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Hollow glass microspheres for temperature and irradiance control in photobioreactors

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HIGHLIGHTS

- Photobioreactors made of a HGM polymer are cheaper to run.
- The broth temperature can be reduced 7 °C using 0.6 vol.% HGM in the reactor wall.
- HGM composites have mechanical properties suitable for bioreactor manufacture.
- Growth rate is improved by up to 33% using 0.6 vol.% HGM comp. in the reactor wall.

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ABSTRACT

The addition of hollow glass microspheres (HGM) to polymers to change thermal insulation and mechanical properties is widely used. In this study HGM were tested as a new construction material for photobioreactors to control irradiance and broth temperature in microalgae cultivation. The heat isolation properties of HGMs of three different densities were tested in a polymer matrix. The transmittance (5–50%) and the thermal conductivity (182.05–190.73 W/mK) of the HGM composite material were analyzed. The results were tested in a model to predict the broth temperature and the growth rate as a function of temperature and irradiance. The addition of 1.3 and 0.6 vol.% of HGM lead to an increase in the growth rate of up to 37% and a reduction in the broth temperature up to 9 °C. The mechanical resistance of the composites tested is similar to the polymer matrix.

1. Introduction

Since early studies in biotechnology the technical focus of the outdoor mass cultivation of microalgae has been the photobioreactor. The design of the photobioreactors should maximize the amount of irradiation received (Chen et al., 2011; Mohsenpour and Willoughby, 2013; Pegallapati et al., 2012) therefore the main concern in biomass productivity is to make effective use of light irradiance in the microalgae culture (Kumar et al., 2013). Besides the effect of direct and reflected solar irradiation, the broth temperature in the reactor also has an impact on microalgae growth rates (Franz et al., 2012; Gomez and Gonzalez, 2005; Pereira et al., 2013; Sheng et al., 2011).

According to Franz et al. (2012) the irradiation rate supplied to the photobioreactor throughout the day can be described as a function of prevailing geographical and climatic conditions. Furthermore, maximum annual yields were achieved in regions with high irradiation and temperature patterns in or near the optimum range of the specific algal strain. The limitations of outdoor full scale production of microalgae imposed by extreme irradiation and high temperatures are generally controlled by shading the reactor surface, using external cooling systems such as water-spray on the reactor or internal heat exchangers (Gutiérrez et al., 2008; Quinn et al., 2012; Sierra et al., 2008). Other solutions have focused on the geometry of the photobioreactors for spatial dilution of light, temperature-controlled greenhouses or installation facilities such as an artificial body of water to moderate the day-night temperature cycles (Carlozzi and Sacchi, 2001; Chen et al., 2011; Hulatt and Thomas, 2011; Masojídek et al., 2003; Oncel and

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Sabankay, 2012). However, most of these solutions are costly and consume large amounts of water and energy.

In fact most research has focused on the modification of the design and geometry of the photobioreactor to enhance biomass productivity. However, most of the novel photobioreactors are not suitable for large scale production of microalgae culture because of the high cost of manufacture and operation. An alternative is to evaluate the use of new materials to build photobioreactors in order to control irradiance and temperature. For example, the development of thermal insulate composite materials for the construction of photobioreactors can be tested. Irradiance can be controlled by changing the construction material of the photobioreactor that will affect the heat exchanged to the environment. The transparent material used in photobioreactors is usually polyethylene (PE), polycarbonate (PC), polyvinyl chloride (PVC), polymethyl methacrylate (PMM), polypropylene (PP), glass and silicate (Richmond, 2004). These are low cost materials and their manufacturing/shaping and transport low cost too. Yet for environmental reasons the photobioreactor should be recyclable and therefore polyethylene terephthalate (PET) should also been tested.

A considerable number of additives have been tested to develop polymer composite materials for different industrial application with low thermal conductivity such as hollow glass microspheres (HGM). However, HGM composite to be used as a construction material for photobioreactors to microalgae cultivation is a new issue. HGM is an inorganic, finely dispersed spherical powder material and the hollow core gives HGM a thermal insulation property. Li et al. (2011) evaluate the mechanism of heat transfer of HGM showing the low thermal conductivity of this material. Low thermal high density polyethylene (HDPE) HGM composite was tested by Patankar and Kranov (2010). Based on their findings and others regarding the insulation property of HGM (Dombrovsky et al., 2007; Gao et al., 2013; Hu et al., 2013; Park et al., 2005) this study focuses on the use of hollow glass microspheres to enhance the thermal insulation of a flat plate photobioreactor controlling light irradiance and broth temperature due to the reduction of the wall transmittance and the insulation property of the material. The results of the characterization of the polymer HGM composite are used as input parameters in the model developed by Béchet et al. (2010) to predict the broth temperature. The microalgae growth rate is estimated according to the model developed by Bernard and Rémond (2012). Thus, the overall aim of this study was to find the ideal concentration of HGM added to photobioreactor construction material in order to increase specific growth rate by controlling broth temperature and wall transmittance.

2. Methods

The materials used in this study included commercially available isophthalic polyester resin (PR) and three different sodium borosilicate hollow glass types marketed by 3 M. The features of the three different HGM tested are presented in Table 1. Other physical parameters provided by the supplier are the density of the micro-spherical shell (2.23 g/cm^3), the thermal conductivity (0.023 W/mK) and the density of the gas phase inside of the HGM (7.50.10^{-5} g/cm^3). The volume fraction of the microspheres in the PR HGM composite tested are 5.0, 2.5, 1.3 and 0.6 vol.% for each type of microsphere. The methods for the characterization and evaluation of the composites are described as follows.

2.1. Synthesis of the polymeric matrix

The synthesis of the polymeric matrix was carried out using polyester resin with the addition of 2 vol.% of methyl ethyl ketone peroxide catalyst (matrix). The matrix was molded by removing it before the formation of polyester and then it was placed into silicone molds.

2.2. Preparation of the composites

The preparation of the composites followed the same method described above. Before the polymer reached the sol–gel state, the HGM was added to the reaction with fixed stirring for 2 min and placing it into the silicone molds.

2.3. Techniques used in the characterization of the materials

2.3.1. Tensile test and flexure test

Tensile and flexure tests were performed using universal testing equipment (EMIC, DL2000) according to ISO 527 and ISO 178 respectively. The displacement speed for the tensile test were 2 mm/min and for flexure test were 3 mm/min, both test used 2000 N load cell and distance between grips equal to 100 mm. In addition for tensile and flexure tests eight and six, respectively, tests were done.

2.3.2. Transmittance

The transmittance of the matrix and composites were carried out on a Cary 60 UV–Vis spectrophotometer. The samples were loaded and polymerized in a plastic flow cell and were measured in the region of 400–1100 nm at room temperature. The mean values obtained by the *t*-Student test are the results from three readings of the matrix and the PR HGM composites C1, V5 and H6 each at four different concentrations.

2.3.3. Thermal conductivity

The thermal conductivity of the PR matrix and PR HGM composites was evaluated according the model presented by Liang and Li (2007):

$$k_{eff} = (1/k_p(1-6\emptyset_f/\pi)^{1/3} + 2(k_p(4\pi/3\emptyset_f)^{1/3} + \pi(2\emptyset_f/9\pi)^{1/3}(k_g((\rho_s-\rho_a)/(\rho_g-\rho_a)) + k_a((\rho_g - \rho_s)/(\rho_g-\rho_a)) - k_p))^{-1})^{-1} \quad (1)$$

where k_{eff} is the specific equivalent thermal conductivity (W/mK); k_p, k_g and k_a are the thermal conductivities of the polyester resin, micro-spherical shell and gas phase of the HGM, respectively (W/mK); $\emptyset_f$ is the volume fraction of the HGM in the composite (vol.%); and ρ_s, ρ_g and ρ_a are the densities of the HGM, micro-spherical shell of the HGM and the gas phase inside the HGM, respectively (kg/m^3).

Table 1
Basic features of the HGM tested.

Sample	Density (g/cm^3)	Size (μm)	Crushing strength (psi)	Thermal conductivity (W/mK) @ 21 °C
HGM C1	0.12	120	250	0.047
HGM V5	0.38	85	5500	0.127
HGM H6	0.60	60	18,000	0.200