Continuous and controlled oxygen production in an air-lift photobioreactor to sustain the activity of an animal crew

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Introduction
The MELiSSA Concept: engineering a closed ecosystem

MELiSSA approach is to perform the most relevant biological functions of an ecosystem in individual compartments (bioreactors and higher plant chambers), in continuous and controlled operation.
The MELiSSA Pilot Plant: technology demonstration and integration

Main objectives

Integration and demonstration of the MELiSSA concept at pilot scale

Technology demonstration:

- In ground conditions
- With an animal crew
- With industry standards
- Long-term continuous operation
- Modelling and Control

Production of Oxygen:
Equivalent to a one person respiration

Production of food:
At least 20% of a person requirements
WP1 Integration. Experimental results
Integration Strategy: C. III / C. IVa / C. V

Top requirements for the MELiSSA Pilot Plant

1/ Progressive demonstration of MELiSSA concept
2/ Stepwise integration
3/ Capitalization of knowledge

First integration steps based on the most advanced compartments in terms of knowledge, model and control

Integration WP1
Integration WP3
Integration WP4
Integration WP6
The MELiSSA Pilot Plant (MPP)

Function in the loop

Light → CO₂ → C. IVa → Biomass O₂

Biological component

Arthospira platensis (Axenic culture)

Technology

83 L
The MELiSSA Pilot Plant (MPP)

**COMPARTMENT** | I | II | III | IVa | IVb | V
---|---|---|---|---|---|---

**Function in the loop**

- $O_2$ Feed
- $CO_2$
- C. V
- Wastes

**Biological component**

- *Laboratory Wistar rats* (1 human ~ 60 rats)

**Technology**

- Max. leak 0.029% vol./h
WP1 Integration. Test conditions

O2 and CO2 measured in C5 = inlet of C4a

O2 and CO2 measured at the outlet of C4a

COMPARTMENT IVa SUBSYSTEM
- Temperature: 36°C
- Pressure: 1.08 atm
- pH: 9.4
- $k_a$: 11 h⁻¹
- Reactor characteristic length: 0.076 m
- Reactor volume: 83 L
- Reactor gas volume fraction: 1%
- Liquid flow rate: 0.75 L/h
- Gas flow rate: 168 L/h

COMPARTMENT V SUBSYSTEM
- Volume: 1600 L
- Temperature: 22 °C
- Pressure: 1.002 bar
- Number of rats: 3
WP1 integration. Main objectives

- Continuous gas phase connection CIVa-CV at different conditions in CV (set points of % O₂)

- CIVa illumination adjusted by the control system to produce the oxygen necessary to maintain set-point of O₂ in CV, according to the knowledge model linking O₂ production and illumination

- Building a mathematical model describing the interconnection of the two compartments, necessary for future integration steps
WP1 integration. Experimental results. CIVa + CV sequential test

Oxygen – Light control system

C.V Oxygen concentration → Control System I

C.IVa Oxygen production → Control System II

Master controller: CLRT=7 hours

Slave controller: CLRT=20 min

Light and Oxygen evolution in CIVa and CV compartments

The system response to CV oxygen set point changes is consistent in the range tested (O2 controlled at SP +/- 0.05%)
WP1 integration. Experimental results. CIVa + CV sequential test

**Light and biomass evolution (dry weight and optical density)**

Biomass concentration during the test was maintained in the same range order.

**Oxygen and carbon dioxide evolution (gas composition)**

Carbon dioxide concentration in C.V compartment was quite stable and lower than the toxic limit ($20 \cdot 10^3$ ppm).
WP1 MODEL. RATIONALE
The proposed model should describe the slightly plug flow behavior while at the same time allowing for the perfectly mixed behavior of the whole system.
System Model

C. IVa Compartment

C. V Compartment

Model equations (liquid phase)

**TOTAL BIOMASS EQUATION**

\[
\int_{V_i} \frac{\partial X}{\partial t} dV + v \int_{V_i} \frac{\partial X}{\partial z} dV - \int_{V_i} \left( \mu_{max} \cdot (X - X_{eps}) \right) \frac{CO_2}{CO_2 + k_s} \frac{J}{\pi_i \cdot r^2} + \mu_{max,eps} \cdot X_{eps} \frac{CO_2}{CO_2 + k_{eps}} \frac{J}{\pi_i \cdot r^2} \left(1 - d_{arc,frac}\right) dV = 0
\]

**INACTIVE BIOMASS EQUATION**

\[
\int_{V_i} \frac{\partial X_{eps}}{\partial t} dV + v \int_{V_i} \frac{\partial X_{eps}}{\partial z} dV - \int_{V_i} \left( \mu_{max,eps} \cdot X_{eps} \right) \frac{CO_2}{CO_2 + k_{eps}} \frac{J}{\pi_i \cdot r^2} \left(1 - d_{arc,frac}\right) dV = 0
\]

**DISSOLVED CARBON DIOXIDE EQUATION**

\[
\int_{V_i} \frac{\partial C_E(t)}{\partial t} dV + v \int_{V_i} \frac{\partial C_E(t)}{\partial z} dV - \int_{V_i} \left( \frac{h_s}{h_x} \mu_{max} \cdot (X - X_{eps}) \right) \frac{CO_2}{CO_2 + k_s} \frac{J}{\pi_i \cdot r^2} \left(1 - d_{arc,frac}\right) + \frac{h_s}{h_{eps}} \mu_{max,eps} \cdot X_{eps} \frac{CO_2}{CO_2 + k_{eps}} \frac{J}{\pi_i \cdot r^2} \left(1 - d_{arc,frac}\right) dV = 0
\]

**CARBON DIOXIDE TRANSFER TO LIQUID PHASE**

1/ Carbon dioxide Kla is determined based on oxygen Kla.

2/ Only dissolved carbon dioxide in the liquid phase is considered for the gas-liquid mass transfer.
**System Model**

**C. IVa Compartment**

**C. V Compartment**

**Model equations (liquid and gas phases)**

**Dissolved Oxygen Equation**

\[
\int_{V_i} \frac{\partial C_B(t)}{\partial t} \, dV + v \cdot \int_{V_i} \frac{\partial C_B(t)}{\partial z} \, dV - \int_{V_i} \left[ \frac{h_g}{h_x} \cdot \frac{\mu_{\text{max}} \cdot (X - X_{\text{eps}})}{CO_2 + k_s \cdot \left( 1 - \text{dark}_{\text{frac}} \right)} + \frac{h_g}{h_x} \cdot \frac{\mu_{\text{max_{ep}}}}{CO_2 + k_s \cdot \left( 1 - \text{dark}_{\text{frac}} \right)} \right] \, dV = 0
\]

**Oxygen Production Due to Photosynthesis**

**Carbon Dioxide Gas Equation**

\[
\int_{V_{\text{i,gas}}} \frac{\partial C_B(t)}{\partial t} \, dV_{\text{gas}} + v \cdot \int_{V_{\text{i,gas}}} \frac{\partial C_B(t)}{\partial z} \, dV_{\text{gas}} + \int_{V_{\text{i,gas}}} \left[ k_{\text{ia}} \cdot 0.91 \cdot \left( \frac{C_B(t)}{K_i} - \frac{C_B(t)}{\text{frac}} \right) \cdot \frac{V_{\text{liquid}}}{V_{\text{gas}}} \right] \, dV_{\text{gas}} = 0
\]

**Carbon Dioxide Transfer to Liquid Phase**

1. Carbon dioxide $K_{\text{ia}}$ is determined based on oxygen $K_{\text{ia}}$.
2. Only dissolved carbon dioxide in the liquid phase is considered for the gas-liquid mass transfer.
3. Since the gas-liquid mass transfer is considered in the liquid phase, the transfer per unit of gas volume needs to be recalculated.

**Oxygen Gas Equation**

\[
\int_{V_{\text{i,gas}}} \frac{\partial C_B(t)}{\partial t} \, dV_{\text{gas}} + v \cdot \int_{V_{\text{i,gas}}} \frac{\partial C_B(t)}{\partial z} \, dV_{\text{gas}} + \int_{V_{\text{i,gas}}} \left[ k_{\text{oa}} \cdot \left( \frac{C_B(t)}{K_i} - C_B(t) \right) \cdot \frac{V_{\text{liquid}}}{V_{\text{gas}}} \right] \, dV_{\text{gas}} = 0
\]

**Oxygen Transfer to Gas Phase**

\[
\int_{V_{\text{i,gas}}} \frac{\partial C_B(t)}{\partial t} \, dV_{\text{gas}} + v \cdot \int_{V_{\text{i,gas}}} \frac{\partial C_B(t)}{\partial z} \, dV_{\text{gas}} + \int_{V_{\text{i,gas}}} \left[ k_{\text{oa}} \cdot \left( \frac{C_B(t)}{K_i} - C_B(t) \right) \cdot \frac{V_{\text{liquid}}}{V_{\text{gas}}} \right] \, dV_{\text{gas}} = 0
\]
CIVa gas out composition (%)

Gas flow rate (L/h)

Crew Activity

C.V. (RATS)

CV gas out composition (%)

Gas flow rate (L/h)

Rats consumption/production rates

C. IVa Compartment

C. V Compartment

FOR EACH “RAT STATE” AN OXYGEN CONSUMPTION AND CARBON DIOXIDE PRODUCTION IS ASSUMED BASED ON EXPERIMENTAL DATA (considered perfectly mixed tank)

CASE 1: Active

CASE 2: Inactive

RQ = 0.97 coherent with diet specifications

Fig 3. Oxygen consumption and carbon dioxide production by the rats (mock crew) in animal compartment at different oxygen set points. Blue 19% oxygen (n=2), Orange 20% oxygen (n=3), Yellow 21% oxygen (n=5), Purple 22% oxygen (n=1).
WP1 MODEL. RESULTS
System modelization. Results

CIVa COMPARTMENT – GAS PHASE

CV COMPARTMENT – GAS PHASE
System modelization. Results

CIva COMPARTMENT – LIQUID PHASE

Test 1
(a)

Test 2
(b)

(d)

(d)
The proposed model is capable of describing the gas profiles in the riser that lead to specific gas-liquid mass transfer in each control volume.

The proposed model is able to describe the reactor macroscopic behavior as a perfectly mixed reactor with accuracy.
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