas drying, and \( Q_{out} \) is the heat output from the condenser and flue gas emissions.

3 Results and discussion

The sites of the biomass system are shown in Fig. 3. According to thermodynamic calculations, the mass flow rates, temperatures, and pressures for each site are shown in Table 1.

<table>
<thead>
<tr>
<th>Site</th>
<th>Material</th>
<th>( \dot{m} ) (kg/s)</th>
<th>T (℃)</th>
<th>P (kPa)</th>
<th>Site</th>
<th>Material</th>
<th>( \dot{m} ) (kg/s)</th>
<th>T (℃)</th>
<th>P (kPa)</th>
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<tr>
<td>1</td>
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<td>25</td>
<td>101.3</td>
<td>11</td>
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<td>13</td>
<td>164</td>
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<td>101.3</td>
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<td>164</td>
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<tr>
<td>3</td>
<td>SMS</td>
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<td>50</td>
<td>101.3</td>
<td>13</td>
<td>water</td>
<td>13</td>
<td>200</td>
<td>1554.9</td>
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Figure 4 illustrates the effect of evaporation temperature on overall system efficiency and output power at the SMS moisture content of 50%. Figure 4(a) shows that when the working fluid's evaporation temperature increased from 130°C to 180°C, the efficiency of the ORC system increased from 6.85% to 10.91%. This was because the heat extraction from the system decreased with an increase in the evaporation temperature. This leads to reduced heat dissipation requirements and fan power consumption, resulting in a slight improvement in the efficiency of the biomass system. These results have been compared to simulation results obtained by Ustaoglu et al[11], revealing a similar trend. The fan power consumption decreased from 150.71kW to 57.44kW when the evaporation temperature increased from 130°C to 180°C. Because the fan power consumption was affected by the airflow rate, increasing the evaporation temperature of the system resulted in a decrease in condenser heat dissipation. By increasing the evaporation temperature from 130°C to 180°C, the fan power consumption could be reduced by 61.88%. However, as can be seen from Figure 4(b), the maximum power was achieved at an evaporation temperature of 150°C and then decreased...
with an increase of the evaporation temperature. Although the reduction in fan power consumption at higher evaporation temperatures, there is a decreasing trend in the net power output of the biomass system, Ustaoglu et al. [11] demonstrated the same trend in their study.

Figure 5 shows the effect of increasing the pre-dryer moisture content of the SMS from 50% to 65% at a given evaporation temperature of 150°C. Figure 5(a) shows that when the pre-drying moisture content increased from 50% to 65%, the drying efficiency of the pre-dryer increased from 65.12% to 69.89%. This was because the thermal energy required for drying increased with an increase in moisture content; therefore, the waste heat from the condenser can be effectively utilized, leading to an improvement in the pre-dryer efficiency. However, the energy used for drying from boiler flue gas cannot be used efficiently, resulting in a decrease in flue gas drying efficiency from 69.95% to 22.29%. Figure 5(b) shows that the efficiency of the biomass system decreased slightly. The maximum thermal efficiency of the system is achieved when pre-drying SMS with 50% moisture content, reaching 58.60%. The research by Abbasfard et al. [12] also confirmed that the initial moisture content of the material affects the drying effect.

4 Conclusions

This study investigated the effect of evaporation temperature and pre-drying moisture content on system performance. The results show that increasing the evaporation temperature of the
working fluid from 130°C to 180°C reduced the heat input to the system. As a result, the power consumption of the fan decreased, leading to a gradual improvement in the thermal efficiency of the biomass system and the ORC efficiency. However, the ORC reached its maximum output at 150°C.

By adjusting the pre-drying moisture content from 50% to 65%, the condensation waste heat from the ORC can be utilized more effectively. The pre-drying efficiency increased from 65.12% to 69.89%, while the flue gas drying efficiency decreased from 69.95% to 22.29%. Therefore, in the case of pre-drying with 50% moisture content, the power generation system achieved the highest thermal efficiency of 58.60%.

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References

3. Taiwan Power Co. (n.d.)