Evaluation of applicability and limitations of existing scaling techniques: Advanced methods for the assessment of distortions

EDF R&D
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Summary

1. Scaling applications at EDF R&D
2. Advanced Scaling with CFD code
3. Conclusion

1.

Scaling applications at EDF R&D

More than a design tool

Scaling at EDF R&D

Experimental facility design

To ensure that phenomena of interest are reproduced to be experimentally investigated.

Historical application of “scaling” and main application.

Understanding

Advanced scaling methods provide a powerful framework to quantify the relevance of phenomena and their influence on interest figure of merits.

Systematic and quantitative framework to investigate complex systems.

Scaling as an understanding tool

Example of two-phase flow instability in natural circulation loop

P. Boyer, PHD Thesis (2024)

Sun-Kyu Yang (2014)

- **Lot of experiments at different scale**

Manera et al. (2003, 2005)

- **Lot of different observations**

Manthey et al. (2019)

And much more …

Direct comparison

- Widespread zoology of instabilities
  Not clear. Not consistent.
- Limited comparison between different experiments

Dené et al https://doi.org/10.1016/j.nucengdes.2024.113279

Advanced scaling method

- Quantitative and objective classification based on dominant phenomena
- Universal framework for various experimental data comparison

2.

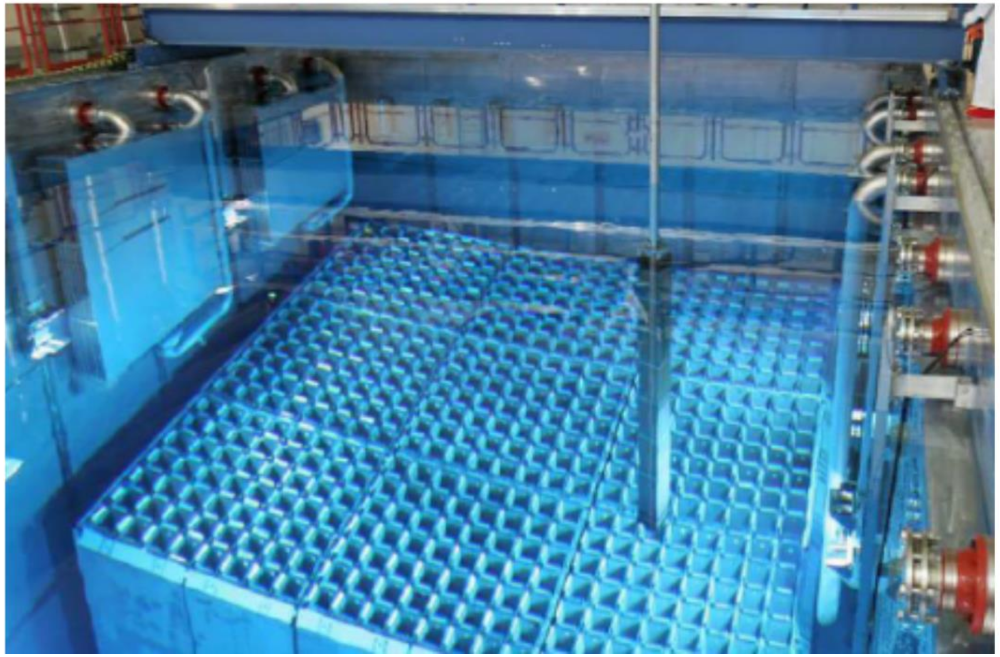
Advanced scaling with CFD code

Going beyond the System Scale

Use case : immerged exchanger in spent fuel pool

Reasons for choosing this application case for a scaling exercise:

- Passive system
- Well known phenomenology (single phase natural convection)
- Available input data
- Experimental facility scaling is known:
  Reynolds and Grashof similarity (Zvirin model)



Gösgen Power Plant (Switzerland): Spent Fuel Pool

Advanced scaling with CFD code

Inputs

- CFD input deck of experimental facility (reduced scale)
- CFD input deck of the prototype (full scale)

Study Objectives

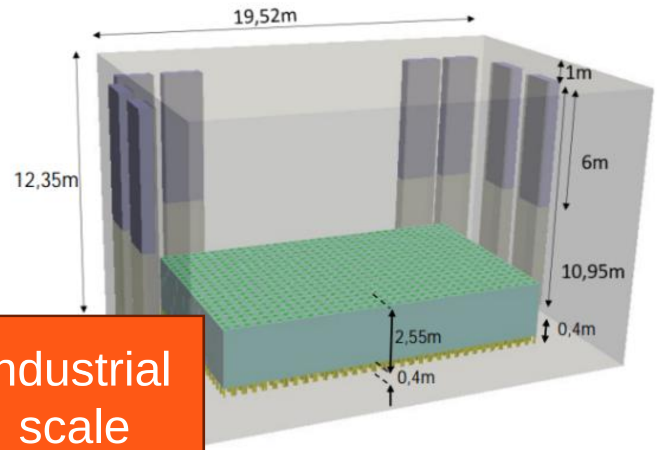
- Application cases of the H2TS method
- Compatibility of the method with a 3D CFD code
- Identification of best practices
- A posteriori critical analysis of design choice

Advanced scaling method : H2TS (similar to FSA)

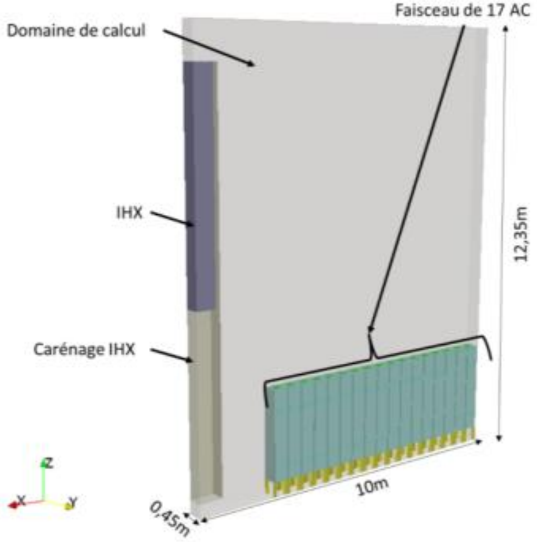
+ Main assumptions

- Physical models are valid and scalable
- CFD code (mesh, model and solver) is scalable

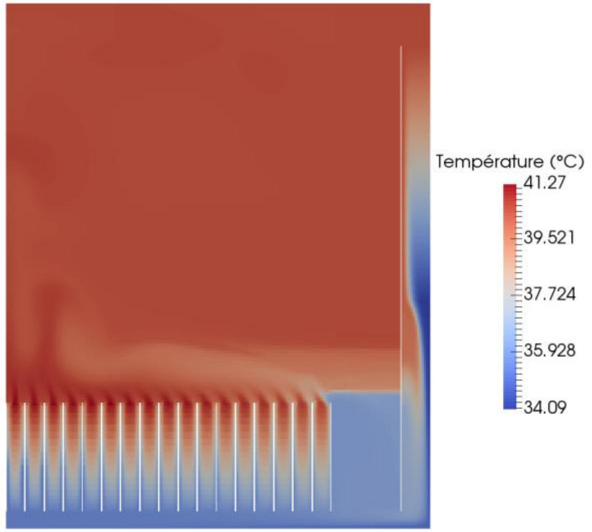
Numerical configuration



Industrial scale

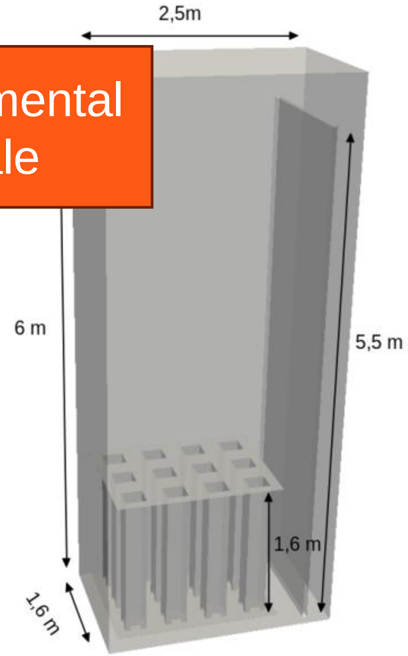


code.saturne



2 CFD models:

Experimental scale



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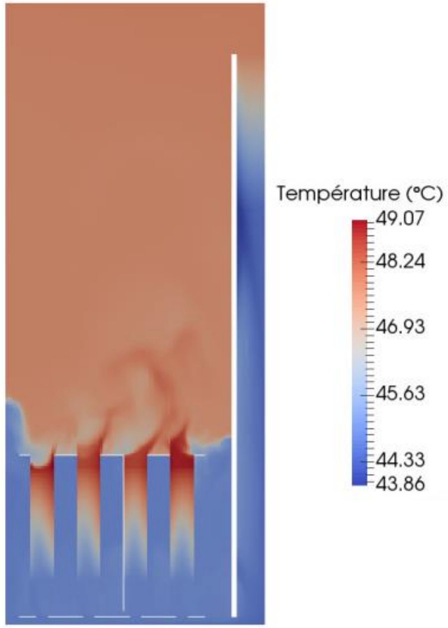
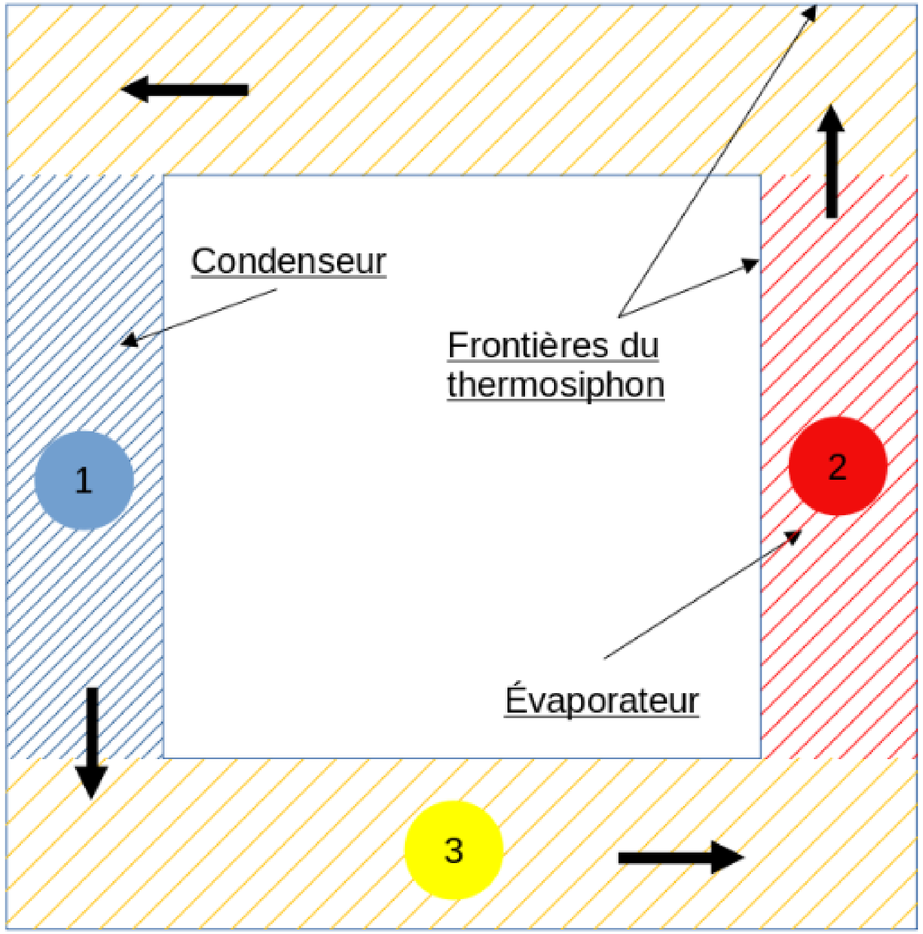
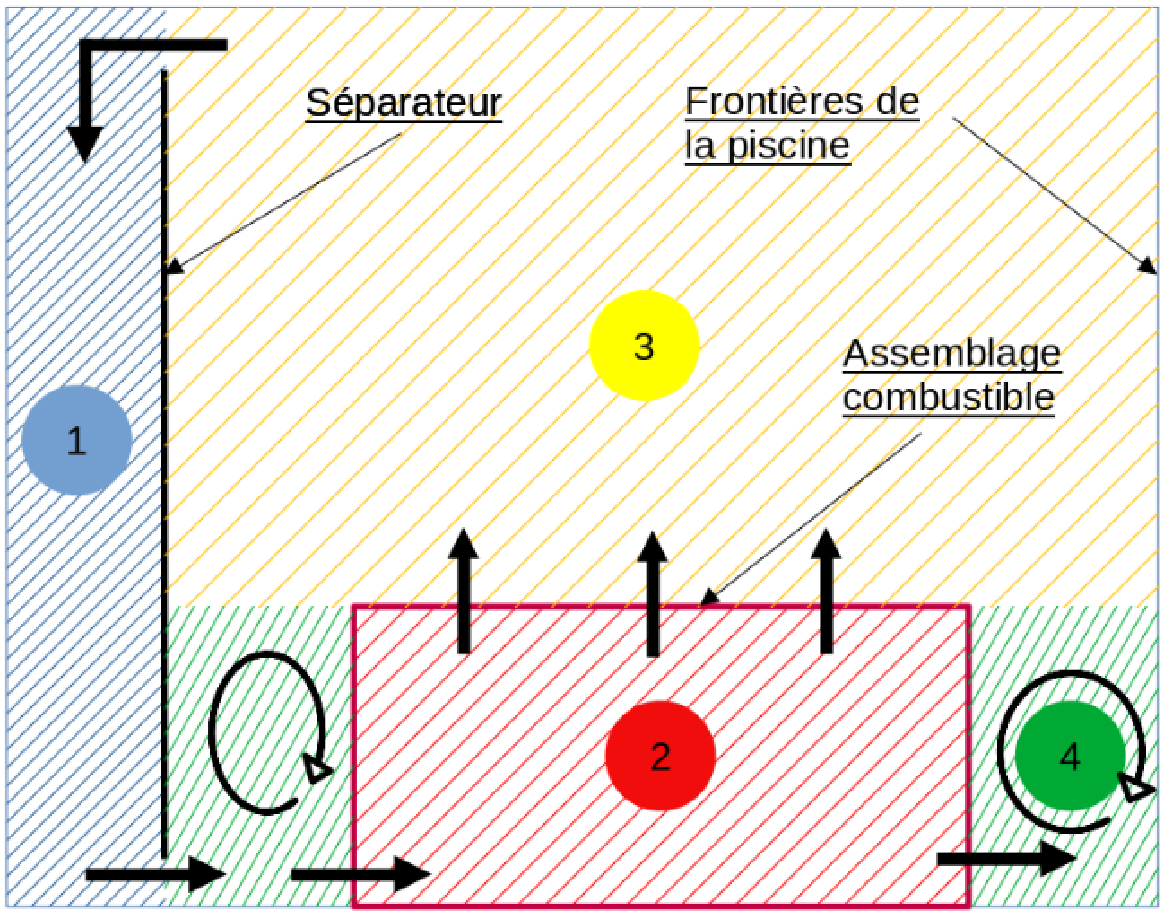


- Natural convection in a pool
- Submerged heat exchangers
- Imposed heating power
- RANS model : k - ω

Thermosiphon analogy



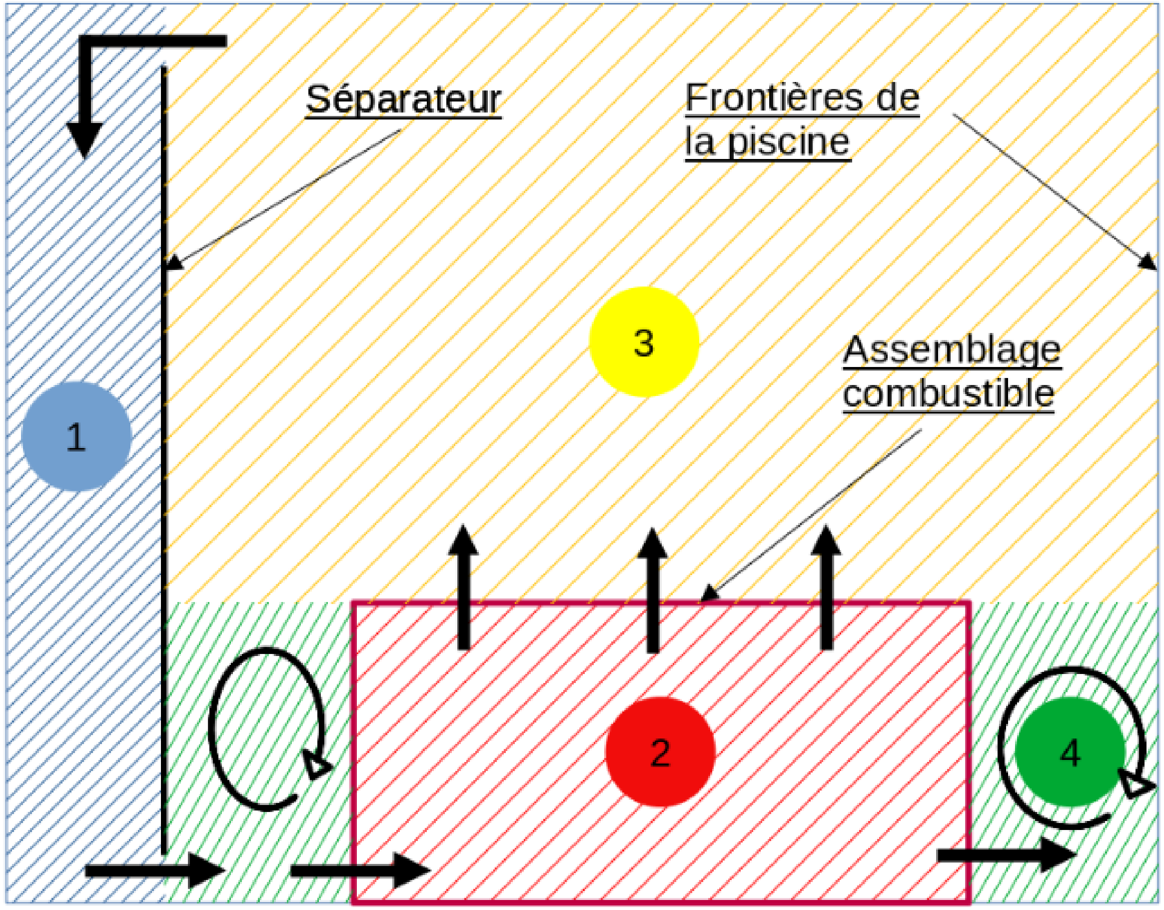


Calculation of the variables of interest using CFD

Control volumes

In order to calculate average values at the input and output of each zone, it is necessary to define volumes

- Several choices are possible
- Each choice modifies the results
- It's a user choice



H2TS method and π-groups

Local approach

The number $\boldsymbol{\pi_{\phi,i\,k}}$ allows quantifying the effect of the phenomenon **k** on a quantity $\boldsymbol{\phi}$ in volume **i**.

- Local $\boldsymbol{\pi}$-groups provide information on **the local contribution of each phenomenon** to mass, momentum and energy balances.

Groupe-π	Phénomène	IHX (1)	AC (2)	Bulk (3)	Bi-passe (4)
$\pi_{\rho,i,\text{vap}}$	Évaporation	0	0	$-\frac{\dot{m}_{lv}}{[SU\rho]_{in}}$	0
$\pi_{\rho U,i,g}$	Gravité	$\frac{gS_1Z_1\rho_{1,moy}}{[S\rho U^2]_{in}}$	$-\frac{gS_2Z_2\rho_{2,moy}}{[S\rho U^2]_{in}}$	$-\frac{gS_3Z_3\rho_{3,moy}}{[S\rho U^2]_{in}}$	$-\frac{gS_4Z_4\rho_{4,moy}}{[S\rho U^2]_{in}}$
$\pi_{\rho U,i,\text{pdc}}$	Friction	$\frac{S_1\Delta P_{dyn}}{[S\rho U^2]_{in}}$	$\frac{S_2\Delta P_{dyn}}{[S\rho U^2]_{in}}$	$\frac{S_3\Delta P_{dyn}}{[S\rho U^2]_{in}}$	$\frac{S_4\Delta P_{dyn}}{[S\rho U^2]_{in}}$
$\pi_{\rho C_P T,i,\text{ech}}$	Échange paroi/air	$-\frac{S_{IHX}\Phi_{IHX}}{[\rho UC_PST]_{in}}$	$\frac{P_{th,AC}}{[\rho UC_PST]_{in}}$	$-\frac{S_3\Phi_{HL}}{[\rho UC_PST]_{in}}$	0
$\pi_{\rho C_P T,i,\text{vap}}$	Évaporation	0	0	$-\frac{\Delta h\dot{m}_v}{[\rho UC_PST]_{in}}$	0
$\pi_{\rho C_P T,i,\text{cond}}$	Conduction (liq.)	$-\frac{\lambda S_1\Delta T_1}{H_1[\rho UC_PST]_{in}}$	$-\frac{\lambda S_2\Delta T_2}{H_2[\rho UC_PST]_{in}}$	$-\frac{\lambda S_3\Delta T_3}{H_3[\rho UC_PST]_{in}}$	$-\frac{\lambda S_4\Delta T_4}{H_4[\rho UC_PST]_{in}}$

H2TS method and Π-groups

Global approach

In the H2TS method, a well-defined procedure makes it possible to move up from the global scale towards the **system scale** by weighting the π groups by the effective volume of each component.

- This approach allows for prioritizing the weight of each component on the system
- It allows the comparison of global Π-groups to characterize the overall functioning of the system at different scales.

Groupe-π	Phénomène	IHX (1)	AC (2)	Bulk (3)	Bi-passe (4)
$\Pi_{\rho,i,\mathrm{vap}}$	Évaporation	0	0	$-\frac{\dot{m}_{1_v}}{[SU\rho]_1}$	0
$\Pi_{\rho U,i,g}$	Gravité	$\frac{gZ_1\rho_{1,moy}}{\Delta P_{IHX}}$	$-\frac{gZ_2\rho_{2,moy}}{\Delta P_{IHX}}$	$-\frac{gZ_3\rho_{3,moy}}{\Delta P_{IHX}}$	$-\frac{gZ_4\rho_{4,moy}}{\Delta P_{IHX}}$
$\Pi_{\rho U,i,\mathrm{pdc}}$	Friction	$\frac{\Delta P_{dyn}}{\Delta P_{IHX}}$	$\frac{\Delta P_{dyn}}{\Delta P_{IHX}}$	$\frac{\Delta P_{dyn}}{\Delta P_{IHX}}$	$\frac{\Delta P_{dyn}}{\Delta P_{IHX}}$
$\Pi_{\rho C_P T,i,\mathrm{ech}}$	Échange paroi/air	$-\frac{S_{IHX}\Phi_{IHX}}{P_{th,AC}}$	1	$-\frac{S_3\Phi_{HL}}{P_{th,AC}}$	0
$\Pi_{\rho C_P T,i,\mathrm{vap}}$	Évaporation	0	0	$-\frac{\Delta h\dot{m}_v}{P_{th,AC}}$	0
$\Pi_{\rho C_P T,i,\mathrm{cond}}$	Conduction (liq.)	$-\frac{\lambda S_1\Delta T_1}{H_1P_{th,AC}}$	$-\frac{\lambda S_2\Delta T_2}{H_2P_{th,AC}}$	$-\frac{\lambda S_3\Delta T_3}{H_3P_{th,AC}}$	$-\frac{\lambda S_4\Delta T_4}{H_4P_{th,AC}}$

Conclusion of this exercise

Points of attention related to the application of the H2TS method:

- The definition of control volumes (more complex when multiple flow paths are present and less suitable for components with large volumes);
- The scaling of boundary conditions;
- The selection of balance equations;
- The choice of quantities used to nondimensionalize the balance equations;
- The post-processing of averaged quantities (more challenging with high-fidelity CFD codes than with system or component codes).

The quality of the results is limited by:

- The **validation** of the simulation code used;
- The consistency of the models applied at different scales
  Ex : primarily mesh, turbulence model, code scalability

The H2TS method helps structure the approach, but it is not self-sufficient; **user choices have a significant impact** on the quality and relevance of the results.

EDF R&D intends to investigate additional applications of the H2TS/FSA method to confirm these findings.

Conclusion

The maturity level of scaling methods is progressing towards industrial applications.

There is still a long way to go.

Main technical points still to be addressed:

- Code scalability
- Practical application of scaling methods
- From distortion metrics to effect on FoM

Challenges and needs identified by EDF R&D:

- Guidelines and internal expertise
- Specific post-processing tool
- Raise user awareness of the limitations of both codes and methodology

References

General report on scaling including advanced methods:
OCDE-NEA 2016 Report

H2TS and FSA:
Zuber et al. (1998)
Zuber et al. (2007)

Example of natural circulation scaling:
Roberto et al. (2023)

Code_saturne
Archambeau et al 2004

EDF R&D research on two-phase flow instability :
Dené et al (2024)

Merci

EDF R&D

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