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Review

Radiation transfer in photobiological carbon dioxide fixation and fuel production by microalgae

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ABSTRACT

Solar radiation is the energy source driving the metabolic activity of microorganisms able to photobiologically fixate carbon dioxide and convert solar energy into biofuels. Thus, careful radiation transfer analysis must be conducted in order to design and operate efficient photobioreactors. This review paper first introduces light harvesting mechanisms used by microorganisms as well as photosynthesis and photobiological fuel production. It then provides a thorough and critical review of both experimental and modeling efforts focusing on radiation transfer in microalgae suspension. Experimental methods to determine the radiation characteristics of microalgae are presented. Methods for solving the radiation transfer equation in photobioreactors with or without bubbles are also discussed. Sample measurements and numerical solutions are provided. Finally, novel strategies for achieving optimum light delivery and maximizing sunlight utilization in photobioreactors are discussed including genetic engineering of microorganisms with truncated chlorophyll antenna.

Contents

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1. Introduction

1.1. World energy challenges

Industrial and developing nations are facing an unprecedented combination of economic, environmental, and political challenges. First, they face the formidable challenge to meet ever expanding energy needs without further impacting the climate and the environment. Second, the continued population growth in developing countries and the emergence of a global economy are creating unprecedented stress on the resources of the Earth. Emerging countries are claiming access to the same standard of living as that of industrial nations, resulting in large needs for energy sources, fast and reliable transportation systems, and industrial equipment. From the standpoint of international security, energy issues include the potential for conflict over access to remaining supplies of inexpensive fossil fuels, which are often concentrated in politically unstable regions.

Currently, fossil fuels supply more than 81% of the world's energy needs estimated at about 137 PWh/year (1 PW$=1^{15}$ W) or 493 EJ/year (1 EJ$=10^{18}$ J) [1]. Oil meets more than 92% of the world transportation energy needs [1]. However, its production is expected to peak between 2000 and 2050 after which its production will enter a terminal decline [2]. Simultaneously, the world energy consumption is expected to grow by 50% between 2005 and 2030 [2]. Thus, the end of easily accessible and inexpensive oil is approaching.

Moreover, intensive use of fossil fuels increases the concentration of carbon dioxide (CO_2) in the atmosphere and contributes to global climate changes [3]. For example, 71.4% of the electricity consumed in the United States is generated from fossil fuel, mainly coal and natural gas [4]. In 2006, electricity generation alone contributed to 33% of the total CO_2 emissions of the United States, which in turn represented approximately 23% of the total global CO_2 emissions [2].

Flue gases from fossil fuel power plants consist of 4–14 vol% of CO_2 and up to 200 ppm of NO_x and SO_x, depending on the type of fuel and on the combustion process [5]. Overall, the concentration of CO_2 in the atmosphere in 2006 varied between 360 and 390 part per million by volume (ppmv) during that year and continue to increase [6]. It is predicted that CO_2 levels above 450 ppm in the atmosphere will have severe impact on sea levels, global climate patterns, and survival of many species [3]. Consequently, growing energy needs calls for greater reliance on a combination of fossil fuel-free renewable energy sources and on new technologies for capturing and converting CO_2.

1.2. Solar radiation

Seen from the earth, the sun is approximately a disk of radius 6.96×10^8 m at an average distance of 1.496×10^{11} m and viewed with a solid angle of 6.8×10^{-5} sr. The Sun is often approximated as a blackbody at 5800 K emitting according to Planck's law [7]. The solar constant is defined as the total energy incident per unit time per unit surface area at the outer surface of Earth's atmosphere and oriented perpendicular to the sun's rays; it is estimated to be 1367 W/m^2 [7,8]. As the solar radiation travels through the Earth's atmosphere it is absorbed by atmospheric gases (e.g., CO_2, H_2O) and scattered by gas