Applied Energy 140 (2015) 246–255

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Optimization of novel photobioreactor design using computational fluid dynamics

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HIGHLIGHTS

- A novel photobioreactor design combining airlift and flat plate designs is proposed.
- CFD is used to compare performance of novel and airlift PBR.
- Novel design is optimized using CFD simulations by varying design parameters.
- Novel design has better light–dark cycling and has higher surface to volume ratio.
- Better hydrodynamics are expected to improve microalgae yield.

ARTICLE INFO

Article history:
Received 2 August 2014
Received in revised form 28 November 2014
Accepted 29 November 2014
Available online 18 December 2014

Keywords:
Biofuel
Microalgae
Photobioreactor
CFD
Hydrodynamics

ABSTRACT

The high cost of microalgae cultivation is one of the major hurdles in large scale production of microalgal biofuels. Cultivation in closed photobioreactors (PBR) to achieve high culture concentrations is a potential solution. However, existing PBR designs do not have the desired efficiencies, and lead to high material and energy costs. Therefore, novel PBR designs need to be developed and benchmarked against existing designs. This work has proposed a novel PBR design by combining two existing designs, namely, the airlift and flat plate PBRs. The novel design uses the concept of riser and downcomer from the airlift PBR. However, the downcomer has flat surfaces resembling a flat plate PBR. The hydrodynamic performance of the novel PBR was studied using Computational Fluid Dynamics (CFD), and the performance was compared with that of the conventional airlift PBR. The dimensions of the novel design were then optimized using CFD simulations. The results showed that the novel design had superior liquid circulation properties that resulted in a regular and alternative exposure to light and dark regions of the PBR. The novel design also had about 7% higher surface area to volume ratio as compared to a conventional airlift PBR.

1. Introduction

Several renewable and sustainable energy alternatives are being currently investigated to replace non-renewable fuels in the future. This has been driven not only by the limited stock of the non-renewable fuels, but also by the deleterious effect their consumption has on the environment and society. Among the various renewable alternatives such as solar, wind, biomass, and hydro, biomass is expected to play a crucial role. This is because biomass resource availability is relatively stable. Moreover, biomass can be converted to liquid fuels such as biodiesel, ethanol, and butanol that readily fit into the existing transportation infrastructure. The significantly lower energy content of typical biomass than fossil fuels on a per unit basis mean that substantial land and water resources will be required to meet the projected fuel demands. However, productive and arable land is limited globally and required to grow food crops. This is especially true for countries like India and China, where most of the arable land is taken up for agriculture and resources are scarce.

Microalgae are a biomass option that can address these concerns to a great extent. The fuels produced from microalgae are popularly known as the third generation of biofuels. Microalgae have significantly higher productivity on a per unit area basis as compared to terrestrial biomass. Moreover, microalgae can be grown on non-arable and degraded lands. The growth of microalgae requires water, carbon source, and nutrients. Certain strains of microalgae can be grown in sea water, which opens a vast resource for utilization. Carbon can potentially be provided by exhaust gases from thermal power plants that are rich in

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http://dx.doi.org/10.1016/j.apenergy.2014.11.072
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carbon-di-oxide. This achieves carbon capture and reduces environmental emissions. Moreover, essential nutrients can be supplied by waste streams containing nitrogen and phosphorous. Thus, microalgae offer the twin benefits of addressing the energy as well as environmental issues.

However, despite these potential benefits, the commercial implementation of microalgae to biofuel systems has not materialized due to several bottlenecks [1–4]. Several studies have shown that production of biodiesel from microalgae is not techno-economically feasible. Wijffels and Barbosa [1] have reported that the cost of microalgal biodiesel needs to decrease by 10 times from its current value for it to become cost competitive.

One of the major bottlenecks in the microalgae-to-biofuel value chain is the growth of microalgae [4]. The two primary methods of microalgae cultivation are using open ponds and closed photobioreactors. Open ponds, such as raceway ponds, are cost efficient but lead to other problems such as very low culture density, typically less than 1 kg/m^3, low productivity, typically 10–20 g/m^2 day, contamination, susceptibility to weather events such as rainfall, and high evaporative losses [5–7]. In contrast, photobioreactors (PBR) overcome many of these limitations through better control over growth parameters such as light availability, light intensity, and temperature. Most importantly, PBRs lead to more concentrated cultures with densities higher than 80 kg/m^3 [8] and higher productivity of 20–45 g/m^2 day as compared to that for open ponds [9]. The higher concentration reduces the water removal and drying requirements downstream and therefore helps in achieving better energy efficiency. Airlift and flat plate photobioreactors are promising design configurations for industrial scale production of microalgae. However, high capital and operating costs of PBRs is a major hurdle for their large-scale implementation, especially for a low value, high volume product such as biofuel. Consequently, novel designs of PBRs that achieve high productivity, reduce costs and energy requirement, and are easy to scale-up are needed [10].

The goal of this work was to address this research gap and design a novel PBR that integrated the beneficial design aspects of both airlift and flat plate PBR. It was postulated that the novel design would have better surface to volume ratio and improved hydrodynamic properties. This was verified by developing a Computational Fluid Dynamics (CFD) model for the novel design, and comparing the performance of that design with a standard airlift PBR. CFD simulations were then used to study the impact of different design modifications on these hydrodynamic properties, and perform simulation based optimization of the design.

The paper is organized as follows. Section 2 discusses the importance of photobioreactors and further reviews various design and modeling aspects of a photobioreactor. Section 3 describes the proposed novel design of a photobioreactor. Section 4 describes the CFD model set-up details, while section 5 presents the results and discussion. The article ends with important conclusions and directions for future extensions of this work in section 6.

2. Photobioreactor: design considerations and modeling

This section reviews the key design criteria, important conventional designs, and modeling work presented in the literature. This serves as the basis for discussing the novel features of the PBR design proposed later in this work.

2.1. Important PBR design considerations

The most important factors for growth of algae are light, mixing, temperature, CO_2, O_2 removal, nutrient supply, and pH [11,12]. The design of a PBR can have a significant impact on these factors [13]. A key PBR design principle is to maximize the surface area to volume ratio, which can also serve as a benchmark to compare different reactors [12]. Light intensity/penetration, frequency of cellular exposure to light, and wavelength of light are some of the important properties that can be enhanced by an improved reactor design. As distance from the irradiated side of the photobioreactor increases, there is an exponential decrease in the light flux [41]. Erickson and Lee [14] showed the creation of three zones with different growths resulting from an exponential decay of illuminance in an externally irradiated bioreactor. It is also desirable to have cells experience alternating light and dark cycles, which benefit algal growth. The frequency of such cycles has a significant influence on the specific growth rate μ, with slow cycles in the range of seconds reducing μ whereas fast cycles in the milliseconds range leading to higher μ when the net irradiance intensity is kept constant. Fast cycles require more mixing energy [10]. Brindley et al. [15] reported that a correct light/dark regime enabled higher photosynthetic rates with the possibility of efficiency reaching close to the optimum 8 quanta/O_2.

Apart from light, the hydrodynamics play an important role in the performance of a PBR. Gas holdup and liquid circulation velocity are important hydrodynamic parameters [16]. Mixing also plays an important role in photobioreactor performance [13]. Mixing can increase productivity by enhancing mass transfer as well as by altering the frequency of light–dark cycle in a photobioreactor [17]. Mixing and associated heat transfer is also important if the PBR is to be used to sequester carbon from flue gases. Such gases are generally available at high temperatures, and improper mixing may lead to localized hotspots causing cell death. However, high levels of mixing can lead to cell death, and hence mixing rates must be optimized carefully [12]. The minimum amount of CO_2 that must be provided is 1.65 g CO_2 per gram of biomass, while 3 g CO_2 per gram biomass is recommended for oil rich algae [10]. Gas injection rate is also an important design factor [11].

In summary, there are several PBR design challenges that need to be addressed. Some of the important ones are:

- Ensuring a high surface area to volume ratio for the illumination.
- Consideration of both light penetration and distribution, which in turn are affected by the mixing and distribution of gas within the PBR [11,38].
- Achieving higher light/dark cycle frequency, preferably close to 1 Hz [31].
- Improving the overall hydrodynamics so that the issues of settling are overcome with minimum mixing energy.

2.2. Important PBR designs

There are several PBR designs proposed in literature [18,13,19,7]. The two important designs of interest are the airlift and flat plate PBRs. These are briefly discussed here.

- Airlift PBR: The airlift PBR is a vertical column PBR. It is composed of an outer column, which is usually transparent, an internal draft tube, and an air sparger at the bottom [7]. The two difference fluid zones act as riser and downcomer depending on the placement of the sparger. Airlift PBRs allow rapid mixing and exert low shear stress [20,19]. They also experience less photoinhibition even under high light intensity and require lesser land area. They exhibit better liquid flow, enhanced gas exchange, and improved irradiation cycle. Airlift PBRs do not employ moving parts and mechanical pumping, and are thus suitable for shear sensitive cells [42].
- Flat plate PBR: Flat plate PBRs provides a narrow light path with illumination being provided from either one or both sides of the flat-plate PBR [13]. They exhibit superior surface to volume