Design and test of a mass exchanger for oxygen control in liquid lead bismuth eutectic

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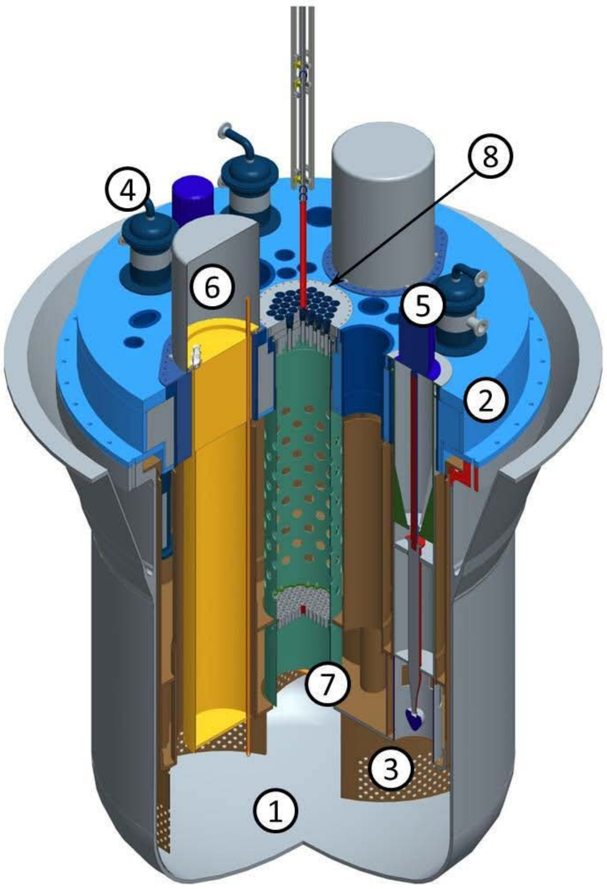
MYRRHA

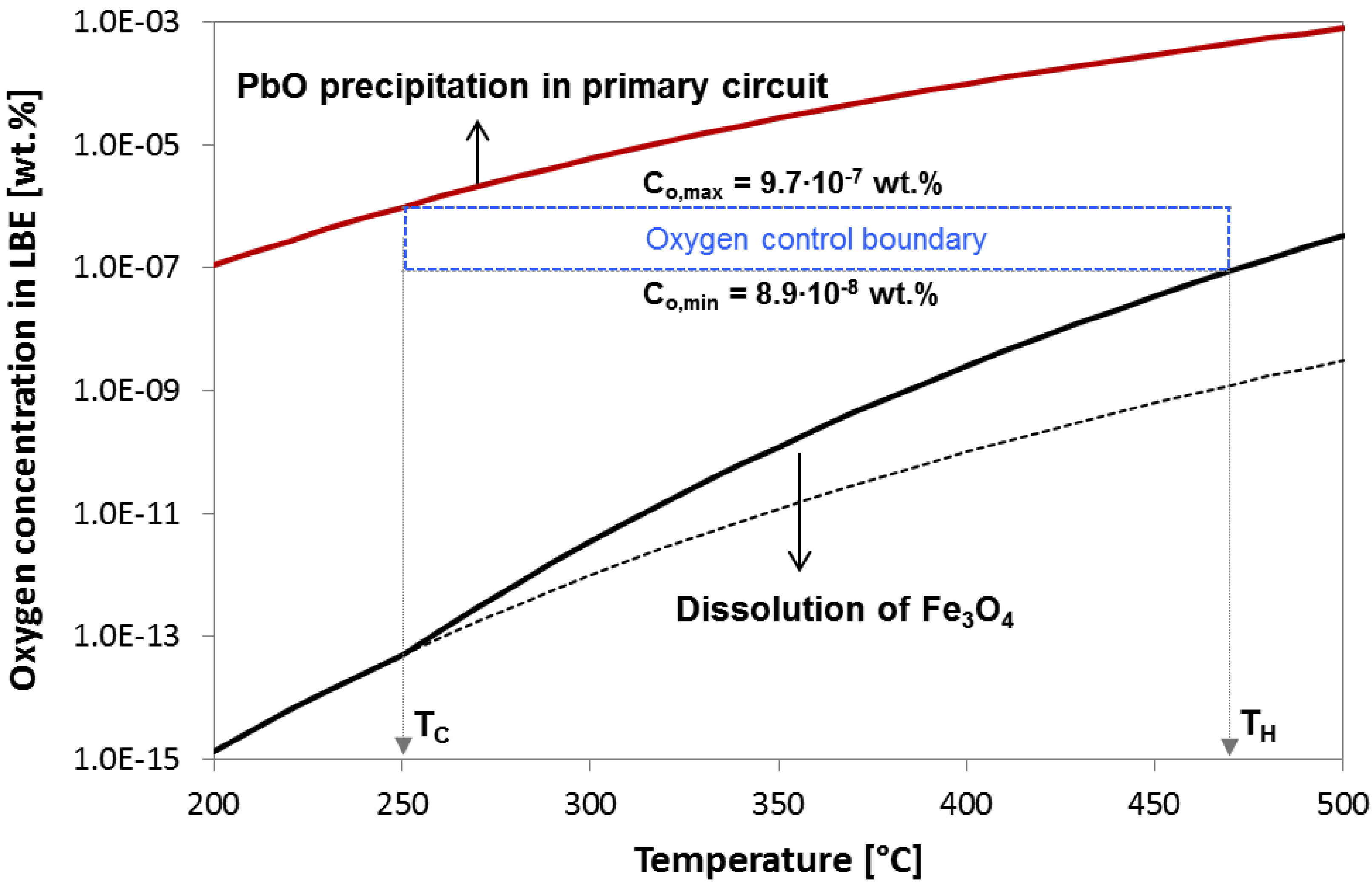
- **Lead-bismuth eutectic (LBE)** is the spallation target and primary coolant of MYRRHA:
- Opportunity
  - Excellent neutron yield
  - Low neutron reaction cross sections
  - Low melting point
  - High boiling point
  - Excellent thermal properties
- Challenge
  - Corrosive to steel
  - Liquid metal embrittlement



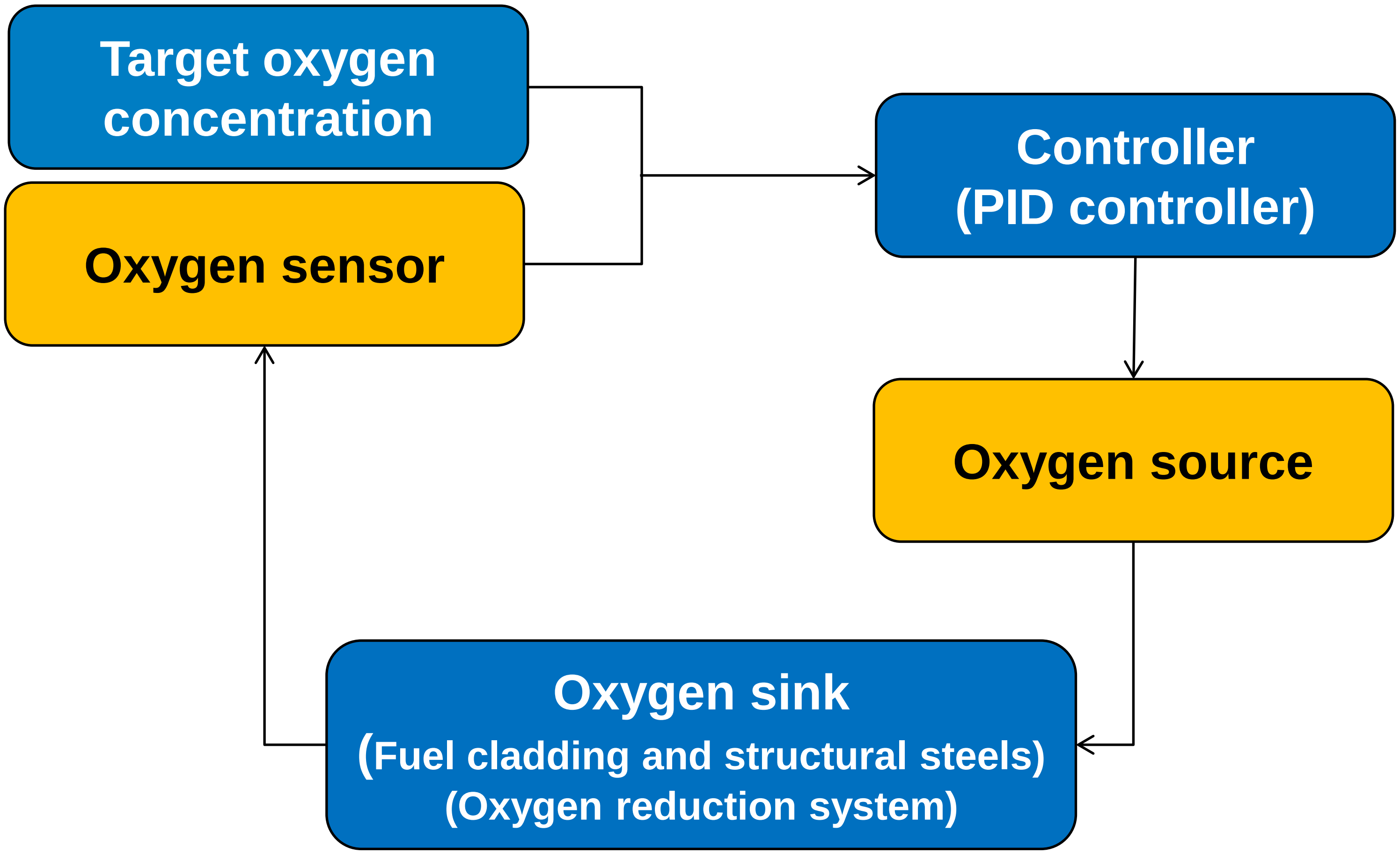
Issues and the importance of oxygen control in the use of LBE

- Material compatibility
  - Liquid metal corrosion
    - depends on material, temperature, flow rate, ***oxygen***, etc
  - Liquid metal embrittlement
    - depends on material, temperature, ***oxygen***, etc
- Risk of plugging
  - PbO formation
    - resulting from excessive ***oxygen***
  - Corrosion products
    - depends on materials, temperature, flow rate, ***oxygen***, etc

Oxygen control boundary

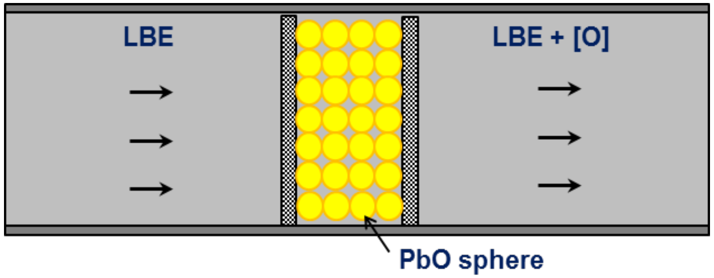


How to control dissolved oxygen in liquid LBE ?



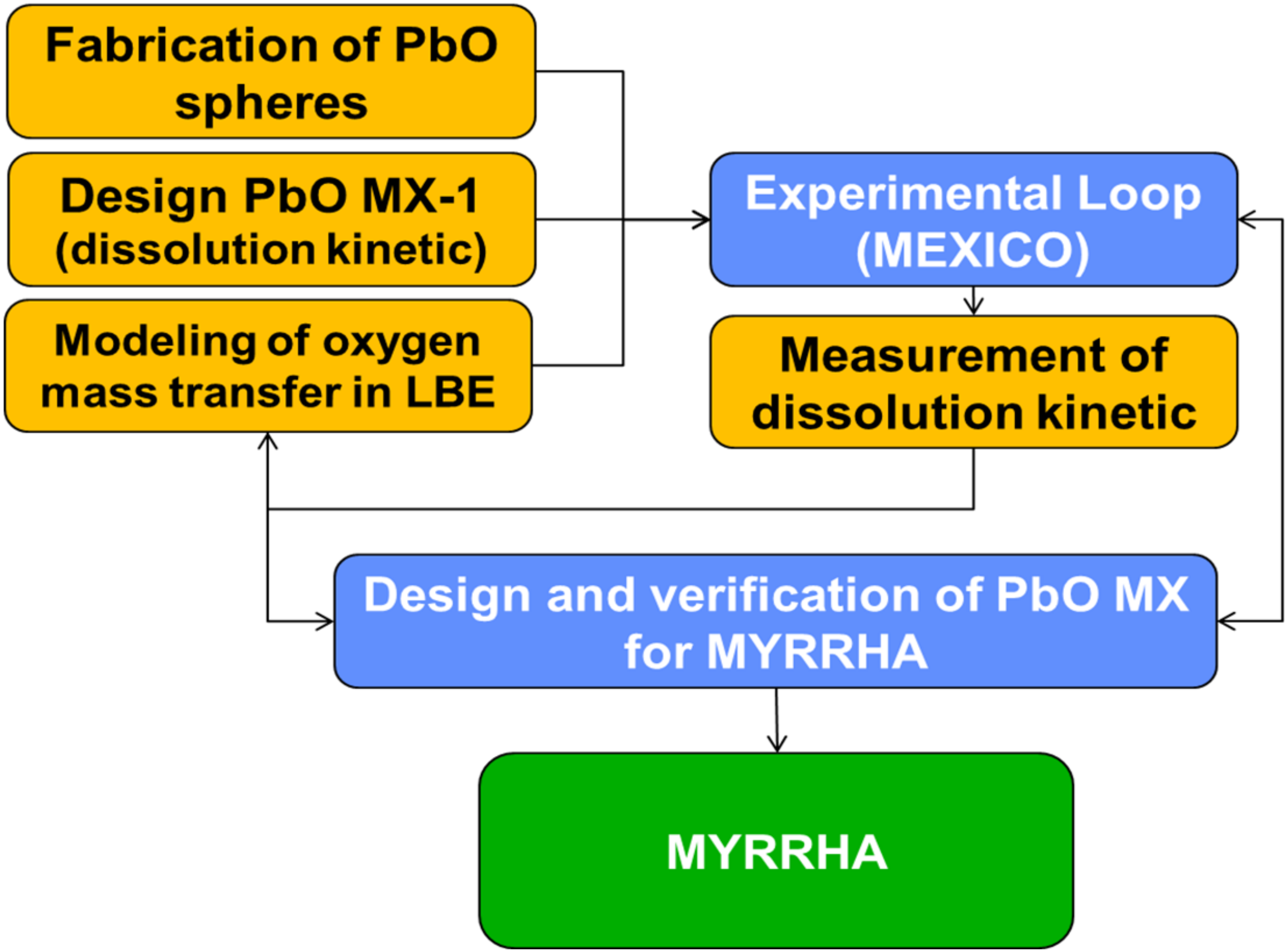
Oxygen control techniques

- Gas phase
  - Pulse injection of oxygen with continuous gas injection
  - Mixture gas *H_2 / H_2O mixture*
- Electrochemical method
- **Solid phase**
  - Control dissolution rate of solid oxide (PbO)
  - Solid PbO pebbles mass exchanger (PbO MX)

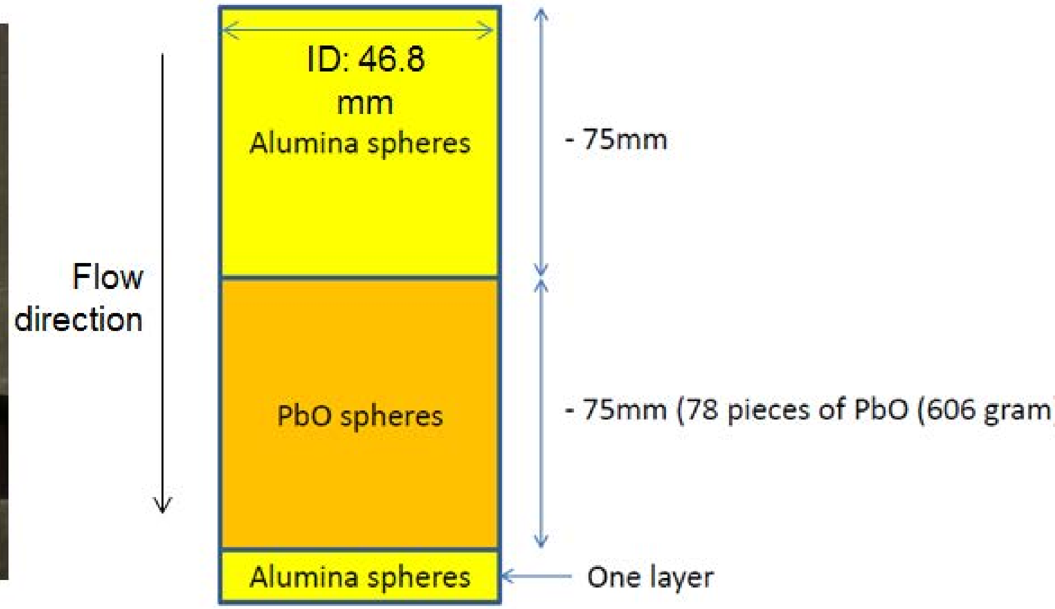


$$[PbO]_{surface} \rightarrow [Pb]_{LBE} + [O]_{LBE}$$

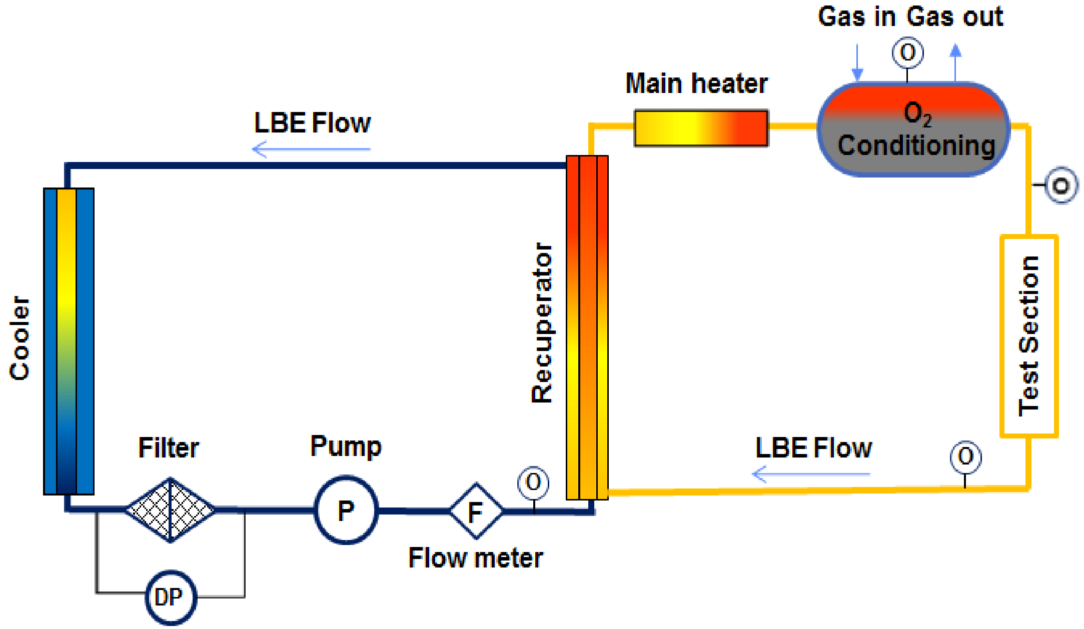
PbO MX design: overview



PbO MX for CRAFT loop



Experimental loop: CRAFT

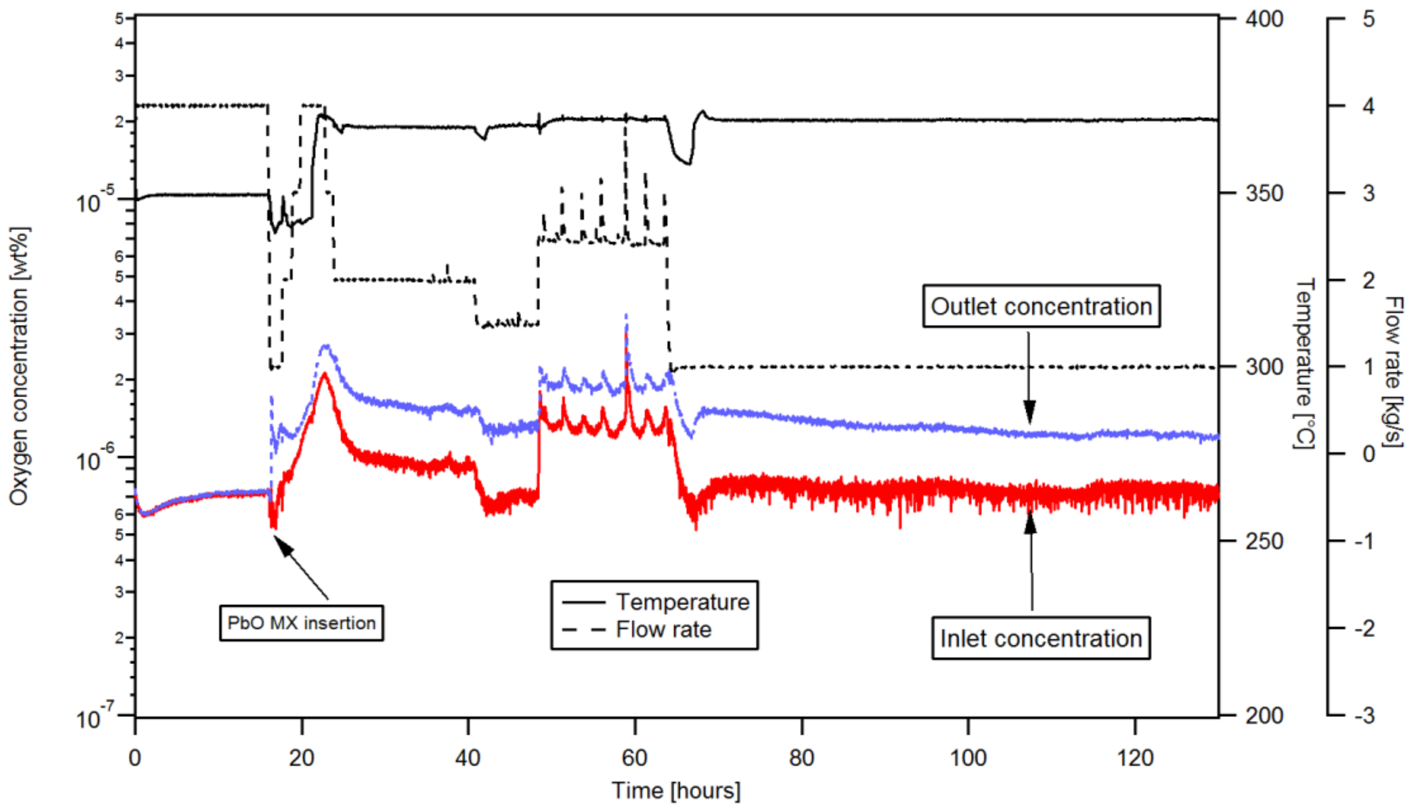


- Non-isothermal loop
- Oxygen conditioning system
- Wide range of operating conditions

CRAFT

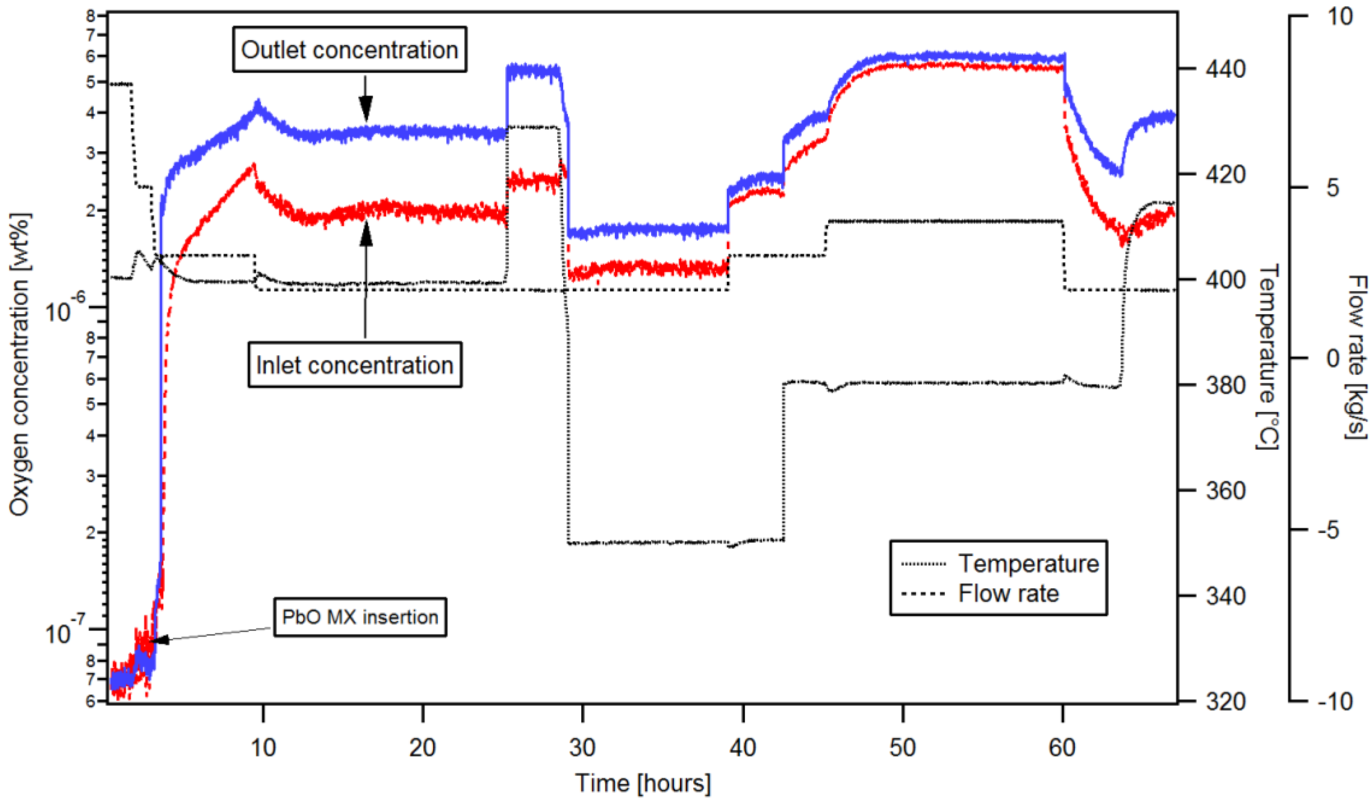
Corrosion in flowing LBE

Dissolution rate measurments



- Fixed temperature
- Flow rate variation

Dissolution rate measurments



- Temperature variation
- Flow rate variation

Method

- Calculation of the **dissolution rate** of PbO packed bed of spheres from oxygen concentration measurments in CRAFT :

$$\dot{q} = \dot{m} \cdot (c_{out} - c_{in}) \qquad [g/h] \qquad (1)$$

- Calculation of **mass transfer coefficient for** each condition (temperature and velocity) :

$$\dot{q} = KA \cdot (c_s - c) \qquad [g/h] \qquad (2)$$

o c_{out} =average outlet oxygen concentration, c_{in} =average inlet oxygen concentration, k =average mass transfer coefficient [g/cm^{2}h], c =average oxygen concentration , A= surface area of PbO [cm^2].

Method

- Calculation of the **Sherwood number** from mass transfer coefficient :

$$Sh = K \cdot \frac{l}{D \cdot 360} \qquad [-] \qquad (3)$$

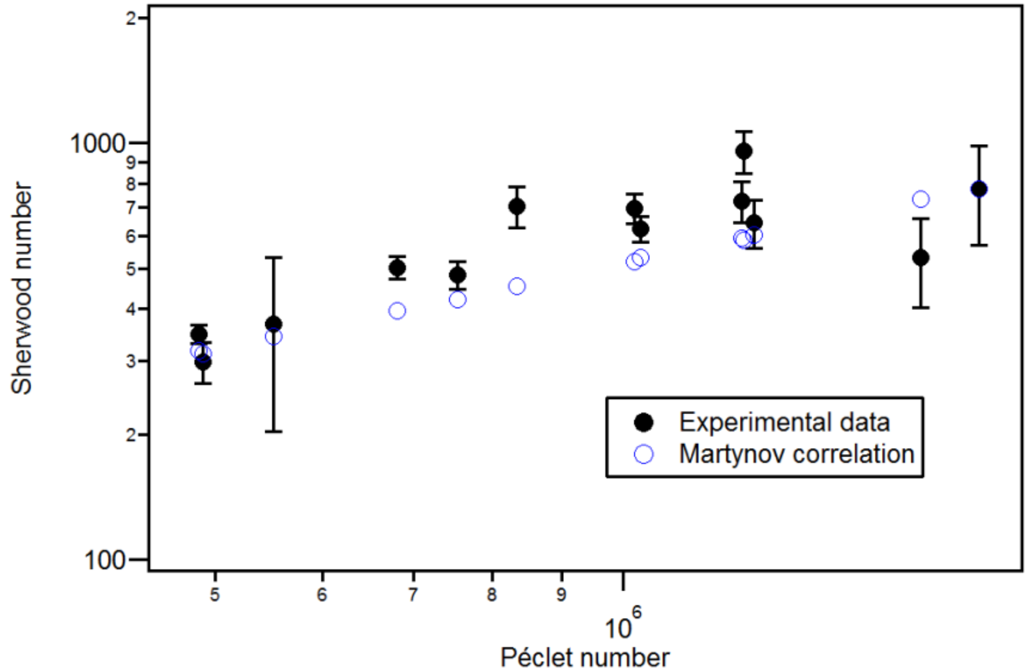
- Correlation of **Sherwood number** based on all measured data (temperature and velocity) :

$$Sh = A \cdot Re^{n} Sc^{m} \qquad (4)$$

$$Sc = \frac{v}{D}, \quad \mathrm{Re} = \frac{w \cdot l}{v} \quad l = \frac{2}{3}\frac{\varepsilon \cdot d}{1-\varepsilon}$$

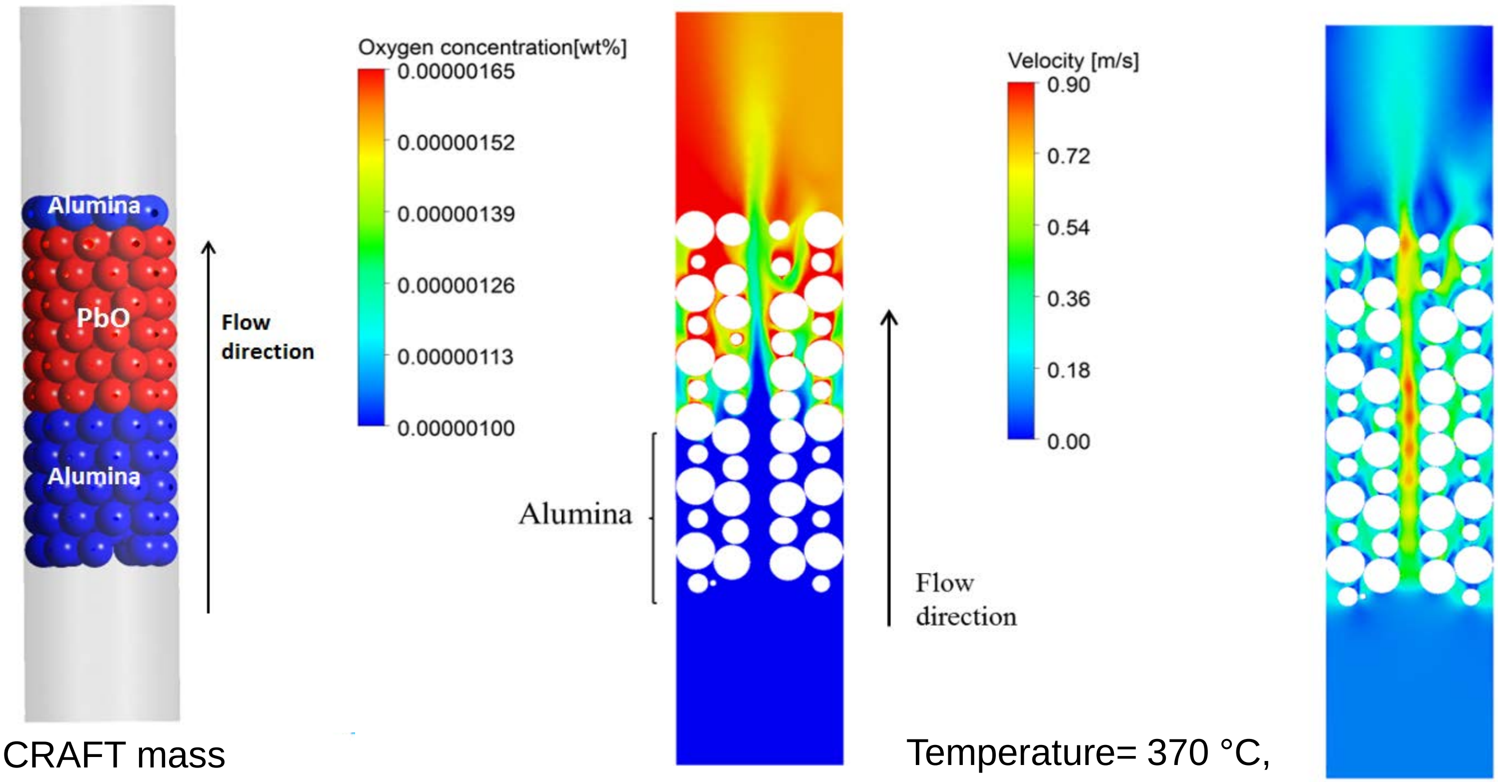
- Sh= Sherwood number, D=oxygen diffusion coefficient [m^2/s], l=characteristic lenght [m^2], v= kinematic viscosity [m^2/s], w = velocity [m/s], ε =porosity

Experimental results



- Good agreement with Russian data
- Flat maximum at high velocity

Modeling: full scale simulation

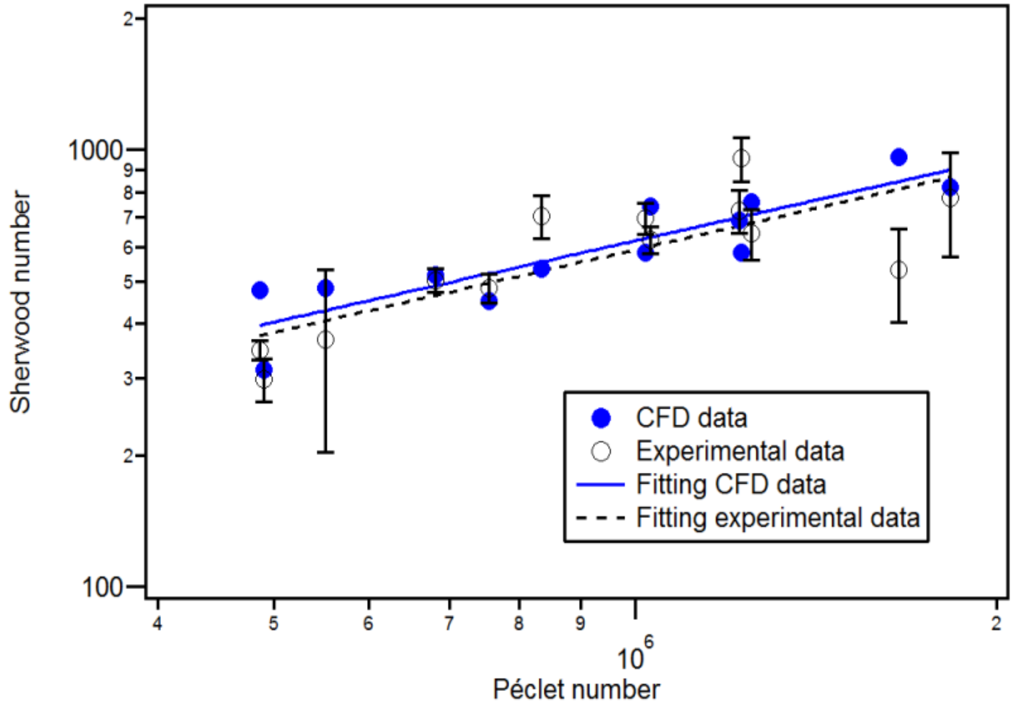


CRAFT mass exchanger

Temperature= 370 °C, Flow rate =2 kg/s

- A. Marino, J. Lim, S. Keijers, J. Van den Bosch, J. Deconinck, "**Numerical modeling** of oxygen mass transfer from PbO spheres packed bed to liquid lead bismuth eutectic: A venturi-type PbO mass exchanger", Nuclear Engineering and Design, 265 (2013), 576–581
- A. Marino, J. Lim, S. Keijers, J. Van den Bosch, J. Deconinck, F. Rubio, K. Woloshun, M. Caro, S. A. Maloy, "Temperature dependence of **dissolution rate of a lead oxide** mass exchanger in lead-bismuth eutectic", Journal of Nuclear Materials, 450, (2014) 270-277
- A. Marino, J. Lim, S. Keijers, S. Vanmaercke, A. Aerts, K. Rosseel, J. Deconinck, J. Van den Bosch, "**A mass transfer correlation for packed bed of lead oxide spheres** in flowing lead-bismuth eutectic", International journal of heat and mass transfer, 80 (2015) 737-747

Modeling validation

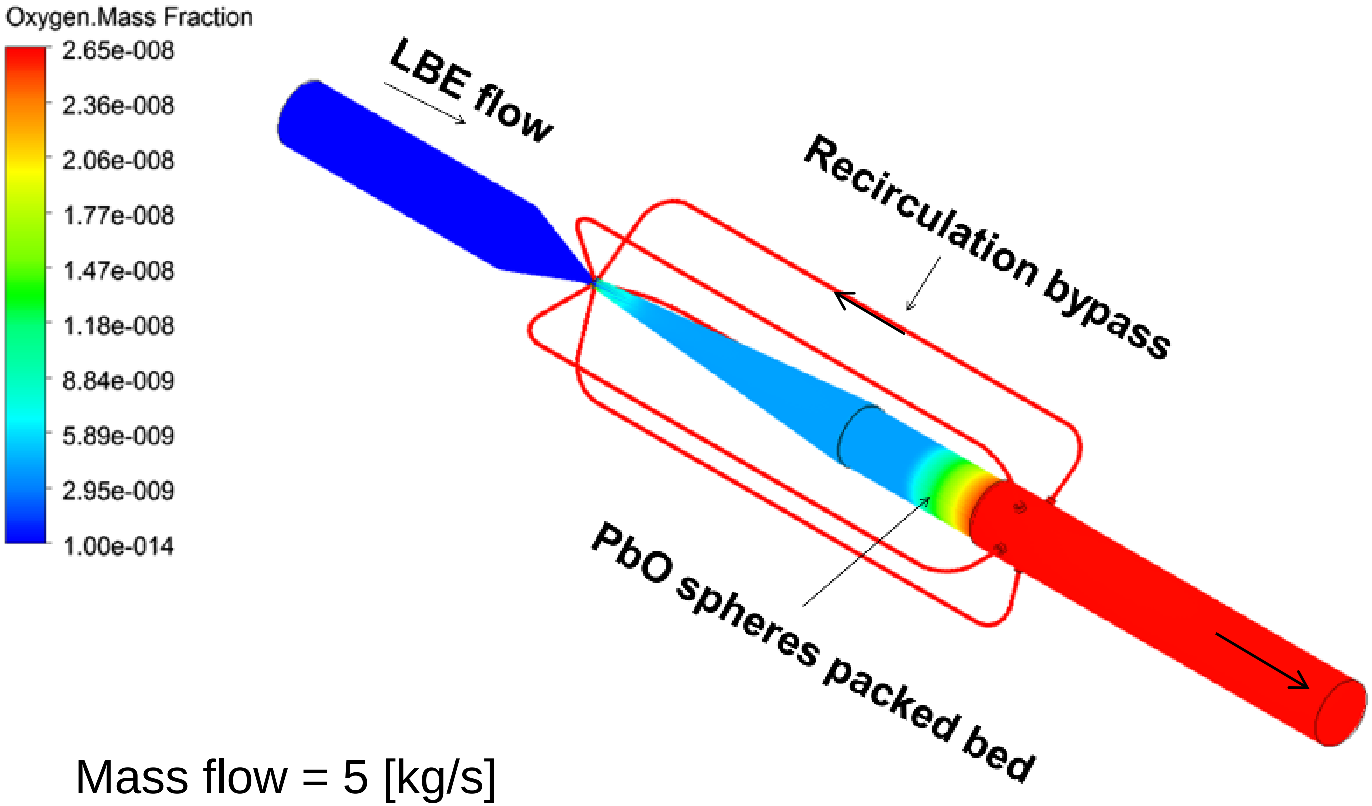


$$Sh = 0.07 \cdot \mathrm{Re}^{0.87}\, Sc^{0.32}$$

Preliminary correlation

$$2000 < \mathrm{Re} < 9000,\ 30 < \mathrm{Sc} < 600$$

Venturi-type mass exchanger



Mass flow = 5 [kg/s]

Venturi-type mass exchanger

Venturi (top view)

- **Tungsten carbide (Hardide T) coating** on the inner surface of venturi neck to prevent erosion
- Pipe ID = 78 mm
- Venturi neck D = 12 mm

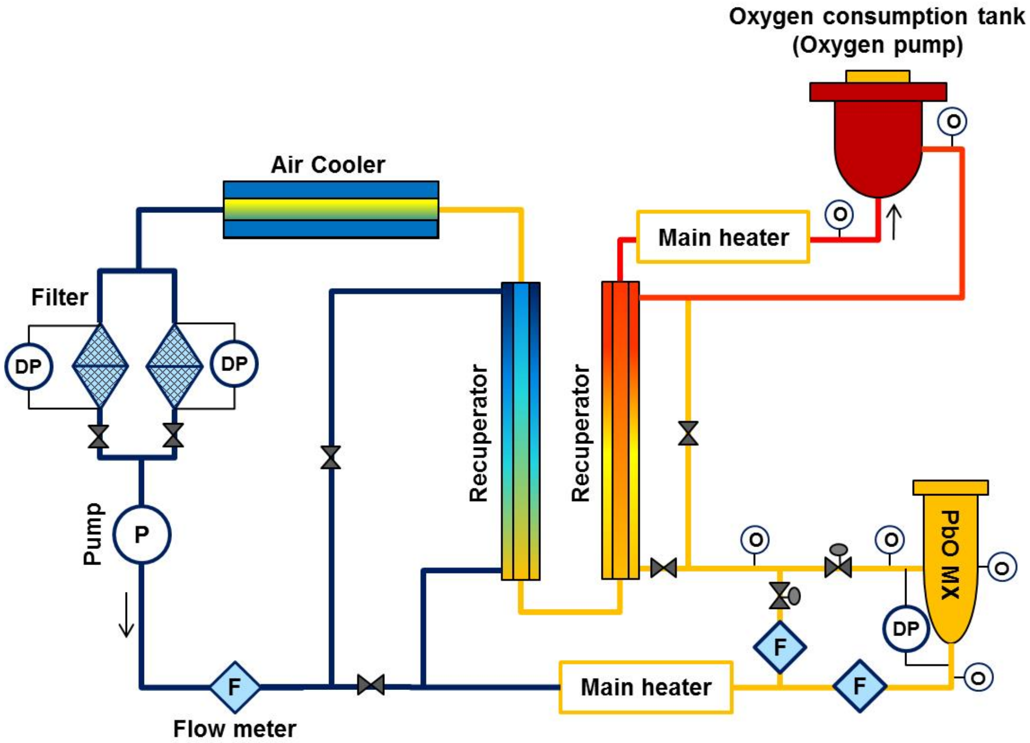
PbO basket (top view)

PbO sphere

: 12 mm diameter

: 92.4% of theoretical density

Experimental loop: MEXICO



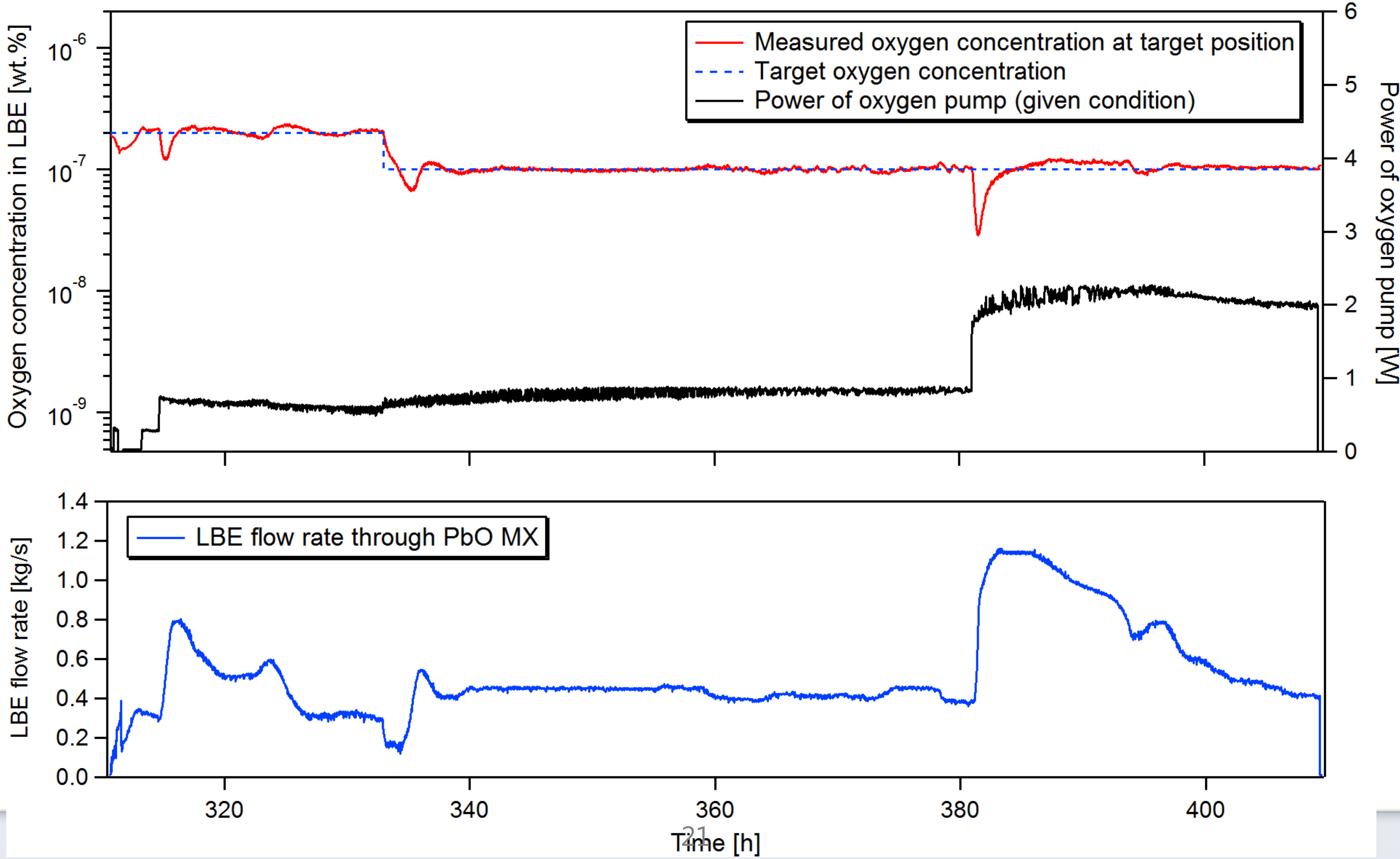
- Non-isothermal loop
- Oxygen conditioning system
- Wide range of operating conditions

MEXICO

Integrated LBE chemistry

MEXICO

Results : Oxygen control by PbO MX



Conclusion

Experiments on PbO MX dissolution have been successfully carried out at the CRAFT loop, SCK•CEN, Belgium:

- PbO spheres showed good mechanical and heat resistance
- Nearly-linear relation between velocity and dissolution rate: mass transfer limited kinetics
- No evidence of PbO poisoning
- Highly accurate oxygen control achieved by oxygen control systems during first experimental campaign.

Thank you for your attention!

Results : PbO spheres after test

PbO particles might be cracked in the area of equator.