

Simulation-based study of the energy requirements linked to the temperature control of micro-algae culture in outdoor photobioreactors.

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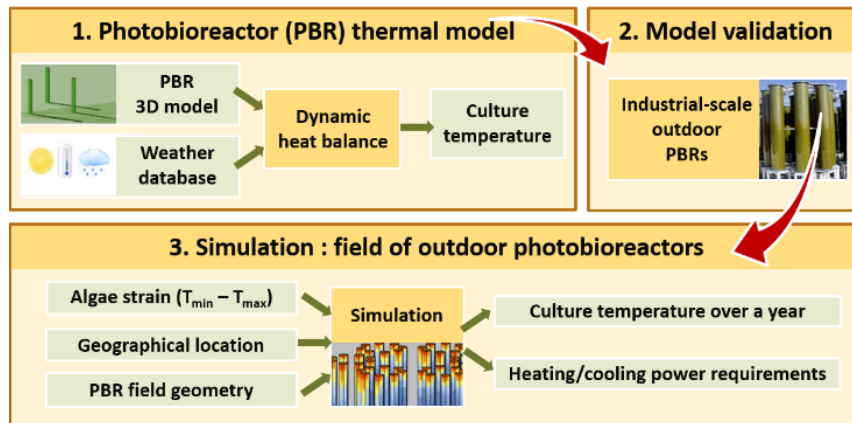
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ABSTRACT

Outdoor microalgae photobioreactors are exposed to continuously variable weather conditions, causing permanent fluctuations of culture temperature that must be limited within a strain-dependent range. The optimization of photobioreactor performance requires to be able to predict the culture temperature evolution and related power requirements as a function of weather conditions as well as photobioreactor design. Based on this perspective, a thermal model for vertical tubular photobioreactors was proposed and validated using experimental data

from industrial-scale photobioreactors. The model was then used to predict the annual amount of energy required to maintain the culture temperature within a desired range, for different reactor configurations and for several locations in the world. The use of weather databases is of major importance to choose the best location to build microalgae production facilities and to optimize influent geometrical and operating parameters, which can play wanted or unwanted roles depending on the meteorological conditions of the site.

1. Introduction

Autotrophic microalgae, which use photons as energy source to fix carbon dioxide, are one of the most attractive new sources for chemicals, food, biofuels and high-value bioactives ([1]; [2]; [3]). Thanks to their high photosynthetic yield compared to terrestrial plants, microalgae appear to be a major source of renewable biodiesel that is capable of meeting the global demand for transport fuels [4]; however, although microalgal biodiesel is technically feasible, its cost of production needs to be reduced by exploiting the biorefinery concept and achieving progress in PBR1 engineering.

Culture systems to produce microalgal mass have come a long way [5]. Currently, the most widespread large-scale microalgae production systems are open ponds and closed PBR technologies [6]. Open ponds are cheaper, but less efficient than closed PBRs, which ensure higher biomass productivity, better mixing, light and carbon dioxide utilization, less contamination, and require less land area ([7]; [8]; [9]). In particular, column PBRs offer the most efficient mixing, the highest volumetric mass transfer rates and the best controllable algae growth conditions [10]. However, the control of process parameters at an affordable cost is still a challenge. The space and light requirements of massive biomass production imply that microalgae farms will be outdoor and exposed to continuous fluctuations of climate variables such as solar radiation, air temperature or wind speed. And, as light availability and culture temperature have a strong influence on the rate of photosynthesis [11], it is crucial not to shift too far away from the optimal temperature of the produced algae species, while ensuring sufficient available solar radiation. Consequently, PBR design must balance contradictory requirements: their ratio of surface area to culture volume is generally maximized to ensure light availability, which makes the system very sensitive to its environment regarding heat transfer. As a result, sunlight may overwarm the culture medium, even in vertical tubular PBRs, which tend to heat less than horizontal ones, while at night the temperature can decrease below acceptable levels [12]. In most locations, temperature control is then necessary to maintain the culture within a favourable temperature range, which induces high infrastructure and operating costs [13]. This aspect cannot be neglected when evaluating the economic feasibility of large-scale algae production systems.

For a given location, finding a layout that allows an almost passive thermal regulation or at least limits the energy requirements could hence break a main limitation of this technology. This implies to analyse and model the thermal exchange between the PBR and its environment. In this perspective, Gutiérrez et al. [14] used a lumped parameter model to show that conventional energy usage could be reduced by optimizing the geometry and the shading device of an outdoor tank PBR. Béchet et al. [15] were the first to apply this kind of approach to a column PBR, in order to predict the evolution of culture temperature as a function of location, reactor geometry and environmental variables. The

¹ PBR: photobioreactor

resulting model enables to predict the culture medium temperature, its changes and the energy required to maintain it within acceptable ranges, and so to compare possible layouts. Pereira et al. [16] adapted this model to flat plate PBRs in order to investigate the effect of various design parameters on broth temperature. Goetz et al. [17] proposed a dynamic thermal model for intensified closed flat panel PBRs.

However, none of the existing models can be directly applied for the optimisation of industrial-scale tubular photobioreactor configurations with complex three-dimensional geometry, in which shading effects can have significant impact on solar heat gain and thus on the evolution of culture temperature throughout the day.

In this perspective, the present work aims to propose a mathematical modelling and simulation methodology to simulate heat transfers in a field of industrial-scale tubular PBRs, taking into account the shading effects generated by complex three-dimensional PBR geometries, and to validate it experimentally.

2. Experimental

The present work is based on the study of a real microalgae production facility based in Alicante (Spain). The system to be modelled, namely the photobioreactors, is described in Section 2.1. The thermal model and the methodology used for its validation are presented in Sections 2.2 and 2.3, respectively. Finally, the simulation tests performed with the validated model are presented in Section 2.4.

2.1. Photobioreactors

The PBR used for this study is described in Patent EP2135937A1 [18]. The PBR is composed of an arrangement of vertical annular columns, and each column is composed of an outer tube and an inner tube (Fig. 1).

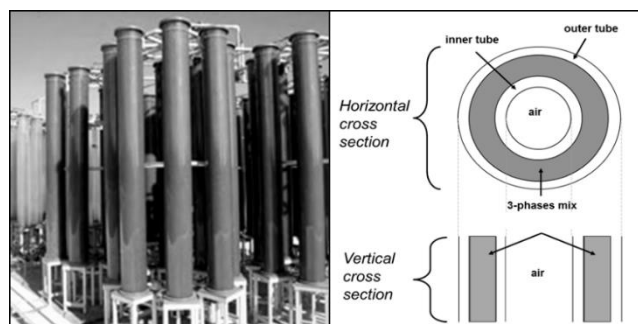


Fig. 1. Vertical tubular PBR and cross sections of a single column (BFS, Alicante, Spain).

A triphase culture medium, composed of sea water, air bubbles and solid particles, flows in the annular space between the outer and the inner tube. The inner tube is opened to the atmosphere and thus in contact with the surrounding air.

The culture from all the columns is mixed and recirculated, making the culture temperature uniform among the different columns. The measuring point for evaluating the average culture temperature in the PBR is located just after the mixing operation.

Due to the vertical structure of the PBR, the columns shade one another. As a result of this, only a fraction of the total external surface of the PBR is exposed to direct sun radiation. The parts and proportion of PBR surface exposed to direct solar radiation vary with sun position, which depends on geographical location, day of the year and hour of the day.

2.2. Thermal model

The model accounts for the thermal exchanges between the microalgae culture contained in the PBR and its environment. It predicts the temporal evolution of culture temperature.

2.2.1. Energy balance

The model is based on the following assumptions: (1) The culture is considered perfectly mixed and its temperature is thus assumed uniform in all columns; indeed, on-site measurements on a sunny day showed that temperature is uniform inside each single column due to the high turbulence, and that the coolest column is generally 1.5 to 2 °C fresher than the temperature in the measuring point, while the hottest one is 1.5 to 2 °C warmer. It is important to note that on cloudy days these temperature differences will be lower and that the measured temperature after mixing will always be in between the hottest and freshest values. As the temperature gradient between columns is significantly lower than the amplitude of culture temperature variation during 24 hours, and that the scope of this study is to evaluate the evolution of the average culture temperature, the assumption of a uniform culture temperature throughout the whole PBR volume is acceptable. (2) The thermal radiations emitted by the PBR, the air and the ground are neglected. Thermal radiation refers to the energy emitted by objects due to their temperature and the corresponding radiative transfer can be calculated according to the Stefan-Boltzmann law. However, according to Wien's displacement law, and given their expected range of temperature values, the PBR, air and ground emit thermal radiation in the far infrared, namely above 5000 nm. And yet, the constitutive material of PBR outer tube is PMMA (polymethyl methacrylate) which is transparent at visible and near infrared wavelengths, but opaque in the infrared region beyond 2200 nm. As the majority of solar radiation lies within the wavelength range of 200 – 2500 nm, solar radiation is almost totally transmitted through PMMA and absorbed by the culture, thus contributing to culture warming. However, the thermal radiation

emitted by the culture is not transmitted by PMMA: this phenomenon is referred to as greenhouse effects and contributes to culture warming. Similarly, thermal radiations emitted by the surrounding air and ground are almost not transmitted to the culture by PMMA. (3) The variations of enthalpy associated to air and CO₂ inlet flows and water evaporation were evaluated and appeared negligible in comparison with other contributions (1% of the total energy exchanged between the PBR and the environment). This is due to the fact that the gas flows are very low compared to the total amount of culture, and the system is closed, limiting evaporation to the exchange with these gases. These terms are thus neglected in the heat balance.

Therefore, the thermal model accounts for the solar radiation and for the heat transfer between the culture and the surrounding air by convection and conduction. Consequently, the temporal evolution of culture temperature can be modelled by the following ordinary differential equation:

$$\rho_l V_{cult} C_{pl} \frac{dT_{cult}}{dt} = Q_{rad_sol} + h_{inner_tube} S_{inner_tube} (T_{air} - T_{cult}) + h_{outer_tube} S_{outer_tube} (T_{air} - T_{cult}) \quad (1)$$

where V_{cult} (m³) is the total culture volume contained in a PBR, T_{cult} (K) is the culture temperature, ρ_l (kg.m⁻³) is the culture density, C_{pl} (J.kg⁻¹.K⁻¹) is the culture specific heat, Q_{rad_sol} (W) is the solar radiation flux received by the culture, h_{inner_tube} (W.m⁻².K⁻¹) is the overall heat transfer coefficient between the culture and the air contained in the inner tube, S_{inner_tube} (m²) is the total cylindrical area of inner tubes of the PBR, T_{air} (K) is the outside air temperature, h_{outer_tube} (W.m⁻².K⁻¹) is the overall heat transfer coefficient between the culture and the air surrounding the outer tube, and S_{outer_tube} (m²) is the total cylindrical area of outer tubes of the PBR.

2.2.2. Solar radiation flux

Solar radiation impinging on the field of PBRs includes three terms [19]: (1) The direct, or beam solar radiation, which is the solar radiation received from the sun without having been scattered by the atmosphere; (2) The diffuse solar radiation, received from the sun after its direction has been changed due to scattering by the atmosphere. (3) The reflected radiation, coming from surrounding objects and depending mainly on ground albedo [20]. The sum of direct and diffuse solar radiations is referred to as total solar radiation.

Depending on sun position, the amount of total solar radiation received by the culture can be significantly reduced, either by mutual shading between PBR columns, or by cast shadows created by surrounding buildings or objects. Therefore, it is essential to take into account the effect of shadows in the dynamic heat balance.

In order to generalize the method to any PBR geometry and surrounding environment, an approach based on 3D modelling of the PBR geometry was adopted to calculate the solar radiation. A single

PBR (Fig. 2 (a)) and a field of nine PBRs (Fig. 2 (b)) were drawn using Rhino/Grasshopper3D modelling tool. Then, the Ladybug Grasshopper3D plugin [21] was used to estimate the total solar radiation impinging on the single PBR, and on the central PBR in the middle of the field, for each hour of the year. One advantage of Ladybug is that it can import hourly values of climate data from files in Energy Plus Weather format (EPW) and use them to calculate solar radiation impinging on a 3D geometry, taking into account the shading effects. In this way, any PBR configuration can be tested over an entire year and for different locations on Earth. For this study, weather data downloaded from the US Department of Energy website [22] were used.

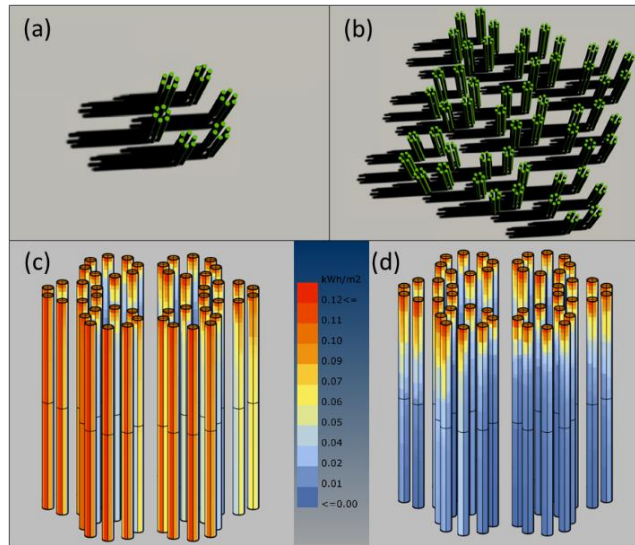


Fig. 2. 3D modelling of an isolated PBR (a) and of a field of nine PBRs (b) and corresponding average radiations (direct and diffuse, in kWh.m⁻²) impinging on one PBR between 3 and 4 pm, on January 1st in Alicante (Spain) for an isolated PBR (c) and a surrounded one (d).

Examples of solar radiation calculations performed with Ladybug are shown on Fig. 2 (c) and (d). The different colours represent the different intensities of total solar radiation impinging on the structure, and enable to apprehend the effect of shading. In comparison with the case of an isolated PBR (Fig. 2 (c)), the intensity of solar radiation impinging on the structure is significantly reduced when the PBR is in the middle of a field of nine PBRs (Fig. 2 (d)).

For a given hour of the year, the solar radiation flux of the culture dynamic heat balance is calculated as follows:

$$Q_{rad_sol} = \tau \varepsilon S_{PBR} (I_{PBR} + \rho I_{ground}) \quad (2)$$

where ε is the emissivity of the culture, τ is the transmittance of the PBR wall, S_{PBR} (m²) is the external surface of the PBR, I_{PBR} (W.m⁻²) is the hourly mean value of total solar radiation impinging

on PBR surface, ρ is the ground albedo and I_{ground} (W.m^{-2}) is the hourly mean value of solar radiation impinging on the ground. I_{PBR} is calculated with Ladybug from PBR 3D geometry and I_{ground} is extracted from a data file downloaded from the US Department of Energy website.

It has been reported in the literature that the effect of dust deposits on PBR walls can significantly reduce their transmittance [23]. To take this effect into account in the heat balance, a percentage of reduction can be applied to the value of the transmittance of PBR wall in Eq. 2.

2.2.3. Convective and conductive heat transfer

Heat is transferred by convection and conduction through the walls of the outer and inner tube of each vertical column of the PBR. The overall heat transfer coefficient between the culture and the air surrounding the outer tube is obtained by considering three thermal resistances in series:

$$h_{\text{outer_tube}} = \left(\frac{1}{h_{\text{TPB}}} + \frac{1}{h_{\text{wall}}} + \frac{1}{h_{\text{ext}}} \right)^{-1} \quad (3)$$

with h_{TPB} ($\text{W.m}^{-2}.\text{K}^{-1}$) the convective heat transfer coefficient between the culture and the outer tube, h_{wall} ($\text{W.m}^{-2}.\text{K}^{-1}$) the conductive heat transfer coefficient through the outer tube wall, and h_{ext} ($\text{W.m}^{-2}.\text{K}^{-1}$) the convective heat transfer coefficient between the outer tube and the external air.

h_{TPB} depends on the hydrodynamics of the triphase air-culture-solid mix and is modelled by the following empirical correlation, proposed by Suh et al. [24] according to Kim and Yang [25]:

$$h_{\text{TPB}} = 0.0647 \left[k_l \rho_l C_{pl} \left\{ \frac{[(V_l + V_g)(\varepsilon_s \rho_s + \varepsilon_l \rho_l + \varepsilon_g \rho_g) - V_l \rho_l] g}{\varepsilon_l \mu_l} \right\}^{1/2} \right]^{1/2} \quad (4)$$

where k_l ($\text{J.m}^{-1}.\text{s}^{-1}.\text{K}^{-1}$) is the liquid thermal conductivity, C_{pl} ($\text{J.kg}^{-1}.\text{K}^{-1}$) the liquid heat capacity, V_l and V_g (m.s^{-1}) the liquid and gas superficial velocities, ρ_s , ρ_l and ρ_g (kg.m^{-3}) the solid, liquid and gas densities, g (m.s^{-2}) the gravitational acceleration, ε_s , ε_l and ε_g (-) the solid, liquid and gas volumetric fractions and μ_l ($\text{kg.m}^{-1}.\text{s}^{-1}$) the liquid viscosity.

h_{wall} is given by:

$$h_{\text{wall}} = \frac{k_{\text{wall}}}{R \ln \left(\frac{R_2}{R_1} \right)} \quad (5)$$

with k_{wall} ($J.m^{-1}.s^{-1}.K^{-1}$) the wall thermal conductivity, R (m) the mean radius and R_1 and R_2 (m), the internal and external radii respectively.

The expression of h_{ext} depends on the situation. When there is wind, only forced convection is taken into account and h_{ext} , which depends on wind speed, is modelled by the following empirical correlation proposed by Mitchell [26]:

$$h_{ext} = 8.6 \frac{v_{wind}^{0.6}}{D^{0.4}} \quad (6)$$

where v_{wind} ($m.s^{-1}$) is the wind speed and D (m) the outer tube diameter.

When there is no wind, only free convection is taken into account. The corresponding heat transfer coefficient is calculated using the correlation recommended by McAdams [27] for vertical cylinders:

$$h_{ext} = 0.13 \frac{k_{air} Ra_{H-air}^{1/3}}{H} \quad (7)$$

where k_{air} ($J.m^{-1}.s^{-1}.K^{-1}$) is the air thermal conductivity, H (m) the height of cylinder, and Ra_{H-air} (-) the air Rayleigh number.

The overall heat transfer coefficient between the culture and the air inside the inner tube is obtained by considering three thermal resistances in series:

$$h_{inner_tube} = \left(\frac{1}{h_{TPB}} + \frac{1}{h_{wall}} + \frac{1}{h_{int}} \right)^{-1} \quad (8)$$

with h_{TPB} ($W.m^{-2}.K^{-1}$) the convective heat transfer coefficient between the culture and the inner tube, h_{wall} ($W.m^{-2}.K^{-1}$) the conductive heat transfer coefficient through the inner tube wall, and h_{int} ($W.m^{-2}.K^{-1}$) the convective heat transfer coefficient between the inner tube wall and the fluid contained in it.

The h_{int} heat transfer coefficient is modelled by the following empirical correlation for gas free convection in vertical enclosures [28]:

$$h_{int} = 0.073 \frac{k_{air} Ra_{D-air}^{1/3}}{D} \left(\frac{H}{D} \right)^{-1/9} \quad (9)$$

where k_{air} ($\text{J}\cdot\text{m}^{-1}\cdot\text{s}^{-1}\cdot\text{K}^{-1}$) is the air thermal conductivity, H (m) the height of cylinder, D (m) the tube diameter and $\text{Ra}_{\text{D_air}}$ (-) the air Rayleigh number.

2.2.4. Thermal model implementation

The thermal model was coded using Visual Basic .NET language in the Grasshopper3D graphical algorithm editor, in order to perform the calculation of hourly values of solar radiation and the resolution of the ordinary differential equation (1) in a single program.

The values of solar radiation term ($Q_{\text{rad_sol}}$), air temperature (T_{air}) and wind speed (v_{wind}) are assumed to be constant during the one-hour intervals and fed to Eq. (1) which is solved numerically using a time step of one minute. In this way, the calculation of culture temperature evolution for a whole year, namely 8760 hours, can be achieved in a single run.

2.3. Model validation methodology

The model validation was performed using industrial PBRs such as described in section 2.1. The following experimental data were collected: (1) average culture temperatures measured in the PBR measuring point every hour; (2) air temperatures measured on site every two hours; (3) average wind speed measured in the nearest weather station every hour. All these data were collected during several months - from November 2011 until April 2012.

The simulated culture temperatures obtained with the thermal model presented in section 2.2 have been compared with the experimental culture temperatures.

2.4. Power requirement simulations

The simulation results obtained with the PBR thermal model are used to calculate the energy necessary to maintain the culture temperature within a desired range over a given time period. In this perspective, a maximal and a minimal value of culture temperature are set for a given algae strain.

The energy requirements are calculated from the simulated culture temperature profiles: if, during a time step, the culture temperature exceeds the maximal allowed temperature, then the necessary cooling power is equal to the net positive global energy that inputs into the system, expressed as:

$$Q_{\text{cooling}} = Q_{\text{rad_sol}} + h_{\text{inner_tube}} S_{\text{inner_tube}} (T_{\text{air}} - T_{\text{cult}}) + h_{\text{outer_tube}} S_{\text{outer_tube}} (T_{\text{air}} - T_{\text{cult}}) \quad (10)$$

where T_{cult} is taken equal to the maximal culture temperature.

Similarly, if the culture temperature drops below the minimal temperature, then the heating power is equal to the net negative global energy that exits the system, calculated with Eq. (10) in which T_{cult} is taken equal to the minimal temperature.

In this study, annual power requirements are calculated for a 48-columns PBR such as described in section 2.1. To study the behaviour of the structure in a full scale industrial application in which PBRs shade one another and assess the impact of shadow effects on the heat balance, two possible layouts are examined: (1) a single PBR standing with no surrounding objects shading it; (2) a PBR in the middle of a square with eight PBRs surrounding it as illustrated on Fig. 2 (a) and (b). Moreover, the effect of the thickness of the outer tube wall is studied by modifying its value between 3 mm and 7 mm.

Annual power requirements are calculated for a culture able to produce in a range of temperatures between 10°C (T_{MIN}) and 25°C (T_{MAX}). Several geographical locations characterized by different Köppen-Geiger climate classes [29] were selected to study the behaviour of the system: (1) hot desert climate (Phoenix, USA); (2) Mediterranean climate (Perth, Australia and Montpellier, France); (3) oceanic climate (Paris, France) and its subtropical highland variety (Quito, Ecuador); (4) semi-arid climate (Alicante, Spain); (5) tropical rainforest climate (Belem, Brazil) and tropical savanna one (Belo Horizonte, Brazil).

3. Results and discussion

3.1. Model validation results and temperature prediction accuracy

Fig. 3 shows the simulated culture temperatures as a function of the measured ones. More than 90% of values of the culture temperature are predicted with less than 2°C of difference.

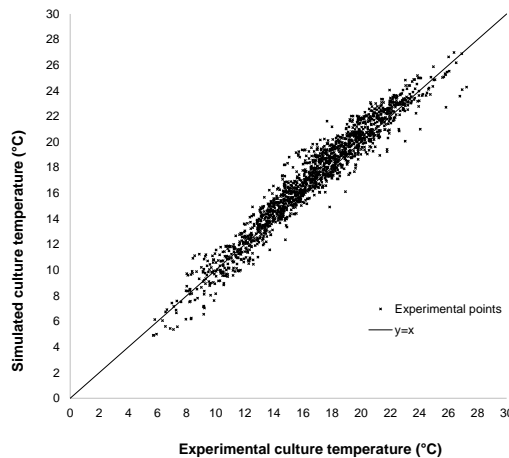


Fig. 3. Simulated versus experimental culture temperatures (°C) between November 2011 and April 2012 (Alicante, Spain).

Fig. 4 shows the integration of the thermal model during seven consecutive days. Although the model neglects the infrared thermal radiation emitted by the culture and surroundings, the comparison of simulation results with experimental points is highly satisfactory during the day, confirming the assumption that the contribution of thermal radiation is negligible with respect to the contribution of solar radiation. This assumption does not affect the capacity of the model to predict the peak temperatures during the day, but could account for the slightly increased difference between simulated and experimental values during the night.

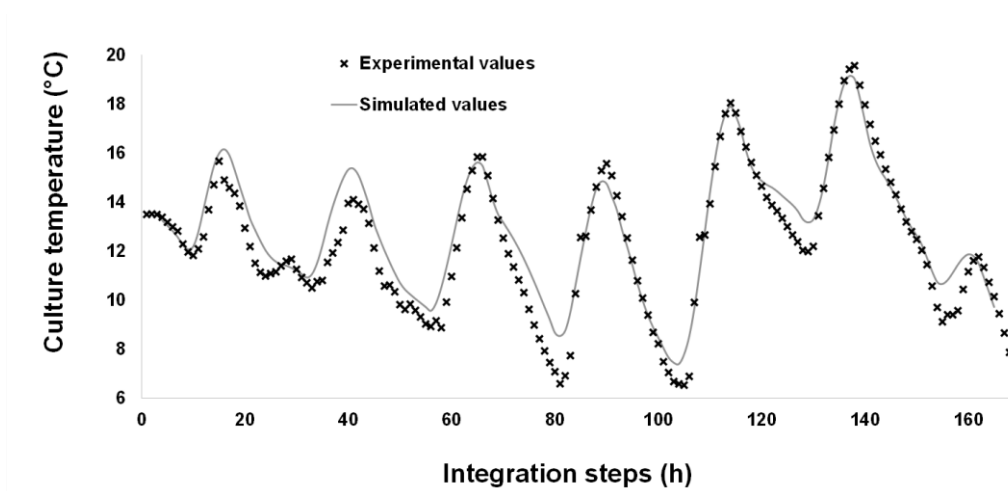


Fig. 4. Simulated (line) and experimental (crosses) culture temperatures (°C) during seven consecutive days in February (Alicante, Spain).

In view of these results, the thermal PBR model can be considered validated.

3.2. Heat balance analysis

The analysis of thermal resistances of equation (3) highlights that the heat exchange between the external air and the culture depends primarily on wind speed, and secondly on the thickness and conductivity of the outer tube. When the wind speed is low (below $2 \text{ m}\cdot\text{s}^{-1}$), its related thermal resistance is by far the biggest and limiting one in the series of thermal resistances for this PBR system. In other words, at low wind speeds, reducing the thermal resistances related to wall conduction or convective transfer through culture mixing has a negligible effect on the heat exchange rate between the culture and the surrounding air. However, when the wind speed exceeds $2 \text{ m}\cdot\text{s}^{-1}$, the thermal resistance associated to wall conduction starts to have an appreciable effect on the evolution of culture temperature.

Depending on the meteorological situation, the thermal insulation of PBR walls can have wanted or unwanted effects. This is summarized in Fig. 5. In case a) of Fig. 5, culture temperature is at its upper limit and an improvement in the heat exchange with surrounding air can only worsen the situation. In such a situation, a strong wind would be deleterious and wall thickening could help to reduce the cooling power required to control the culture temperature. In case c), the culture temperature is also at its upper limit, but enhancing the heat exchange with surrounding air would instead improve the performances of the system, leading to directly opposite conclusions. We can hence conclude that the optimisation of the system must take into account the climate data and how often each one of the exposed situations recurs in the studied location.





		Increase in wind speed	Increase in wall conduction resistance
a) Cooling $T_{cult} > T_{MAX}$ $T_{air} > T_{cult}$ 		Increased power consumption	Reduced power consumption
b) Heating $T_{cult} < T_{MIN}$ $T_{air} < T_{cult}$ 		Reduced power consumption	Increased power consumption
c) Cooling $T_{cult} > T_{MAX}$ $T_{air} < T_{cult}$ 		Reduced power consumption	Increased power consumption
d) Heating $T_{cult} < T_{MIN}$ $T_{air} > T_{cult}$ 		Increased power consumption	Reduced power consumption

Fig. 5. Summary of possible meteorological situations and effect of wind and wall conduction resistances on power consumption for culture temperature control.

3.3. Simulated power requirements

The model was fed with climate data from files downloaded from the US Department of Energy to perform simulations. The annual heating and cooling power requirements of an isolated PBR for different locations and wall thicknesses are reported on Fig. 6 a) and b), respectively. As the final objective is to have an industrial field of PBR, the effect of mutual shading between PBRs has to be investigated. The differences in total power consumption between a PBR in an industrial field and an isolated PBR are reported on Fig. 6 c), thus showing the impact of shading effects on PBR energy requirements. The values represent the thermal energy to be subtracted or added to the system. In case heat pumps are used, the electrical requirement can be estimated equal to one third of the ones reported in Fig. 6.

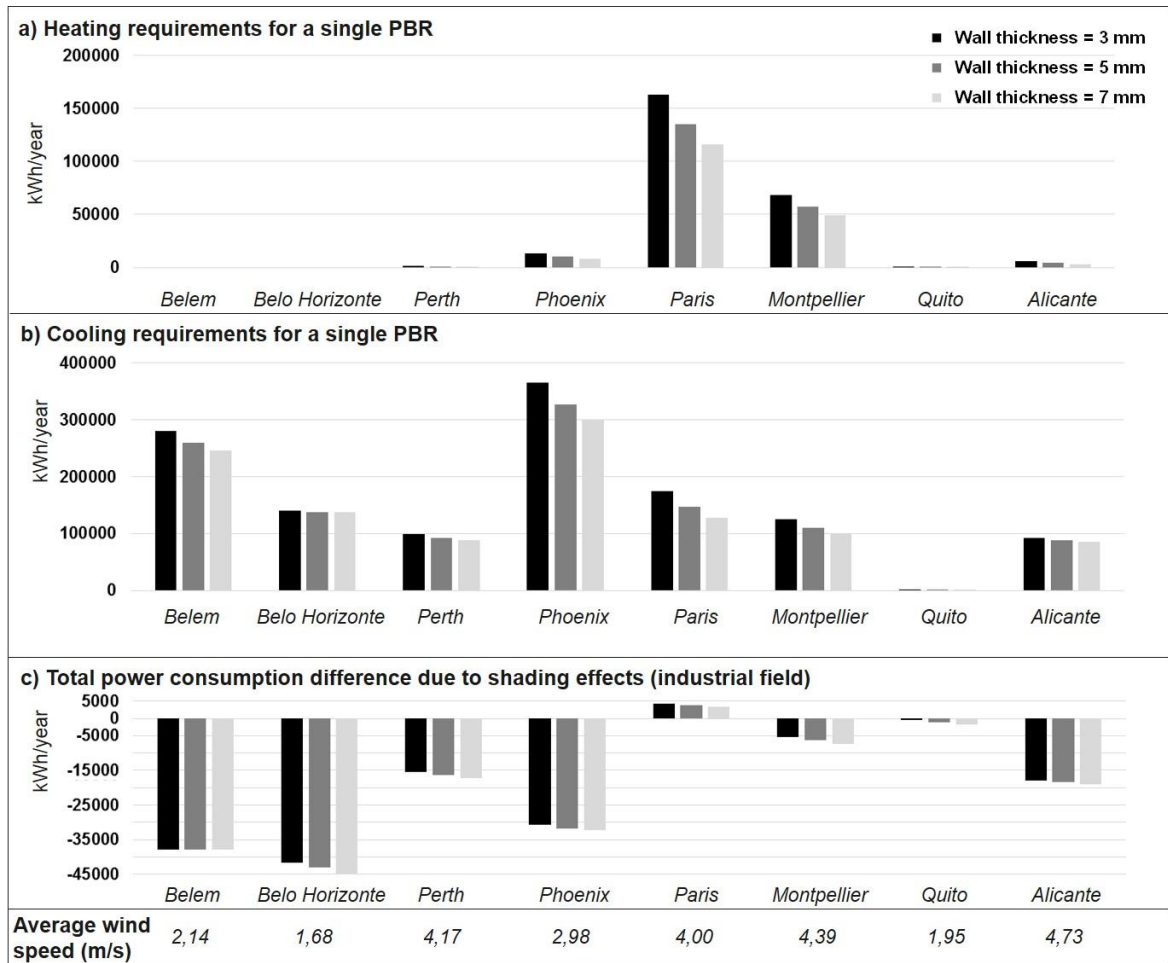


Fig.6. Simulation of annual heating (a) and cooling (b) power requirements of a single PBR for various geographical locations; analysis of the shading effects in industrial field configuration (c) on the total power consumption (negative values indicate less power consumption).

3.3.1. Impact of the site

As expected, the choice of the production site is of paramount importance. In Quito, energy requirements are almost null, due to the very stable day and night temperature changes and average minimal and maximal temperatures between 10 and 20°C all year long, which are in line with the minimal and maximal culture temperatures considered in the simulations. The highest energy requirements are observed in Phoenix; indeed, this site presents an annual average of 107 days with air temperatures reaching at least 38°C. For the studied system, we could hence direct our attention towards sites classified as subtropical highland variety of the oceanic climate. This is a type of climate characteristic of the highlands inside the tropics in Mexico, Peru, Bolivia, Madagascar, Zambia, Zimbabwe, but it is also found in central Argentina and South Africa, outside the tropics. Of course very different climates can fall inside this classification, as we can appreciate from the

very different results of simulations in Perth and Montpellier, which both are classified as Mediterranean climate. Moreover, energy requirements are only one criterion for identifying potential sites for microalgae production, even if it is very important. Other criteria that could be limiting in these areas could be the slope of the ground, the accessibility of the site, the proximity to stationary sources of CO₂ emissions and not very far from the coast, without considering economic and political situation of the hosting country.

3.3.2. Impact of outer tube thickness

In the studied sites, an increase in the outer tube thickness induces a reduction of global energy requirements. Depending on the location, the outer tube thickness can have a strong influence on the thermal balance of the PBR. The locations where this variable has the biggest absolute energetic impact are in the descending order: (1) Phoenix, where we can save up to 20000 kWh per year per PBR by increasing the outer tube thickness from 3 to 7 mm, (2) Paris, where a bigger thermal insulation can save up to 13000 kWh per year per PBR, followed by (3) Belem, (4) Alicante, (5) Montpellier, (6) Perth, (7) Belo Horizonte and (8) Quito. It is worth noting that the outer tube thickness has a very low impact in locations where the average wind speed is low, and hence the limiting resistance of the system (Quito and Belo Horizonte). Nevertheless, the average wind speed is not the best and only variable to look at, since the wind can vary considerably depending on the season and moment of the day, and its effect can be either positive or negative depending on its association to air and culture temperatures. This is why, in a site with low average wind speed, where occasionally a stronger wind can be linked to high temperature differences between air and culture, as it is the case in Phoenix, we can observe a strong impact on the energy requirements of the outer tube thickness. Using detailed climate data – and not averaged – over large periods of time is therefore very important to assess the optimum value of some geometrical parameters. Indeed, meteorological averages could lead to misleading conclusions because they can hide specific trends, like a frequent concomitant presence of hot air temperature and strong winds in the middle of the day during a particular season, which would strongly affect the heat balance of the PBR.

3.3.3. Impact of mutual shading between different PBRs

More shading results in a decrease in total energy consumption (15% on average), except in Paris where total energy consumption is slightly higher in the PBR field configuration than in the isolated PBR. Indeed, when a PBR is surrounded, and hence shaded by the other ones, the energy required to heat the culture tends to increase, while the one needed to cool it tends to decrease. Amongst the studied sites, Paris is the only place where annual heating requirement is much higher than cooling demand, which explains the deleterious effect of shading on power consumption in this location.

Wind velocity may be impacted in a field of PBRs and affect the thermal balance, this potential effect has been neglected in the present study. However, this should be investigated when performing a feasibility study concerning the implantation in a specific site.

4. Conclusion

In the continuity with modelling approaches described in the literature, this study presents a mathematical model predicting culture temperature in a vertical concentric tubular photobioreactor with complex geometry. The model considers the heat transfer phenomena involved in the heat exchange between the system and the surrounding environment. Its implementation in a simulation tool based on 3D-modelling enables to take into account the effects of shading and real meteorological conditions in the dynamic energy balance. The model was validated on industrial-scale photobioreactors with a large number of hourly experimental data. The model allows to calculate the annual energy requirements and how to reduce them by choosing the most appropriate values of key parameters, taking into account the geographical location and the strain-dependent temperature range. Results confirm the interest of a modelling approach to get a better assessment of the plant profitability and of the environmental impact, that can largely depend on the energy consumption related to temperature control.

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