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TEMPERATURE BASED MASS FLOW RATE SENSOR FOR ALGAE PHOTOBIOREACTORS

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ABSTRACT

Photobioreactors are an alternative to traditional methods for microalgae growth of open ponds and lakes. In spite of their construction cost, photobioreactors exhibit higher productivity and avoid contamination problems. The current work is aimed at improving the use of photobioreactors for continuous growth through the development of minimally invasive mass flow rate sensor that can be used as an alternative to more expensive commercially available sensors (e.g. ultrasonic). A mathematical model that allows for the determination of the system temperature distribution is developed using a Volume Element Model (VEM) approach to assist in the sensor design. The VEM combines principles of classical thermodynamics and heat transfer and discretizes the system in space, resulting in a system of ordinary differential equations with respect to time. The mathematical model is implemented in Fortran and the data acquisition and information processing of the sensors is handled with a microcontroller.

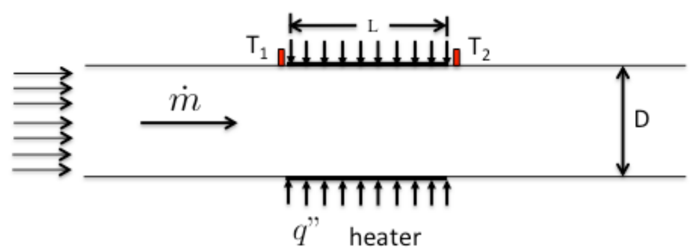
INTRODUCTION

The Center for Research and Development in Self-sustainable Energy (NPDEAS) in Department of Mechanical Engineering, at Federal University of Paraná, was established in 2008 for the purpose of cultivating microalgae in compact horizontal tubes photobioreactors, with the interest of producing biodiesel with the oil isolated from microalgae [1-3]. NPDEAS is collaborating with Florida State University's Energy and Sustainability Center in the development of sensor for microalgae growth [4].

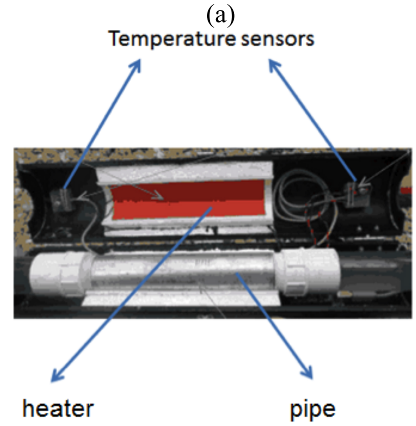
Batch cultivation is the form of operation being used at the moment to grow the microalgae. In this mode, microalgae is added to the reactor along with the culture medium containing nutrients and the system continue to operate until the cell growth stabilizes. An alternative to this mode of operation is a continuous cultivation, in which the photobioreactor continues to operate with the highest cell concentration for a longer time. In this system dillution and cell-collection are done in a continuos way and integrated mass flow and concentration sensors are then needed to properly monitor the process.

MASS FLOW SENSOR

The mass flow sensor is based on a thermoanemometer (Figure 1), in which a know heat flux is applied in a section of the pipe, and measurement of temperature differences between two points (1 and 2) separated by a known distance in the flow direction (L), in conjuction with in conjunction with knowledge of the specific heat of the fluid leads to the mass flow rate.



(a)



(b)

Figure 1– (a) Schematic representation of mass flow rate sensor; (b) prototype.

The first law requires that, in steady state operation, the mass flow rate be given by,

$$\dot{m} = \frac{q''\pi DL}{c(T_{m1} - T_{m2})} \tag{1}$$

where T_{m1} and T_{m2} represent the fluid bulk temperatures at locations 1 and 2. Despite the simplicity suggested by Equation (1), there are several aspects that may complicate the actual implementation of the sensor for specific applications. In the case of algae photobioreactors, these complications include the fact that the specific heat of water and the typical flow rates found are such that large heat inputs are required to produce a significant (measurable) temperature difference, and that pipe overheating should be controlled to avoid possible melting (in the case of PVC pipes) and killing of algae close to the pipe walls.

Figure 2 illustrates the expected temperature difference for different heat inputs and mass flow rates. As expected at lower flow rates, temperature differences (~1K) are obtainable with lower heat input rates, in which the sensor can operate without affecting the mechanical integrity of the photobioreactor and the algae.

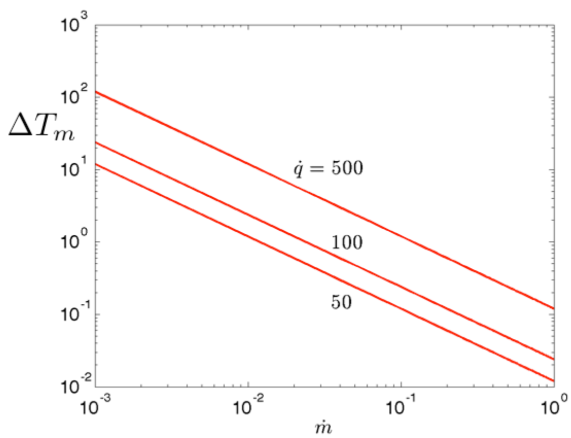
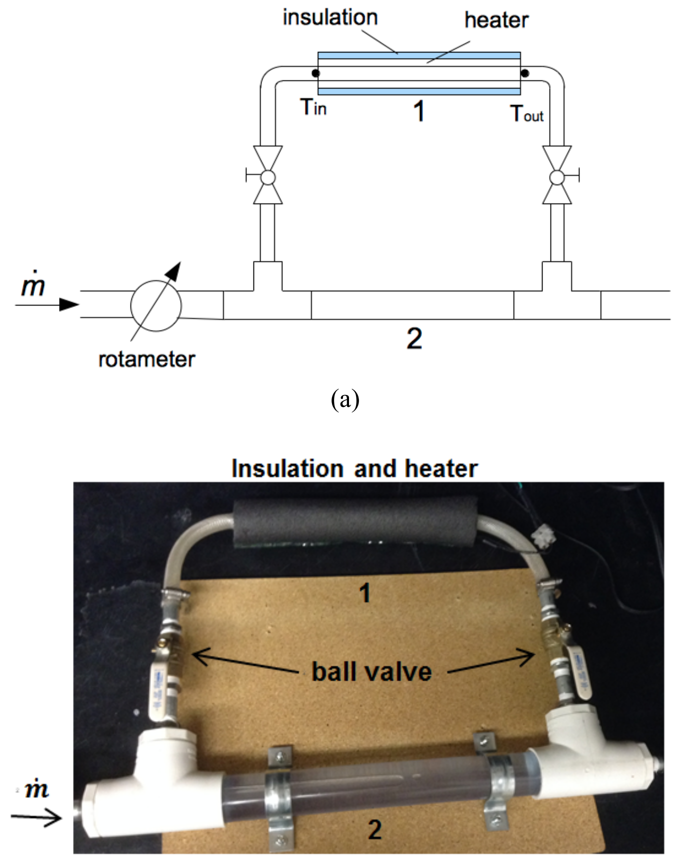


Figure 2– Expected temperature gain for different heat inputs in an algae photobioreactor (***c*** ≈ 4180 J/(kg K)).

In order to reduce the flow rate going through the sensor, a modified version of the configuration illustrated in Figure 1 is proposed. In this new configuration the main photobioreactor pipe is branched into a section of reduced diameter to which the heating element is attached (see Figure 3). The rotameter in Figure 3 is used to calibrate the sensor.

The relationship between the flow rate in the main photobioreactor ($\dot{m}$) and the mass flow rate going through the heater derivation ($\dot{m}$) is dictated by the difference in flow resistance in branches 1 and 2 and can be obtained from the solution of the simple flow network of Figure 3, using mass conservation,

$$\dot{m} = \dot{m}_1 + \dot{m}_2 \tag{2}$$



(b)

Figure 3 – (a) Branching used for the proposed mass flow sensor; (b) Prototype temperature based mass flow rate sensor using a derivation.

and the fact the pressure drop (due to major and minor losses) along branches 1 and 2 must be equal,

$$\left(\frac{\dot{m}_1}{\dot{m}_2}\right)^2 = \frac{\left(\frac{K_2}{2} + 2f_2\frac{L_2}{D_2}\rho\right)\left(\frac{D_1^4}{D_2^4}\right)}{\frac{K_1}{2} + 2f_1\frac{L_1}{D_1}\rho} \tag{3}$$

In which K_1 is the sum of the minor loss coefficients in branch one due to the two tees (branching flow), a sudden contraction, two valves, two 90-degree turns and a sudden contraction (see Table 1),

$$K_1 = K_{T(bf),1} + K_{sc} + K_{val,1} + K_{90,1} + K_{90,2} + K_{val,2} + K_{se} + K_{T(bf),2} \tag{4}$$

K_2 represents the sum of minor loss coefficient in branch 2: two tees (through flow),

$$K_2 = K_{T(tf),1} + \mathrm{K}_{\mathrm{T(tf),2}} \tag{5}$$

f_1 and f_2 represent the Fanning friction factors, which can be obtained from the Moody diagram or appropriate correlations. ρ, represents the fluid density, L_1 and L_2 the length of the straight ducts and D_1 and D_2 the hydraulic diameters in branches 1 and 2 respectively.

Table 1– Loss coefficients expressions and values used in the simulation [5].

Component	Loss coefficient
Sudden expansion	$K_{se} = \left[1 - \left(\frac{D_2}{D_1}\right)^2\right]^2$
Sudden contraction	$K_{sc} = \frac{0.5\left[1 - \left(\frac{D_2}{D_1}\right)^2\right]}{\left(\frac{D_2}{D_1}\right)^4}$
Tee (branching flow)	$K_{T(bf),1} = K_{T(bf),2} = 1.62$
Tee (through flow)	$K_{T(tf),1} = K_{T(tf),2} = 0.54$
Ball valve	$K_{val,1} = K_{val,2} = 9.2$
90^o elbow	$K_{90,1} = K_{90,2} = 0.8$

THERMAL MODEL

In order to compute the temperature distribution in the sensor branch (branch 1), a Volume Element Model (VEM) [4] is developed. The solution domain is divided in small Volume Elements (VE) in the *z* direction as illustrated in Figure 4. Each VE is comprised by 3 systems: S1-algae/water; S2-pipe wall; S3- heater. The First Law of Thermodynamics is applied to each system in the VE. Constitutive equations are used to evaluate the physical properties and heat fluxes between the VEs. A similar approach has been employed in the modelling and optimization of energy systems (e.g. [6-8]).

Figure 4 illustrates a schematic diagram of the problem geometry. The top part illustrates the different systems considered: the algae-water in the inside, the pipe, the heater, and an insulation layer, and the lower part illustrates volume elements.

Figure 5 illustrates the heat fluxes interactions between all systems and VEs.

Energy balances:

System 1 (algae/water):

The First Law of Thermodynamics applied to the S1 shown in Figure 5 states that:

$$M_{Al}c_{Al}\frac{\partial T_1^i}{\partial T} = \dot{Q}_{12}^i + \dot{m}_{Al}c_{Al}\left(T_1^{i-1} - T_1^i\right) \quad (6)$$

where *M* is the mass [kg], $\dot{m}$ the mass flow rate [kg/s], *T* the temperature [K], *t* the time [s], $\dot{Q}$ the heat transfer rate [W], c the specific heat [J/kg K]. The subscripts *1*, *12, i* and *Al* indicate the system 1 (algae), interface between systems 1 and system 2 (pipe), VE number as shown in Figure 4, and algae, respectively.

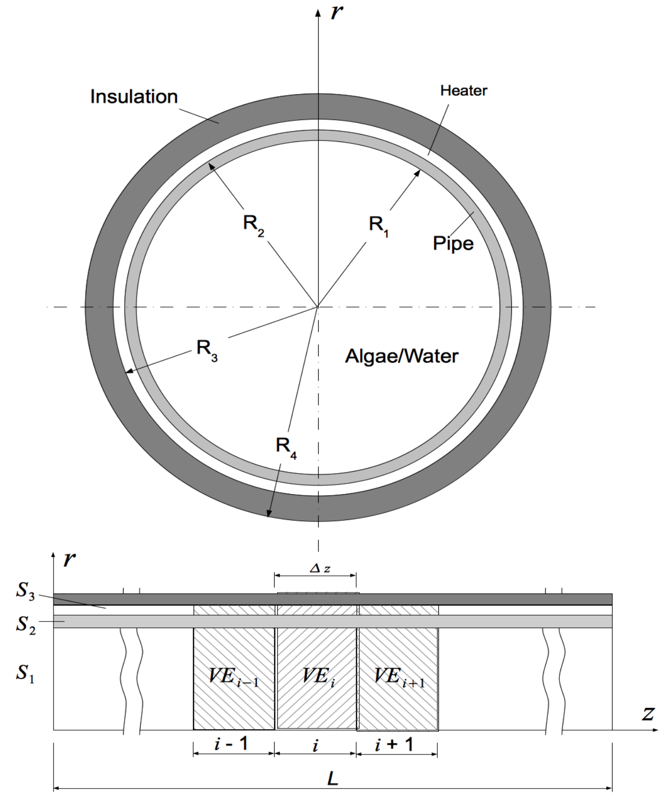


Figure 4– Schematic representation of the sensor volume elements.

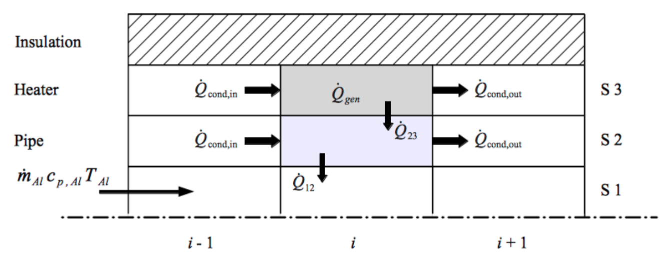


Figure 5– Heat fluxes through the systems and VEs.

The heat removed by convection from S2 that appears in Equation (6) is given by

$$\dot{Q}_{12}^i = UA_{12}^i\left(T_2^i - T_1^i\right) \quad (7)$$

where UA_{12}^i is given by,

$$UA_{12}^i = \left[\frac{\ln\left(\frac{(R_1+R_2)/2}{R_1}\right)}{2\pi K_2 \Delta_Z^i} + \frac{1}{2\pi R_1 \Delta_Z^i h_{Al}}\right]^{-1} \quad (8)$$

The Dittus-Boelter correlation can be used to evaluate the convective heat transfer coefficient in the turbulent regime. The Nusselt correlation for both laminar and transient regimes is given by [9].

$$\begin{cases} Nu = 4.36 \text{ - (Laminar - constant heat flux)} \\ Nu = 0.023\, Re^{0.8} Pr^{n} \text{ - (Turbulent - Re > 10000)} \end{cases} \quad (9)$$

where *Nu* is the Nusselt number, *Re* the Reynolds number, *Pr* the Prandlt number, and $n = 0.4$ when $T_{wall} > T_{\text{fluid}}$ and $n = 0.3$ when $T_{wall} < T_{\text{fluid}}$.

The convective heat transfer coefficient, *h*, is then calculated by

$$h_{Al} = \frac{K_{fluid} Nu}{D_h} \quad (10)$$

where *k* is the thermal conductivity [W/m K] and D_h the hydraulic pipe diameter [m].

System 2 (pipe)

The second system is used to represent the pipe walls. The first law of thermodynamics applied S2 states that,

$$M_{pipe} c_{pipe} \frac{\partial T_2^i}{\partial t} = -\dot{Q}_{12}^i + \dot{Q}_{23}^i + \dot{Q}_{cond,in}^i - \dot{Q}_{cond,out}^i \quad (11)$$

where the subscripts *cond*, *in* and *out* indicate conduction, inlet and outlet, respectively. Equation (11), accounts for the convective heat absorbed by the algae stream ($\dot{Q}_{12}$) and the heat conduction through the pipe walls between two subsequent elements ($\dot{Q}_{cond,in}^i$ and $\dot{Q}_{cond,out}^i$)

In Equation (11) the heat conduction terms between two consecutive (*z* direction) VEs are expressed as

$$\begin{cases} \dot{Q}_{cond,in}^i = -\frac{K_{pipe} A_c \left(T_2^i - T_2^{i-1}\right)}{(\Delta Z^i + \Delta Z^{i-1})/2} \\ \dot{Q}_{cond,out}^i = -\frac{K_{pipe} A_c \left(T_2^{i+1} - T_2^i\right)}{(\Delta Z^i + \Delta Z^{i+1})/2} \end{cases} \quad (12)$$

where the subscript *c* indicates cross section.

The conduction between S2 and S3 is calculated by

$$\dot{Q}_{23}^i = UA_{23}^i \left(T_3^i - T_2^i\right) \quad (13)$$

where U_{23}^i is given by the added resistances of the cylindrical layers

$$UA_{23}^i = \left[\frac{ln\left(\frac{R_2}{(R_1+R_2)/2}\right)}{2\pi K_2 \Delta_Z^i} + \frac{ln\left(\frac{(R_2+R_3)/2}{R_2}\right)}{2\pi K_3 \Delta_Z^i}\right]^{-1} \quad (14)$$

where the R_1, R_2 and R_3 are given in Figure 4.

System 3 (heater)

For the heater system, the first law requires,

$$M_{heater} c_{heater} \frac{\partial T_3^i}{\partial t} = \dot{Q}_{cond,in}^i - \dot{Q}_{cond,out}^i - \dot{Q}_{23}^i + \dot{Q}_{gen} - \dot{Q}_{ext} \quad (15)$$

The conduction heat fluxes $\dot{Q}_{cond,in}^i$ and $\dot{Q}_{cond,out}^i$ for the heater are calculated in the same form as done for the pipe, $\dot{Q}_{gen}$ represent the heat generated by the heater and $\dot{Q}_{ext}$ the heat leak through the insulation to the ambient.

$$\dot{Q}_{ext} = UA_{ext}^i \left(T_3^i - T_{amb}\right) \quad (16)$$

$$UA_{ext}^i = \left[\frac{ln\left(\frac{R_4}{R_3/2}\right)}{2\pi K_4 \Delta_Z^i} + \frac{ln\left(\frac{R_3}{(R_2+R_3)/2}\right)}{2\pi K_3 \Delta_Z^i} + \frac{1}{h_\infty (2\pi R_4 \Delta_Z^i)}\right]^{-1} \quad (17)$$

PHYSICAL PROPERTIES

The thermodynamic properties of the algae/water (k, ν , *c*) were calculated at atmospheric pressure (101325Pa) and 20^{0}C, the dimensions and additional physical properties used in the simulation are reported in Table 2.

Table 2– Values of physical properties used in the simulation.

Quantity	Value	Quantity	Value
Sensor length	0.3 m	K_{pipe}	401 W/(mK)
R_1	0.0067 m	K_3	11.3 W/(mK)
R_2	0.00795 m	K_4	1 W/(mK)
R_3	0.0125 m	c_{Al}	4180 J/(kg K)
R_4	0.0245 m	c_{pipe}	385 J/(kg K)
T_{amb}	293.15 K	c_{heater}	450 J/(kgK)

NUMERICAL SOLUTION AND RESULTS

Figure 6 illustrates the temperature evolution toward steady state in the first volume element.

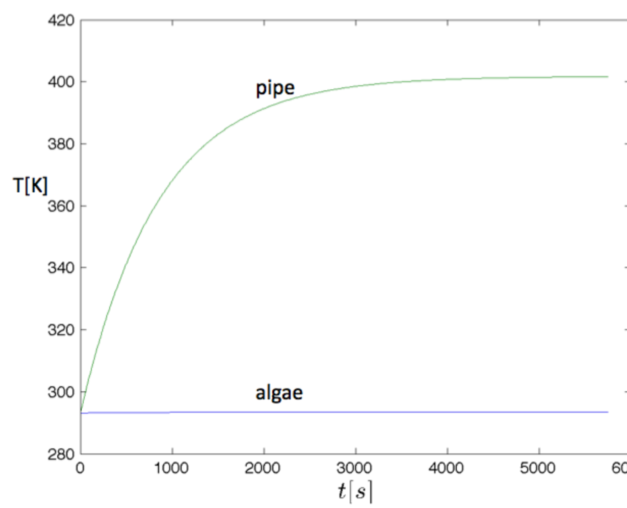


Figure 6– Temperature evolution in VE1 (z =0.0075m) for two of its systems (algae and pipe). Heat applied along the total length, $\dot{\boldsymbol{Q}}_{gen} = 30$ W, $\dot{m} = 0.1$ kg/s.

It can be seen that the system takes ~1.5 hours to reach steady state. The steady state temperature distribution in the pipe and the algae/water are illustrated in Figure 7. An important finding that follows from Figure 7 is that the algae/water system exhibits a higher temperature difference, $\Delta T = (\mathrm{Tout} - \mathrm{Tin})$, between the end points of the sensor. Suggesting that the temperature sensor should be put in contact with the alage/water instead of with the pipe wall.

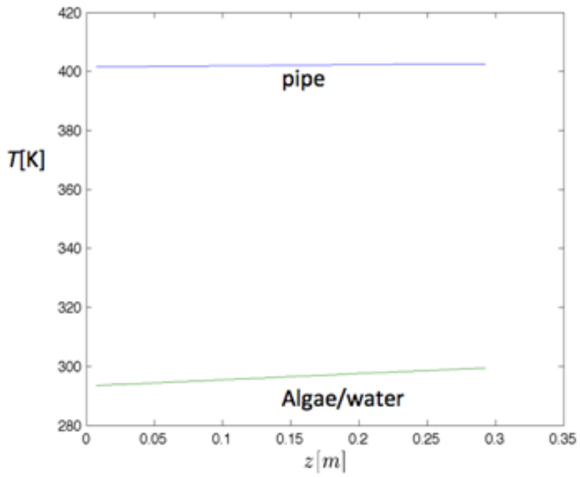


Figure 7 – Temperature distribution along the systems (algae and pipe) after reaching steady state. Heat applied $\dot{Q}_{gen} = 30\ \mathrm{W}, \dot{m} = 0.1\ \mathrm{kg/s}$.

Figure 8 illustrates the Relationship between the total mass flow rate ṁ and the temperature difference reading in the derivation branch. Comparison with Figure 2, indicates the clear advantage of the new system. Even with low heat input rates, temperature differences that are easily measured can be obtained.

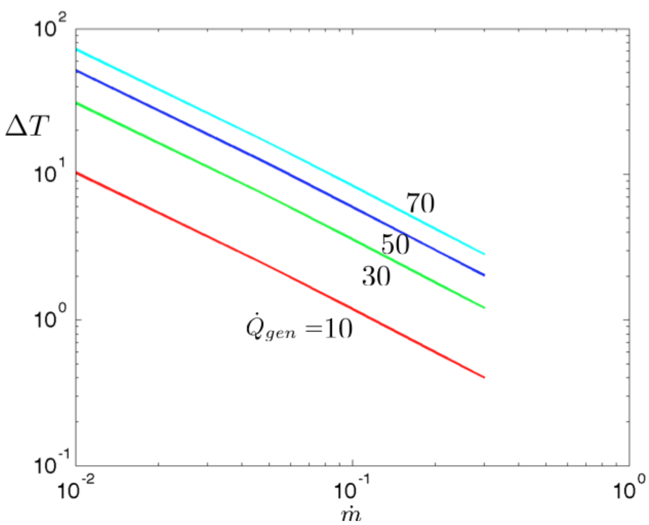


Figure 8– Relationship between the total mass flow rate $\dot{m}$ and the temperature difference reading in the derivation branch.

CONCLUSION

A Volume Element Model has been developed to compute the temperature distribution in a mass flow rate sensor to be used in algae photobioreactors. The temperature based sensor is placed in a derivation branch of the photobioreator, where only a small fraction of the flow is routed. The temperature difference across the sensor is later correlated to the total mass flow rate. The model can be used in the sizing and optimization of the sensor (e.g. minimum power consumption, increase sensitivity)

Computational results indicate that it is possible with heat inputs of the order of 10W to obtain temperature gradients of the order ~1K in the derivation branch, for total flow rates in the typical range used in existing photobioreactors.

A prototype mass flow sensor is being built (Figure 3(b)) and will be used for experimental validation and model calibration.

It is expected that the new sensor will allow continuous monitoring of the photobioreactor and improve the ability to control the algae growth processes without negatively affecting the algae.

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