Enhanced Energy Utilization System of Algae: Integrated Drying, Gasification and Combined Cycle

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Abstract

A highly energy-efficient integrated energy utilization system consisting of drying, gasification and combined cycle for algae is proposed. The integration is performed based on the concept of exergy recovery and process integration technologies. The energy involved in each process is basically recovered thoroughly through exergy recovery. In addition, the unrecoverable energy in a single process will be utilized in other processes using the principle of process integration. The combination of these technologies can minimize the total exergy destruction throughout the integrated system. Hence, significant improvement in energy efficiency can be achieved leading to high total power generation efficiency. Alga Laminaria digitata was used as sample during process calculation. Two main analyses have been performed relating to drying performance and total power generation. As the results of the study, the proposed integrated-system showed a very high energy efficiency. A significantly positive energy harvesting from algae with the total power generation efficiency of about 40% can be achieved.

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Keywords: algae, supercritical water gasification, combined cycle, energy efficiency, exergy recovery, process integration

1. Introduction

Algae have received a lot of interests and broad range of applications as material for goods production and energy resource. As energy resource, energy harvesting from algae is considered very potential due to their characteristics on high solar energy conversion, nutrient acquisition, CO₂ fixation, capability to grow under conditions that are not favorable for terrestrial biomasses, etc. [1, 2]. The capability of algae to fix effectively CO₂ leads to possibility of co-locating algae cultivation to near CO₂ emitter industrial points including power plants. Matsumoto et al. found that algae could be cultivated effectively under high
concentration of CO2 up to 15% concentration [3]. Power generation from algae, as well as other renewables including hydro and geothermal, becomes one option for base load power supply in future replacing the current base load power plants fueled mainly by fossil fuels and nuclear.

Energy harvesting from algae can be performed through thermochemical or biochemical processes. Generally, thermochemical conversion, especially gasification, shows faster conversion rate and higher conversion efficiency. Furthermore, algae gasification can be conducted through conventional thermal gasification or supercritical water gasification. Unfortunately, supercritical water gasification is still under research and far from its deployment. Furthermore, to achieve high total power generation efficiency from biomass, an integrated gasification and combined cycle (IGCC) has been developed with some advantages of high carbon conversion, high power generation efficiency and low environmental influence [4].

Although the potential of algae as energy resource is very high, almost no study is focusing on the idea to produce electricity from algae effectively. Moreover, as algae have very high moisture content, ranging up to 90 wt% on wet basis (wb), the utilization of algae faces some difficulties. To overcome those problems, drying is usually conducted to remove the water as well as to improve the calorific value. This study proposes an integrated system for power generation from algae including drying, gasification and combined cycle with high energy efficiency based on the principles of exergy recovery and process integration technologies.

2. Developed integrated-system

To achieve a high overall energy efficiency, an integrated system for algae utilization is developed employing the principles of exergy recovery and process integration. The combination of exergy recovery and process integration technologies is adopted with the objective of exergy destruction minimization throughout the integrated system. Fig. 1 shows the basic principle of exergy recovery technology and two examples of the way to elevate the exergy of the stream. The exergy recovery is conducted in each single process through exergy elevation and heat coupling to recirculate efficiently the energy/heat involved in the process. The exergy of cold stream is initially elevated to facilitate an effective heat coupling among hot and cold streams. This elevation can be conducted by means of compression, heat pump, etc. [5]. Furthermore, an effective heat coupling between hot and cold streams is performed in consideration of heat type and amount to achieve the largest amount of heat exchange. In addition, the amount of exergy elevation depends strongly to the performance of heat coupling. This exergy recovery concept is significantly different to the conventional heat recovery technology which is basically developed based on heat cascade utilization or pinch technology. In this conventional method, only a small part of energy/heat can be recovered leading to large amount of exergy destruction over the whole integrated system.

![Fig. 1. Principle of exergy recovery technology: (a) exergy elevation and heat coupling to minimize the exergy destruction, (b) two examples of the way to elevate the exergy of the stream.](image-url)
The proposed integrated processes consist of drying, gasification and combined cycle. Fig. 2 shows the schematic process flow diagram of the proposed integrated system. The harvested algae from the cultivation having high moisture content flow to drying module to reduce their moisture content, hence, improve their calorific value. Subsequently, the hot dried-algae are flown to gasification module which are converted to syngas consisting of hydrogen, methane, carbon monoxide, etc. The produced syngas flows to the combined-cycle-based power generation comprising combustor, gas turbine, heat recuperator and steam turbine. Moreover, a CO₂ rich flue gas exhausted from the power generation module is recycled and utilized for both heat and materials in drying and cultivation, respectively.

![Fig. 2. Schematic process flow diagram of the proposed integrated-system for energy harvesting from algae](image)

In the proposed integrated drying process, a preheater, a main dryer, and a superheater are required. In the preheating stage, wet algae are preheated using the sensible heat of the condensed water of the compressed steam. Next, the wet algae enter the evaporation stage which is performed in the steam tube rotary dryer. To facilitate an effective heat exchange inside the dryer, steam tube rotary dryer with an internal heat exchangers is considered to be the most appropriate candidate for algae drying [6, 7]. The heating tubes inside the rotary dryer are filled with the compressed steam and arranged in concentric circle inside the dryer. On the other hand, the wet algae are fed continuously at a uniform rate and are tumbled and agitated by the rotation of the rotary dryer. Furthermore, the rotary dryer is designed to have a slope rotating cylinder, hence, it is able to move the algae inside the dryer from the feeding inlet to the discharging outlet by the gravity force. The steam exhausted from the steam tube rotary dryer is split into recirculated and purged steams. The amount of the purged steam is equivalent to the water evaporated from the wet algae and is used as the heat source for subsequent drying. On the other hand, the amount of recirculated steam is fixed and constant and it will be recirculated back to steam tube rotary dryer.

For gasification, a fluidized bed type gasifier is adopted due to its characteristics of high mass and heat transfer, high efficiency, high heating value, etc. Hot syngas flows to cyclones for particle separation before it is cooled down to preheat the steam as fluidizing gas for gasification. Subsequently, syngas will be cleaned up, removing the particulates and sulfur. The clean syngas is then used as fuel for combustion, creating a high temperature pressurized gas to rotate the gas turbine. As the temperature of the flue gas from the gas turbine is still high, the rest of the heat will be utilized basically to generate steam in heat recovery steam generator (HRSG) which is used to rotate the steam turbine to generate the electricity.
3. Modeling and Calculation

In this study, brown algae *Laminaria digitata* (Oarweed) is selected as the sample due to their high proportion of carbohydrate and low ash content [8]. The initial moisture content and flow rate of wet algae are 80 wt% wb and 100 t h\(^{-1}\), respectively. Table 1 shows the properties of the used algae including both proximate and ultimate analysis. Target moisture content in drying is fixed at 5 wt% wb and to evaluate the effect of target moisture content to the energy required for drying, target moisture contents are set to be lower than 40 wt% wb with interval of 5 wt% wb.

Table 1. Proximate and ultimate analysis of used *Laminaria digitata*

<table>
<thead>
<tr>
<th>Component</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Proximate analysis (wt% db)</td>
<td>Volatile matter: 64.1;</td>
</tr>
<tr>
<td></td>
<td>Ash: 21.1</td>
</tr>
<tr>
<td>Ultimate analysis (wt% db)</td>
<td>C: 33.3; H: 5.1; N: 1.7;</td>
</tr>
<tr>
<td></td>
<td>S: 0.7; O: 37.8</td>
</tr>
<tr>
<td>Calorific value (MJ kg(^{-1}))</td>
<td>13.8</td>
</tr>
</tbody>
</table>

Drying is a complicated moisture removal process because it deals not only with the free water inside the material, but also water held in capillaries and chemically bound water. Therefore, drying to a specific moisture content depends strongly on the equilibrium moisture content, which in turn is dependent on the moisture content of the environment. The equilibrium moisture content, *MC\(_{eq}\)* of *Laminaria digitata* is approximated as follows [9].

\[
MC_{eq} = \frac{1.0078 e^{\frac{-1076}{RT}} e^{\frac{1526}{RT}} \left( \frac{p}{P_{sa}} \right)}{1 - 1.3638 e^{\frac{-1076}{RT}} \left( \frac{p}{P_{sa}} \right) + 0.1124 e^{\frac{-1076}{RT}} e^{\frac{1526}{RT}} \left( \frac{p}{P_{sa}} \right)}
\]  

(1)

where, *R* and *T* are gas constant (8.314 J mol\(^{-1}\) K\(^{-1}\)) and temperature (K), respectively.

Table 2 shows the gasification conditions assumed in this study. To improve the conversion efficiency during gasification, Fe\(_2\)O\(_3\)-90% CeO\(_2\) is used as catalyst and fluidizing medium, at once. The gasification conditions and composition of produced syngas are basically based on the work of Duman et al. [10]. The utilization of Fe\(_2\)O\(_3\)-CeO\(_2\) as catalyst can convert the produced tar completely leading to high gasification
efficiency. Furthermore, fluidizing medium is expected to increase the fluidization performance of the algae particles due to more uniform temperature distribution across the bed. Process modeling and calculation of the proposed system were conducted using a steady state process simulator, Pro/II version 9.2 (Invensys Corp.). The fluidized bed gasifier is assumed consisting of a mixer, a heat exchanger, a conversion reactor, and a separator. To evaluate the total energy efficiency of the proposed integrated processes, the impact of steam fluidization velocity to the total generated power and generation efficiency are calculated. Three different fluidization velocities are evaluated: 3, 4 and 5 $U_{mf}$.

4. Results and discussion

Fig. 3 shows the correlation of total required energy and compressor outlet pressure corresponding to the target moisture content in drying, respectively. In drying to target moisture content of higher than 20 wt% wb, higher moisture content leads to significantly higher total required energy in the proposed integrated drying. This phenomenon is caused mainly by the material imbalance. On the other hand, when drying is progressed to below than 20 wt% wb, the total required energy for drying turn to get higher although in insignificant way. This phenomenon is considered due to ineffective heat exchange between the hot stream (compressed steam) and cold stream (algae) resulting in larger exergy destruction.

Fig. 3. Correlation between the total energy required and compressor outlet pressure with the target moisture content.

Fig. 4. Effect of fluidization velocity to total generated power and generation efficiency.
Fig. 4 shows the relation of fluidization velocity during gasification to the net generated power and overall generation efficiency. Basically, as the fluidization velocity decreases, the total generated power and generation efficiency increases. Furthermore, the total generation efficiency can reach about 40% leading to highly positive energy harvesting from algae. Exergy elevation is basically conducted twice in the integrated processes. The first exergy elevation is in drying process where the purged steam is compressed by a compressor creating high exergy rate of hot stream to be utilized as the heat source for the subsequent drying. In this case, a combination of electrical energy and thermal energy is performed, hence the exergy rate of thermal energy can be elevated. The second exergy elevation is performed in gasification module where the steam for gasification/fluidization is superheated by the hot gas from the combustor. In this case, the combination of both thermal energy is performed hence the exergy rate of thermal energy with lower exergy rate can be elevated.

5. Conclusions

A novel integrated system for energy harvesting from algae based on combination of exergy recovery and process integration has been proposed and evaluated. Significantly high energy efficiency could be achieved with total power generation efficiency of about 40%.

References


Biography

Muhammad Aziz received B. Eng., M. Eng., and D. Eng. degrees from Kyushu University, Japan, in 2004, 2006 and 2008, respectively. He is currently an assistant professor at Tokyo Institute of Technology, Japan. He has authored about 100 peer-reviewed journals, book chapters, and proceedings especially in energy systems, process design, and heat transfer.