Journées du GdR TransInter – Aussois

Experimental characterisation of horizontal or slightly inclined boiling flows

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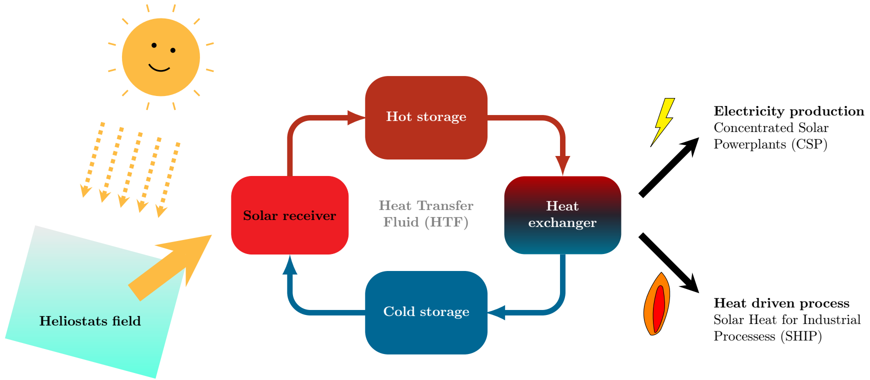
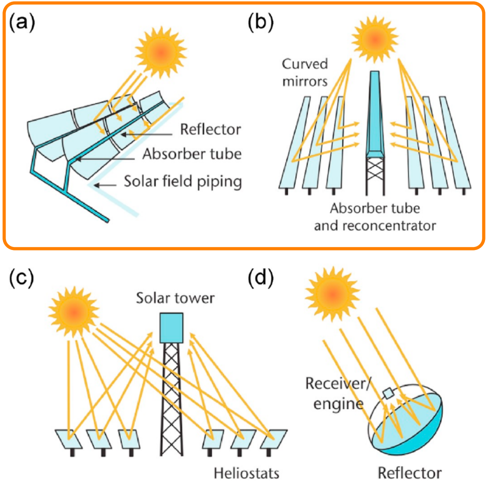
Concentrated Solar Thermal (CST) Technologies



- Mirrors concentrate **solar radiation** onto a receiver
- The resulting **heat** is collected by a heat transfer fluid
- This heat is used to generate **electricity** or **process heat** (**low-carbon**)



[Conroy *et al.* – Renew. Sust. Energy Rev. – 2020]

Linear concentration

$F_c \leqslant 100$

$100^\circ C \leqslant T \leqslant 400^\circ C$

Horizontal flows

Point-focus concentration

$200 \leqslant F_c$

$T \geqslant 400^\circ C$

Vertical flows

Spanish case studies

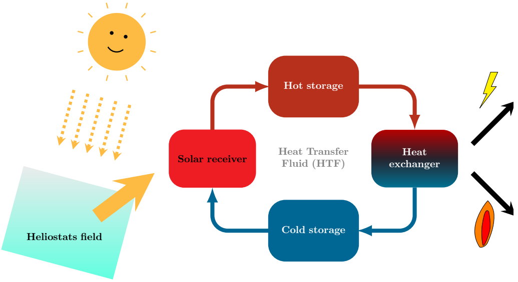
Heineken Brewery – Seville (SHIP)

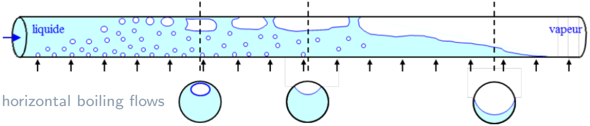
Andasol – Granada (CSP)

Gemasolar – Andalusia (CSP)

Most common Heat Transfer Fluids

- Molten salts (mixture of $NaNO_3$ and KNO_3)
  - ✖ Operating temperature ($T \leqslant 560^\circ C$)
- Synthetic oils
  - ✖ Environmental and operator health risks
- Water for Direct Steam Generation
  - ✔ Suitable for steam-based processes
  - ✔ Reduces the number of components (HEx for CSP)
  - ✔ Lower risk $\searrow \Rightarrow$ Better acceptance
  - ✖ Management of two-phase flow required



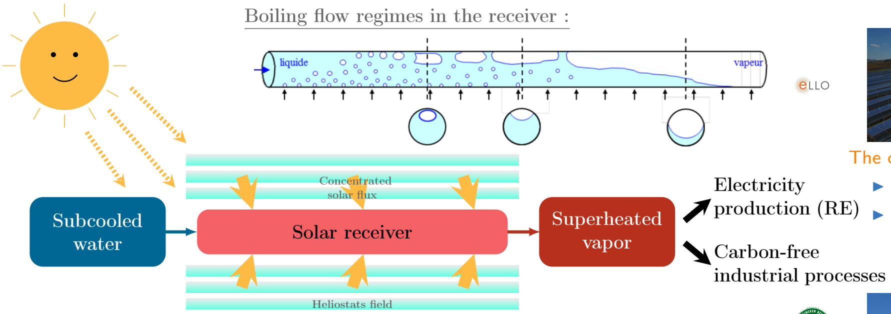


eLLO : the only CSP plant in France

- **Generates electricity** for the grid
- Commissioned in 2019
- Nominal power : 9 MW_{el}
- Fresnel linear concentrator
- Steam storage : $9 \times 120\ m^3$

Heineken brewery in Seville (Spain)

- **Supplies steam** to the brewery
- Commissioned in 2024
- Nominal power : 30 MW_{th}
- Parabolic trough concentrator



The only french CSP plant

- Since : 2019
- $\mathcal{P} = 9\ MW_{el}$

Heineken brewery – Seville

- Since : 2024
- $\mathcal{P} = 30\ MW_{th}$

Industrial objectives

- Optimize boiling flow regimes in the receiver
- Predict the solar field steam production
- Assess thermomechanical stresses on the receiver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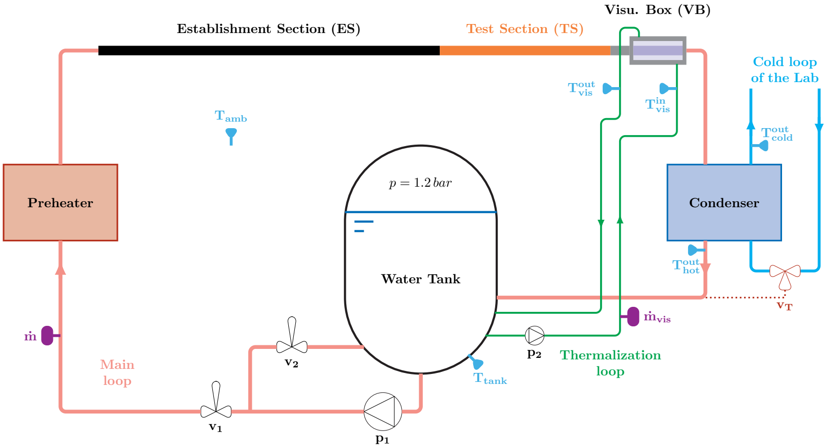

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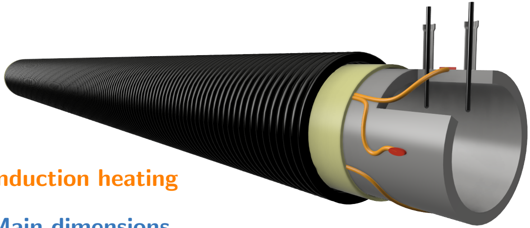
SteamSun

ConBo

ConVective Boiling flow loop

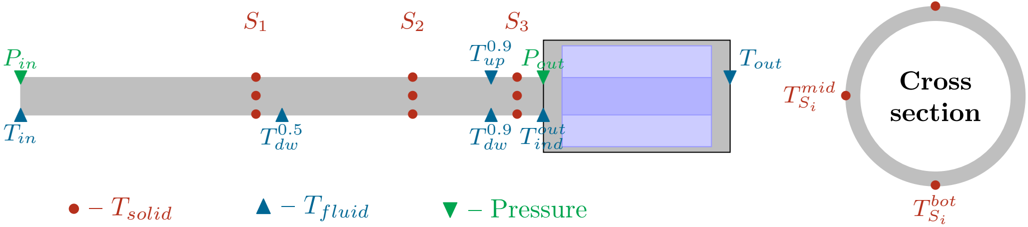
ConBo – Test section



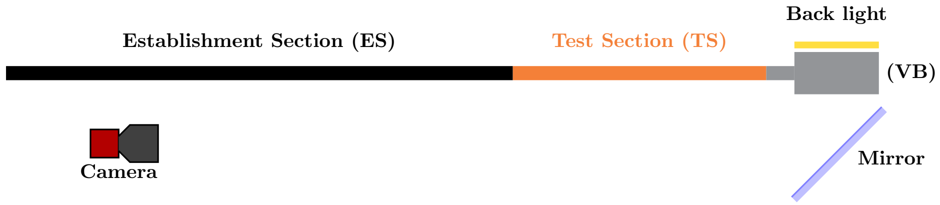
- **Control parameters**
  - $\dot{m} \in [0, 200]\ g/s$
  - $\Delta T_{sub} \in [-10, 0]\ ^\circ C$
  - $\mathcal{P}_{in} \in [0, 22]\ kW$
  - $\theta \in [-5, 5]\ ^\circ$
  - $P_{in} = 1.2\ bar$

- **Induction heating**

- **Main dimensions**
  - $L = 1\ m$
  - $D_{in} = 49.3\ mm$

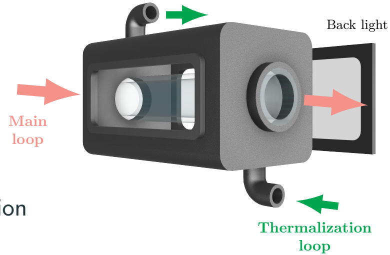


Flow pattern identification using shadowgraphy



Post-processing workflow (Collab. IMFT)

- Correction of oscillations / deformations / illumination
- Flow regime identification
- Contour detection (thresholding, filling)
- Extraction of key parameters
  - Detection of bubble nose and tail for velocity estimation
  - Estimation of vapor volume fraction



- Net heat flux

$$\dot{q} = \frac{Q_{\text{abs}}}{\pi D_{\text{in}} L_{\text{ts}}}$$

- Fluid temperature estimated at saturation with

$$p_{\text{sat}}(z) = p_{\text{out}} - (z - L_{\text{ts}}) \frac{\Delta p}{L_{\text{ts}}}$$

- Wall temperature calculation
  - Outer average section temperature

$$T_{S_i}^{\text{out}} = \frac{T_{S_i}^{\text{top}} + 2\,T_{S_i}^{\text{mid}} + T_{S_i}^{\text{bot}}}{4}$$

  - Assuming steady-state conduction

$$T_{S_i}^{\text{int}} = T_{S_i}^{\text{out}} - \frac{\dot{q}\,\ln\left(D_{\text{out}}/D_{\text{in}}\right)}{2\pi k_{\text{wall}} L_{\text{ts}}}$$

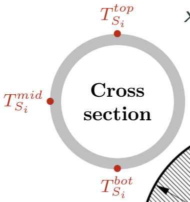
- Heat transfer coefficient and Nusselt number

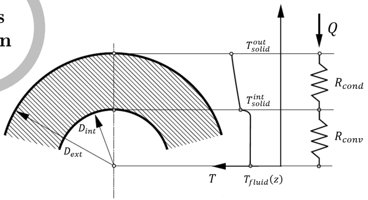
$$h_{\exp,S_i} = \frac{\dot{q}}{T_{S_i}^{\text{int}} - T_{\text{fluid}}(z_{S_i})}$$

$$\text{Nu}_{\exp,S_i} = \frac{h_{\exp,S_i}\,D_{\text{in}}}{k_{\text{fluid}}(T_{\text{fluid}})}$$

- Energy balance fixes the thermodynamic quality

$$x^{\text{th}}(z) = \frac{h_{\text{in}} - h_{f,\text{sat}}}{\Delta h_{lv}} + \frac{\dot{q}\pi D_{\text{in}} z}{\dot{m}\,\Delta h_{lv}}$$



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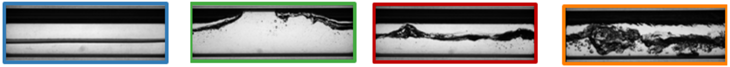
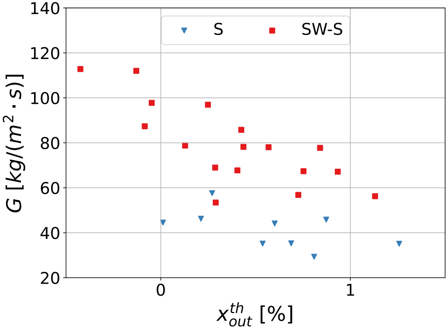
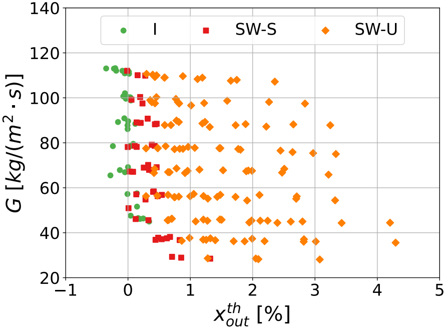


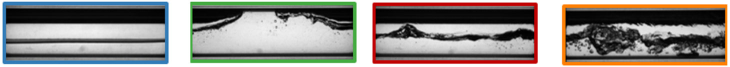
Horizontal flows



Tilted flows

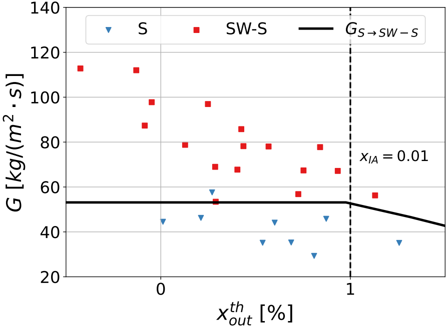


- Vapor appears before saturation ($x_{out}^{th} < 0$)
- Stratified flow disappears for $\theta > 0$

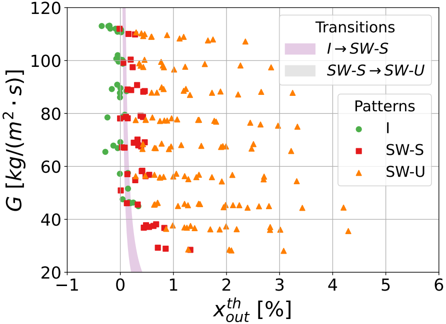


Stratified | Intermittent | Smooth Stratified-Wavy | Unstable Stratified-Wavy

Horizontal flows

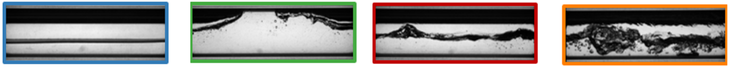


Tilted flows



- Vapor appears before saturation ($x_{out}^{th} < 0$)
- Stratified flow disappears for $\theta > 0$
- Transitions are characterized in :

  Aguilera-Cortes et al. - ATE - 2026



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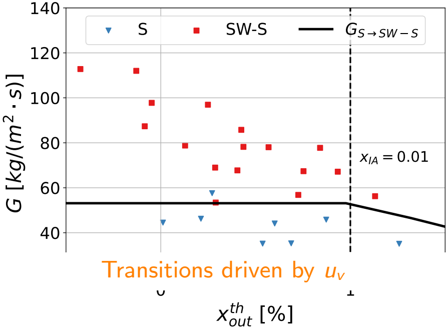
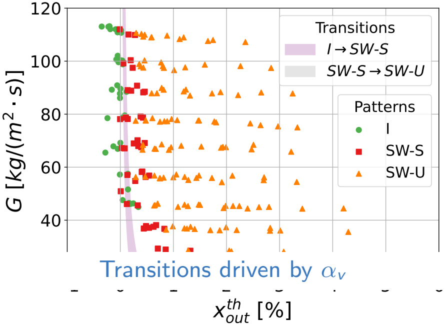
Horizontal flows



Transitions driven by u_v

Tilted flows



Transitions driven by α_v

- Vapor appears before saturation ($x_{out}^{th} < 0$)
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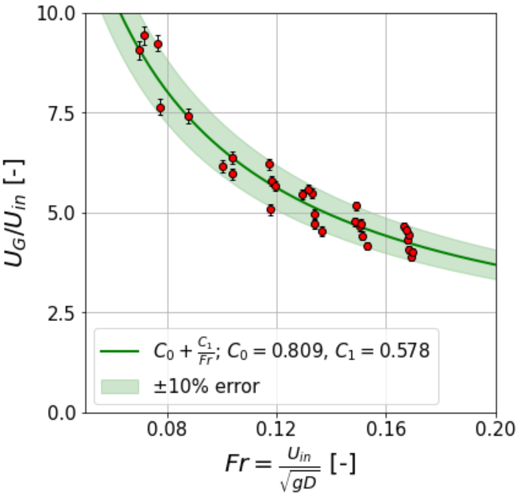
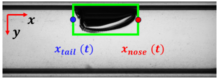
- Transitions are characterized in : Aguilera-Cortes et al. - ATE - 2026





- Measured gas velocities are compared to a *drift-flux* model :

$$U_G = C_0 \cdot U_L + C_1 \cdot \sqrt{gD}$$

  - Literature values : $C_0 = 1.2,\ C_1 = 0.5$
  - Here, best-fit values :

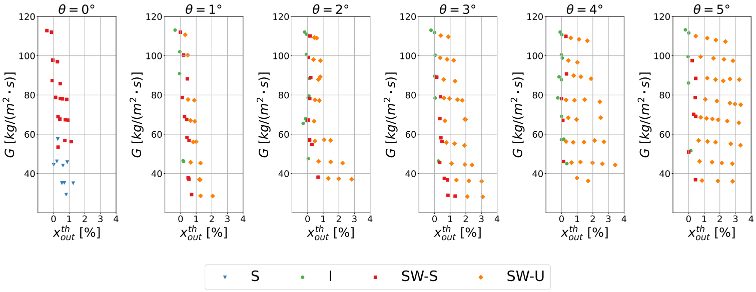
$$C_0 = 0.81, \quad C_1 = 0.57$$

- High gas-to-liquid velocity ratio :

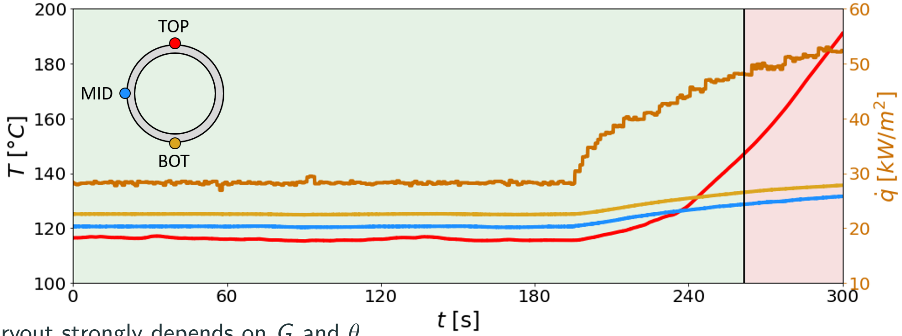
$$4 \lesssim \frac{U_G}{U_L} \lesssim 10$$

[França & Lahey – IJMF – 1992]

Inception of dryout



- Dryout strongly depends on G and θ
- Existing correlations do not predict such effects [Mori et al - 2012, Wojtan et al - 2005]



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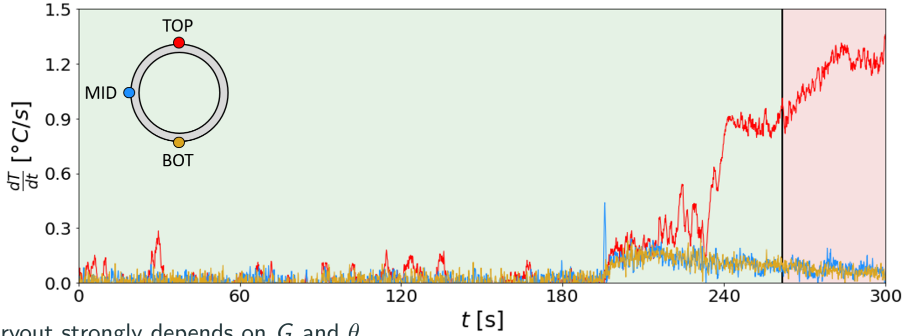
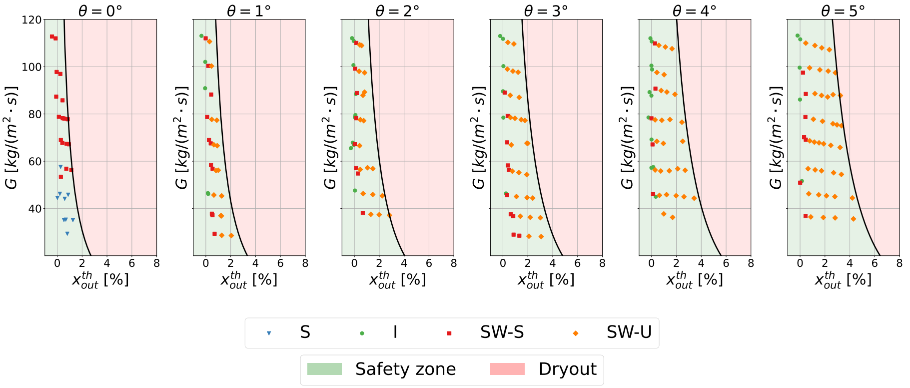


- Dryout strongly depends on G and θ
- Existing correlations do not predict such effects [Mori et al - 2012, Wojtan et al - 2005]
- Multivariate regression allows determining

$$x_{di} = 0.71 \ln\left[Re_v^{-0.02} \left(\frac{\rho_l}{\rho_v}\right)^{0.58} \left(\frac{\mu_l}{\mu_v}\right)^{-1.22} + \sin^{1.35}(\theta)\right]$$



- A reformulation allows deriving the safety operation limit

$$G_{\text{dryout}} = \left\{ \left[\exp\left(\frac{x}{0.71}\right) - \sin^{1.35}(\theta) \right] \left(\frac{\rho_l}{\rho_v}\right)^{-0.58} \left(\frac{\mu_l}{\mu_v}\right)^{1.22} \left(\frac{\mu_v}{D}\right)^{-0.02} \right\}^{0.02}$$

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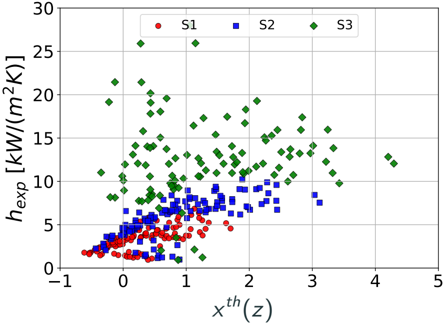
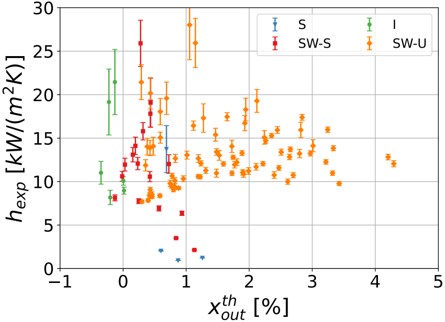
Axial evolution



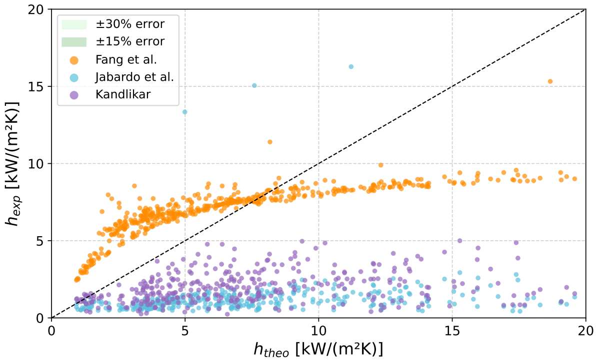
- The HTC rises with the streamwise position
- For S_1 and S_2, nearly linear increase of HTC with x^{th}

Correlation with the flow pattern in S_3



- Stratified flows yield the lowest HTC
- No clear hierarchy between SW-U, SW-S and I
- SW-U exists over a larger x^{th} range

Comparison with existing correlations



- Fang et al. - IJHMT - 2017
  - 20,000 data points with refrigerants
  - Microchannel flows
- Kandlikar et al. - IJHT - 1991
  - Mainly for refrigerants
  - 3% of horizontal water cases
- Jabardo et al. - BJMS - 1999
  - Horizontal refrigerant boiling

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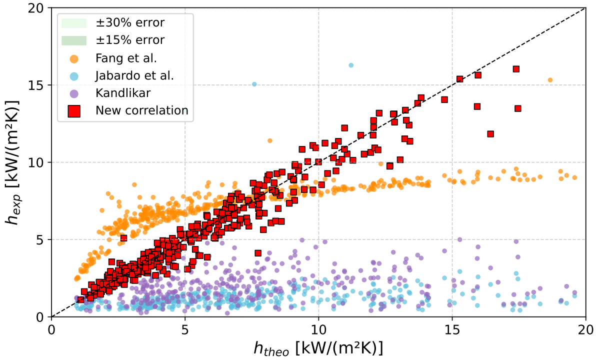
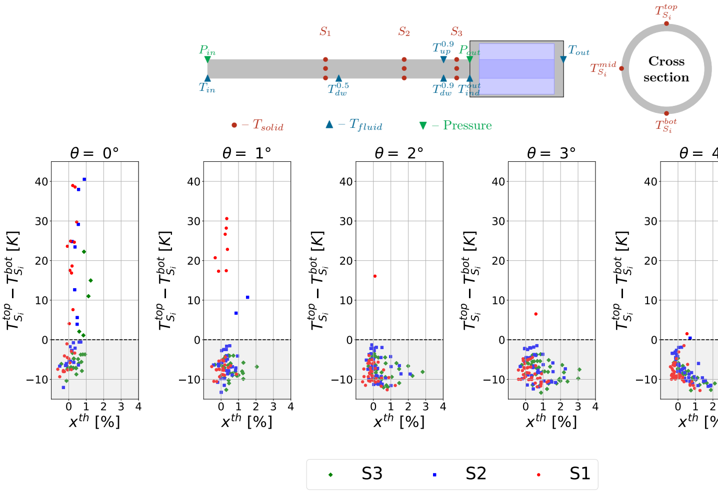
Development of a new correlation

$$h_{\text{new}} = \frac{k_l}{D}\cdot Bo\cdot Re^{1.6}\left(x^{th} - \frac{(h_{\text{in}} - h_{\text{sat}})}{\Delta h_{lv}}\right)^{0.8}\left[\ln\left(\frac{\mu_{lf}}{\mu_{lw}}\right)\right]^{-1.55} \quad \text{, with} \quad Bo = \frac{\dot{q}}{G\cdot\Delta h_{lv}}$$

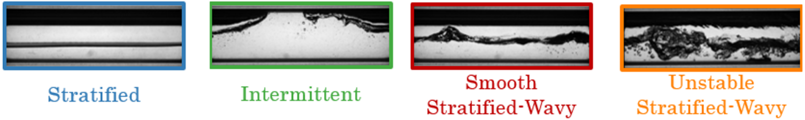


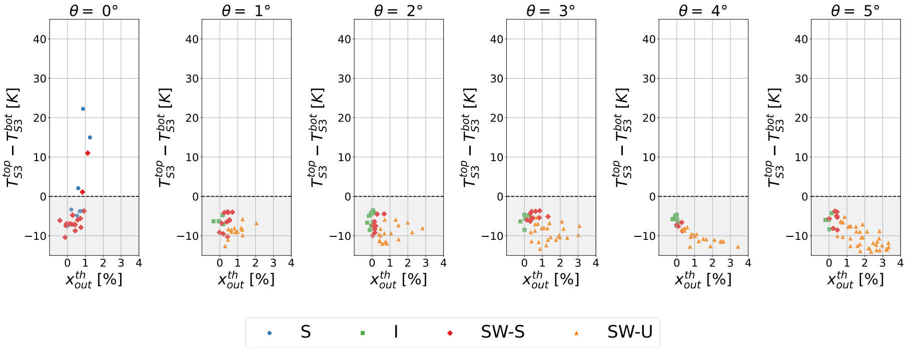
- Newly proposed correlation :
  - MPE $= -2.05\%$
  - MAPE $= 10.43\%$
  - 97% of the points within $\pm 30\%$ EB
- Does not depend on θ (to first order)
  - Likely an effect of section averaging



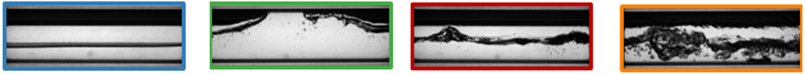
- Positive stratification disappears when $\theta \nearrow$ or $x^{th} \geq 1.5$

Inverse thermal stratification





- In S_3, positive stratification is observed only for S or SW-S flows
- Most of the tests highlight inverse thermal stratification



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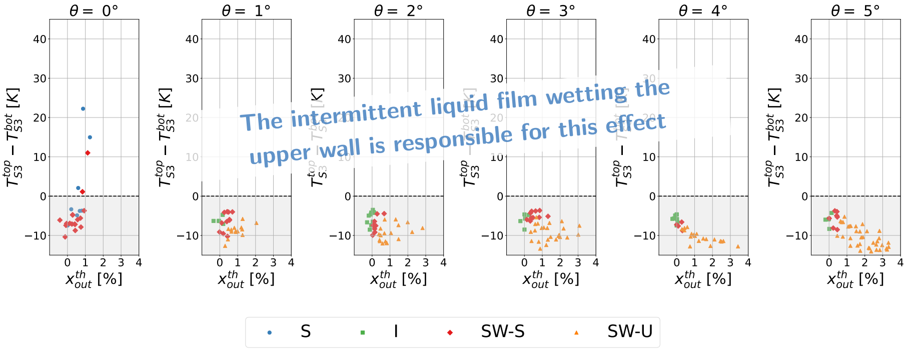
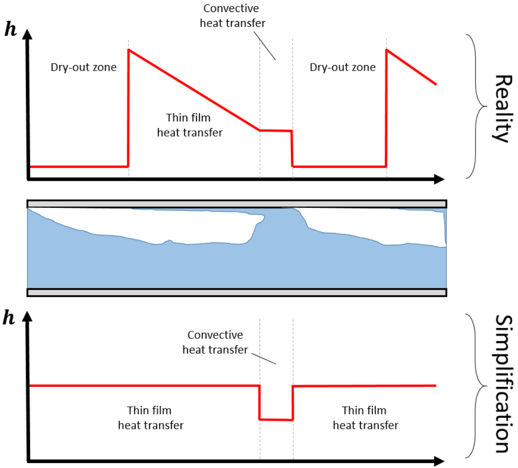
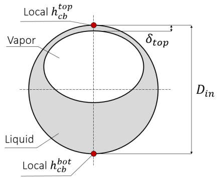


The intermittent liquid film wetting the upper wall is responsible for this effect

- In S_3, positive stratification is observed only for S or SW-S flows
- Most of the tests highlight inverse thermal stratification

Mechanistic model description





- At the top, liquid film HTC [Kattan 1996]

$$h_{cb}^{top} = 0.0133 \left(\frac{\rho_l u_{top} \delta_{top}}{\mu_l} \right)^{0.69} Pr_l^{0.4} \frac{k_l}{\delta_{top}}$$

- At the bottom, bulk liquid HTC [Dittus-B. 1930]

$$h_{cb}^{bot} = 0.023 \left(\frac{\rho_l u_{bot} D_{in}}{\mu_l} \right)^{0.8} Pr_l^{0.4} \frac{k_l}{D_{in}}$$

- The resulting ratio

$$h^* = 0.59 \left(\frac{\mu_l}{\rho_l} \right)^{0.11} \frac{u_{top}^{0.69}}{u_{bot}^{0.8}} \frac{D_{in}^{0.2}}{\delta_{top}^{0.31}}$$

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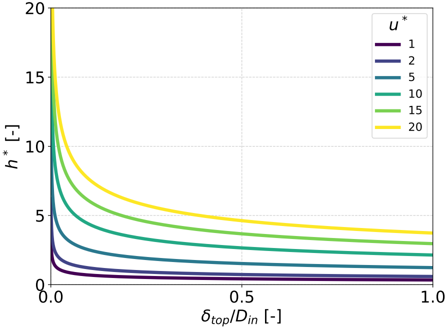
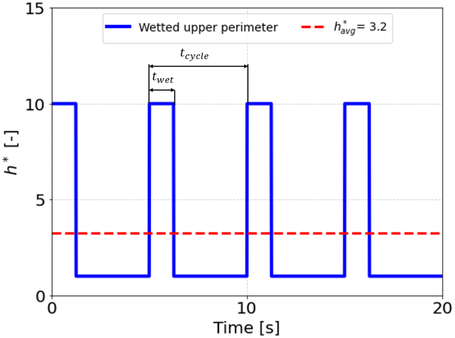
Mechanistic model description



- Thin films lead to high h^*
- Especially for large u^*

- Velocity assumptions
  - $u_{bot} \sim u_{in}$, $u_{top} \sim u_v$, $u^* = u_v / u_{in}$
- Intermittent wetting



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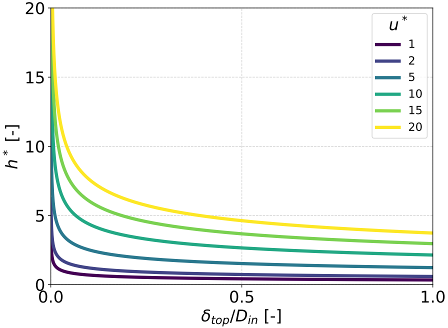
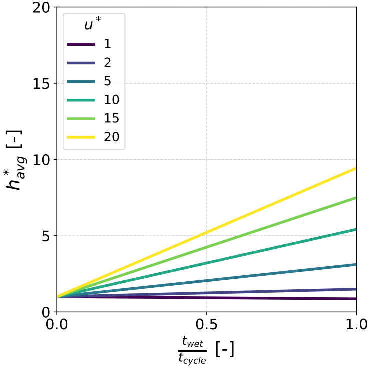


- Thin films lead to high h^*
- Especially for large u^*

- Velocity assumptions
  - $u_{\text{bot}} \sim u_{\text{in}},\ u_{\text{top}} \sim u_v,\ u^* = u_v/u_{\text{in}}$
- Intermittent wetting
- Assuming a film thickness ($\delta_{\text{top}}/D_{in} = 0.05$)



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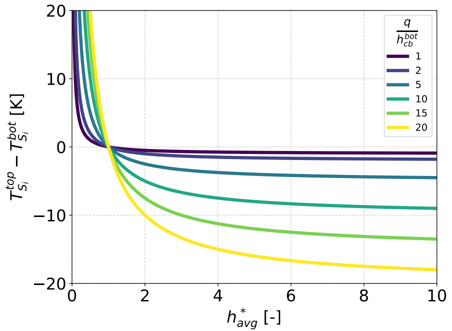
Temperature difference estimation

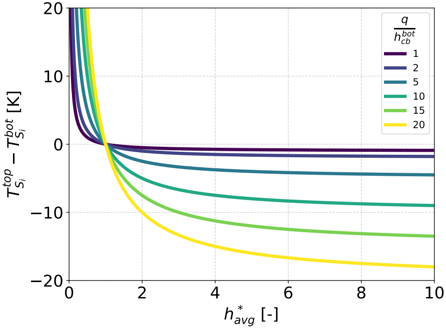


- Assuming a steady thermal resistance network

$$T^{top}_{S_i} - T^{bot}_{S_i} \approx \dot{q}\left(\frac{1}{h^{top}_{cb}} - \frac{1}{h^{bot}_{cb}}\right) \approx \frac{\dot{q}}{h^{bot}_{cb}}\left(\frac{1 - h^*_{avg}}{h^*_{avg}}\right)$$

- Large h^*_{avg} and $\dot{q}$ lead to inverse stratification
- Comparison possible with the intermittent regime (32 points) u_{in}, u_v, t_{wet}, t_{cycle}, δ_{top}

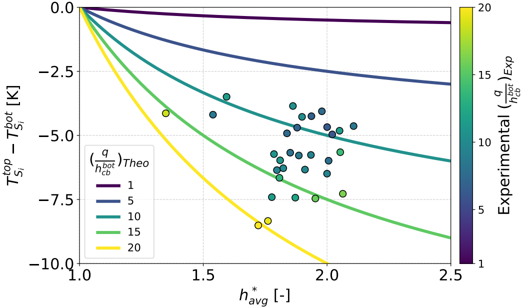
Temperature difference estimation



- Large h^*_{avg} and $\dot{q}$ lead to inverse stratification
- Comparison possible with the intermittent regime (32 points) u_{in}, u_{v}, t_{wet}, t_{cycle}, δ_{top}

- Assuming a steady thermal resistance network

$$T_{S_i}^{\text{top}} - T_{S_i}^{\text{bot}} \approx \dot{q}\left(\frac{1}{h_{cb}^{\text{top}}} - \frac{1}{h_{cb}^{\text{bot}}}\right) \approx \frac{\dot{q}}{h_{cb}^{\text{bot}}}\left(\frac{1 - h^*_{\text{avg}}}{h^*_{\text{avg}}}\right)$$



- Error minimization yields $\delta_{top} = 0.2\ mm$
- [Aussilous and Queré - PoF - 2000]

1. Context
2. Experimental facility and data curation
3. Results and discussion
4. Conclusions & perspectives

Conclusion

- The ConBo facility allows comprehensive boiling flow analysis
- Image processing allows pattern identification and physical parameter assessment
- Heat transfer analysis enables :
  - Dryout inception characterization
  - Proposition of a new correlation for HTC
  - Understanding the role of intermittent film wetting

Perspectives

- Enhancement of the instrumentation (Wire-mesh sensor HZDR)
- Effect of tube diameter ($D_{in} = 50 \rightleftarrows 35$ mm)
- Deepening the physical analysis

Thank you for your attention !

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