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Integration of energy-efficient drying in microalgae utilization based on enhanced process integration

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A B S T R A C T

We propose an integration of drying with gasification and combined cycle-based power generation for microalgae. This system is based on enhanced process integration, which includes two core technologies: exergy recovery and process integration. Exergy recovery is achieved by exergy elevation and efficient heat coupling, according to each type of heat. Process integration is implemented to minimize the exergy destruction, and hence the remaining energy from one process can be used effectively in other processes. This improves the total energy efficiency. The microalga *Chlorella* sp. is selected for study because of its high CO_2 absorption and high growth rate. The total energy required in the proposed process is calculated based on the target moisture content. It is observed that drying to a lower target moisture content generally consumes less total energy and has a higher coefficient of drying performance than drying to a higher moisture content. A coefficient of drying performance of about 18.5 can be achieved through the proposed process.

1. Introduction

The total area of the earth's oceans is greater than that of its land surface. This leads to an abundance of marine resources, including marine biomass. Unfortunately, this substantial asset has been managed poorly. The technologies required for large-scale cultivation, processing, and conversion are still under development, which means use of marine biomasses is still inefficient in energy harvesting. Hence, it has become crucial to develop highly efficient utilization technologies and deploy them to exploit marine biomass.

Microalgae are one type of marine biomass and are promising for a broad range of applications from chemical manufacture to green energy production. Wang et al. explained that microalgae are a unicellular and versatile polyphyletic group with the common ability to fixate CO_2 photosynthetically, leading to the generation of various algal cell components, energy and molecular oxygen [1]. Using microalgae has some benefits over lignocellulose because of higher growth rates, reduced need for plentiful freshwater for irrigation, and the ability to grow under severe conditions including heat, drought, salinity, etc. which are not favorable for the production of terrestrial biomass [2]. They also have the potential for sustainable growth via the extraction of macro- and micronutrients from wastewater and industrial flue stack emissions. Microalgae have a more efficient solar energy conversion and nutrient acquisition, and therefore exhibit greater rates of areal productivity than those associated with traditional terrestrial crops such as corn and soybean [3]. Furthermore, microalgae can be grown anywhere, even in sewage and salt water, for example, and do not require fertile land or the use of crops, which could otherwise be used as food and produce positive net energy. Microalgae can also absorb CO_2 effectively, which makes them attractive because their use can facilitate carbon neutrality [4].

Regarding CO_2 adsorption by microalgae, combining CO_2 fixation and effluent gas components for energy conversion is one of the most efficient strategies for abating the greenhouse gases. Biological sequestration of CO_2 through microalgae cultivation and utilization as an energy source lead to a reduced need for fossil fuels. The cultivation of microalgae is usually limited by such factors including the availability of water, nutrients, CO_2, sunlight, and an appropriate temperature. Establishing microalgae cultivation facilities near industrial sites emitting CO_2 is an attractive strategy for growing large quantities of microalgal biomass, and subsequently recycling the exhausted CO_2 for fuel production. Usui and Ikenouchi claimed that microalgae can fix CO_2 using solar energy with an efficiency 10 times greater than that of terrestrial plants [5]. The flue gas from industrial plants usually contains CO_2, NO_x, SO_x, Ni, V, and Hg. From previous work [6,7], the emitted NO_x dissolved in the

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growth medium presents no problem to algal growth because it undergoes conversion to NO_2^-, which is, in turn, used as a nitrogen source. In addition, SO_x also showed no harmful effects on the microalgae as long as the concentration in the flue gas was below 400 ppm. However, high concentration of N (more than 1.0 ppm) and V (more than 0.1 ppm) could decrease algal growth productivity. Ceng et al. concluded that microalgae could be cultivated effectively under a CO_2 concentration of approximately 15 vol % [8]. Because the microalgae grow in an aqueous environment, the most efficient way of capturing CO_2 is by direct passage of the flue gas into the water. Currently, the discussion on carbon capture and storage (CCS) usually focuses on geological sequestration, which is still problematic with regard to reliability, safety, and cost.

Fig. 1 shows the utilization processes using microalgae as the energy source. Energy harvesting of microalgae could be performed by thermochemical or biochemical conversion. Microalgae are a very promising energy source because of their richness in lipids, which can be converted to many types of biofuels including biodiesel, biogas, bio-oil, and biohydrogen [9,10]. In thermochemical conversion, energy from the microalgae can be obtained by direct thermal combustion, gasification, pyrolysis, or hydrogenation, for example, producing heat, synthetic gas (syngas), and liquid biofuels. Microalgae could also be used for power generation either through co-combustion with other fuels, such as coal, or independently by direct combustion or combination of conversion technologies and power generation, such as integrated gasification and combined cycle (IGCC).

Unfortunately, the use of microalgae faces some challenges involving both technological and economic factors. Therefore, an advanced high-performance technology that uses microalgae is urgently required. To address the problems previously mentioned, the present research focuses on the enhanced process integration of microalgae for energy utilization with very high energy efficiency. The core idea of enhanced process integration is exergy recovery and process integration throughout the whole process. The proposed integrated process involving microalgae consists of drying, gasification and power generation using combined cycle technology.

The processes for using microalgae comprise several steps. This study focuses mainly on the performance evaluation of the pretreatment process, which involves drying and its integration with gasification and power generation, referred to as the integrated gasification combined cycle (IGCC). Using the proposed enhanced process integration, it is expected that the total energy which is required for microalgae utilization can be reduced significantly. Hence, the energy returned on energy invested (EROEI) can be significantly improved.

Drying is a highly energy-intensive process and becomes one of the biggest problems in microalgae utilization. Microalgae drying requires approximately 85% of the total energy consumption in microalgae usage [11]. Thermal drying of microalgae consumes up to 3556 kJ kg^{-1} of fossil fuel-based energy [12], making it necessary to develop a drying process with very low energy consumption to make microalgae utilization more competitive in power generation and other areas. Recently, various thermal energy-efficient drying technologies have been developed, including conventional heat recovery-based technologies [13], use of heat pumps [14], and pinch technology [15]. Unfortunately, almost all of these drying processes still cannot efficiently recover the energy involved in drying. Furthermore, these technologies were generally developed for standalone applications. Hence, exergy destruction from drying processes is relatively large, leading to high energy demand for the drying stage and for the whole utilization process.

2. Proposed integrated utilization process

This paper proposes an enhanced process integration technology to achieve an optimal utilization process with high energy efficiency. In conventional process integration, heat integration is conducted basically through pinch technology. Hence, the heat cannot be recovered effectively, causing a still large amount of exergy destruction. In the proposed enhanced process integration technology, the heat involved in the whole process is recovered to a significantly larger extent. To achieve this, the concepts of exergy recovery and process integration are introduced. Exergy recovery is introduced in each process to circulate the heat involved in that process. Theoretically, exergy elevation and heat coupling are conducted to achieve this exergy recovery. First, the exergy of the process stream is elevated by means of compression and heat pumps, before heat exchange occurs between the hot and cold streams. Second, to achieve an optimally balanced heat situation, coupling of an equal amount of heat for the streams is performed. This leads to the coupling of the same type of heat including sensible, latent, endothermic, and exothermic heats. Unfortunately, because of some factors including chemical and physical changes, the amounts of the same type of heat can be slightly different. For example, as the pressure increases, the amount of latent heat of the water decreases. As a result, there will be an inequality in the

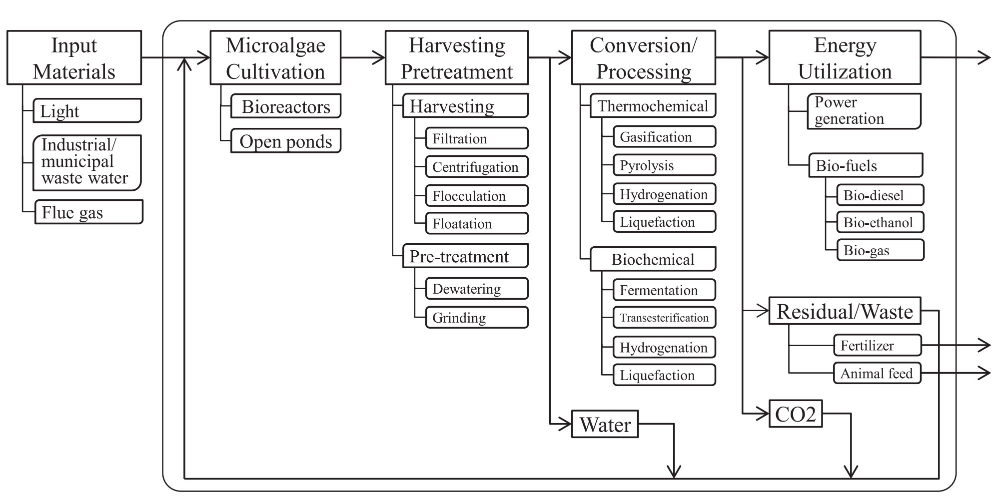

Fig. 1. Microalgae utilization for energy production.

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