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Experimental study of a two-phase nitrogen natural circulation loop

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Introduction (1/2)

- Two-phase circulations loops included in the refrigeration system of large superconducting magnets with **helium as a working fluid**
  - ALEPH magnet at CERN, the CLEO II magnet at Cornell University, the G0 magnet at Jefferson laboratory, CMS magnet at CERN, The R3B-Glad at GSI
- Extensive studies in helium
  - Thermo-hydraulic characteristics (steady-state and transient)
  - Parietal heat transfer
- Natural circulation loops with nitrogen as a working candidate to be included in the cooling scheme of high-Tc superconductors devices
- **Limited number of studies for nitrogen** have been reported in the literature
- Umekawa and Ozawa reported the experimental results on heat transfer in two-phase natural circulation loop in the saturated boiling and post-dryouts regimes
  - Heat transfer coefficients in the saturated boiling predicted by the Schrock-Grossman's correlation developed for non cryogenic fluids for steady flow

Introduction (2/2)

- Kim and Chang studied a sub-cooled nitrogen circulation loop
  - Heat transfer and mass flow rates results in single phase and two-phase conditions for low mass flow rate up to 1.5 g/s

- On 2-m loop, an experimental study for heat flux below 12 kW/m^2
  - Mixed convection (natural and forced convection) analysis in single phase flow

- We report the experimental study performed on our 2-m high circulation loop in two-phase flow nitrogen around atmospheric pressure
  - Range limits are **40 g/s**, **25%** and **30 kW/m^2** for the total mass flow rate, the vapor quality and the heat flux density
  - Modeling the thermo-hydraulic behavior with a **simple separated flow model**
  - Wall **heat transfer coefficients** are compared with known correlations in both single phase natural convection and boiling flow
    - Dittus-Boelter's correlation
    - One of the Sha's correlation

Open circulation loop principle

- Open reservoir/phase separator

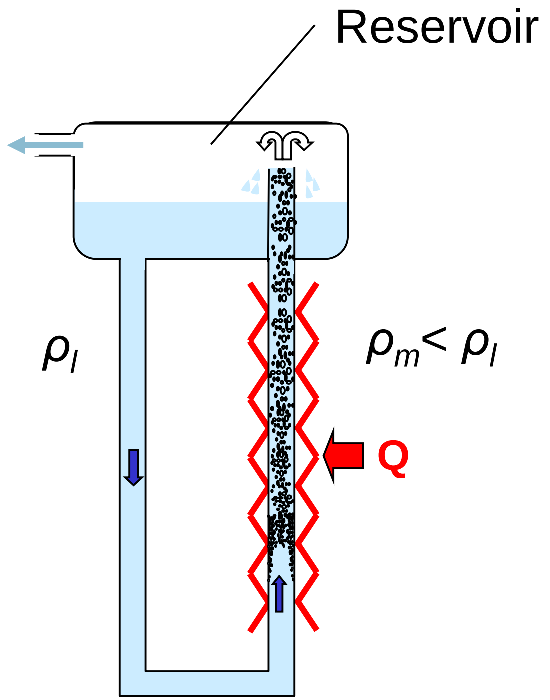
- No re-cooling of the warm liquid or re-condensation of the vapor

- Power to be extracted
- Decrease in liquid density and/or vaporization
- Branch weight unbalance
- Flow induced

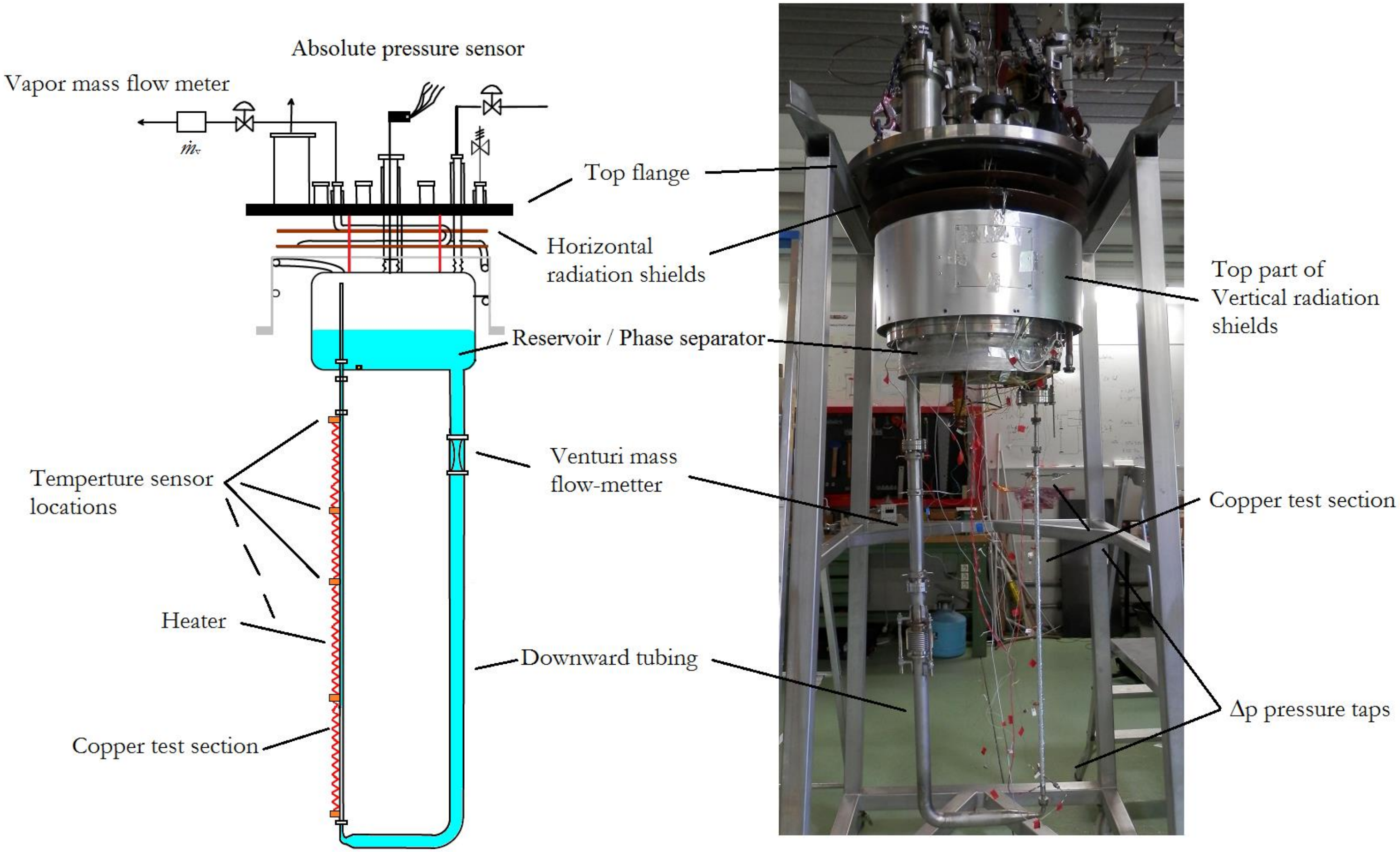
- **Two-phase flow heat exchanger**

- Suppression of any pressurization system

- Liquid level needs to be controlled to avoid dry-out
- Minimum heat flux to start the flow
- Flow oscillations at low heat flux



Experimental facility and instrumentation



- Test section
  - 10 mm inner diameter
  - 1 m heated length
  - CX 1080 ± 25 mK @ 77 K

- Ranges
  - P 1.00 ± 0.03 10^5 Pa
  - q : 0-30 kW/m^2
  - $\dot{m}$: 0-40 g/s; Re max : 8 10^4

Thermo-hydraulic model (1/2)

- Mass, momentum and energy conservation equations
  - modeling in single or two-phase flow

$$\frac{\mathrm{d}}{\mathrm{d}z}(\rho u) = 0$$

$$\rho u \frac{\mathrm{d}u}{\mathrm{d}z} = -\frac{\mathrm{d}p}{\mathrm{d}z} + \rho g cos\theta - \frac{P}{A}\tau_w$$

$$\rho u \frac{\mathrm{d}}{\mathrm{d}z}(h + \frac{u^2}{2} + gz) = \frac{P}{A}q$$

  - Darcy friction factor $\tau_w = \frac{1}{2} C_{f,l} \rho_l u_l^2$ with the Blasius correlation $C_f{=}0.0791.\mathrm{Re}^{-0.25}$
  - In two phase, $C_{f,l}$ is multiplied by ϕ given by the Lockhart-Martinelli correlation

$$\phi = (1-x)^{1,75}\left[1 + \frac{20}{X_{tt}} + \frac{1}{X_{tt}^2}\right]$$

Thermo-hydraulic model (2/2)

- **Simple separated flow model** for the two-phase flow with a **slip ratio**

  - Density $\rho_m = \alpha\rho_v + (1-\alpha)\rho_l$

$$\boxed{S = u_v / u_l}$$

  - Velocity $u_m = \dfrac{(1-\alpha)\rho_l u_l + \alpha\rho_v u_v}{\rho_m}$

  - Slip ratio given by the Huq and Loth expression

$$S = \frac{\rho_l}{\rho_v}\frac{2x(1-x)}{2x(1-x) + \sqrt{1 + 4x(1-x)\left(\frac{\rho_l}{\rho_v} - 1\right)} - 1}$$

  - Void fraction given by the Lockhart-Martinelli correlation

$$\alpha = 1 - \left[1 + \frac{20}{X_{tt}} + \frac{1}{X_{tt}^2}\right]^{0{,}5} \qquad X_{tt} = \left(\frac{1-x}{x}\right)^{0{,}875}\left(\frac{\rho_v}{\rho_l}\right)^{0{,}5}\left(\frac{\mu_l}{\mu_v}\right)^{0{,}125}$$

Modeling implementation

- System of 4 unknown variable, u, p, h and x for 3 equations

- In the single phase flow
  - No vaporization then x=0 → 3 unknown variables
  - Ends when the fluid reaches the saturation conditions

- In two-phase flow
  - The assumption is to consider the fluid at saturation → 3 unknown variables
  - $h = x.h_v + (1-x).h_l = h_l + x.L_v \approx h_{sat} + x.L_v$

- Model identifies in the loop where the saturation conditions are reached and separates the loop in single and two-phase flow domains

- All singular and regular pressure drops included

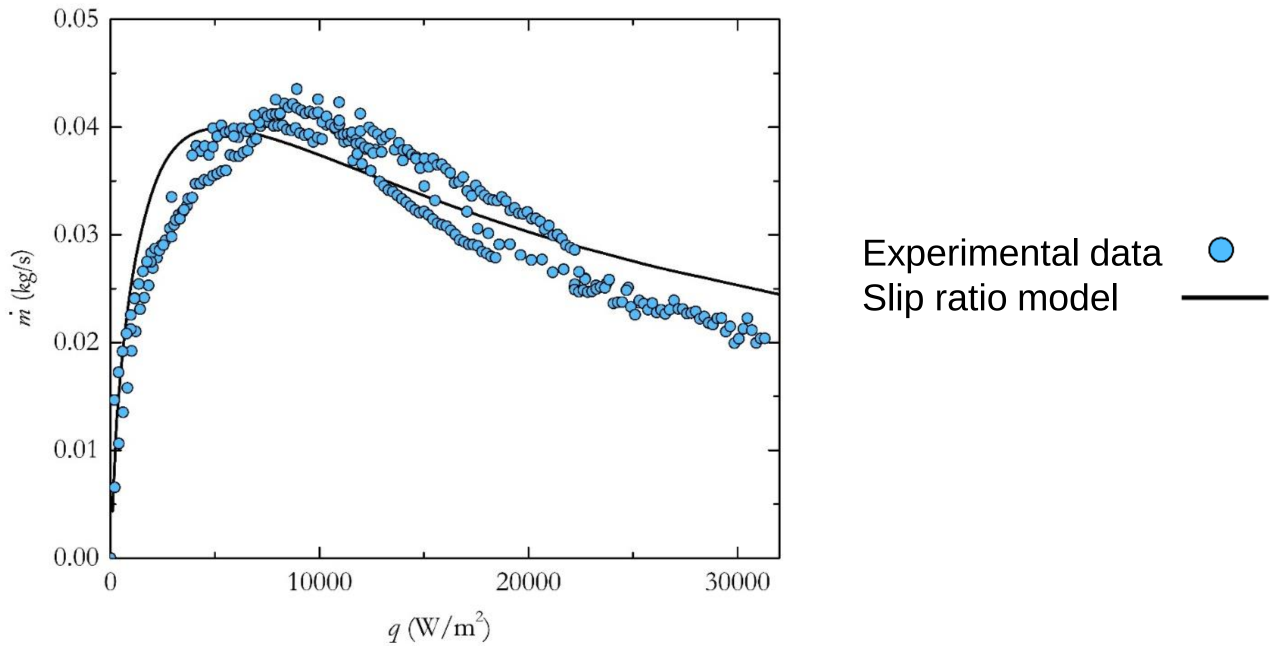
- Comsol 5.2a, 1D, 1000 *dz*

Total mass flow rate, $\dot{m}_t$

- Two flow regimes : a gravity dominant regime and a friction dominant regime
  - **Gravity dominant regime**: change in vapor quality creates change in the void fraction
  - Increase of the buoyancy force creates an important increase of $\dot{m}$
  - **Friction dominant regime**: increase of the velocity increase of the frictional force
  - Decrease of $\dot{m}$ as q increases

$$\dot{m}_t = \rho\, u\, A$$

$$\dot{m}_t = \rho_m\, u_m\, A$$

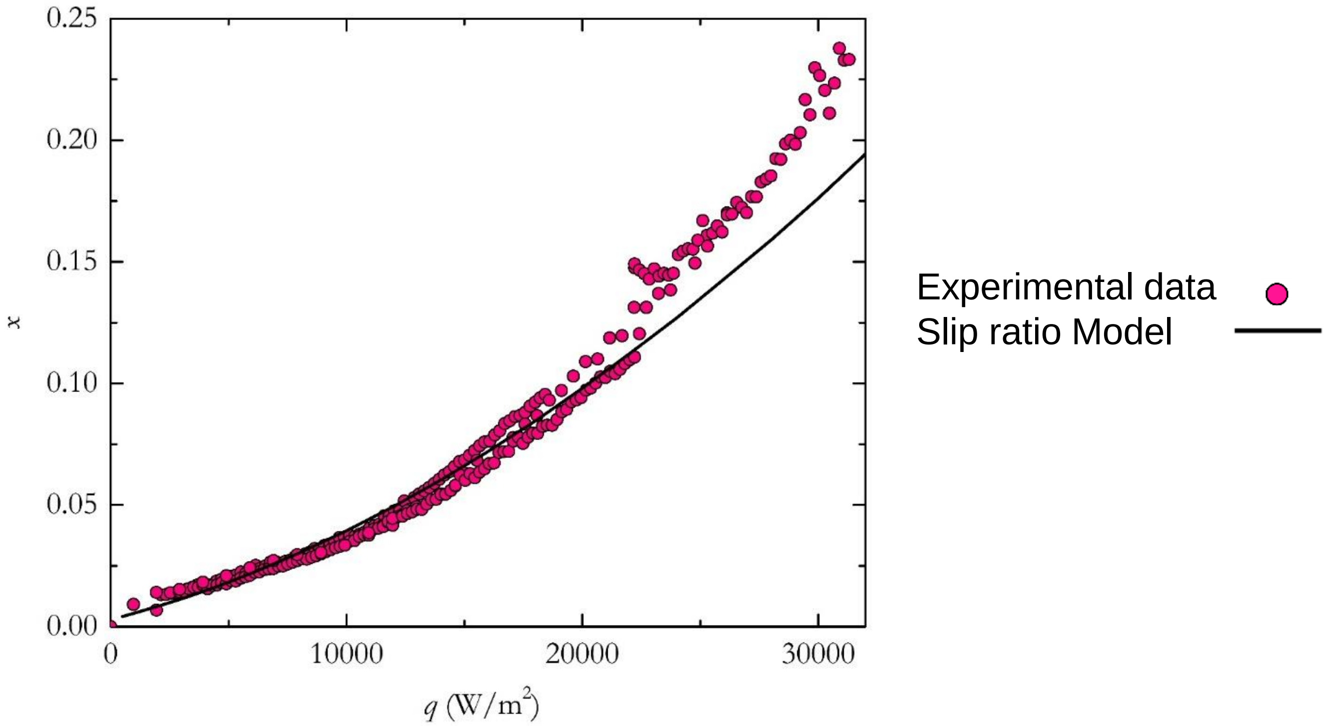


- Computed $\dot{m}$ peaks too soon (in q) and at lower value
- Evolution of α too important with q ?

Vapor quality at the exit, x

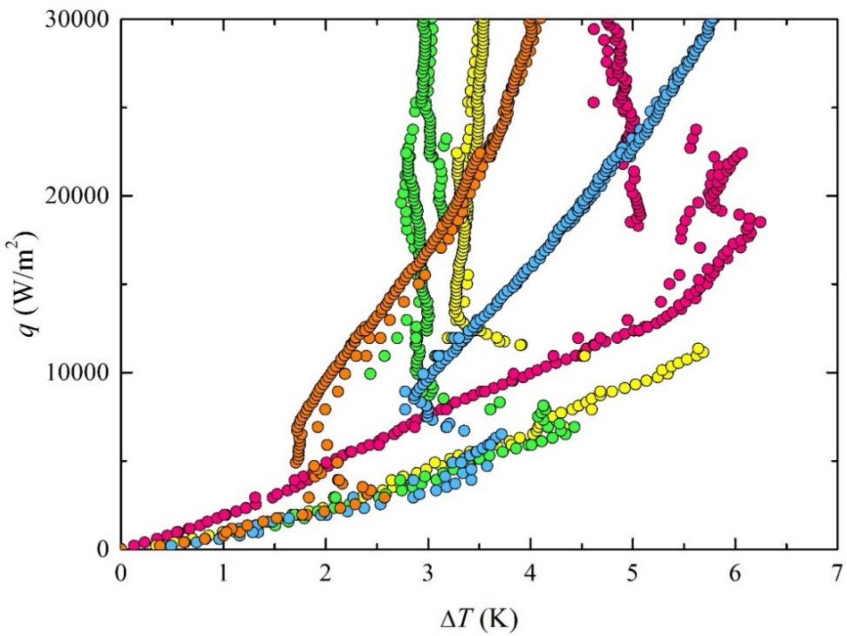
- Computations reproduce with an acceptable accuracy the evolution of *x*
  - Small deviation at heat flux density above 20 kW/m^2
  - Consequence of the overestimation of $\dot{m}_t$ by our model, *x* is underestimated

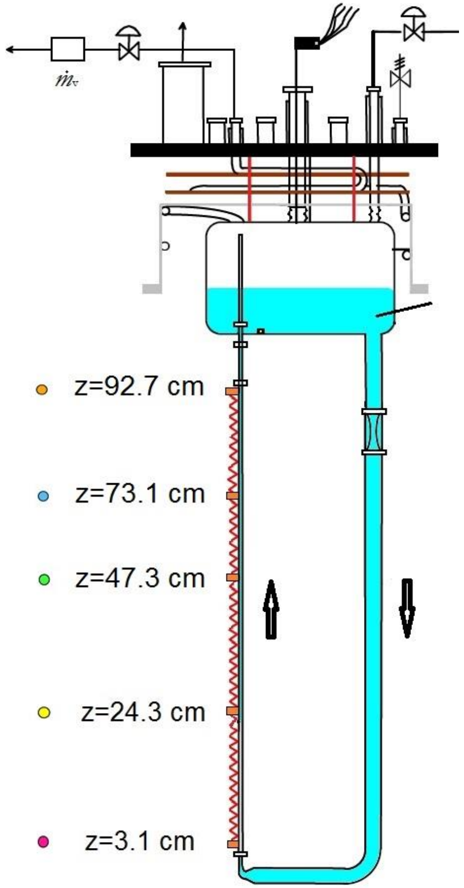
$$x = \dot{m}_v / \dot{m}_t$$



Boiling curve

- Typical boiling curve, $q = f(\Delta T)$; $\Delta T = T_w - T_f$
- T_f computed with an energy equation or T_{sat}
- At low q, linear curves typical of a single phase flow





- Onset of Nucleate Boiling depends on the height (sub-cooling)
- Decrease of ΔT : apparition of nucleate boiling
- Development of nucleate boiling

Wall heat transfer coefficient (1/2)

- Modeling in single phase with the Dittus-Boelter correlation

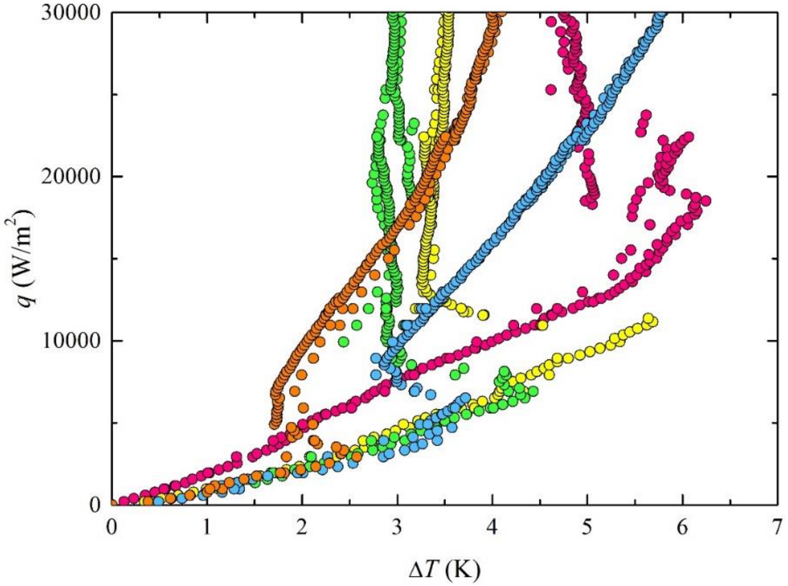
$$h_l = 0.023 \cdot Re_l^{0,8} Pr_l^{0,4} \cdot \frac{k_l}{D}$$

- Modeling in the two-phase with the Sha's Correlation (1976)

$$h_{tp} = \Psi \cdot h_l$$

$$h = \frac{q}{(T_w - T_f)}$$

$$h_l = 0.023[Re_l \cdot (1-x)]^{0,8} Pr_l^{0,4} \cdot \frac{k_l}{D}$$



$$\Psi = \begin{cases} max\left[\frac{1.8}{Co^{0.8}}; \Psi_0\right] & \text{if } Co > 1 \\ max\left[\frac{1.8}{Co^{0.8}}; F\Psi_0 \cdot exp(2.74 \cdot Co^{-0.1})\right] & \text{if } 0.1 < Co \leq 1 \\ max\left[\frac{1.8}{Co^{0.8}}; F\Psi_0 \cdot exp(2.47 \cdot Co^{-0.15})\right] & \text{if } Co \leq 0.1 \end{cases}$$

$$\Psi_0 = 230 \cdot Bo^{0.5} \qquad Co = \left(\frac{1}{x} - 1\right)^{0.8} \left(\frac{\rho_v}{\rho_l}\right)^{0.5}$$

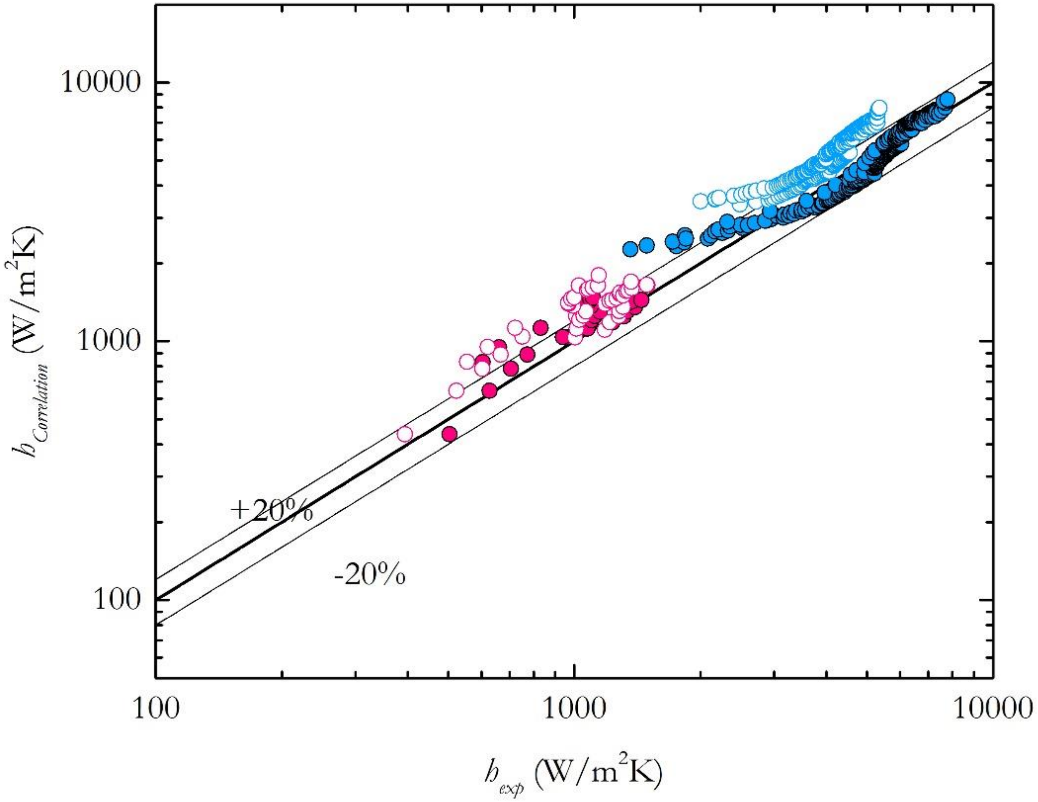
$$Bo = \frac{q}{GL_v} \qquad F = \begin{cases} 0.064 & \text{si } Bo \geq 11.10^{-4} \\ 0.067 & \text{si } Bo < 11.10^{-4} \end{cases}$$

Wall heat transfer coefficient (2/2)

- Single phase flow
  - Acceptable accuracy of the correlation for most of the heights (±30%)
  - Experimental value are, overall, slightly lower than the correlation
  - Excepted for z=3.1 cm (natural convection effect ?)

- Two-phase flow
  - Good accuracy for z=92.7 cm, excepted in the NB development
  - Lower value for z=73.1 cm; still in NB boiling development?
  - For the other heights, within ±30% but evolutions different

	Single phase	Two-phase
z= 73.1 cm	○	○
z= 92.7 cm	●	●



Conclusions and future work

- Heat and mass transfer of a nitrogen circulation loop
  - Range limits of 40 g/s, 25% and 30 kW/m^2 around the atmospheric pressure
- Results show that the thermo-hydraulic measurements can be modeled with a **slip flow model** with an **acceptable accuracy**
  - Nevertheless, more work must be done to improve the model
  - Other correlations for S, α and C_f
- Single phase wall heat transfer
  - Slightly lower than modeled by the Dittus-Boelter's correlation
  - Investigation on the interaction with natural convection
- In the two-phase regime
  - For lower heights, boiling curve shows unusual evolutions of the ΔT_w
  - At the highest heights, the flow boiling is fully developed
  - Sha's correlation (1976) insufficient for all heights
  - Other correlations should be tried with the improved model

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