

Model analysis of an *Arthrospira* photobioreactor running on ISS

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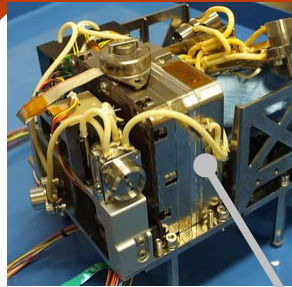


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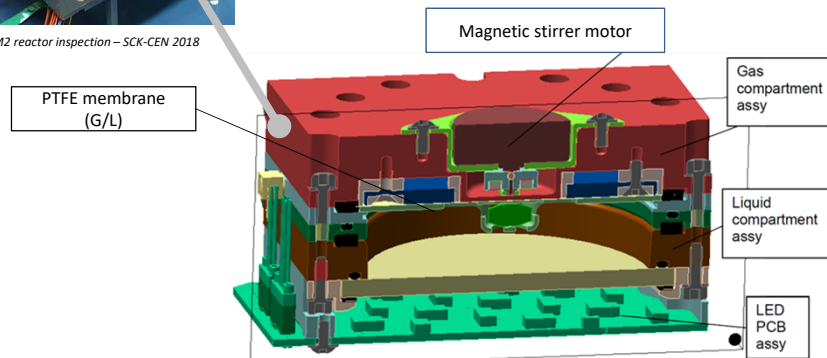
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Source : GM2 reactor inspection – SCK-CEN 2018

ArtemiSS :

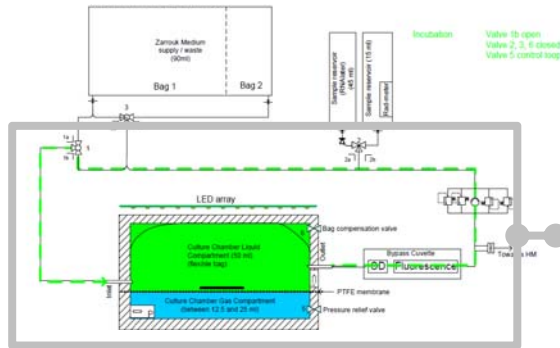
- on-line assessing of growth of *A. platensis* on ISS by gas pressure measurement
- Photobioreactor → analysis using a classical approach for bioprocesses : modelling and simulation



Source : Design report ArtemiSS B – QINETIQ Space nv 2016

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Photobioreactor diagram (batch incubation operation)

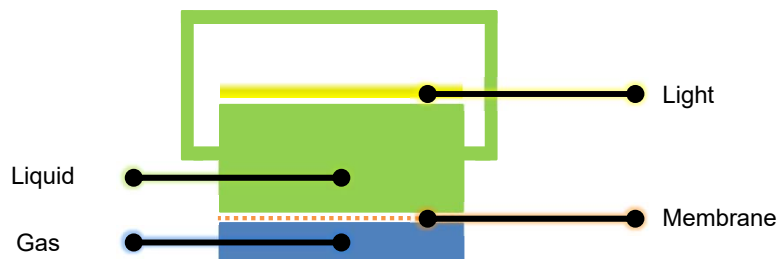


Model of the photobioreactor

Objectives :

- Use of a predictive model built from the knowledge of previous works (MASK, MELISSA photobioreactor, lab scale photobioreactors)
- Analysis of results
- Comparison Ground / ISS (? Differences)

ArtemISS photobioreactor model principles



Liquid : Model of a batch culture (light dependent)

Several consecutive batches:

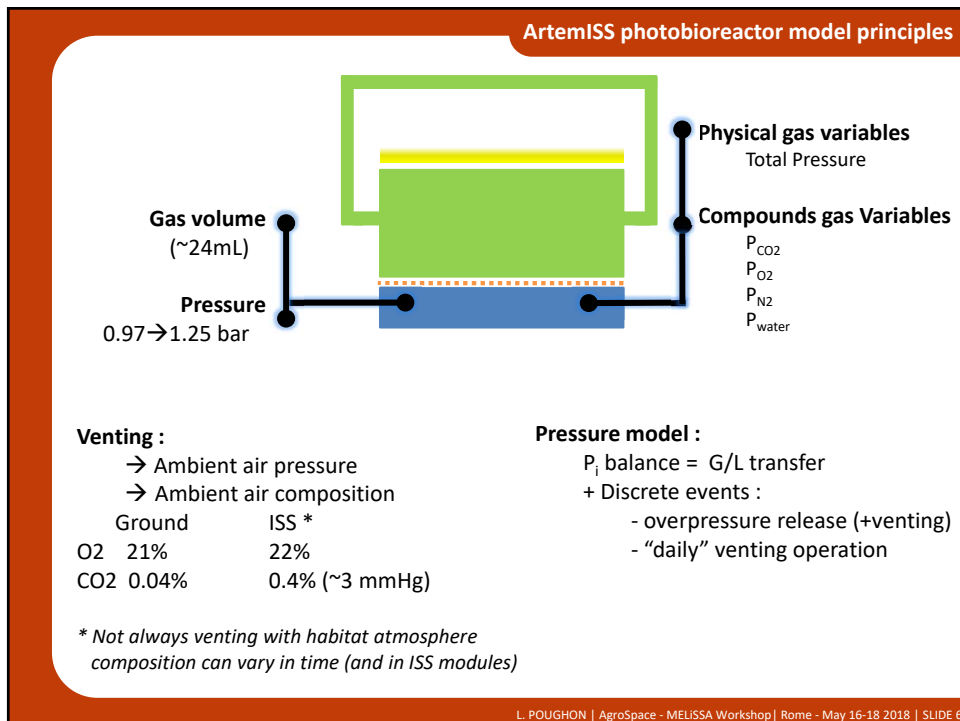
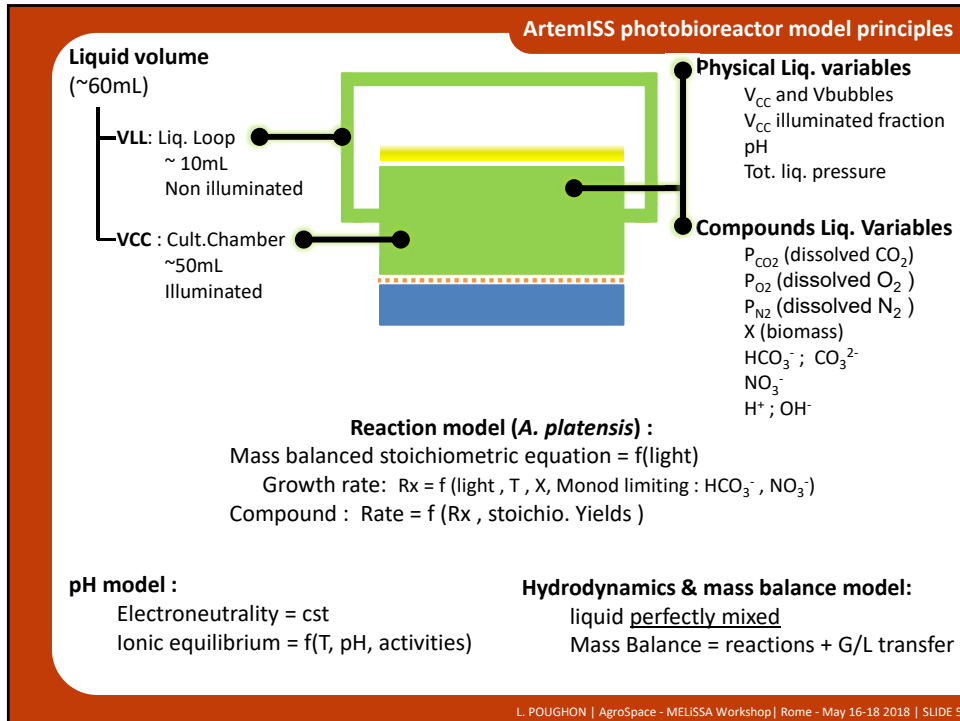
Resetting initial conditions of a batch after a volume dilution with Zarruk medium

Gas : Model of a pressure increase up to a threshold → venting with air

Periodic manual venting with air (discrete events)

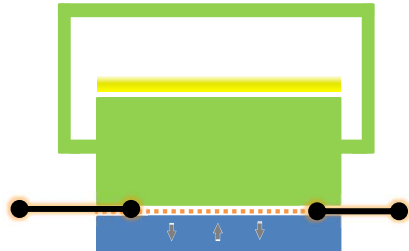
Membrane : Model of Liquid ↔ Gas transfer (O_2 / CO_2 / N_2 / Water)

Light : Model of light transfer in culture chamber



ArtemISS photobioreactor model principles

Membrane
PTFE hydrophobic
and porous (0.2 μm)
membrane
O₂, N₂, CO₂



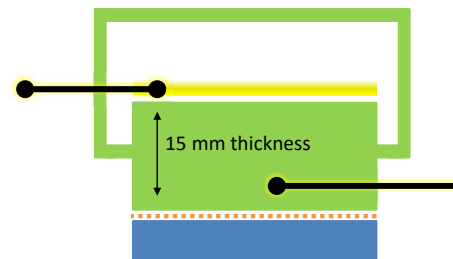
Parameters
Area (A) : 2.6 10⁻³ m²
Permeability (k) * :
O₂ : 2 10⁻⁵ mol.Pa⁻¹.m⁻².h⁻¹
**Fitted from previous experiments*

G/L equilibrium constant :
Henry constant (H) = f(temp.)

G/L mass transfer rate model :
 $R_{G/L} = k \cdot A \cdot (P_{liq} - P_{gaz})$

ArtemISS photobioreactor model principles

Light (white LEDs)
light flux (q₀)
Off
~7.6 W.m⁻²
~9.2 W.m⁻²

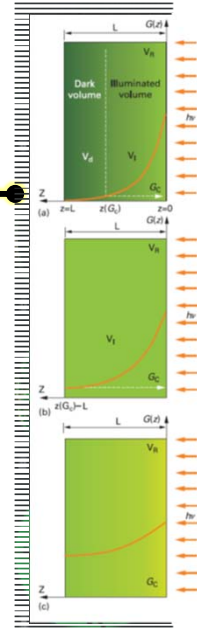


Light diffusion model :

L (illuminated thickness) and V_{cc} illuminated = f(q₀, X)

$\langle J \rangle = f(L, q_0, X) \leftarrow$ radiant light energy absorbed

$\langle R_x \rangle = f(\langle J \rangle, T, X, \text{Monod limiting : HCO}_3^-, \text{NO}_3^-)$



ArtemISS photobioreactor model principles

Model equation (example for O₂)

$$\frac{dP_{O_2.liq}}{dt} = \underbrace{(-k \cdot A \cdot (P_{O_2.liq} - P_{O_2.Gas}))}_{\text{G/L transfer}} + \underbrace{Y_{O_2} \cdot \langle R_x \rangle}_{\substack{\text{Stoich. Equation} \\ f(\langle \rangle, T, X, \text{Monod limiting: } HCO_3^-, NO_3^-)}} \cdot \underbrace{\frac{H}{V_{Liq}}}_{\text{G/L equilibria}}$$

$$\frac{dP_{O_2.Gas}}{dt} = \underbrace{(k \cdot A \cdot (P_{O_2.liq} - P_{O_2.Gas}))}_{\text{G/L transfer}} \cdot \underbrace{\frac{R \cdot T}{V_{Gas}}}_{\substack{\text{Light diffusion model} \\ \text{Ionic equilibria} \\ \text{pH model}}}$$

Model computing

Matlab : ODE/DAE + overpressure event detection "ode15s" solver used

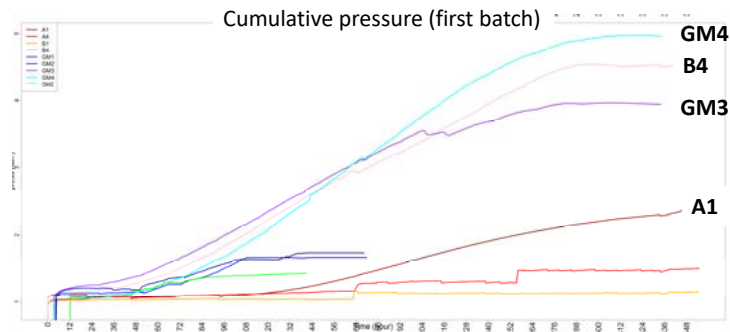
Model(s) references & validation

- Light diffusion model (J-F. Cornet , MELISSA + lab scale photobioreactors)
- pH model : MASK experiments (G. Cogne, 2003, pH range 9,5-10)
- G/L membrane transfer model (G. Cogne, 2003, MASK photobioreactor)
- *A. platensis* growth & mass balance model : MELISSA (since 1992 .. up to 2017)

→ Predictive model : no parameters fitted from ArtemISS experiments

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ArtemISS results



ArtemISS experiments analysed using the predicted model

→ Ground reactors

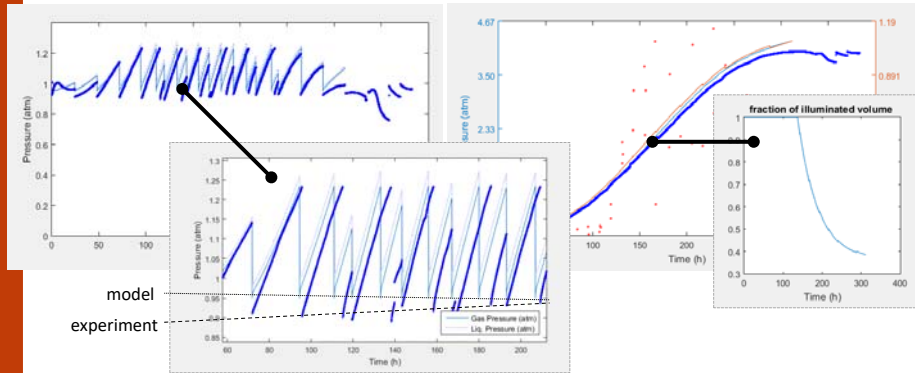
- GM3
- GM4

→ ISS reactors

- A1
- B4

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GM4 Ground experiment vs Model

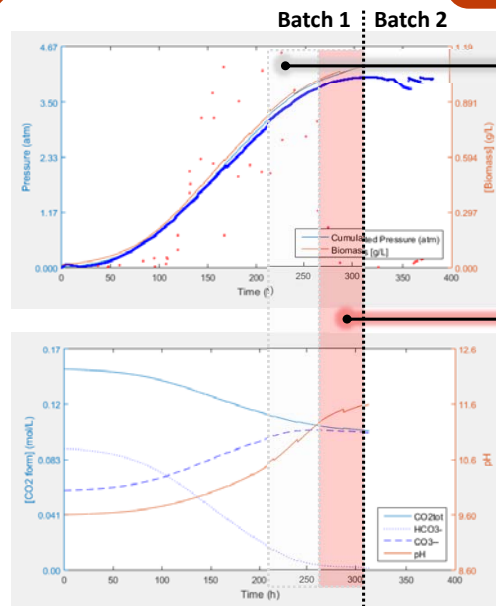


C6

- Very good fitting of the predictive model with the GM4 – batch 1 experiment (pressure)
- At 150h decrease of the illuminated volume → light limitation → linear growth (model slightly higher, probably small difference of the light flux value)
- Differences in overpressure sequences are due to a different pressure baseline after venting between model and experiment (not constant in experiment).

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GM4 Ground experiment vs Model



Limitation :

- high pH →
- 1) Lower quantity of HCO_3^- (← Monod limitation in model)
 - 2) Direct pH effect: biomass lysis

Biomass death at high pH:

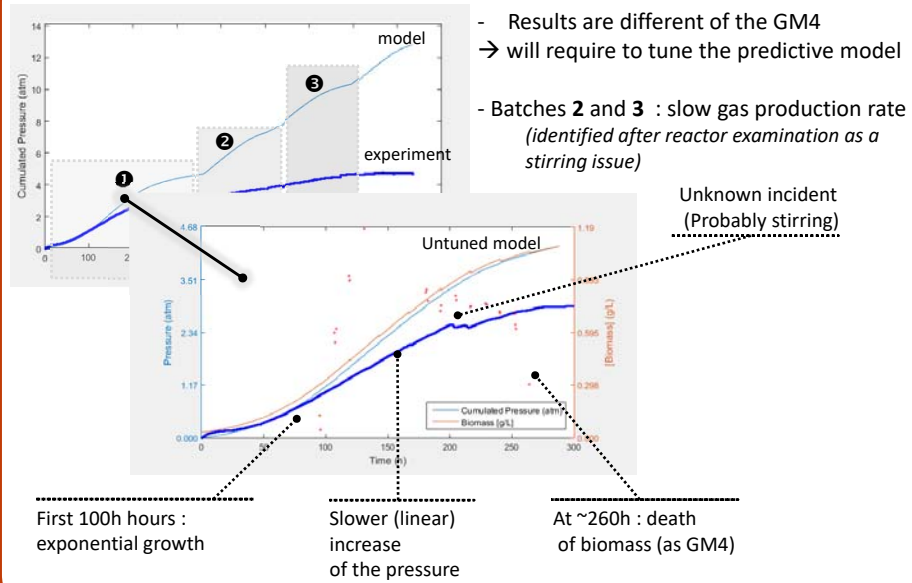
- At 275h predicted pH=11.39
- Biological model not developed for pH higher than 10.5
- **No recovery of biomass activity** after dilution for 2nd batch

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Slide 11

C6 je vois pas ce que représente la petite figure à droite
Céline, 04/05/2018

GM3 Ground experiment vs Model



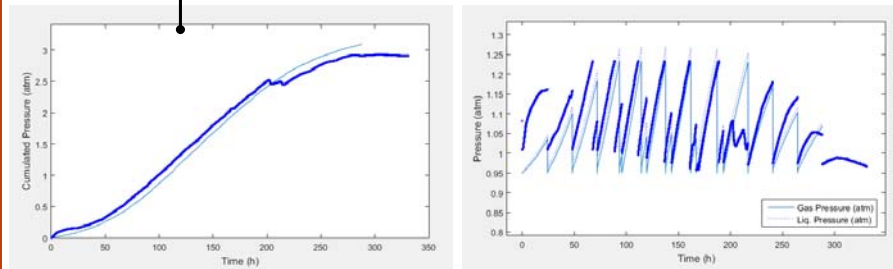
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GM3 Ground experiment vs Model

Slower increase of the pressure may be due to:

- 1) a lower light flux ←checked – not fitting
- 2) a mixing issue ←cannot be tested – required new model (CFD approach)
- 3) a gas bubble in Vcc contributing to the total gas volume of the reactor

6 mL (= 25% of the volume of gas compartment)

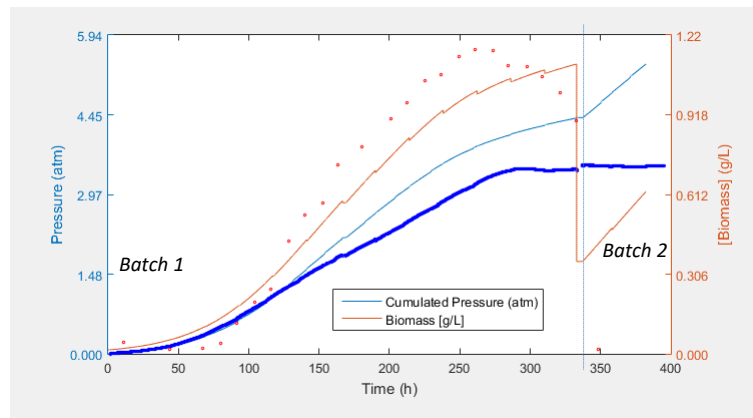


Cumulative pressure and pressure sequence perfectly fitted
Biomass collapse at a predicted pH = 11.4

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B4

ISS experiment vs Model



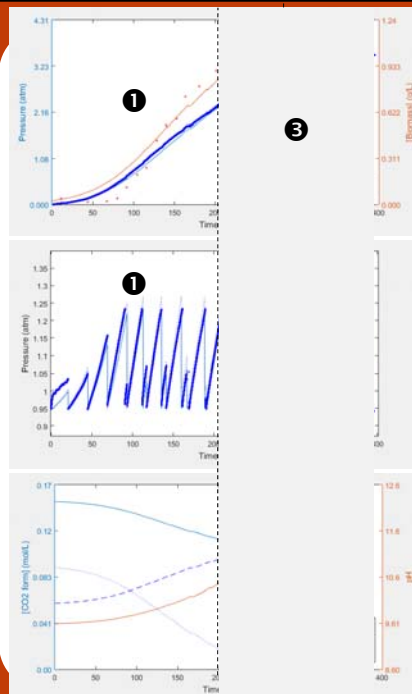
- Exactly the same trend as the ground reactor GM3 (untuned model cannot perfectly fit the experiment)
- Biomass decrease after 275h
- No recovery of the growth after the batch

Same trend as for GM3 → testing the same assumption for tuning the model :
Bubble of 6mL contributing to the gas phase

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B4

ISS experiment vs Model



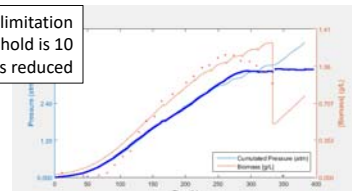
① Model perfectly fit experiment while there is no substrate limitation

② Limitation is not observed

- **Biological** : threshold for HCO_3^- limitation appears to be lower in microgravity

- **Physical** : P_{CO_2} of gas used for venting higher on ISS (~0.3% -0.4%) when it is 0.04% on Earth. Higher P_{CO_2} in liquid → passive diffusion of CO_2 in cells while active transport for HCO_3^- → bypass of the limitation for high pH value

Results if limitation threshold is 10 times reduced



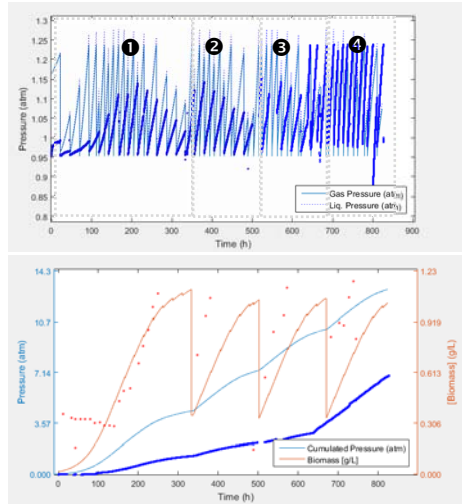
③ Biomass death (no activity + lysis)

At predicted pH = 11.38

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A1

ISS experiment vs Model



A1 : ISS exp. with 4 batches:

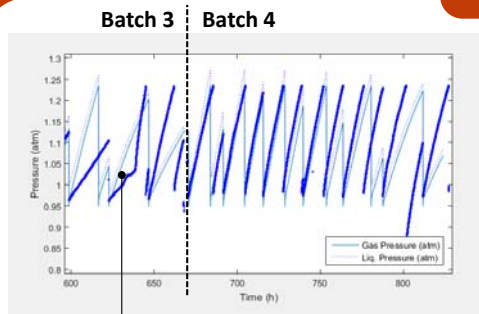
- Low gas production rate for batch 1, 2 and 3
→ Not fitted by model
- Recover a « normal » behavior for batch 4
→ fitted by model
- No biomass death :
! lower growth → lower pH

Mixing (stirrer) problem is suspected (same as GM3 batches 2 and 3) :

Cumulative pressure slope : | A1 batch1 : $\sim 700 \text{ Pa}\cdot\text{h}^{-1}$ A1 batch2 : $\sim 580 \text{ Pa}\cdot\text{h}^{-1}$
GM3 batch 2 ; batch3 : $460 \text{ Pa}\cdot\text{h}^{-1}$

A1

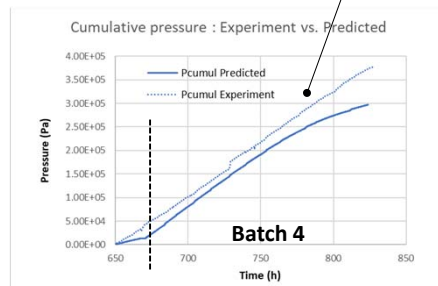
ISS experiment vs Model



Magnetic stirrer working again ?

Batch 4 : fitted by predictive model (without assumption of gas bubbles)

Same trend as GM4 for the end of the batch : limitation is not observed



Predictive Model :

Pressure increase measurement is an excellent method for on-line assessing of growth rates. It is **challenging in terms of modeling** both on ground and in space. Predictive **model fits experimental values on ground and on ISS**, even if the few available repetitions obtained in experiments limits the ability to verify the model

Two main experimental issues for model application :

- pH (predicted by model) and biomass death
- Mixing (stirrer failure), or presence of gas bubble

Ground vs. ISS :

- No differences in low pH (<10.5) conditions → low or limited effect of μ gravity
- When HCO_3^- limitation (low HCO_3^- concentration at high pH value) the behavior is different in ground and ISS condition.

Perspectives

Flow model :

Reactor operated without mixing (A1) → model for not perfectly mixed reactor

Growth model :

Need to be developed for high pH (>11) ,
.... or experiments must avoid high pH (reducing batch duration of at least 2 days)

Experiment :

Low HCO_3^- + high pH + high PCO_2 in ground condition must be tested to check if HCO_3^- growth limitation is reduced

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Thank you for your attention

Questions ?

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