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Integrated supercritical water gasification and a combined cycle for microalgal utilization

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ABSTRACT

Integrated energy utilization processes for microalgae based on enhanced process integration are proposed in this study. They consist of supercritical water gasification and combined cycle for power generation. The enhanced process integration is developed based on exergy recovery and process integration technologies. Exergy recovery deals with effective heat circulation throughout a single process which is achieved by exergy elevation and efficient heat coupling. In addition, process integration utilizes the unrecoverable heat from a single process for other processes, thus minimizing the total exergy destruction of the whole integrated processes. Microalga *Spirulina* sp. is selected as the sample due to its higher gasification and carbon conversion efficiencies than any other microalgae. Process simulation is performed to evaluate the total energy efficiency, specifically the effect of steam flow rate (fluidization velocity), gasification pressure and turbine inlet temperature. Simulation reveals that the proposed integrated processes harvest the energy from microalgae with total energy efficiency exceeding 40%. A temperature–enthalpy diagram shows that the heat involved in the whole processes is recovered effectively.

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1. Introduction

Microalgae are remarkable and efficient organisms capable of assimilating CO_2 through photosynthesis to produce a source of energy. Furthermore, microalgae can be used as raw materials for the production of chemicals, nutrition, supplements and energy in respect of economic, environmental and sustainable points of view. Microalgae have potential benefits compared with land crops including a high growth rate, the possibility of highly efficient CO_2 mitigation, no need for arable land, and the ability to grow in environments unsuitable for terrestrial crops [1–3]. Microalgae can more effectively convert sunlight to chemical energy in photosynthesis than traditional terrestrial crops [4,5]. Furthermore, as microalgae can absorb CO_2 effectively, the use of microalgae as energy source leads to energy harvesting with a minimum CO_2 emission. In addition, microalgae have a uniform cell structure allowing easier extraction and higher cell utilization [6]. Unfortunately, microalgae have high moisture content ranging from 70 to 90 wt.% on a wet basis (wb), which introduces difficulties in their utilization.

The conversion technologies of microalgae in terms of energy harvesting include thermochemical and biochemical routes. Thermochemical conversion covers pyrolysis, gasification, and liquefaction, whereas biochemical conversion can be performed through fermentation and transesterification. Compared with biochemical conversion, thermochemical conversion generally has advantages of a faster conversion time and a more complete conversion product. The higher heating value in dry basis (db) of microalgae grown under optimum conditions ranges from 19 to 25 GJ t^{-1}, which is almost the same as that of sub-bituminous coal [7]. In the case of microalgae utilization for power generation, conversion technologies including direct combustion and co-combustion with other fuels are available. Among those technologies, integrated gasification and combined cycle (IGCC) technology is considered to have higher total power generation efficiency. IGCC technology has greater carbon conversion and lower environmental impact compared with a conventional combustion-based power plant [8–11]. In addition, the integration of gasification and power generation is significantly more efficient than standalone gasification producing syngas that will be transported for other energy utilization.

Due to its high potential and characteristics, biomass, as well as geothermal energy, is considered as an appropriate candidate of future energy source to supply base-load electricity replacing current base-load power plants utilizing coal and nuclear as fuels. This replacement can mitigate the greenhouse gases. Compared to other renewables, such as wind and solar, biomass-based power

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Nomenclature

Ar	Archimedes number (–)
C	specific heat capacity (J kg^{-1} K^{-1})
c	conversion factor (1 kg m N^{-1} s^{-2})
d	diameter (m)
Ex	exergy (J)
ex	specific exergy (J kg^{-1})
g	acceleration due to gravity (m s^{-2})
H	height (m)
h	specific enthalpy (J kg^{-1})
p	pressure (kPa)
m	mass (kg s^{-1})
R	universal gas constant (8.314 J mol^{-1} K^{-1})
Re	Reynolds number (–)
s	specific entropy (J K^{-1})
T	temperature (K)
U	velocity (m s^{-1})
W	work (W)
x	molar fraction (–)
Greek letters	
ε	fraction (–)
μ	dynamic viscosity (Pa s)
ρ	density (kg m^{-3})
φ	particle sphericity (–)
Subscript	
cold	cold side
comb	combustion
comp	compressor
f	fluidization
g	gas
hot	hot side
in	inlet
mf	minimum fluidization
out	outlet
p	particle
Abbreviations	
COMB	combustion
GT	gas turbine
HRSG	heat recovery steam generator
HX	heat exchanger
SCWG	supercritical water gasification
SEP	separator
SH	superheater
ST	steam turbine

generation can produce constantly the electricity with very minimum influence of surrounding weather and climate. Furthermore, huge potential of microalgae leads to the possibility of concentrated large scale power plants which operates continuously throughout the year. Hence, an application of new IGCC technology to utilize optimally the harvested microalgae is highly expected.

Unfortunately, in conventional IGCC technology employing thermal gasification, the harvested microalgae must be dried to a low moisture content to maintain a stable conversion and realize high efficiency. For example, in the conventional gasification process, to achieve a gasification temperature of 900 °C, it is necessary to dry microalgae to moisture content of about 10 wt.% wb [12]. Drying is an energy-intensive process that further decreases significantly the energy profit ratio in microalgae utilization. The conversion of microalgae in their aqueous phase is an alternative method to obviate the drying process.

This work investigates the utilization of microalgae with no drying process. Specifically, supercritical water gasification (SCWG) is applied to microalgae utilization. Unfortunately, although SCWG bypasses the drying process, it still requires large energy input to achieve the required gasification temperature and pressure. To improve the total energy efficiency in energy harvesting from microalgae, an integration of SCWG and combined-cycle-based power generation is proposed in this study based on enhanced process integration (EPI) technology. The developed EPI technology consists of two main core technologies: exergy recovery and process integration. The combination of both technologies and their application to the proposed integrated processes is expected can minimize the exergy destruction, hence all the energy/heat involved throughout the integrated processes can be circulated well leading to high total energy efficiency.

2. SCWG for microalgae

SCGW is a thermochemical conversion technology that applies the advantages of supercritical water properties (pressure and temperature above 22.1 MPa and 374 °C, respectively) to decompose biomass feedstock into syngas containing hydrogen, carbon monoxide, methane, carbon dioxide, and water vapor. As this produced syngas has high calorific value, it can be used as fuel for power generation. Water, which acts as both reactant and reaction medium, is required as solvent. Above the critical point, the density of water decreases significantly causing a significant drop of the static relative dielectric constant [13]. In addition, water consequently behaves like a non-polar solvent [14]. It has good transport properties and a strong ability to break down hydrocarbons and carbohydrates [15]. Under the supercritical-water condition, hydrogen bonds becomes weaker significantly. This condition allows complete miscibility among gases, and the reaction can thus occur in a single homogeneous phase of fluid. This leads to a faster chemical reaction and higher gasification efficiency compared with conventional gasification [16]. Tar and char formation can be prevented and almost complete gasification can be achieved [17–19]. In addition, the supercritical condition avoids the requirement of latent heat for the phase change of water [20]. As SCWG takes the advantages of supercritical water properties, the gasification can be achieved at lower temperature relative to conventional gasification. Furthermore, by employing SCWG, energy-intensive drying can be eliminated [16,21]. SCWG can produce very clean syngas containing almost no NO_x and SO_x; hence, no further cleaning of gas is required. In addition, the concentration of CO is very low.

Conversion of microalgae through SCWG is advantageous because microalgae easily dissolve in water and it only requires a simple treatment to make them slurry. A creation of homogeneous slurry becomes one important key of success in continuous feeding, hence, it could be pumped well and continuously to the gasifier. In addition, although there is no evaporation heat required to bring water to a supercritical condition, the total energy required to raise the water to a temperature of 600 °C at 30 MPa is almost the same as the energy required for water evaporation and its temperature increase from room temperature to boiling point under atmospheric pressure [13]. Furthermore, according to some reports [18,22,23], the total energy required to perform SCWG approaches the heating value of the feedstock, hence, an efficient heat recovery technology must be employed to solve this problem.

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