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Solar tracker development based on a POF bundle and Fresnel lens applied to environment illumination and microalgae cultivation

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ABSTRACT

Although within the group of countries with the highest solar irradiation index in the world, Brazil still underuses its natural power. Brazil's hydropower energy today makes up 68,5% of the total energy produced, in contrast however, photovoltaic energy production is still only 0.01%. As an effort to open up new frontiers for solar energy uses, the main objective of this project was to use solar energy in form of light to reduce the power consumption required for continuously lighting any kind of environment as well as to propose a new technology for illuminating a conventional window-type photobioreactor (PBR) in the cultivation of microalgae for biofuel production in order to reduce their associated costs. The system is composed by a solar tracker, an electromechanical control, a Fresnel lens and a plastic optical fiber (POF) bundle, in which tip the lens concentrates the solar radiation. Therefore, at the other end of the bundle, the POFs can be distributed homogeneously in any local where one wants to illuminate. The solar tracker is able to track the Sun from sunrise to sunset using an algorithm whose function is to calculate the Sun position according to the local time and latitude using an equatorial mount structure. In addition, some sensors are employed for monitoring relevant parameters, for instance, the light intensity inside the POF bundle, the right ascension and declination angles of the tracker and the solar radiation. These parameters can be downloaded in real time through a specially designed mobile application. As application of the solar tracker, two projects were developed and described in this paper: two kinds of solar luminaires for illumination of internal ambiences and a closed photobioreactor by POF illumination, with nontransparent material, free of outside contamination with low cost and the study of the produced biomass through the lipid content. Both applications were compared in performance with their conventional counterparts and, as a conclusion, it is shown that in both cases they can substitute their conventional counterparts with advantages.

1. Introduction

Belonging to the group of countries with the highest solar irradiation index in the world, Brazil still underuses its natural power. Although BrazilÍs hydropower makes up 68,5% of total energy produced, we have only 5.3% in eolic production and a meagre 0.01% in photovoltaics (Matriz Energética Brasil, 2018).

In fact, considering the solar irradiation all over the word, Brazil is among the regions with the highest solar irradiation, according to Solargis (2018). Table 1 summarizes the average annually solar energy for some countries with high irradiation on the planet.

Notice that Brazil's solar radiation is just below that of Saudi Arabia. In contrast, Germany, despite having a very small solar irradiation, is investing heavily in photovoltaics.

In 2015, solar power covered only about 1% of global electricity demand in the world. In three countries in Europe – Italy, Germany and Greece – solar photovoltaic supplies more than 7% of the electricity demand (REVE, 2018).

Contrasting with the relatively low solar power harvested on the planet, of the total energy usage all over the world, illumination consumes about 20%, catalysing the research in solar energy for illumination.

Inspired in these facts, the objective of this work was to develop a solar illumination system by the use a solar tracker that follows the Sun from sunrise to sunset. The objective is to apply the system two interfaces: first, as an alternative and innovative technology in the lighting

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Table 1
Average yearly solar irradiation of some countries (Solargis, 2018).

Country	Average energy (kWh/m^2)
Australia	3000
Chile	2740
Sub-Saharan Africa	2560
Saudi Arabia	2400
Brazil	2300
South Africa	2270
USA	2200
China	2120
Spain	1800
Germany	1200

of a photobioreactor (PBR) for microalgae cultivation in the biomass process, aiming the production of biofuel, and second, as a light generation in environments such as study rooms, museum, warehouses, underground parking, commercial buildings, for instance.

The solar tracker consists of an opto-electromechanical project, which uses a motor, an electronic set up for control and an optical system comprised of a Fresnel lens and a plastic optical fiber (POF) bundle. In addition, some sensors are employed to monitor the process such as the light intensity captured by the optical fibers, ascension and declination angles by the use of an accelerometer, and the overall measurement of the solar radiation with a pyranometer. These parameters are stored in the main computer and can be downloaded via web to a mobile application in order to be possible to control the system performance at distance. The sensors data are stored in real-time via a web system, entitled "LIF-Remoto", which allows access to the sensor data remotely.

The tests in ambience illumination were carried out at the same building where the solar tracker is used to illuminate the photobioreactor. For this, a study room was totally darkened with windows sealed against external natural illumination to be used as a laboratory for the solar illumination tests.

The system was totally developed at the Photonics and Instrumentation Laboratory (LIF) of the Electrical Engineering Program at the Universidade Federal do Rio de Janeiro. Currently, the system is installed on the terrace of the building were microalgae is studied at the biofuel process.

2. A review on solar illumination systems

This section it will cover a review of some applications of solar energy by exploring its illumination capability. We concentred the review in photobioreactor for microalgae cultivation, illumination systems, solar tracking techniques and polymeric optical fibers.

2.1. Solar tracking techniques

There are two main assemblies or mounts for tracking an object in the sky, termed as azimuthal (or alt-azimuth) and equatorial. These mounts are applied in telescopes, both large and portable. Alt-Azimuth assembly has two axes of movement: altitude (up/down), and azimuth (left/right). As an object like the Sun moves across the sky, it will be necessary to adjust both of these directions continuously to keep the star in the center of the scene. The equatorial mount moves the telescope in an arc, allowing to track objects much easier as they move across the sky. This means that one has to adjust a single axis to track the object to keep it in the field of view. Alt-azimuth needs two motors to track an object, one for each axis and their speed is not constant as the object crosses the sky. On the other hand, the equatorial mount needs only one motor and its speed is constant during all the time of observation.

In equatorial mounting, there are two axes. The primary axis is fixed and mounted parallel to the Earth axis, that is, at the local latitude angle. The secondary axis, fixed to the primary one, allows movement in the east-west direction. With this single movement, it is possible to follow the Sun just by rotating this axis. Therefore, this axis rotates at a constant speed, equal to that of the sidereal day. By adjusting the system to the direction of the sunrise, it is just necessary to start the motor at a constant speed and it will follow the Sun during its journey through the sky. The rotation shall be done at a rate of one turn (360°) for each sidereal day (23 h 56 min and 4 s) in the opposite direction to that in which the Earth rotates. This speed represents approximately 15° per hour or four minutes for each degree of rotation.

As it will be detailed in the next sections, fixed at the main axis, a Fresnel lens tracks the Sun, projecting the focus at the tip of a POF bundle. Since the Sun rises every day in a slightest different position at the horizon, this axis has to be adjusted by a few degrees each day. However, as this displacement is very small compared with the focus area, it can be manually adjusted at a periodicity of about five days. It is just necessary to know the corresponding declination of the sunrise for each day.

2.2. Solar illumination systems

The technique of illumination by light guides has been studied since before the time of the invention of low attenuation optical fiber in the 70's. More recently, with the greater availability of POFs, these studies have intensified and many researchers have developed lighting designs using optical fibers. The advantage of POFs is their larger diameter when compared to silica fibers, which allows the capture of more light, in addition to presenting a density 2.5 times smaller than that of silica. On the other hand, the maximum temperature of 80 °C for POFs of PMMA (Poli-methyl methacrylate) or 105 °C for POFs of polycarbonate limits the solar concentration, making necessary the use of filters.

There are many examples in the literature describing the use of optical fibers for illumination purposes. Cariou et al. (1982), suggested the possibility of using a fiber bundle to guide the light, aiming an environment illumination. Although rather outdated paper, it is useful as a guide in how to model and calculate light concentration from a parabolic mirror into optical fibers.

Matsunaga et al. (1991), used a 1.5-m POF bundle for the production of glutamate from a culture of cyanobacterium. They used a special type of POF, made of PMMA core with a sheath of fluororesin around the core to diffuse the light along the fiber. They did not use the Sun, but rather a metal-halide lamp to simulate sunlight. When dealing with optical fiber illumination, it is important to design means of distributing the light at the end of the light guide by a diffusor, instead of simply pointing the fiber end to an object. With this idea in mind, in the present work we designed our own diffusor, as it will be described later.

Lianga et al. (1998), concentrated the Sun in optical fibers, using parabolic mirrors. The concentration leads to an increase in temperature, which motivated Jaramillo et al. (1999), to study the thermal behavior of a solar concentration system in optical fibers. The idea to use POF as light guide is not new, but when concentrating the solar radiation into a POF bundle, thermal problems arise. As it will be seen in this work, we tested several approaches to circumvent the low glass transition temperature (T_g) of PMMA, which is about 80 °C.

Feuermann et al. (2002) designed a solar fiberoptic mini-dish concentrator with 200 mm in diameter. They transported concentrated sunlight in a one-millimeter-diameter optical fiber to distances up to 20 m away. The authors did not provide information on the illumination results, but it is possible to notice from their work that the parabolic mirror has to focus into a very small dot, just over the optical fiber end. Since in our work the idea is a cheap and robust system, we avoided parabolic mirrors for their cost and fragility.

It is worth mention the work of Munisami and Kalymnios (2008) in which they present a review of solar lighting systems, including the use of optical fibers.