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AN EXPERIMENTAL STUDY OF THE GRAVITY-DRIVEN FLASHING OF METASTABLE WATER IN A POOL HEATED FROM BELOW

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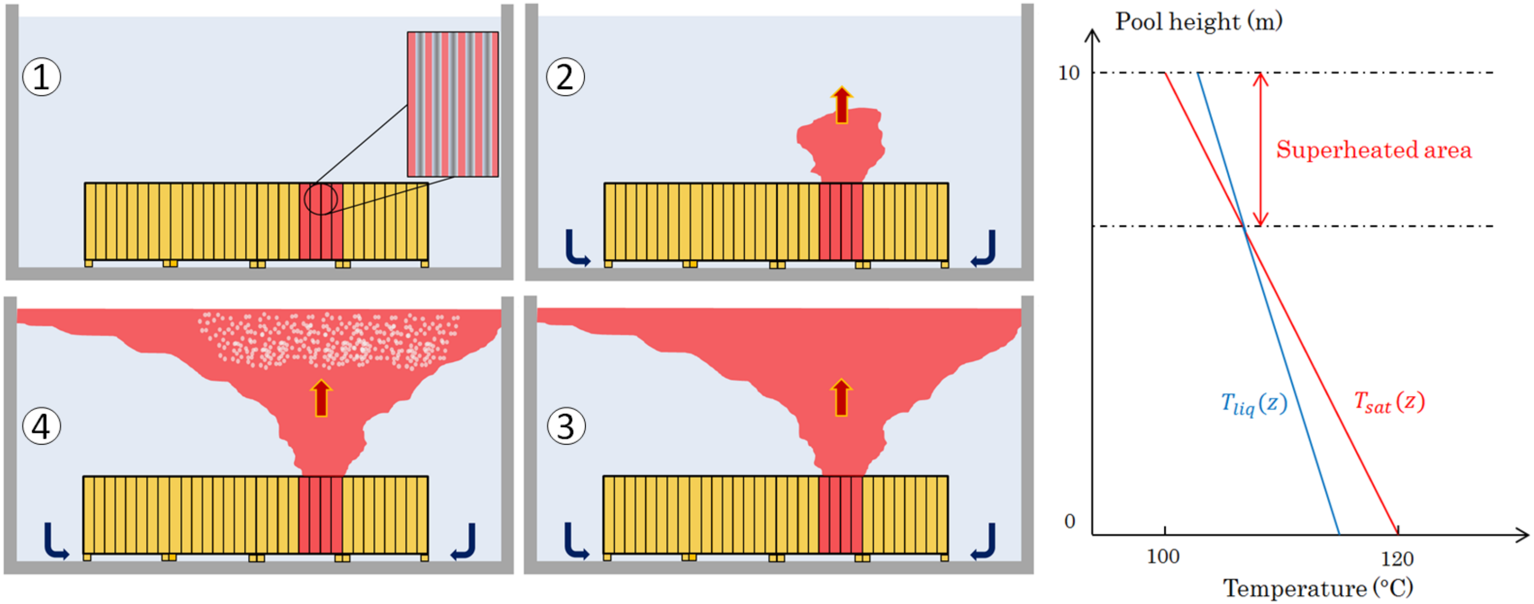
MEMBRE DE ETSON

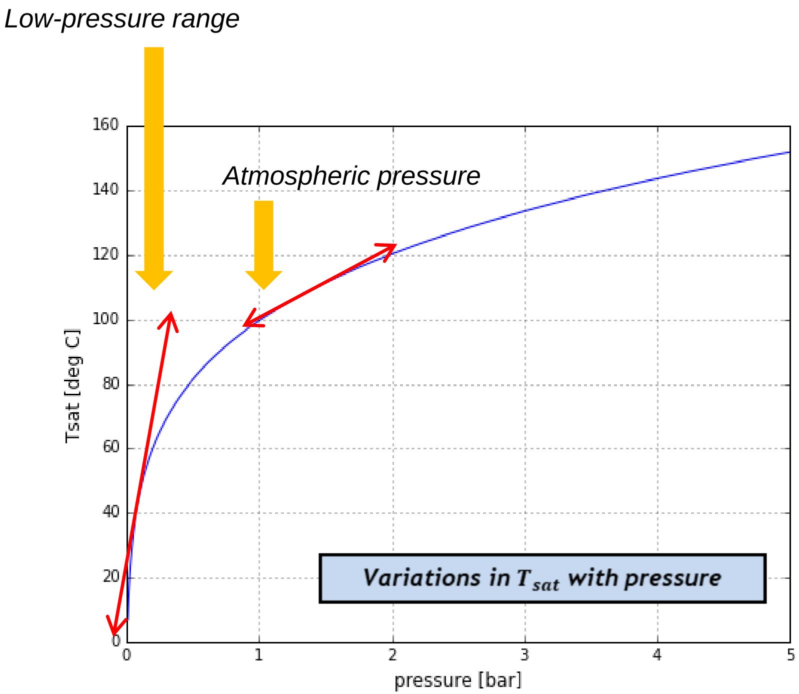
A phenomenon in link with the loss-of-cooling accident of a nuclear spent fuel pool



The gravity-driven flashing of superheated water: a non-equilibrium phase change process which has not been studied yet in the specific configuration of a pool heated from below

The phenomenon may contribute to the unwanted early release of radioactive elements from the contaminated water during the accident

A proposed downscaling methodology: a distortion in system's pressure



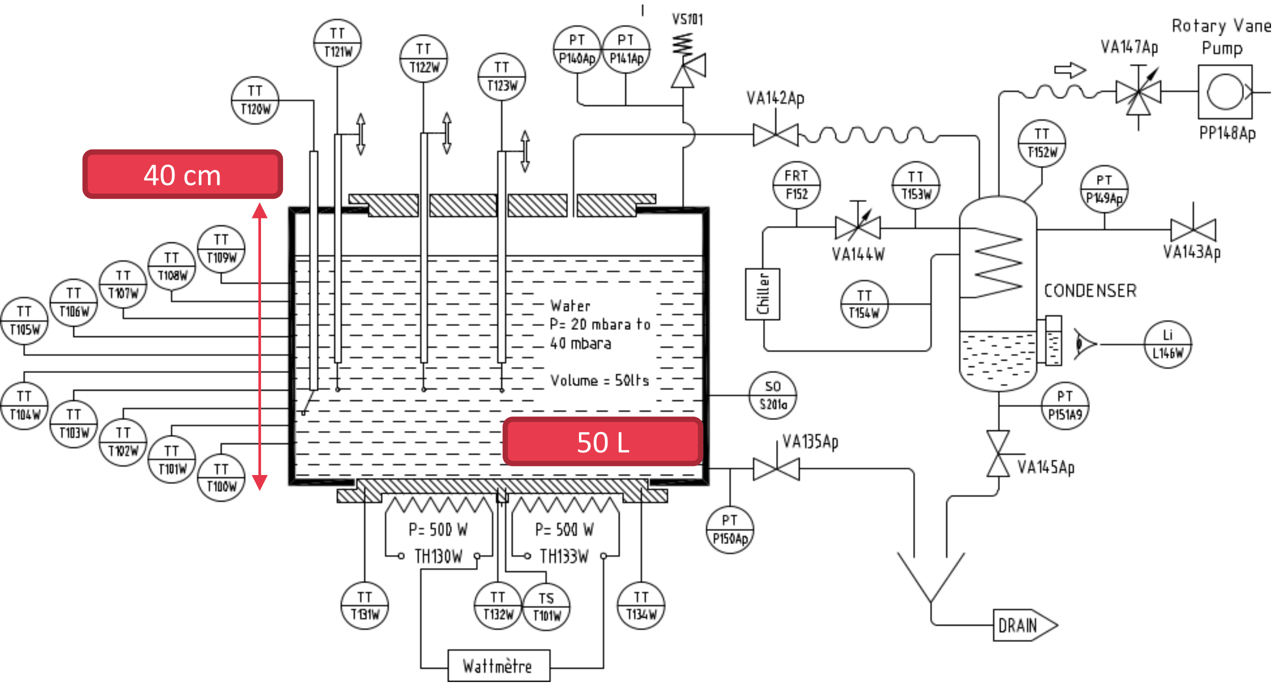
$$[\Delta T_{sat}(z)]_{1:1} = [\Delta T_{sat}(z)]_{mockup}$$

$$\leftrightarrow \left[\frac{\partial T_{sat}}{\partial P}\,\rho\, g\, \mathrm{H}\right]_{1:1} = \left[\frac{\partial T_{sat}}{\partial P}\,\rho\, g\, \mathrm{H}\right]_{mockup}$$

$$\boxed{\leftrightarrow \frac{H_{1:1}}{H_{mockup}} \approx \frac{\left[\frac{\partial T_{sat}}{\partial P}\right]_{mockup}}{\left[\frac{\partial T_{sat}}{\partial P}\right]_{1:1}}}$$

A **reproduction of the gravity-driven flashing** is **theoretically possible at a reduced scale by distorting the system's pressure** (1 bar → 10-100 mbar)

The experimental device: AQUARIUS

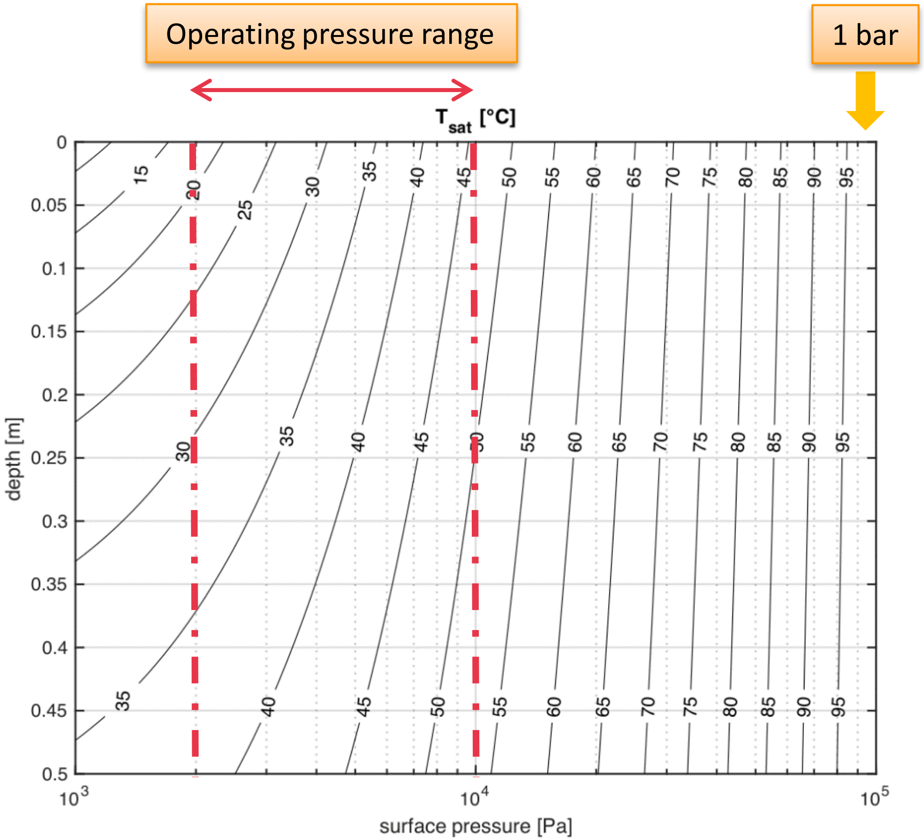


Control parameters
- System pressure
- Initial liquid temperature
- Initial content in dissolved gases
- Heating power
- Spatial distribution of the heat source (homogeneous vs. hot spot)

Performed measurements
- Flow visualization
- Gas / liquid temperatures
- Immersed walls temperatures
- Gas / liquid pressures
- **Dissolved O_2 concentration**

A **small scale pool aiming at reproducing and characterizing the phase change and the degassing processes**

The experimental device: AQUARIUS



A **small scale pool aiming at reproducing and characterizing the phase change and the degassing processes**

The test procedure

- Filling stage: the pool is filled up or partially drained depending on the required initial water level
- Bubbling stage: the liquid pool is bubbled by means of a compressed air system in order to reach a targeted dissolved O2 initial concentration
- Chiller and heaters startup
- Depressurization: once the desired initial pool temperature is reached, the depressurization is initiated by starting up the vacuum pump; the latter is then kept operated throughout the test for compensating the water degassing; pressure regulation ensured by the chiller

→ Startup of a pool flashing test

Targeted physical parameters

$$\Delta T_{eq} = T_l - T_{sat}(P_g)$$

Liquid superheating
(or thermal metastability degree)

$$m_l = 1.39\, \Delta P_{z;pool} + 0.60$$

$$\dot{m}_l \approx \frac{m_l(t+\Delta t) - m_l(t)}{\Delta t}$$

Liquid mass and vaporization rate

$$\Delta C_{O_2-eq} = C_{O_2} - C_{O_2-eq}$$

$$\dot{C}_{O_2} \approx \frac{C_{O_2}(t+\Delta t) - C_{O_2}(t)}{\Delta t}$$

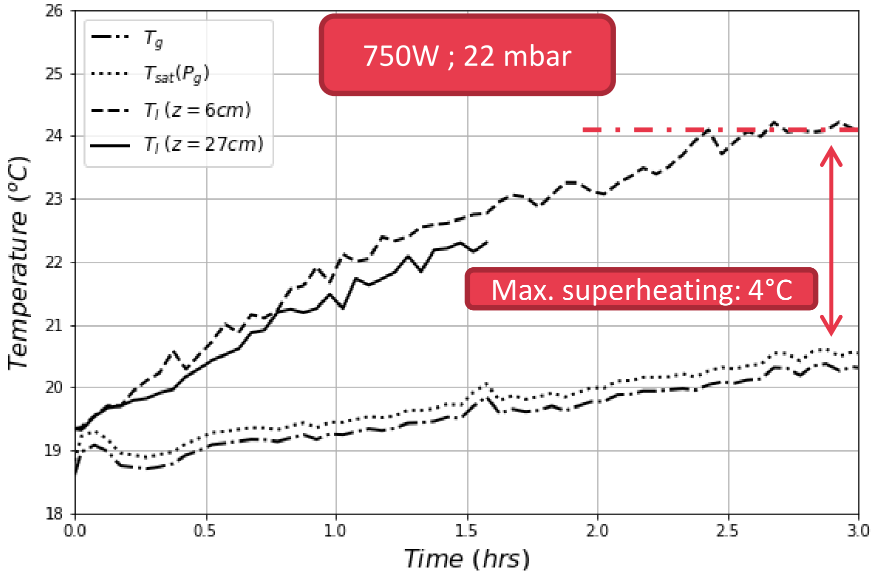
Chemical metastability degree and degassing rate

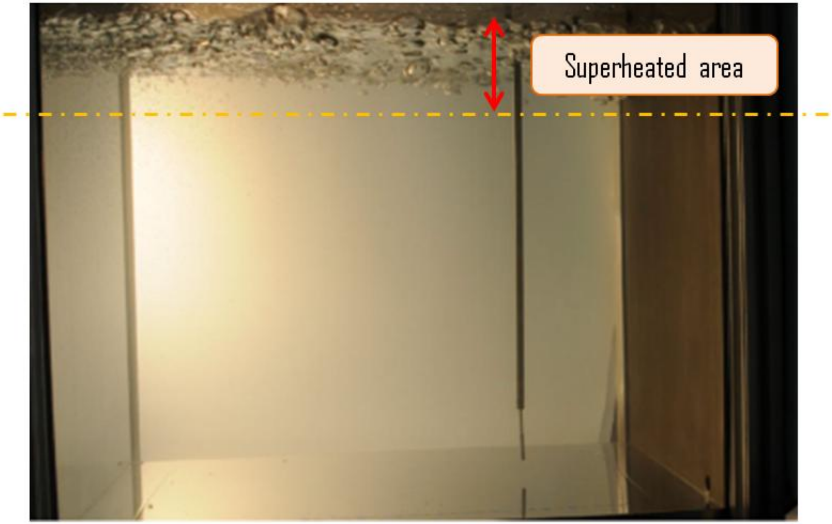
A first observation of the phenomenon at 22 mbar – 750 W

- Observation of a **gravity-driven liquid superheating** which increases over time, up to an asymptotic value
  - **The proposed methodology allows reproducing the phenomenon at the mock-up scale**

- **A flashing of the liquid within its metastability area** (located below its free surface)

Cf. video #1

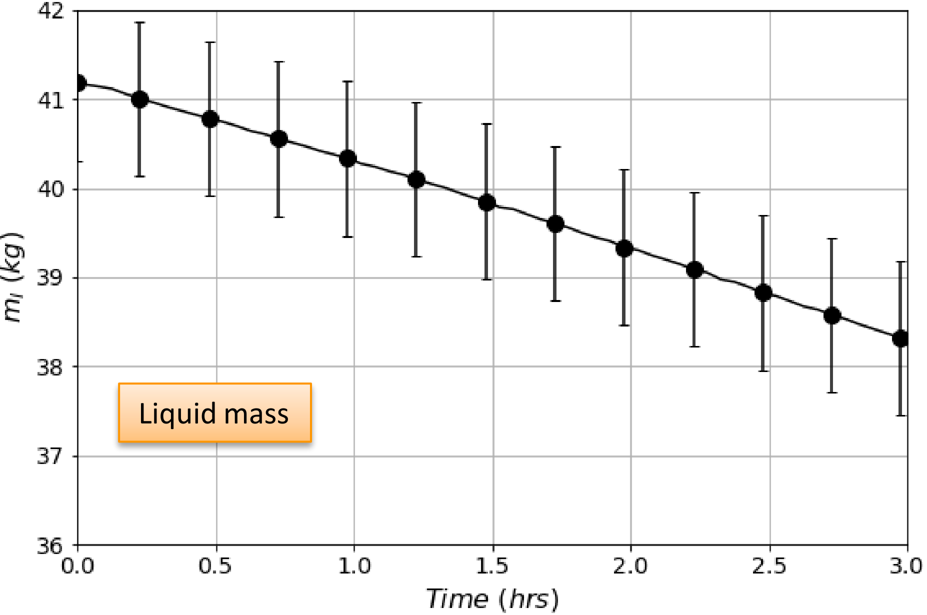


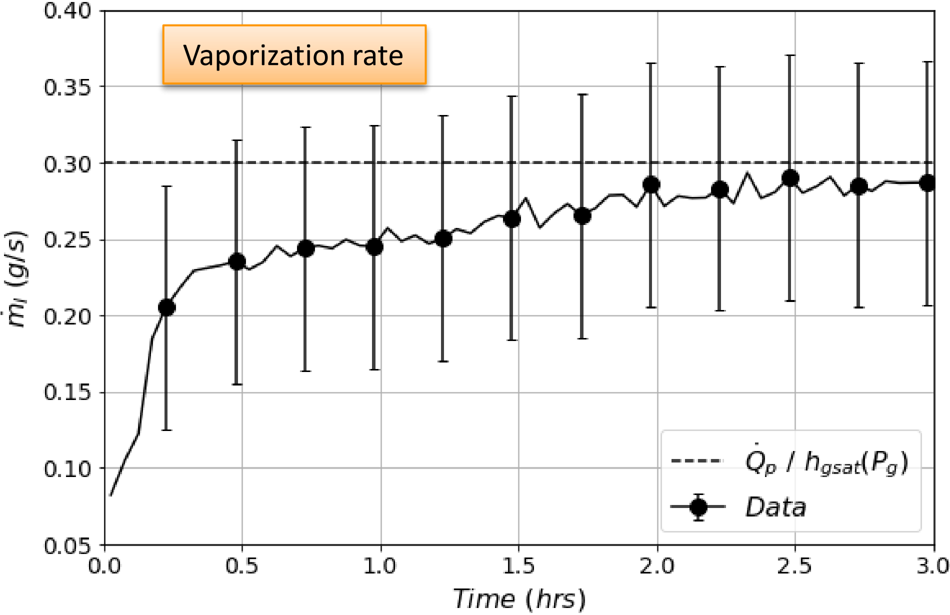


Estimated liquid mass and vaporization rate

A gradual vaporization of the liquid pool which ultimately equilibrates the heating power

750W ; 22 mbar





Note: the imposed low pressure operating conditions allow minimizing the heat losses at system's boundaries

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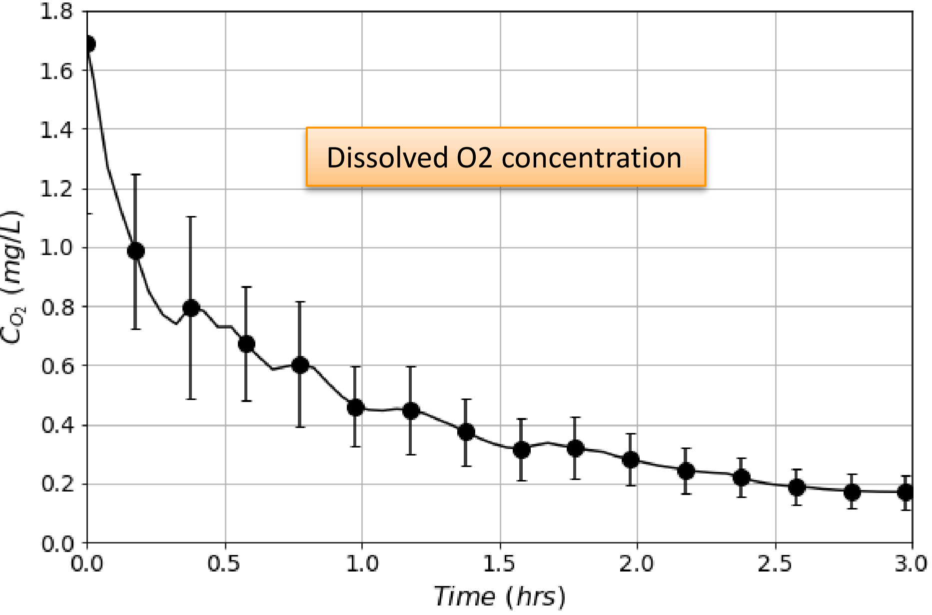
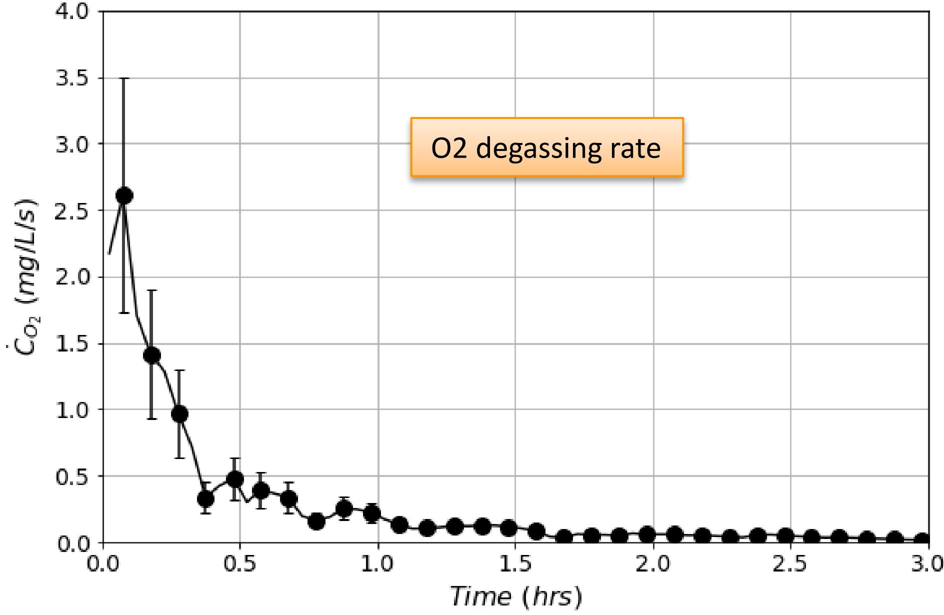
Measured dissolved O2 concentration and O2 degassing rate

- **A gradual degassing of the liquid pool**, evidenced by the dissolved O_2 measurements
- **The degassing flux is maximum at the beginning of the test**

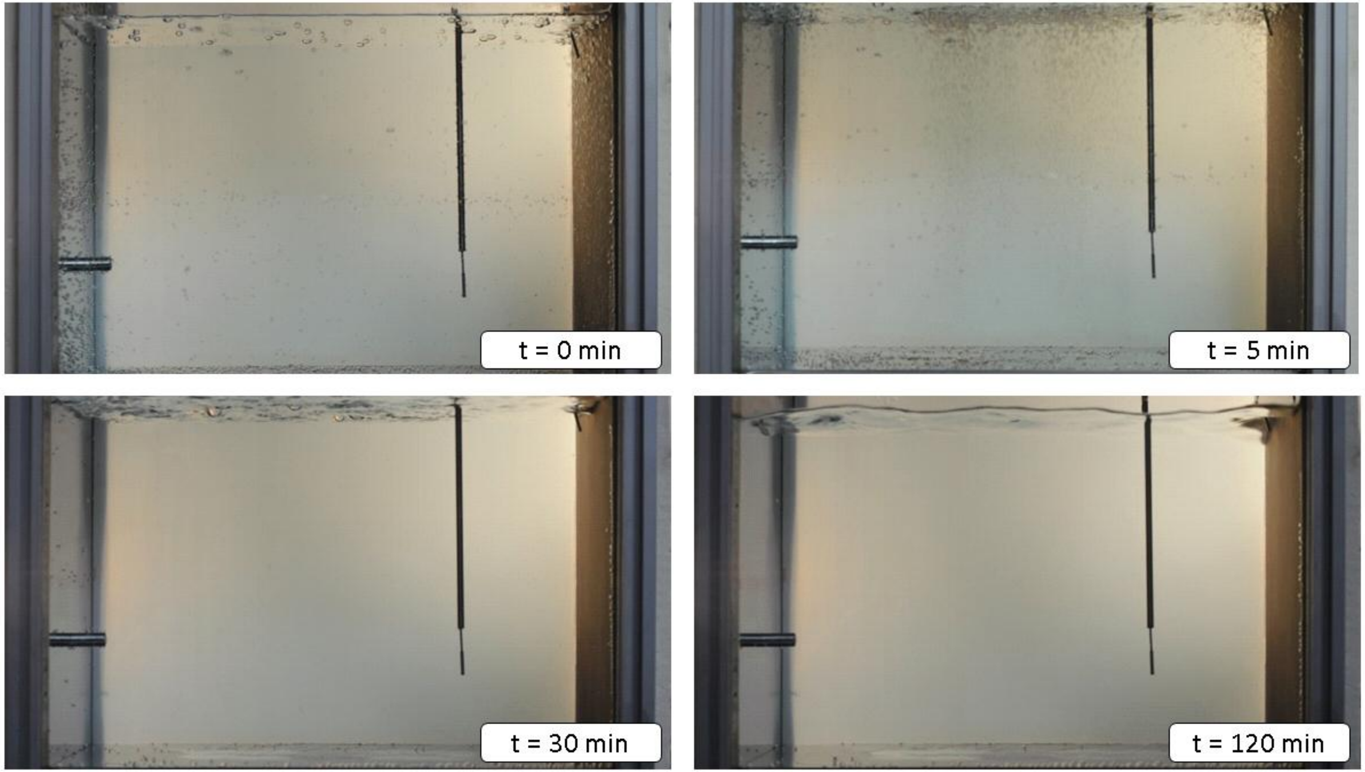
750W ; 22 mbar



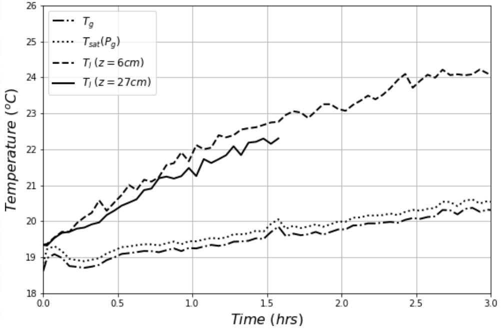


A first observation of the phenomenon at 22 mbar – 750 W

A temporary flashing of the superheated water…



- A paradox at first glance
  - **The liquid flashing, materialized by bubbles, is only observed at the beginning of the test, i.e. at small superheats**



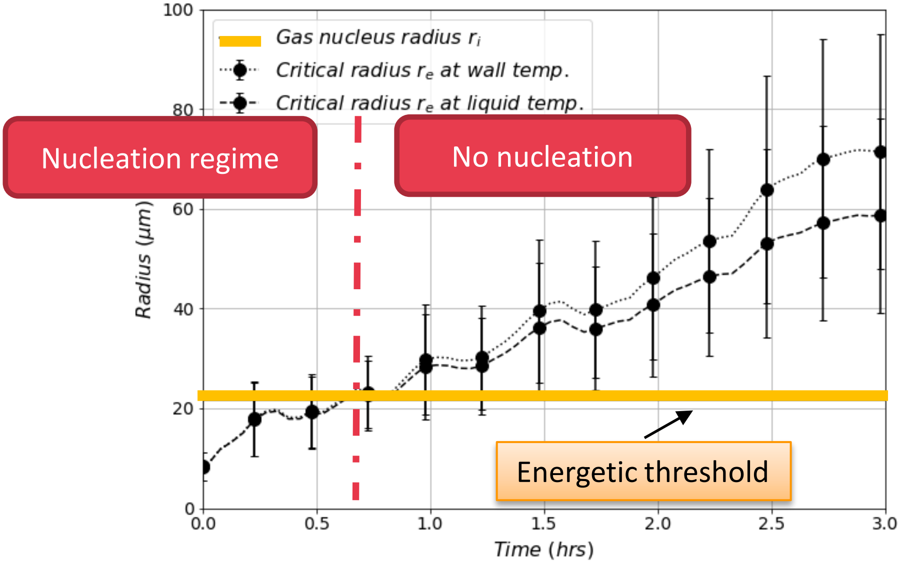
A first observation of the phenomenon at 22 mbar – 750 W

The end of the story: high superheats, rare but violent bubble nucleation events, water vaporization mainly supported by free surface evaporation

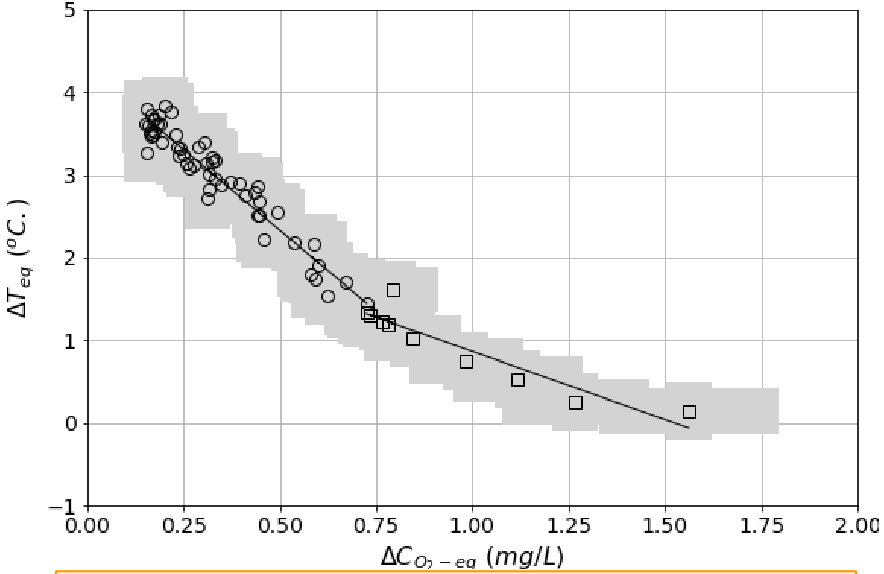
Cf. video #2

A first observation of the phenomenon at 22 mbar – 750 W

- **Strong influence of the water content in dissolved gases on the liquid superheating levels**
  - **A large inventory in dissolved gases promotes nucleation, which in turn limits the liquid superheats**
  - The nucleation vanishes when the energetic conditions for bubble production are no longer met: then the liquid continues to heat up till its free surface evaporation balances the heat power



Study of the energetic conditions for bubble nucleation



Correlation between the liquid superheating and dissolved oxygen supersaturation

Toward a dimensionless characterization of the system's behavior

The followed methodology

- Variations in heating power, system's pressure, and initial pool level, at a fixed initial content in dissolved gases, according to a regular test matrix (24 tests)
- Some complementary tests started with different initial contents in dissolved gases (9 tests)

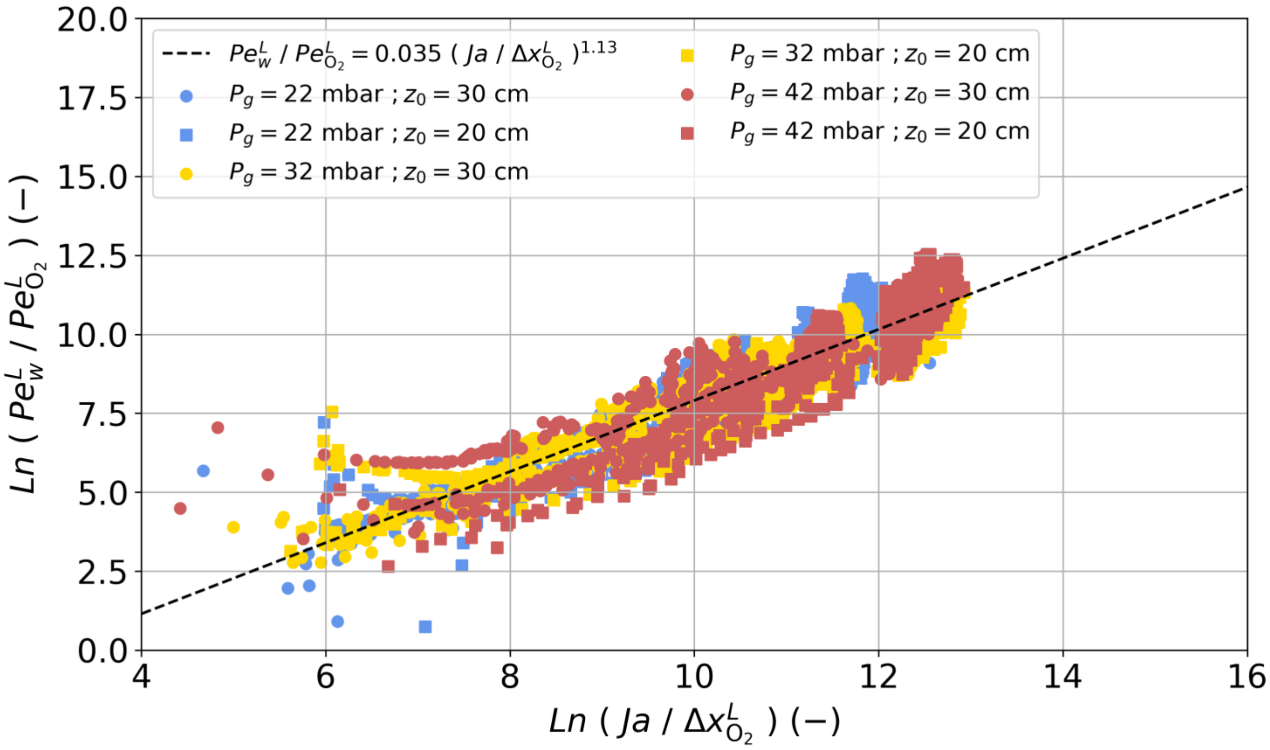
The regular test matrix

Test ref.	$C_{O_2}(0)$ (mg/L)	$\dot{Q}_p$ (W)	P_g (mbar)	$z_p(0)$ (cm)
# 1	6.5	1000	22	30
# 2	6.5	1000	32	30
# 3	6.5	1000	42	30
# 4	6.5	1000	22	20
# 5	6.5	1000	32	20
# 6	6.5	1000	42	20
# 7	6.5	750	22	30
# 8	6.5	750	32	30
# 9	6.5	750	42	30
# 10	6.5	750	22	20
# 11	6.5	750	32	20
# 12	6.5	750	42	20
# 13	6.5	500	22	30
# 14	6.5	500	32	30
# 15	6.5	500	42	30
# 16	6.5	500	22	20
# 17	6.5	500	32	20
# 18	6.5	500	42	20
# 19	6.5	250	22	30
# 20	6.5	250	32	30
# 21	6.5	250	42	30
# 22	6.5	250	22	20
# 23	6.5	250	32	20
# 24	6.5	250	42	20

- **Four power levels**: 1000, 750, 500 and 250 W
- **Three operating pressures**: 22, 32 and 42 mbar
- **Two initial pool levels**: 20 and 30 cm
- **A fixed initial content in dissolved O_2**: 6.5 mg/L

Toward a dimensionless characterization of the system’s behavior

- The **degassing / flashing stage characterization**: a single correlation describes the coupling between both phenomena



Toward a dimensionless characterization of the system's behavior

- The **degassing / flashing stage characterization**: a single correlation describes the coupling between both phenomena

The correlation obtained over the 24 tests of the regular experimental matrix:

$$\frac{Pe_w^L}{Pe_{O_2}^L} = 0.035 \left(\frac{Ja}{\Delta x_{O_2}^L} \right)^{1.13}$$

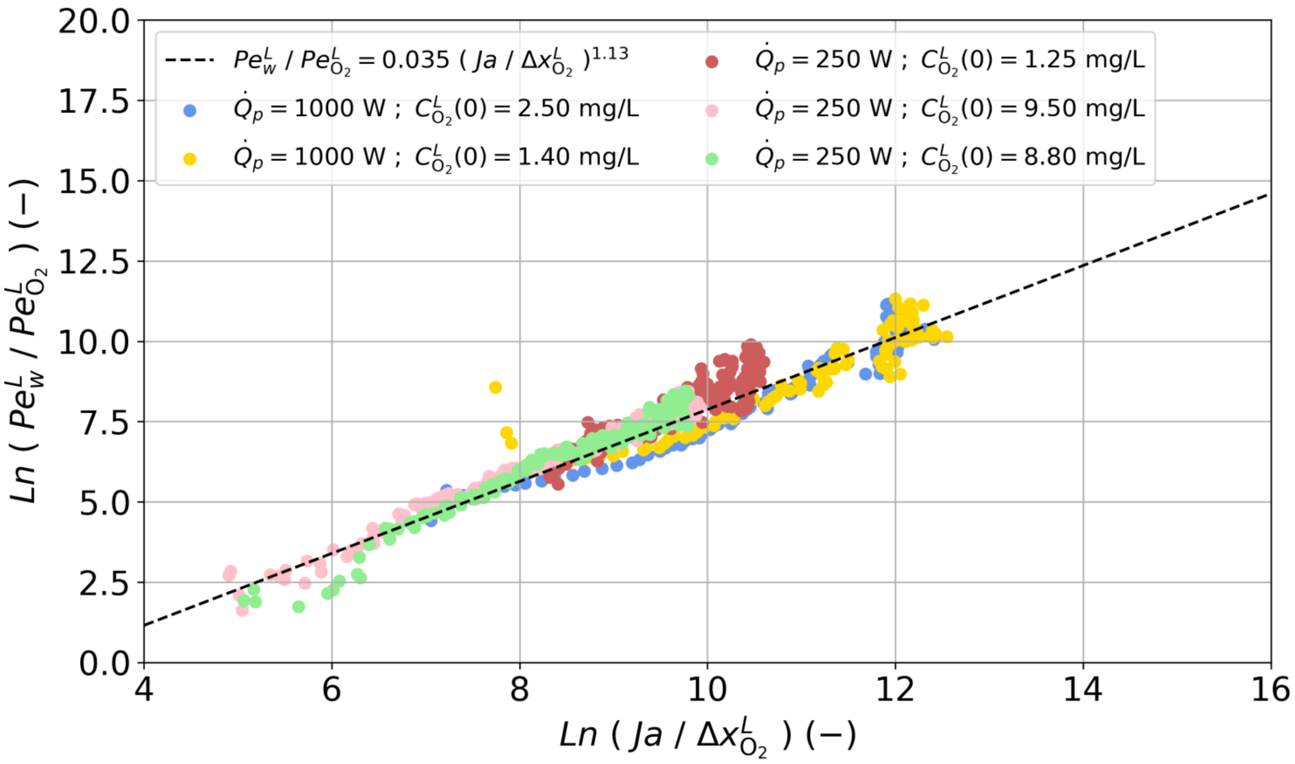
with:

- $Ja = \dfrac{C_p^L \Delta T_{eq}}{\mathcal{L}_w}$; Jakob number
- $\Delta x_{O_2}^L \approx \dfrac{C_{\mathrm{O}_2}^L}{\rho_L}$; Dimensionless driving force of dissolved O_2 degassing
- $Pe_w^L = \dfrac{j_w L}{C_L \kappa_L}$; Water vaporization Péclet number
- $Pe_{O_2}^L = \dfrac{j_{\mathrm{O}_2} L}{C_L \mathcal{D}_{\mathrm{O}_2 - w}^L}$; Dissolved O_2 degassing Péclet number

and L, the flashing/degassing characteristic length appearing in the above Péclet numbers, taken equal to the diagonal of the free surface (**Note:** the defined correlation breaks down when taking L equal to the time-dependent pool level)

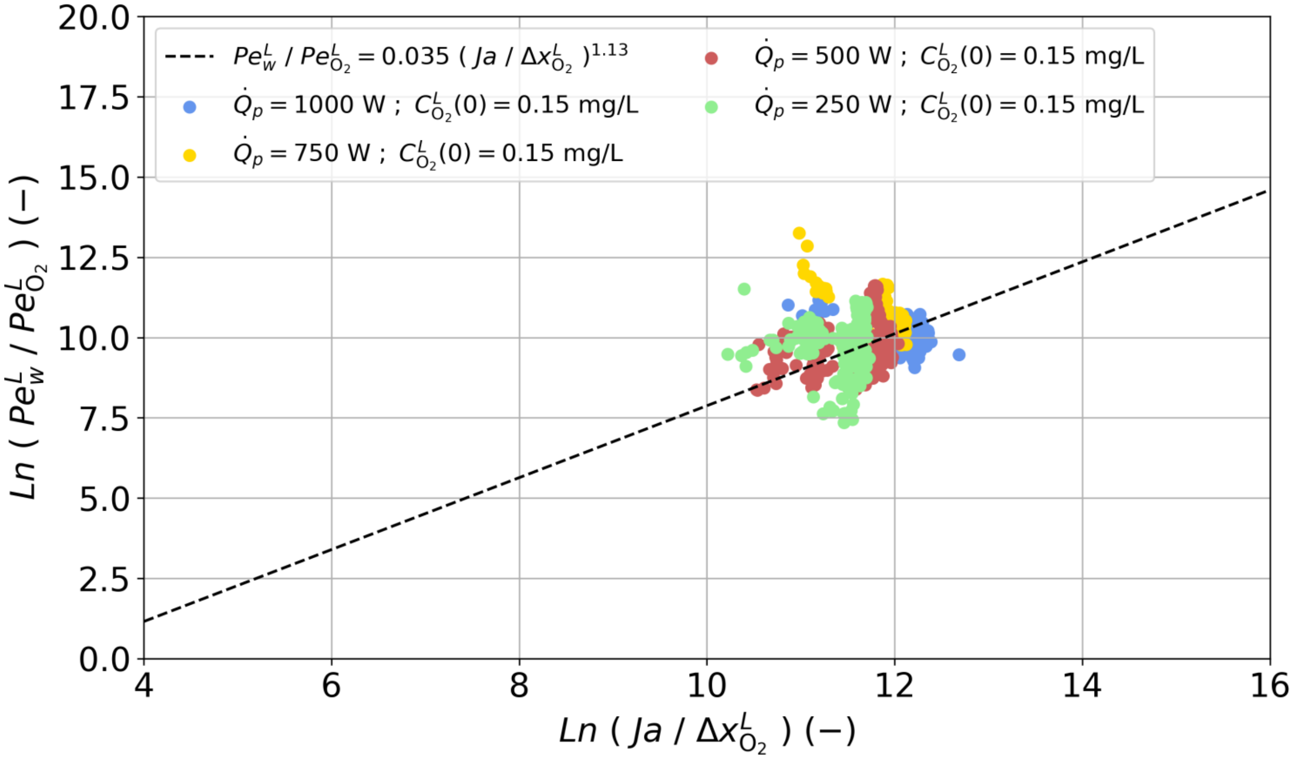
Toward a dimensionless characterization of the system's behavior

- The **degassing / flashing stage characterization**: the determined law does not depend on the initial content in dissolved gases



Toward a dimensionless characterization of the system's behavior

- The **degassing / flashing stage characterization**: the determined law does not depend on the initial content in dissolved gases



Toward a dimensionless characterization of the system’s behavior

The **free surface evaporation stage characterization**: a comparative study of three different test facilities operated at IRSN

Cocotte-MIDI experiment

- Pool type: open vessel
- Pool shape: cylindrical
- Heat source type: planar surface
- Max. heating power: 1 kW
- Diameter: 27 cm
- Max volume: 10 L
- Operating pressure: 1 bar
- Temp. range: 10-100°C
- Atmospheric conditions: free

Aquarius experiment

- Pool type: close vessel
- Pool shape: rectangular
- Heat source type: planar surface
- Max. heating power: 1 kW
- Dimensions: H40 x L45 x W30 cm
- Max volume: 50 L
- Operating pressure: 10-100 mbar
- Temp. range: 10-50°C
- Atmospheric conditions: vapor-saturated

MIDI experiment

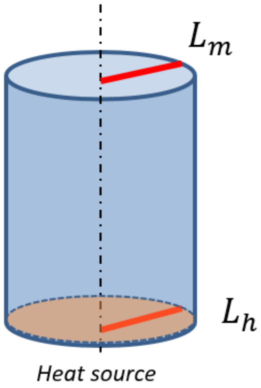
- Pool type: open vessel
- Pool shape: rectangular
- Heat source type: vertical rod bundles
- Max. heating power: 300 kW
- Dimensions: H4.5 x L2.1 x W1.4 m
- Max volume: 12 m3
- Operating pressure: 1 bar
- Temp. range: 10-120°C
- Atmospheric conditions: free

Increasing dimensions and complexity

Toward a dimensionless characterization of the system's behavior

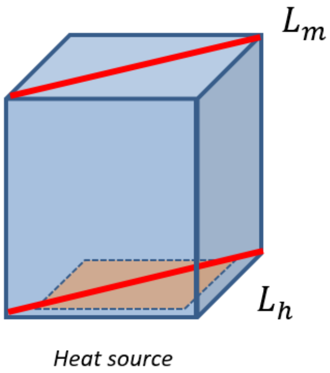
- The **free surface evaporation stage characterization**: a comparative study of three different test facilities operated at IRSN

Cocotte-MIDI experiment



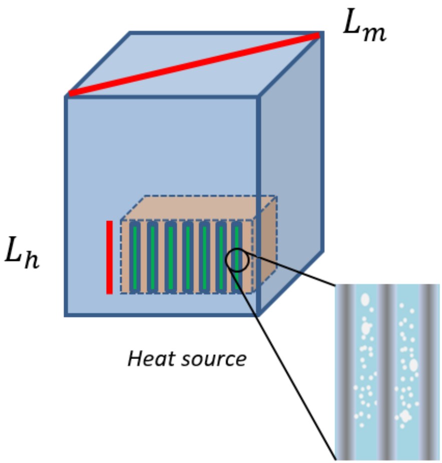
- Mass transfer length scale L_m: pool radius (0.135 m)
- Heat transfer length scale L_h: pool radius (0.135 m)

Aquarius experiment



- Mass transfer length scale L_m: pool free surface diagonal (0.54 m)
- Heat transfer length scale L_h: pool free surface diagonal (0.54 m)

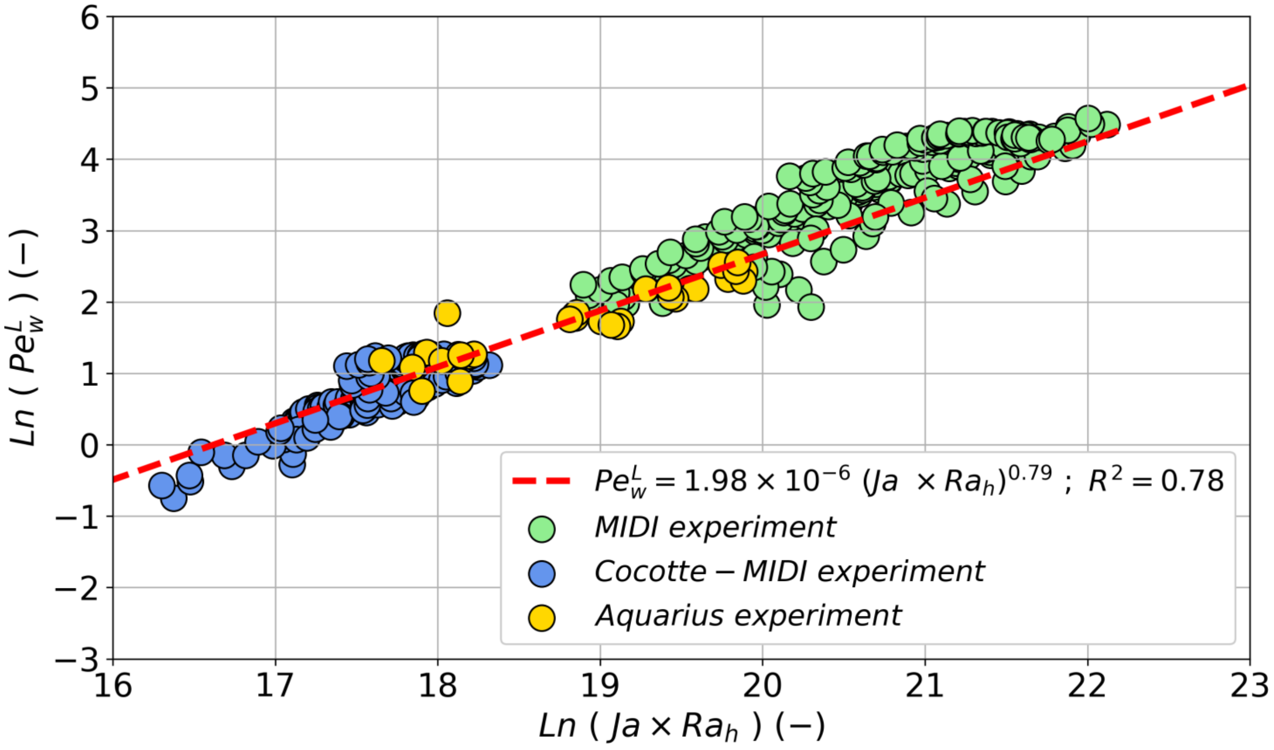
MIDI experiment



- Mass transfer length scale L_m: pool free surface diagonal (2.5 m)
- Heat transfer length scale L_h: rod bundle heated length (0.7 m)

Toward a dimensionless characterization of the system's behavior

- The **free surface evaporation stage characterization**: a comparative study of three different test facilities operated at IRSN



Toward a dimensionless characterization of the system's behavior

- The **free surface evaporation stage characterization**: a comparative study of three different test facilities operated at IRSN

The correlation obtained over the 24 tests of the regular experimental matrix:

$$Pe_w^L = 1.98 \times 10^{-6} \left(Ja \times Ra_h\right)^{0.79}$$

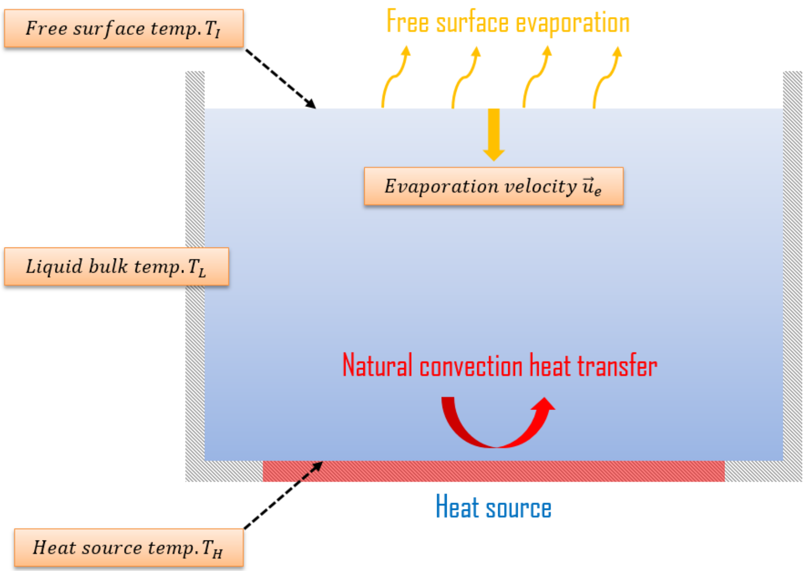
with:

- $Ja = \frac{C_p^L \Delta T_{eq;\infty}}{\mathcal{L}_w}$; the asymptotic Jakob number (dimensionless thermodynamic disequilibrium)
- $Pe_w^L = \frac{j_w L}{C_L \kappa_L}$; Water vaporization Péclet number (dimensionless vaporization mass flux)
- $Ra_h = \frac{g \beta_L \Delta T_h L_h^3}{\nu_L \kappa_L}$; Rayleigh number of the heat source (dimensionless driving force of the flow toward the free surface)

and with L, the characteristic length appearing in the above Péclet number, taken equal to the diagonal of the free surface and L_h appearing in the Rayleigh number taken equal to the diagonal of the heating area.

Toward a dimensionless characterization of the system's behavior

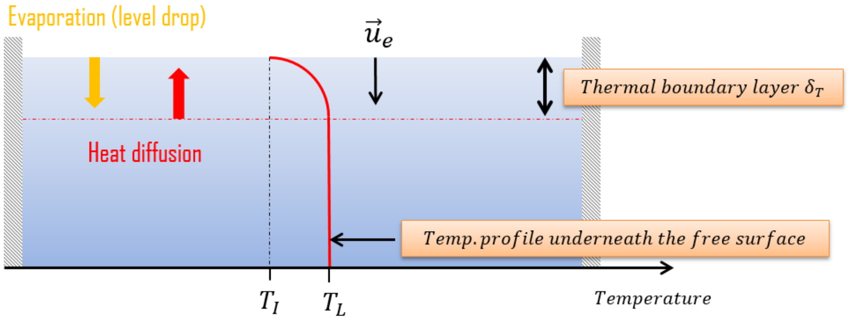
The **free surface evaporation stage characterization**: the physical basis of the obtained scaling law



Heat source Rayleigh number: $Ra_h = \dfrac{g\beta_L\,(T_H - T_L)\,L_h^3}{\vartheta_L\,\kappa_L}$

Free surface evaporation Péclet number: $Pe_w^L = \dfrac{\|\vec{u}_e\|\,L_m}{\kappa_L}$

Thermodynamic disequilibrium Jakob number: $Ja = \dfrac{Cp_w^L\,(T_L - T_I)}{\mathcal{L}_w}$



Conclusions and future work

- **The presented test device allows reproducing the phenomenon in a pool-type geometry at a reduced scale**
  - **Observation of gravity-driven liquid superheating and flashing in a pool !**

- **The importance of the water content in dissolved gases has been evidenced during the first observations**

- **The phenomenon has been investigated with a focus on the observed transition between a bubbling and non-bubbling regime**
  - Variations in heating power, system's pressure, initial content in dissolved gases and heat source spatial distribution
  - Definitions of a set of scaling laws characterizing the phenomenon ; some are consistent with identical observations within two other experimental devices operated at IRSN

- **A CFD modeling within the *Neptune_CFD code* of the presented experiment will be carried out**

Thank you for your attention