

THE TEMPERATURE RESPONSE OF COMPACT TUBULAR MICROALGAE PHOTOBIOREACTORS

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ABSTRACT

A mathematical and computational modeling of a photobioreactor for the determination of the transient temperature behavior in compact tubular microalgae photobioreactors is presented. The model combines theoretical concepts of thermodynamics with classical theoretical and empirical correlations of Fluid Mechanics and Heat Transfer. The physical domain is discretized with the Volume Element Model (VEM) through which the physical system (reactor pipes) is divided into lumped volumes, such that only one time dependent ordinary differential equation, ODE, results for temperature, based on the first law of thermodynamics. The energetic interactions between the volumes are established through heat transfer empirical correlations for convection, conduction and radiation. Within this context, the main goal of this study is to present a numerical methodology to calculate the mixture (algae + water + nutrients) temperature inside the compact photobioreactor. A pilot plant is under construction, in the Center of Research and Development for Self-Sustainable Energy (NPDEAS), located at UFPR, and the experimental data obtained from this research unit will be used to validate the present numerical solution. Temperature is one of the most important parameters to be controlled in microalgae growth. Microalgae that are cultivated outside their growth temperature range may have a low growth rate or die. For this reason a numerical simulation of the system based on the operating conditions and environmental factors is desirable, in order to predict the transient algae growth temperature distribution along the reactor pipes. The VEM creates an “artificial” spatial dependence in the system or process under analysis by dividing the space (physical domain) into smaller sub domains, namely Volume Elements (VE). Each VE interacts with its neighbors by exchanging energy and/or mass. Thus, each VE is treated as a control volume from classical thermodynamics, i.e., with uniform properties and exchanging mass and energy with its neighbors. The problem is then formulated with the energy equation applied to the fluid VE and to the wall VE. These equations form a system of time dependent ODE's, which are not dependent on space, therefore eliminating the need for the solution of a system of partial differential equations, PDE's, depend on time and space, as is the case of traditional numerical methods (e.g., finite element, finite volume and finite differences). The resulting ODE's were solved using a fourth order Runge-Kutta method with adaptive time step.

Keywords: Heat Transfer, Microalgal Growth, Numerical Simulation, Volume Element Method.

NOMENCLATURE

A_e	Area of outside wall (m^2)	\dot{Q}_{rad}	Solar radiation reaching the walls of the tubes in photobioreactor (W / m^2)
A_i	Area of the inner wall of the tube (m^2)	T_∞	Temperature of air (K)
C_f	Specific heat of the fluid (J / kg K)	T_f	Temperature of the fluid (K)
C_w	Specific heat of the plastic (wall)	T_w	Temperature of the wall (K)
G_i	radiation per unit area (W / m^2)	VE	Volume Element
h_e	Coefficient of heat transfer by convection between the outside wall and the air environment ($w / m^2 K$)	VE_f	VE for the fluid that flows inside the transparent tubes
h_i	Coefficient of heat transfer by convection between the fluid and the inner wall of the tube ($W / m^2 K$)	VE_w	VE for the walls of transparent tubes
m_f	Mass of the fluid		
m_w	Mass of the wall (kg)		
neb	Cloudiness		

INTRODUCTION

Numerous investigations have been made using microalgae. Due to its wide biodiversity, it has become the source for various applications such as: increasing the nutritional value of food and feed, capture the CO₂, sewage treatment and biofuel (Lourenço, 2006). The production of biofuels through the oil removed from the cells of microalgae is a field of study on the rise, and according to Xu *et al.* (2006) biodiesel can be a competitive alternative to conventional diesel. Given this broad field of study, the Center for Research and Development of Self-Sustainable Energy (NPDEAS) located at the Federal University of Parana is building a pilot plant with a compact tubular photobioreactor, an operations laboratory, and a biotechnology laboratory for cultivating microalgae, removing the oil and converting it into biodiesel.

In order to achieve a satisfactory growth rate of microalgae in compact photobioreactors tubes, it is necessary to know in advance the effects that can cause variations in light intensity, temperature, nutrients, cellular agitation, and pH in the photobioreactor during the cultivation of microalgae. Nutrients, pH, and cellular agitation of the culture medium can be controlled easily using standard tools and techniques. However, the light intensity and temperature depend on several uncontrollable factors such as air speed, temperature, cloud cover, latitude, time, day and year in which the culture is being grown. If these effects are known in advanced, the control parameters and structure of the photobioreactor can be optimized in order to improve conditions for the growth of microalgae.

Few models exist in the literature for numerical simulation and mathematical modeling of tubular photobioreactors for the cultivation of microalgae. The models that do exist typically focus on the mathematical modeling of the growth rate of microalgae. In more specific cases, software packages such as CFD (Fluent) and Matlab are used to perform numerical approximations of the trajectory of microalgae in a tubular photobioreactor or simulate the 3D behavior of light particles into tubes of a photobioreactor (PAPACEK *et al.*, 2003 and Perner and Nocht-Posten, 2007). This paper proposes a mathematical and computational model for the temperature gradient in the photobioreactor using the Volume Elements Model (VEM) (Vargas *et al.*, 2001). Knowledge of the variation of temperature on the tube walls and in the culture flowing through the photobioreactor tubes is of paramount importance for the cultivation of microalgae. If the temperature is not in the range suitable for the cultivation of microalgae it may result in inhibition of cell growth or even death of microalgal cells.

MATHEMATICAL AND COMPUTATIONAL MODEL

The mathematical and computational model for a tubular photobioreactors proposed in this paper accounts for the prediction of the temperature on the tube walls and also in the fluid. In the present model the temperature in the photobioreactor, which directly affects the growth of micro-algal cells, depends mainly on solar radiation and ambient temperature. Fundamental theories combined with the Volume Element Model, which simplifies the partial differential equations into ordinary differential equations, provides a mathematical model which is handled numerically with substantially low computational effort.

PHOTOBIOREACTOR

Many geometries exist in the literature for the organization of transparent tubes. This article studies the geometry presented by Vargas *et al.* (2007), for a tubular photo bioreactor with 3,250 meters of total tube length distributed in a compact geometry with 13 columns and 50 rows of tubes (Fig. 7). Each tube is 5 meters long (Fig. 1) with a radius of 0.03 meters.

A schematic representation of the bio-reactor is shown in Figure 1: a) transparent tubes where growth will occur from the microalgae, b) tank capable of accumulating a large capacity of the culture medium from the tubes (in some cases the reservoir also serves as a degasser) c) pump for circulating the culture medium of microalgae in the tubes and reservoir and d) valve to control the flow.

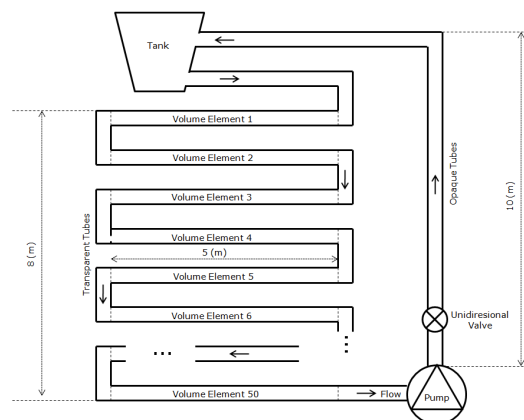


Figure 1. Simplified schematic of the photo bioreactor

The pilot unit under construction is show in Fig. 2.

VOLUME ELEMENTS MODEL

The primary goal for combining accurate numerical methods with low computational time and

user-friendly interfaces is for use in the development of simplified mathematical and computational tools for improving the science and technology of equipment and processes. This study uses the Volume Element Method (VEM) which utilizes the same combination of physical principles found in thermodynamics, heat and mass transfer and fluid mechanics. The method shows the possibility of using objective functions for the optimization of thermodynamic systems or processes in addition to entropy generation minimization (Vargas *et al.*, 2001). This work illustrates the application of VEM for the simple mathematical modeling, computational simulation and thermodynamic analysis of a system or process. Another innovative aspect of VEM is that it allows for the creation of an “artificial” implicit spatial dependency in the system or process by dividing the area into volume elements that interact through energy and/or mass transfer. Each volume element is treated as a control volume of classical thermodynamics with constant properties throughout the control volume. Together they form a system of ordinary differential equations dependent on time and independent in space.

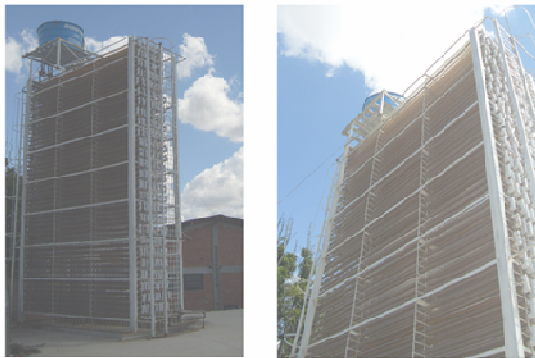


Figure 2. Photobioreactor at NPDEAS

This work presents the development and testing of a new system of compact photobioreactors. The system is modeled using the Volume Element Method, which subdivides the domain into Volume Element (VE) or volume centered cells as shown in Figure 3. This method produces a single differential equation for each cell by applying the principles of energy and species conservation. The energetic interactions between cells are established through empirical correlations of heat transfer by convection, conduction, and radiation.

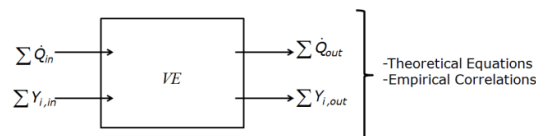


Figure 3. Volume centered cells.

MATHEMATICAL MODEL

In the current formulation algae growth is assumed to occur only in the transparent pipes. The mathematical domain for the transparent tubes is divided into the following Volume Elements (Fig. 4): a) VE_f for the fluid that flows inside the transparent tubes, and b) VE_w for the walls of transparent tubes.

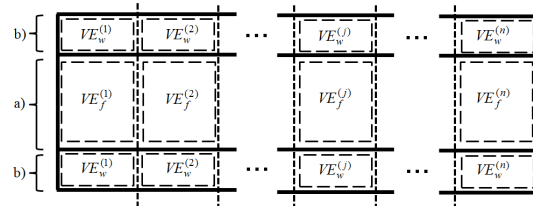


Figure 4. VE used with the transparent pipes model

a. EV for the fluid that flows inside the transparent tubes

A mathematical model was used to calculate the temperature variation between the volume elements of fluid (microalgae + nutrients + H₂O + O₂) and the effects of wall temperature. For each VE_f the energy balance in the fluid by the elements (Fig. 5) is calculated by:

$$\dot{Q}^{(j)} + \dot{m}C_f T_f^{(j-1)} = m_f^{(j)} C_f \frac{dT_f^{(j)}}{dt} + \dot{m}C_f T_f^{(j)} \tag{1}$$

while the heat exchange with the fluid on the wall (\dot{Q}) is calculated by:

$$\dot{Q}^{(j)} = h_i A_i (T_f^{(j)} - T_w^{(j)}) \tag{2}$$

where m_f is the mass of the fluid in, C_f is the specific heat of the fluid (J/kgK), h_i is coefficient of heat transfer by convection between the fluid and the inner wall of the tube (W/m²K), A_i the area of the inner wall of the tube (m²), T_w the temperature of the wall (K) and T_f the temperature of the fluid (K).

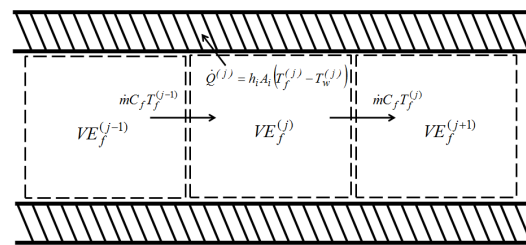


Figure 5. VE j for the equation of conservation of energy in the fluid.

b. EV for the walls of the transparent tubes

The proposed mathematical model accounts for the temperature variation between the volume elements of the wall due to the fluid flow, solar radiation and ambient interactions. For each VE_w the energy balance in the wall of the plastic tubes (Fig. 6) is calculated by:

$$\dot{Q}_{rad}^{(j)} - \dot{Q}^{(j)} - \dot{Q}_{air}^{(j)} = m_w^{(j)} C_w \frac{dT_w^{(j)}}{dt} \quad (3)$$

where C_w is the specific heat of the plastic (wall) (J/kg.K), m_w is the mass of the wall (kg), and \dot{Q}_{rad} is the solar radiation reaching the walls of the tubes in the photo bioreactor (W/m^2).

The transfer of heat between the wall and air (\dot{Q}_{air}) is calculated by:

$$\dot{Q}_{air}^{(j)} = h_e A_e (T_w^{(j)} - T_\infty) \quad (4)$$

where h_e is the coefficient of heat transfer by convection between the outside wall and the air environment (W/m^2K), A_e the area of outside wall (m^2) and T_∞ is the temperature of air (K)

The amount of solar radiation received in the photobioreactor tube (\dot{Q}_{rad}) depends on the locality, time and day of the year and is calculated by:

$$\dot{Q}_{rad} = G_i - G_i(0.9neb + 0.1) \quad (5)$$

where neb is the cloudiness and G_i (Kreith, 1969) is the incident radiation per unit area (W/m^2).

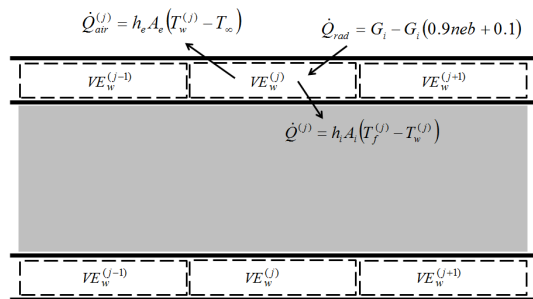


Figure 6. VE_j for energy equation at the wall of the transparent tubes.

Numerical Methods

The set of transient ordinary differential equations formed by Eqs (1) and (3) is solved numerically with a fourth order Runge-Kutta method with adaptive stepping (Kincaid and Cheney, 1991). The initial and operation conditions of the problem are:

Table 1. Initial conditions.

$D_0 = 1$ (day)	$T_{H2O,0} = 296$ (K)
$t_0 = 6$ (hour)	$C_0 = 0,2$ (kg / m ³)
$D_f = 10$ (days)	$neb = 0 \%$
$t_f = 6$ (hours)	

Table 2. Operating conditions.

$V_r = 2$ (m ³)	$L_{T,transp} = 3250$ (m)
$v = 0.01$ (m/s)	$L_{T,opaque} = 10$ (m)
$r_i = 0.029$ (m)	$C_f = 4181$ (J/(kg.K))
$r_e = 0.030$ (m)	$C_w = 980$ (J/(kg.K))
$D_H = 4 r_i$ (m)	$\rho_f = 998$ (kg/m ³)
$D_V = 4 r_i$ (m)	$\rho_w = 1360$ (kg/m ³)
$N_{col} = 13$	$h_e = 50$ (W/(m ² K))
$N_{lin} = 50$	$H_i = 200$ (W / (m ² K))
$\phi = -25,45$	

2.4. Results

Figure 7 shows the numbering of the 650 tubes that make up the photobioreactor.

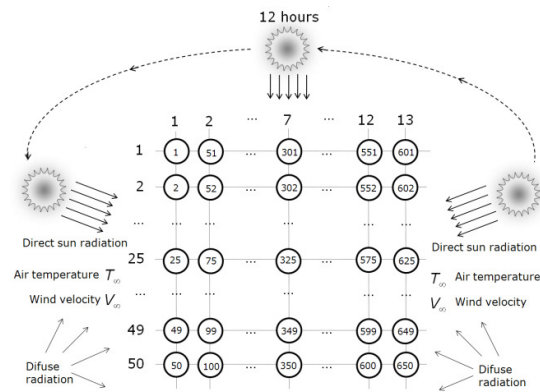


Figure 7. Numbering the tubes of the photobioreactor.

The numerical simulation of the photobioreactor began at 6 am and lasted 216 hours (9 days). This final result shows the temperature variation in the wall of the tubes and transparent fluid. The temperature at the wall and fluid in the Tube 1 during the 216 hours of simulation was analyzed first and is shown in Figure 8 below.

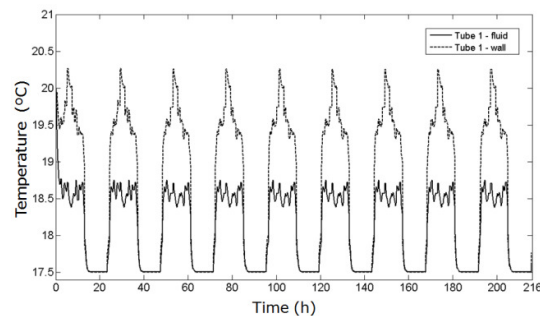


Figure 8. Wall and fluid temperature for Tube 1.

For this simulation the ambient temperature was kept constant and the temperature was repeated every 24 hours. Due to the thermal cycling, it is unnecessary to analyze the temperature over the entire 216 hour period. The behavior of temperatures at the wall of the transparent tubes and in the fluid varies from tube to tube. Depending on the location of the tube, it may receive less sunlight due to shadowing by surrounding tubes. The wall and fluid temperature of tubes 1, 51, 301, 551 and 601 during the first 18 hours of simulation is shown in Figure 9. These tubes are all located in the first row (top) or column-(left and right) of the photobioreactor as shown in Figure 7.

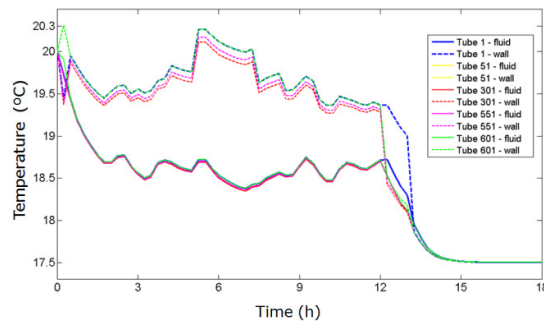


Figure 9. Wall and fluid temperature of tubes the external rows and columns.

Note that the first row consists of the tubes from the upper layer of the photobioreactor. The first row of tubes is the only layer that receives continual light throughout the entire light period. Because of this the walls of the tubes are always hotter than the temperature of the fluid. Figure 10 shows tubes 25, 75, 325, 575 and 625 which correspond to the middle layer of the photobioreactor. The temperature of the fluid and walls of tubes 50, 100, 350, 600 and 650 are shown in Figure 11. These tubes are the last line of tubes which are positioned on the lower part of photobioreactor. Tube placement can be seen in Figure 7.

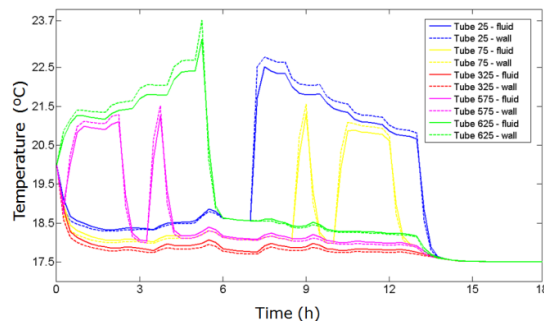


Figure 10. Wall and fluid temperature of the internal tubes.

Note that the tubes 25 and 75 of Figure 10 and tubes 50 and 100 of Figure 11 which are on the left side of the photobioreactor, do not receive a

significant amount of heat until after 13:00 hours or after the seventh hour of simulation. This delayed heating of the left side is due to the orientation of the photobioreactor such that the sun rises on the right hand side (the east) and sets on the left hand side (the west). Tubes 575 and 625 of Figure 10 and tubes 600 and 650 of Figure 11 have already received direct heating of the sun during the first six hours of simulation. It can be seen in Figure 10 that at some times the temperature of the fluid is higher than that of the wall of the transparent tube. An example of this case can be seen in Figure 10 with tube 575. During the fourth hour of the simulation, the temperature of the fluid is greater than that of the wall. This effect is due to the wall losing heat to the ambient air while the fluid in motion takes longer to come into thermal equilibrium with the wall causing the increased temperature of the fluid with respect to the wall. Tube 325 of Figure 10 and tube 350 of Figure 11 which are positioned in the center column of the photobioreactor do not receive direct sunlight and therefore maintain a temperature of approximately 2 °C at the wall and in the fluid.

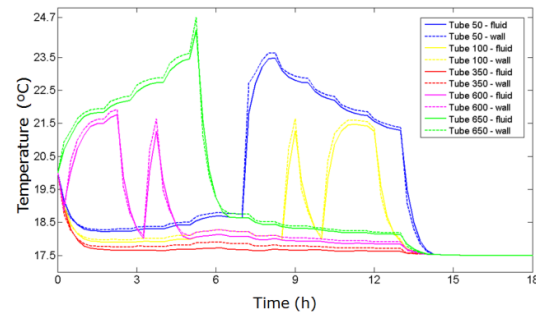


Figure 11. Wall and fluid temperature of tubes the last row (bottom).

Since the photobioreactor will serve to cultivate microalgae, an important observation is that the range of temperatures found in the computational simulations for all 650 tubes is within the optimal range for growth. Goldman and Ryther (1976) found the optimal range for the growth of microalgae to be between 12 °C and 26 °C.

CONCLUSIONS

Transient temperature profiles inside a tubular algae photobioreactor has been determined as a function of the operating (mass flow and inlet temperature) and environment (ambient temperature and solar radiation) conditions. The Volume Element Method has been used to formulate the problem and the resulting ordinary differential system of equations was solved with a fourth order Runge-Kutta method. Low computational effort with the inclusion of the main physical phenomena is the major advantage of the proposed method. In the present solution, heat conduction in the tubes walls,

convection inside the tube and solar radiation were included in the mathematical formulation of the problem. It was also analyzed the temperature dependence with the tube position and day time (position of the sun).

Being temperature a difficult to control, but a very important parameter for the microalgae growth, the prediction of the temperature profiles along the tubes length and its position with respect to the light source (sun light in the current work) is of great importance for the design of this type of bioreactors. Presented results showed that the current model and numerical tool can predict the temperature variations inside the reactor, thus the resulting application is expected to be a useful tool for simulation and design of microalgae photobioreactors.

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