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

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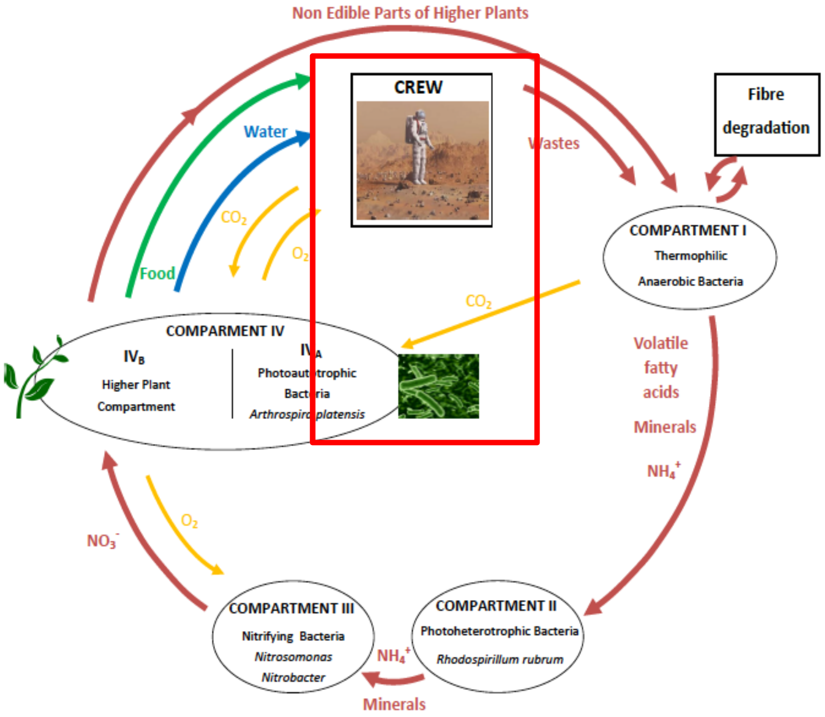
- ☐ WP1 model. Rationale
- ☐ WP1 model. Results

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

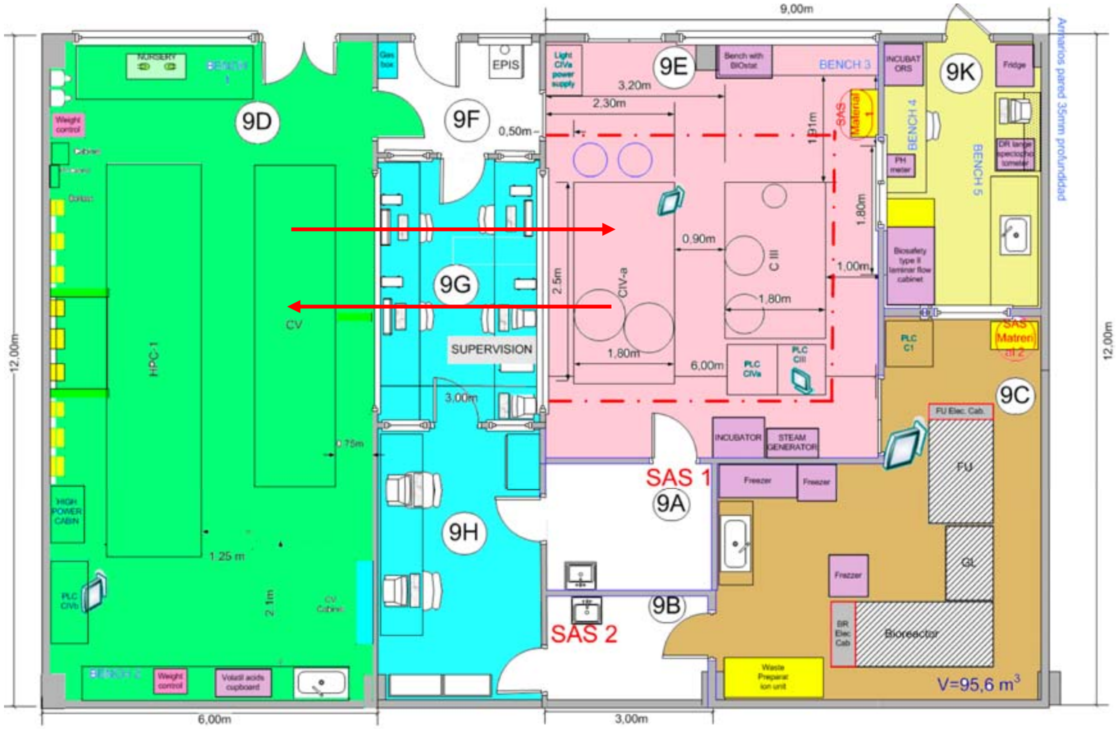
Integration and demonstration of the MELiSSA concept at pilot scale

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

Layout (214 m^2)



Comp. IVb and CV

Comp. III and IVa

Control and supervision

Comp I

Analysis Laboratory

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

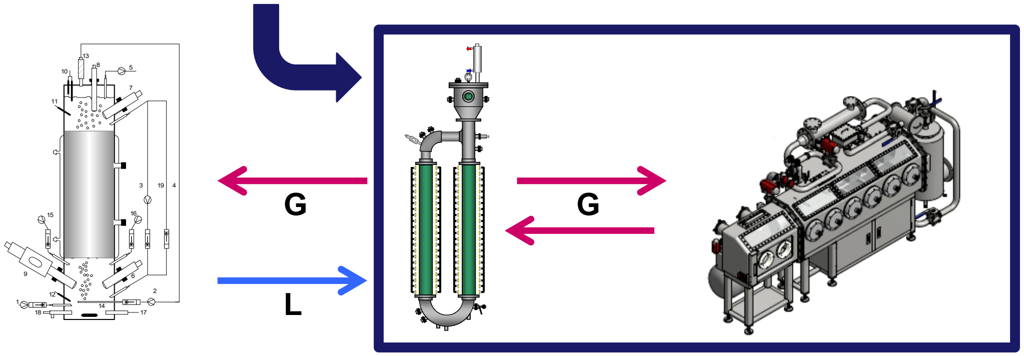
First integration steps based on the most advanced compartments in terms of knowledge, model and control

Integration WP1

Integration WP3

Integration WP4

Integration WP6



The MELiSSA Pilot Plant (MPP)

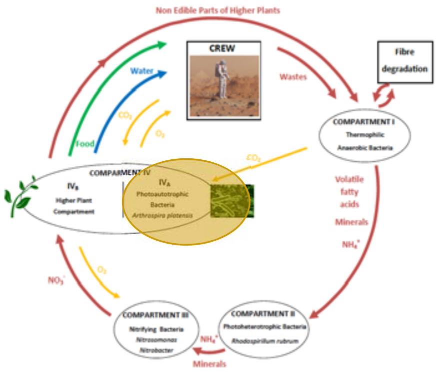
COMPARTMENT | I | II | III | **IVa** | IVb | V

Function in the loop

Light
CO_2

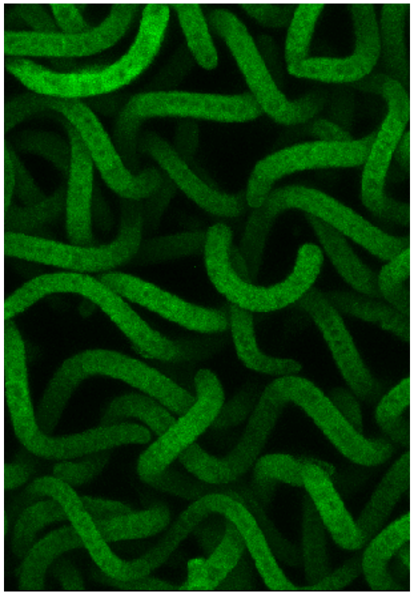
C. IVa

Biomass
O_2



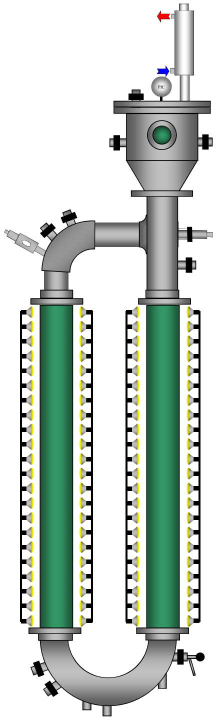
Biological component

Arthrospira platensis
(Axenic culture)



Technology

83 L



The MELiSSA Pilot Plant (MPP)

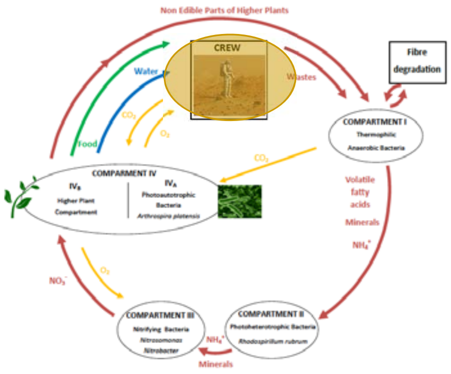
COMPARTMENT | I | II | III | IVa | IVb | **V**

Function in the loop

O_2
Feed

C. V

Wastes
CO_2



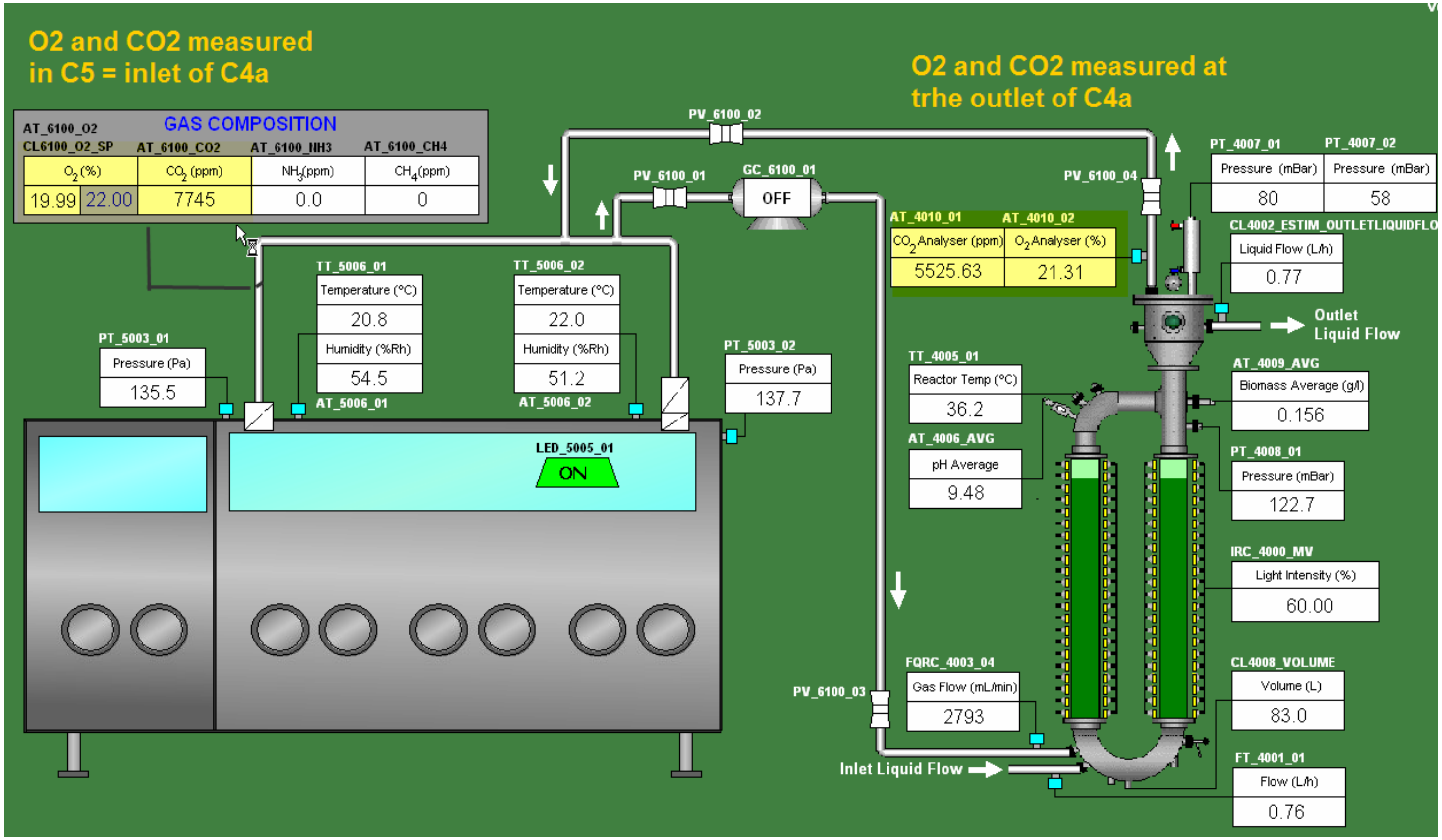
Biological component

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 trhe outlet of C4a

GAS COMPOSITION

AT_6100_O2 / CL6100_O2_SP		AT_6100_CO2	AT_6100_NH3	AT_6100_CH4
O_2 (%)		CO_2 (ppm)	NH_3(ppm)	CH_4(ppm)
19.99	22.00	7745	0.0	0

PT_5003_01 Pressure (Pa): 135.5

TT_5006_01 Temperature (°C): 20.8

AT_5006_01 Humidity (%Rh): 54.5

TT_5006_02 Temperature (°C): 22.0

AT_5006_02 Humidity (%Rh): 51.2

PT_5003_02 Pressure (Pa): 137.7

LED_5005_01: ON

GC_6100_01: OFF

AT_4010_01	AT_4010_02
CO_2 Analyser (ppm)	O_2 Analyser (%)
5525.63	21.31

PT_4007_01 Pressure (mBar): 80

PT_4007_02 Pressure (mBar): 58

CL4002_ESTIM_OUTLETLIQUIDFLO Liquid Flow (L/h): 0.77

TT_4005_01 Reactor Temp (°C): 36.2

AT_4006_AVG pH Average: 9.48

AT_4009_AVG Biomass Average (g/l): 0.156

PT_4008_01 Pressure (mBar): 122.7

IRC_4000_MV Light Intensity (%): 60.00

FQRC_4003_04 Gas Flow (mL/min): 2793

CL4008_VOLUME Volume (L): 83.0

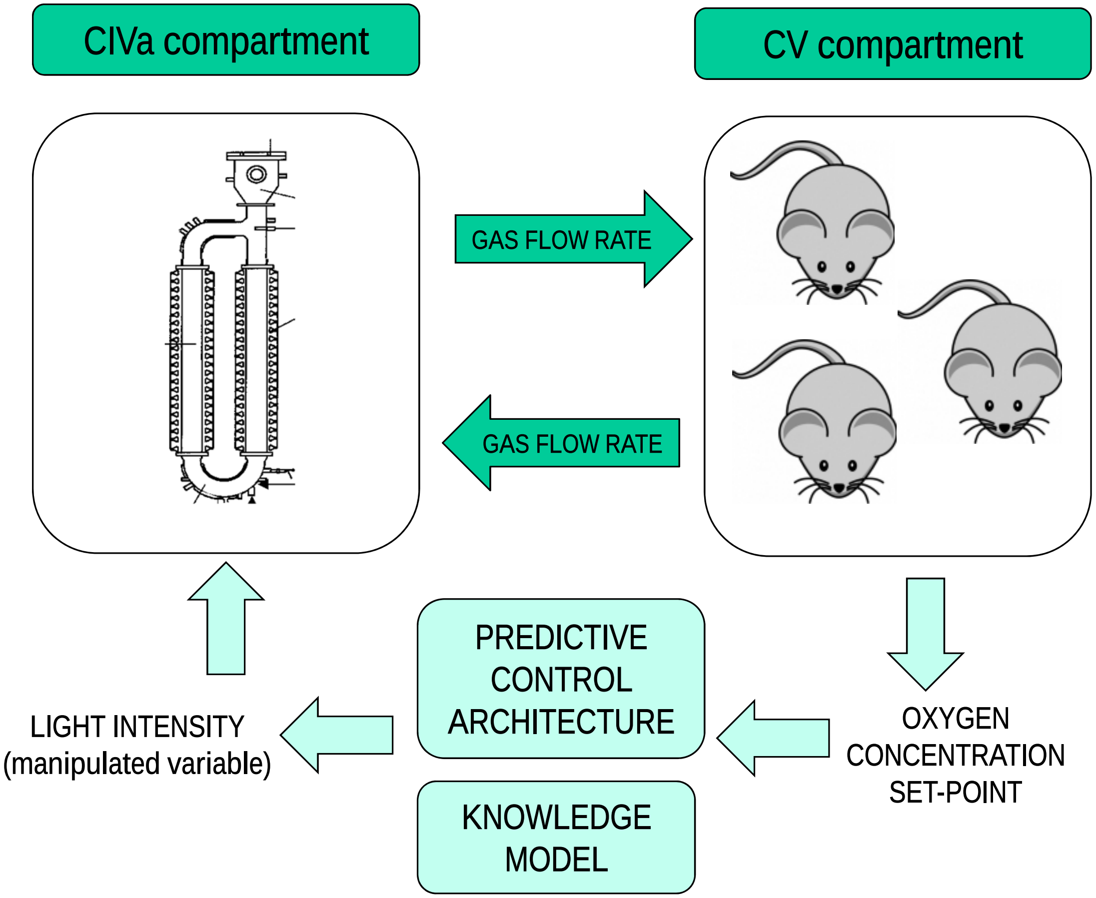
FT_4001_01 Flow (L/h): 0.76

COMPARTMENT IVa SUBSYSTEM	
Temperature	36ºC
Pressure	1.08 atm
pH	9.4
k_La	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 ºC
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 % O_2)**
- CIVa illumination adjusted by the control system to produce the oxygen necessary to maintain set-point of O_2 in CV, **according to the knowledge model linking O_2 production and illumination**
- Building a **mathematical model** describing the interconnection of the two compartiments, necessary for future integration steps



CIVa compartment

CV compartment

GAS FLOW RATE

GAS FLOW RATE

PREDICTIVE CONTROL ARCHITECTURE

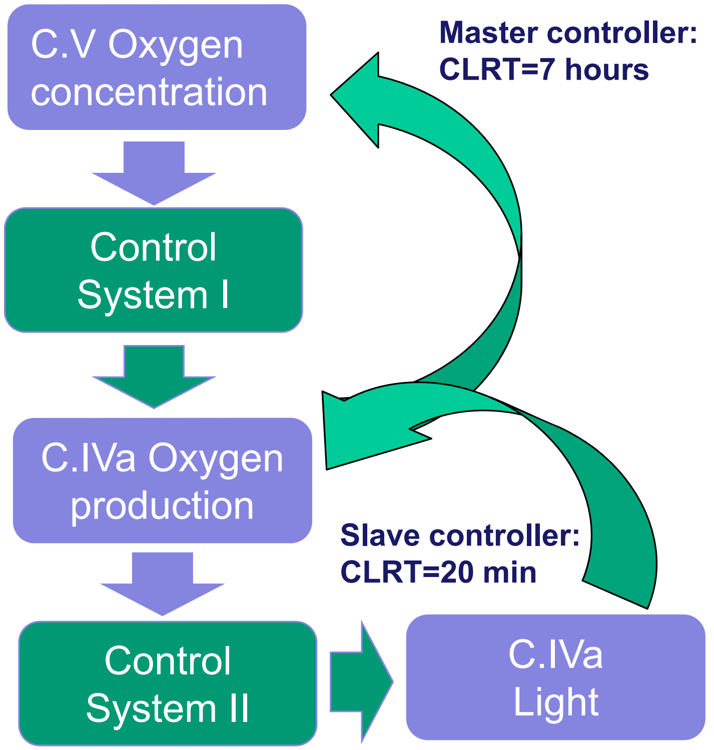
KNOWLEDGE MODEL

LIGHT INTENSITY
(manipulated variable)

OXYGEN
CONCENTRATION
SET-POINT

WP1 integration. Experimental results.
CIVa + CV sequential test

Oxygen – Light control system



C.V Oxygen concentration

Control System I

C.IVa Oxygen production

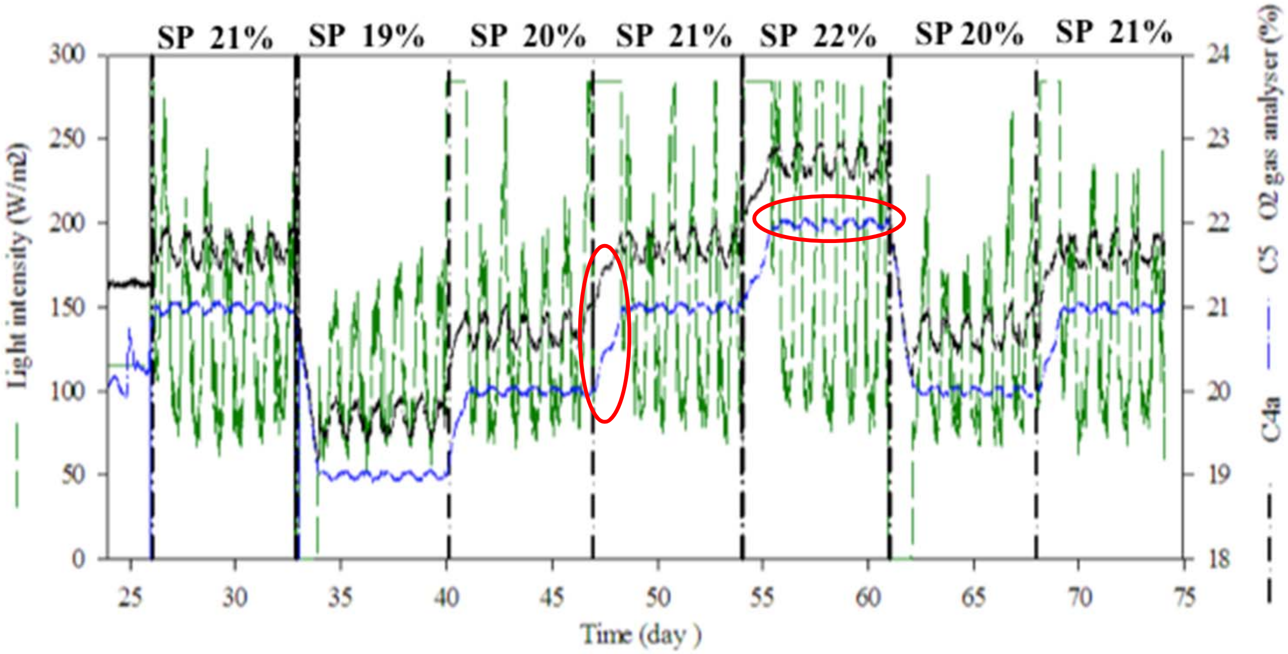
Control System II

C.IVa Light

Master controller:
CLRT=7 hours

Slave controller:
CLRT=20 min

Light and Oxygen evolution in CIVa and CV compartments



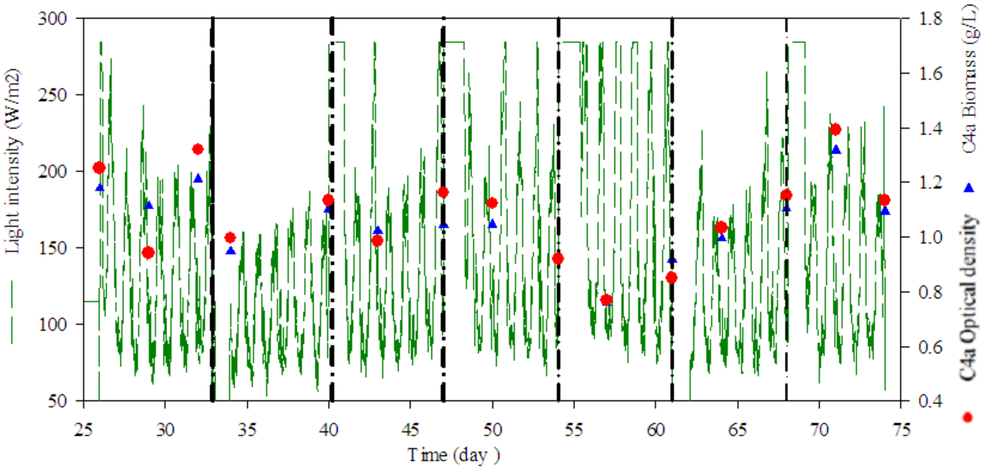
The system response to CV oxygen set point changes is consistent in the range tested (O2 controlled at SP +/- 0.05%)

WP1 integration. Experimental results.

CIVa + CV sequential test

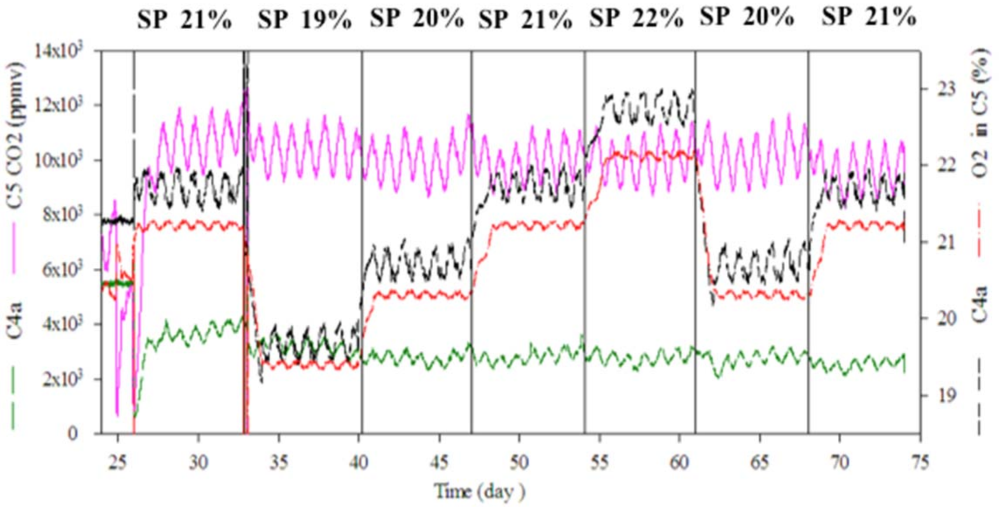
Light and biomass evolution (dry weight and optical density)

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

System Modelization Assumptions

C. IVa Compartment C. V Compartment

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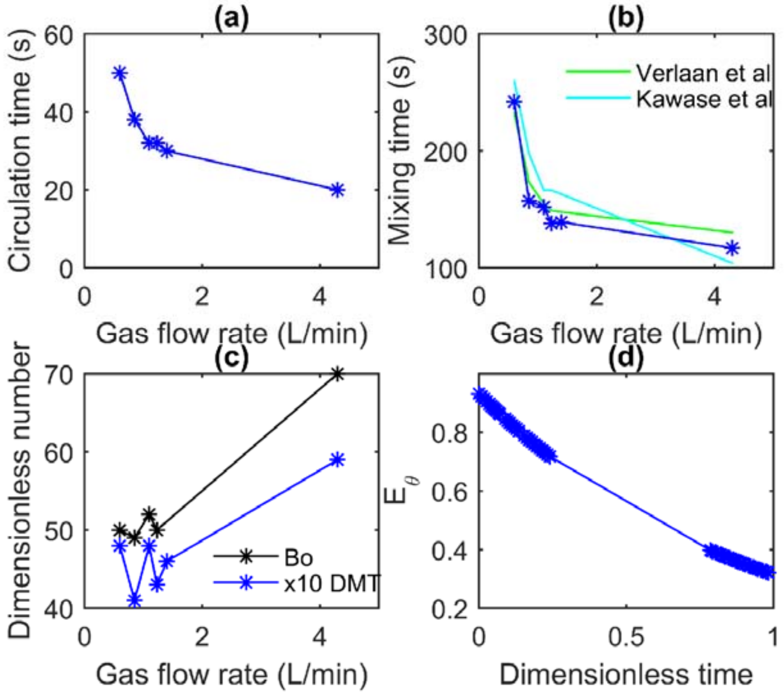
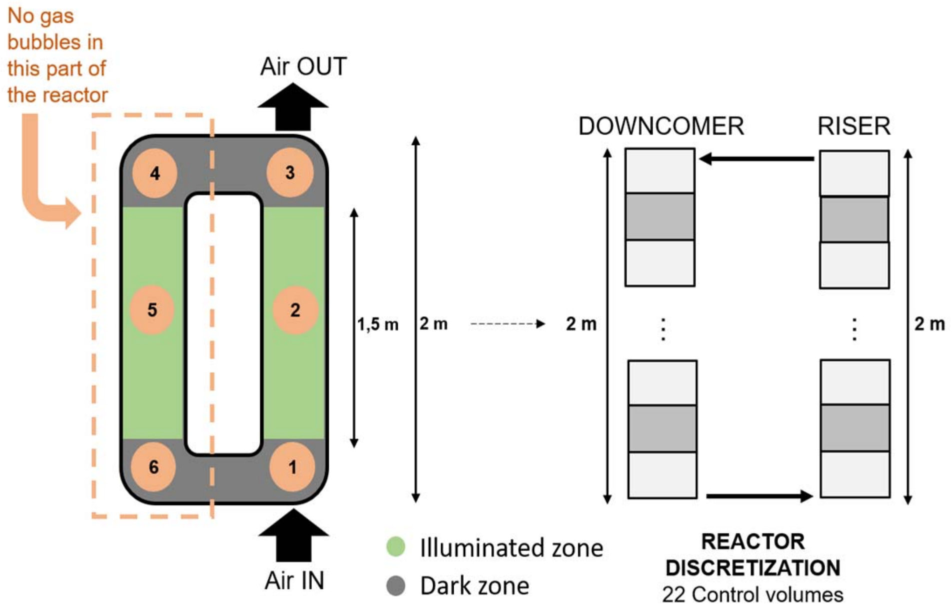
Hydrodynamic studies results



Mixing time << HRT (4,6 days)

Photobioreactor discretization proposal



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

Universitat Autònoma de Barcelona

Model equations (liquid phase)

TOTAL BIOMASS EQUATION

IN – OUT OF THE
CONTROL VOLUME

CONSUMPTION OF CARBON SOURCE
(Growth only dependent on light (CO2 >> Ks).

NON ILLUMINATED ZONE
IN THE REACTOR

$$\int_{V_i} \frac{\partial X}{\partial t}\, dV + v \cdot \int_{V_i} \frac{\partial X}{\partial z}\, dV - \int_{V_i} \left(\mu_{maxX} \cdot (X - X_{eps}) \cdot \frac{CO_2}{CO_2 + ks} \cdot \frac{J}{pi \cdot r^2} + \mu_{maxXeps} \cdot X_{eps} \cdot \frac{CO_2}{CO_2 + ks_{eps}} \cdot \frac{J}{pi \cdot r^2}\right) \cdot (1 - dark_{frac})\, dV = 0$$

INACTIVE BIOMASS EQUATION

$$\int_{V_i} \frac{\partial X_{eps}}{\partial t}\, dV + v \cdot \int_{V_i} \frac{\partial X_{eps}}{\partial z}\, dV - \int_{V_i} (\mu_{maxXeps} \cdot X_{eps} \cdot) * \frac{CO_2}{CO_2 + ks} \cdot \frac{J}{pi \cdot r^2} \cdot (1 - dark_{frac})\, dV = 0$$

GROWTH LINKED TO ILLUMINATION

DISSOLVED CARBON DIOXIDE EQUATION

$$\int_{V_i} \frac{\partial C_{B(l)}}{\partial t} dV + v \cdot \int_{V_i} \frac{\partial C_{B(l)}}{\partial z} dV - \int_{V_i} \left[\frac{h_B}{h_X} \cdot \mu_{max} \cdot (X - X_{eps}) \cdot \frac{CO_2}{CO_2 + ks} \cdot \frac{J}{pi \cdot r^2} \cdot (1 - dark_{frac}) + \frac{h_B}{h_{X_{eps}}} \cdot \mu_{maxXeps} \cdot X_{eps} \cdot \frac{CO_2}{CO_2 + ks} \cdot \frac{J}{pi \cdot r^2} \cdot (1 - dark_{frac}) - k_{la} \cdot 0.91 \cdot \left(\frac{C_{B(g)}}{K_i} \cdot 55.555 - \frac{C_{B(l)}}{frac}\right)\right] dV = 0$$

IN – OUT OF THE
CONTROL VOLUME

CARBON DIOXIDE CONSUMPTION DUE TO PHOTOSYNTHESIS

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

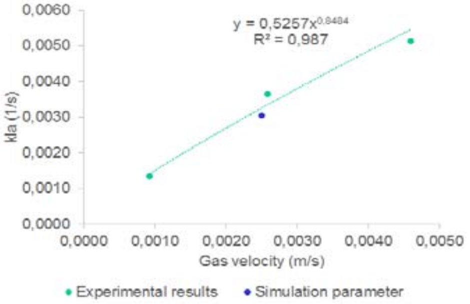
Model equations (liquid and gas phases)

DISSOLVED OXYGEN EQUATION

$$\int_{V_i} \frac{\partial C_{B(l)}}{\partial t} dV + v \cdot \int_{V_i} \frac{\partial C_{B(l)}}{\partial z} dV - \int_{V_i} \left[\boxed{\frac{h_B}{h_X} \cdot \mu_{max} \cdot (X - X_{eps}) \cdot \frac{CO_2}{CO_2 + ks} \cdot \frac{J}{pi \cdot r^2} \cdot (1 - dark_{frac}) + \frac{h_B}{h_{X_{eps}}} \cdot \mu_{maxXeps} \cdot X_{eps} \cdot \frac{CO_2}{CO_2 + ks} \cdot \frac{J}{pi \cdot r^2} \cdot (1 - dark_{frac})} + \boxed{k_{la} \cdot \left(\frac{C_{B(g)}}{K_i} * 55.555 - C_{B(l)} \right)} \right] dV = 0$$

OXYGEN PRODUCTION DUE TO PHOTOSYNTHESIS

OXYGEN TRANSFER TO GAS PHASE



CARBON DIOXIDE GAS EQUATION

$$\int_{V_{igas}} \frac{\partial C_{B(l)}}{\partial t} dV_{gas} + v \cdot \int_{V_{igas}} \frac{\partial C_{B(l)}}{\partial z} dV_{gas} + \int_{V_{igas}} \boxed{\left[k_{la} \cdot 0.91 \cdot \left(\frac{C_{B(g)}}{K_i} - \frac{C_{B(l)}}{frac} \right) \cdot \frac{V_{iliquid}}{V_{igas}} \right] dV_{gas}} = 0$$

IN – OUT OF THE CONTROL VOLUME

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.
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

$$\int_{V_{igas}} \frac{\partial C_{B(l)}}{\partial t} dV_{gas} + v \cdot \int_{V_{igas}} \frac{\partial C_{B(l)}}{\partial z} dV_{gas} + \int_{V_{igas}} \boxed{\left[k_{la} \cdot \left(\frac{C_{B(g)}}{K_i} - C_{B(l)} \right) \cdot \frac{V_{iliquid}}{V_{igas}} \right]} dV_{gas} = 0$$

IN – OUT OF THE CONTROL VOLUME

OXYGEN TRANSFER TO GAS PHASE

System modelization Assumptions

C. IVa Compartment

C. V Compartment

Rats consumption/production rates

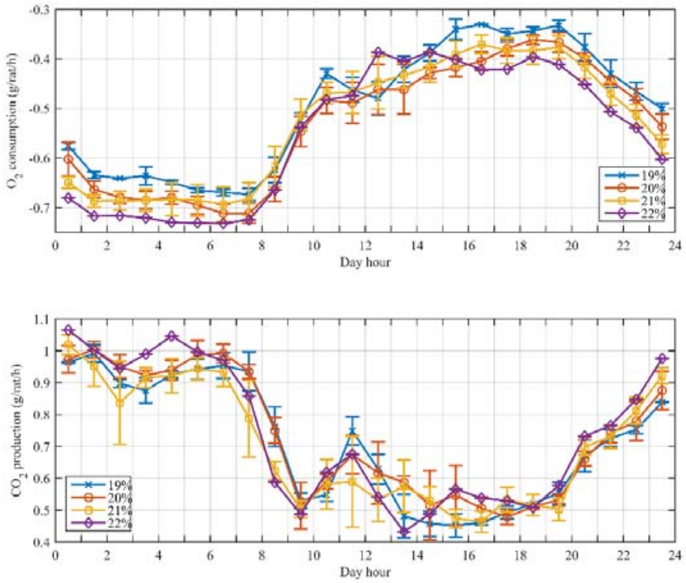
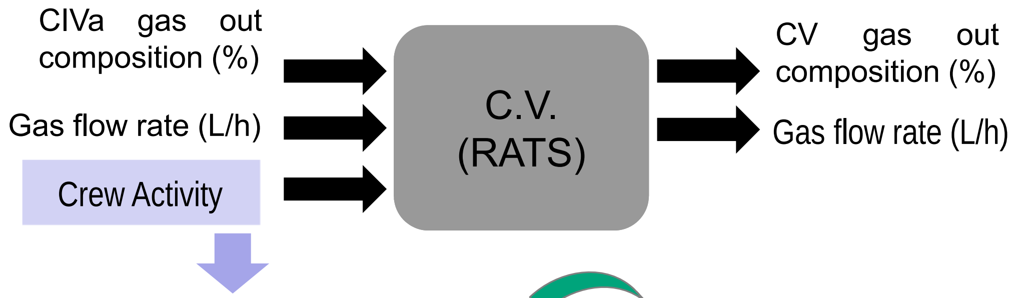


Fig 3. Oxygen consumption and carbon dioxide production by the rats (mock crew) in animal compartment at different oxygen set points. Blue 19% oxygen (n=2). Orange 20% oxygen (n=3), Yellow 21% oxygen (n=5), Purple 22% oxygen (n=1).

Crew compartment modellization



CIVa gas out composition (%)

Gas flow rate (L/h)

Crew Activity

C.V. (RATS)

CV gas out composition (%)

Gas flow rate (L/h)

Defines the rats “timetable”. 12 hours activity, 12 hours inactivity.

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

CASE 1: Active

O2_rate = 0.66g/h * rats_number / 32

CO2_rate = 0.94g/h * rats_number / 44

CASE 2: Inactive

O2_rate = 0.42g/h * rats_number / 32

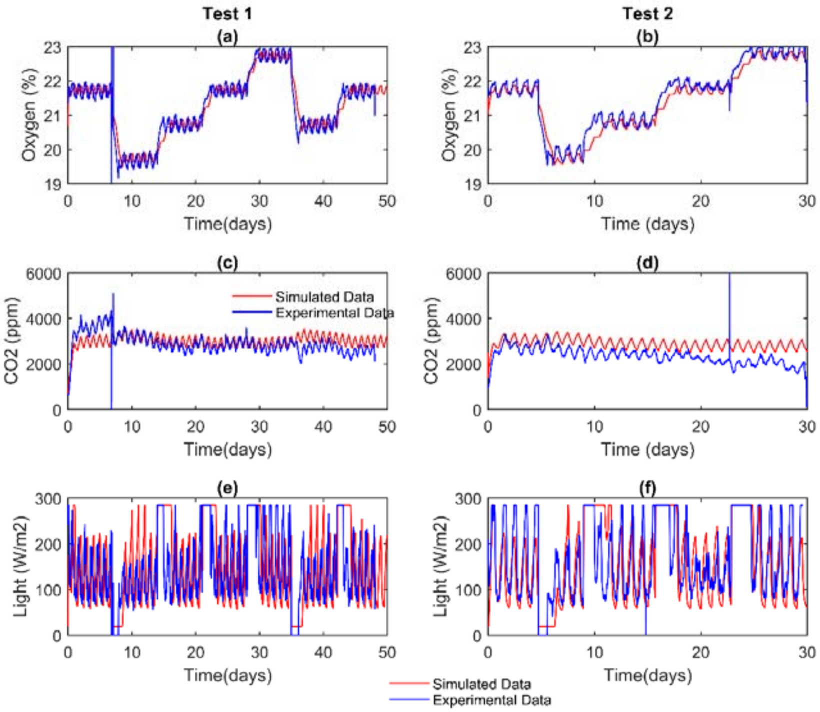
CO2_rate=0.53g/h * rats_number / 44

RQ= 0,97 coherent with diet specifications

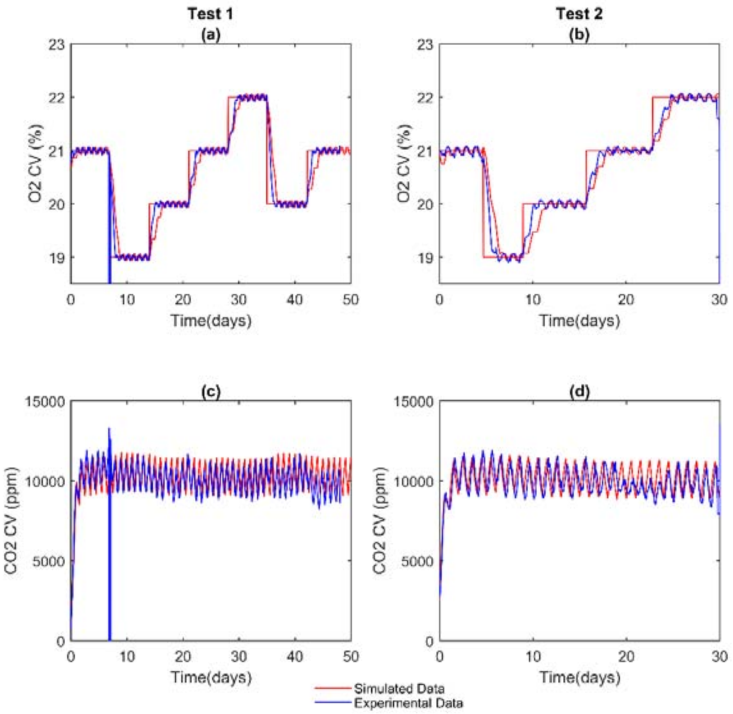
WP1 MODEL. RESULTS

System modelization. Results

CIVa COMPARTMENT – GAS PHASE

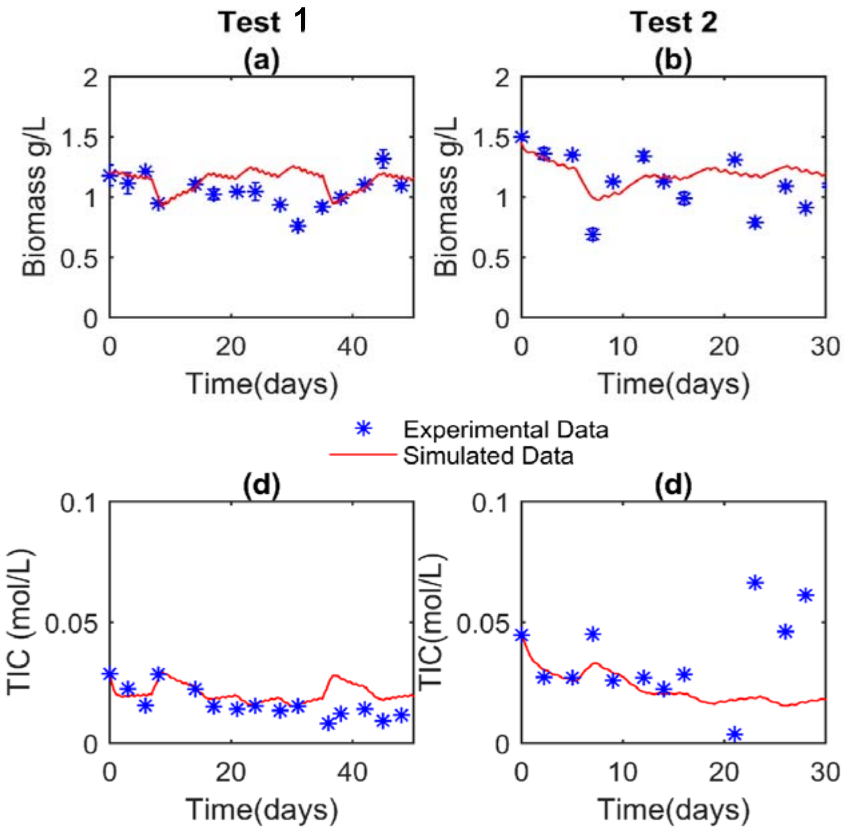


CV COMPARTMENT – GAS PHASE



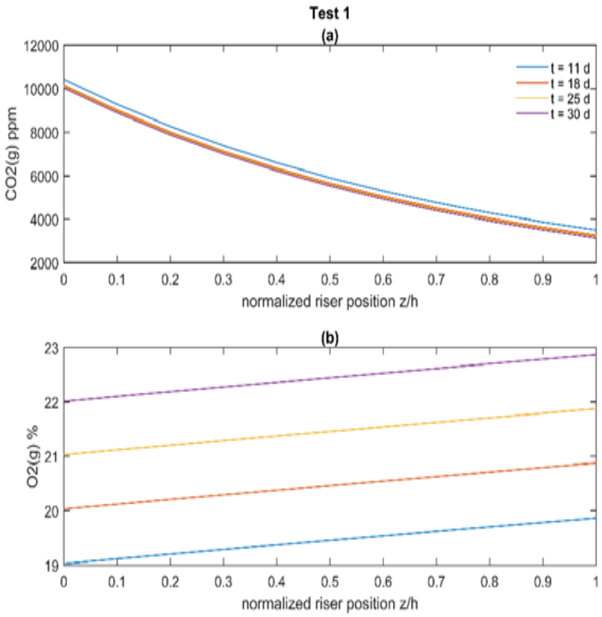
System modelization. Results

CIVa COMPARTMENT – LIQUID PHASE

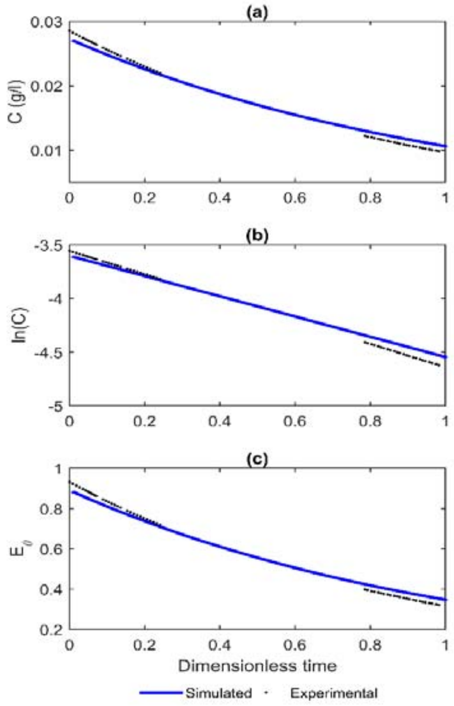


System modelization. Results

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.



RTD simulation

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