Scale Effects and Thermal-Hydraulics: Application to French SFR

Mr. Benjamin Jourdy
CEA, France

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Meet the Presenter

Mr. Benjamin Jourdy graduated in 2019 from the Ecole Centrale de Marseille in the field of Materials & Structure Mechanics. During his studies, he worked part-time for the French Atomic Energy and Alternative Energy Commission (CEA) at Cadarache as an apprentice on the dynamic response of fuel assemblies in PWR under seismic excitation. He designed the instrumental setup of EUDORE, a mock-up with three fuel assemblies at scale 1:2, and performed experimental campaigns in representative conditions of PWR. Now, he is completing his PhD in the field of thermal-hydraulics, on the subject “Scale effects analysis on the thermal hydraulic behaviour of impinging jets in Sodium Fast Reactors”. His PhD focuses on buoyancy effects of the core jets in SFR after impingement of the Upper Core Structure, and their transposition from small-scale mock-ups to the reactor size.

He also won 2nd place in the 2021 Pitch your Gen IV research competition, available at: https://www.youtube.com/watch?v=XwM4eC-K2lg

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Tests on Small-scale Experiments:

What are the Issues in a Multiphysics Problem ?

Scale Effects : Definition

- "Distortion of physical phenomena between a downscaled mock-up and a full-scaled prototype"

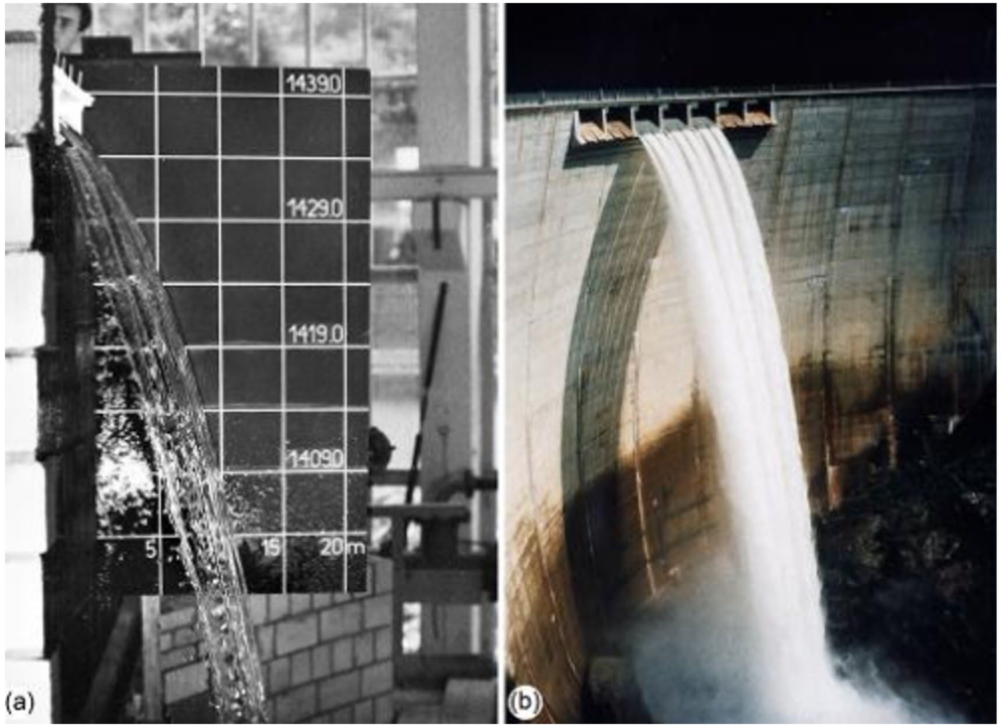
- Come from the variation of the length L:
  - Area are multiplied by L^2 (important for friction forces)
  - Volumes are multiplied by L^3 (important for mass / inertia)

- Example in nature:
  - Mouse: Size L, area L^2, volume L^3
  - Elephant: Size 100 L, area $10^4 L^2$, volume $10^6 L$

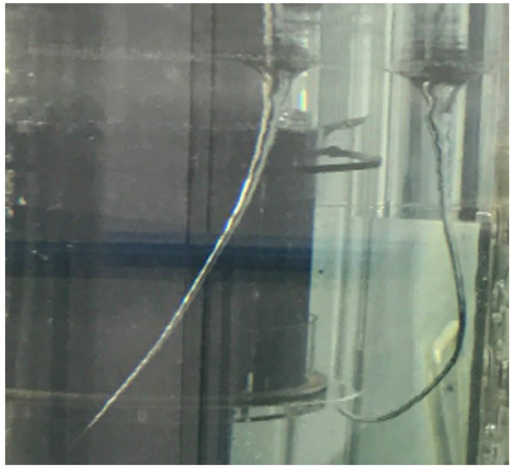
⇨ Surface / Volume 100 times lower for elephant

↳ Mouse has to eat 100 times more than an elephant (relative to weight) to maintain body temperature

Scale Effects: Examples in Fluid Mechanics



Waterfall in similar flow conditions without Weber number conservation (air entrainment), scale 1:30, Heller (2011)



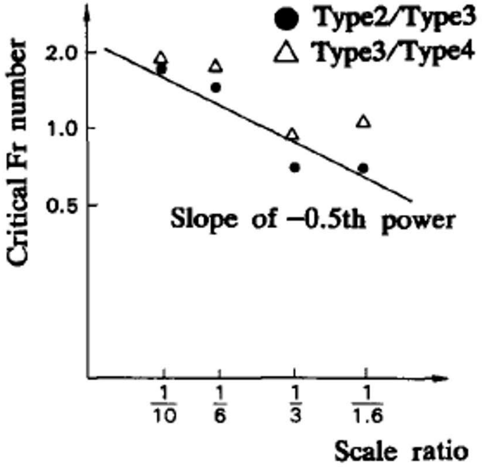


Fig. 9. Scale effect on critical Fr number.

Gas entrainment criterion
Image from Guenadou et al (ICMF 2019)
Study from Eguchi et al (1994)

Scaling in Nuclear: Code Development and Validation

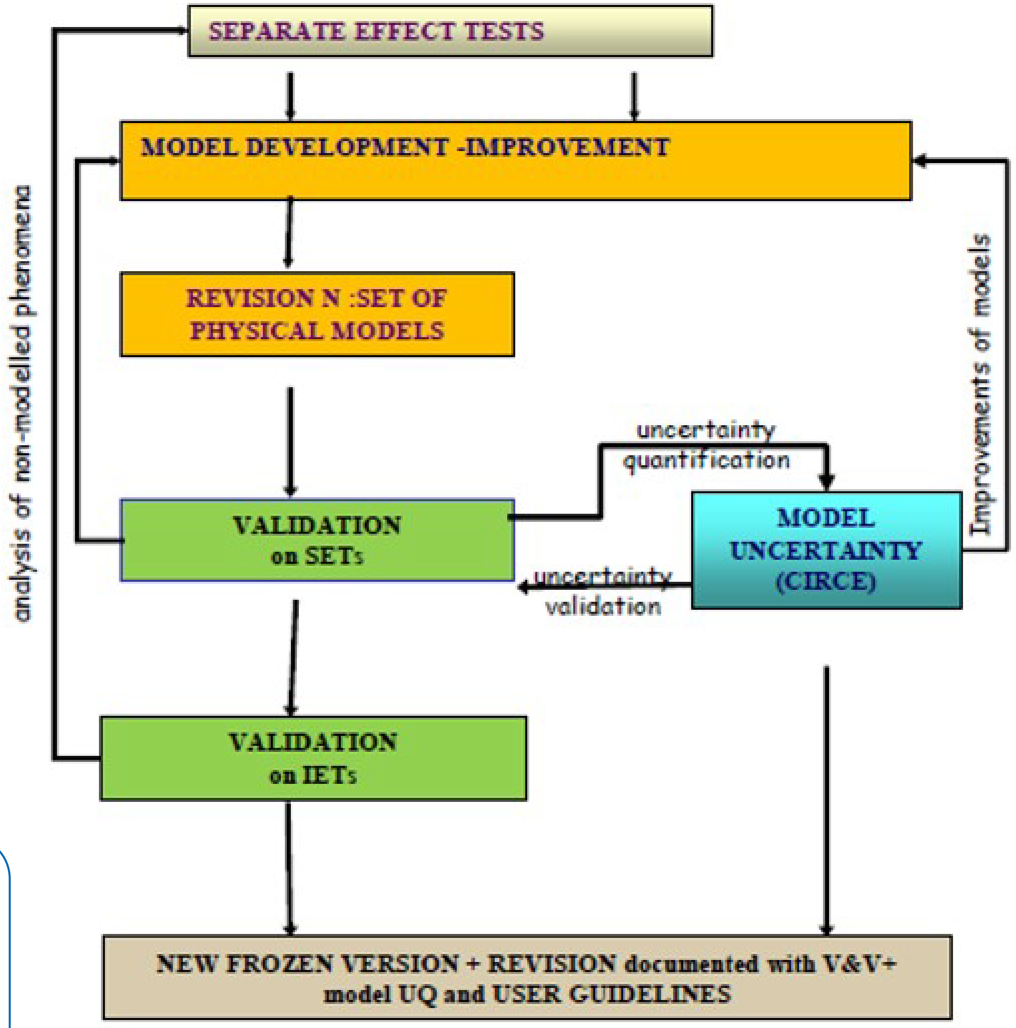
- Nuclear power plant:
  - Complex flow
  - Transient
  - Difficulties to establish closure laws

- Scale 1 reactor for tests only too expensive

⇨ Use of numerical tools for scaling validation

⮡ **Code validation with small-scale experiments**

How to ensure the validity of small scale experiment ?
How to transpose them ?



International School in Nuclear Engineering, Dominique Bestion (2021)

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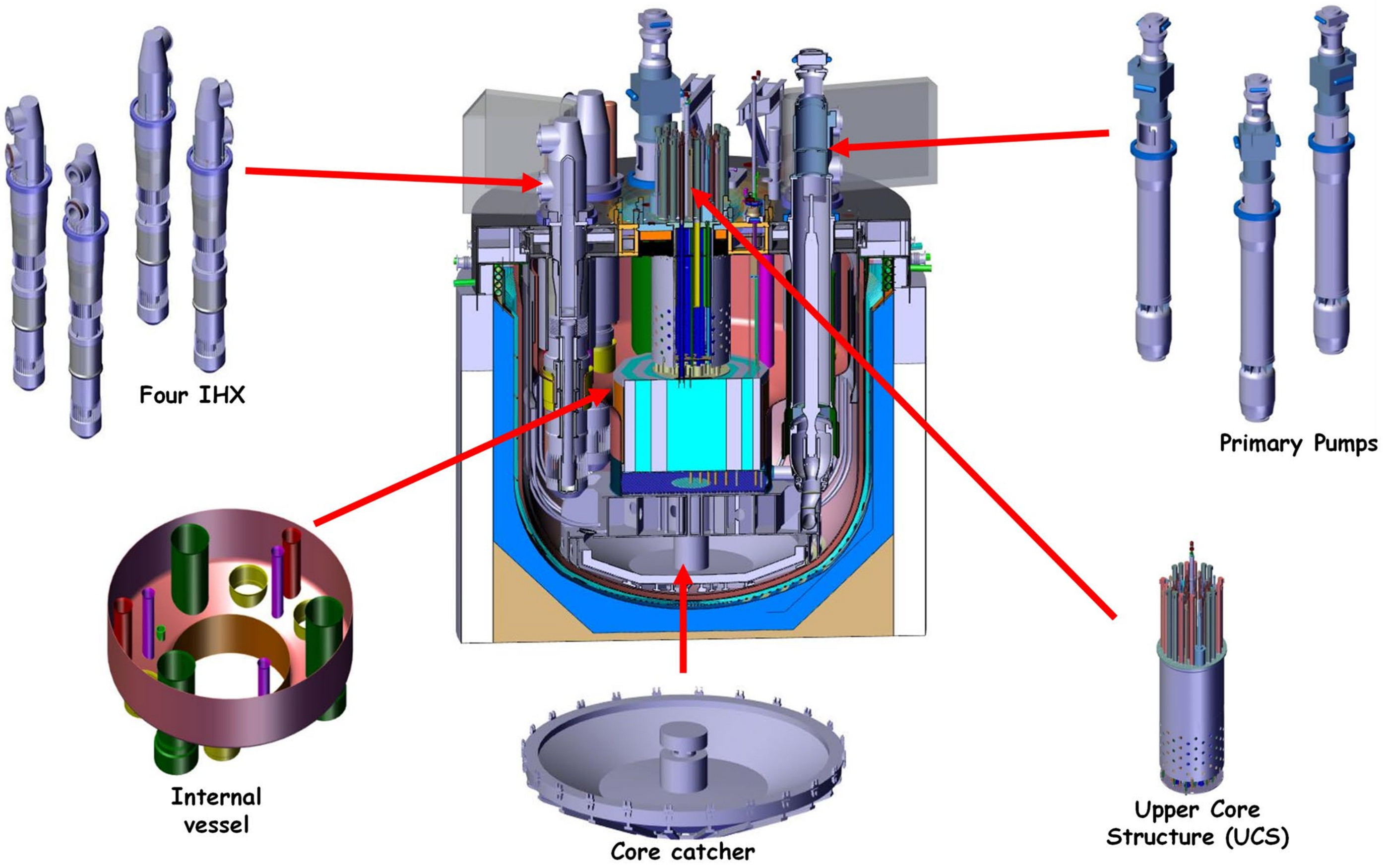
French Sodium-Fast Reactor Problem

French SFR Problem: ASTRID Project

- Advanced Sodium Technological Reactor for Industrial Demonstration
- Launched in 2010
- Stopped in 2019
- Numerical Reactor



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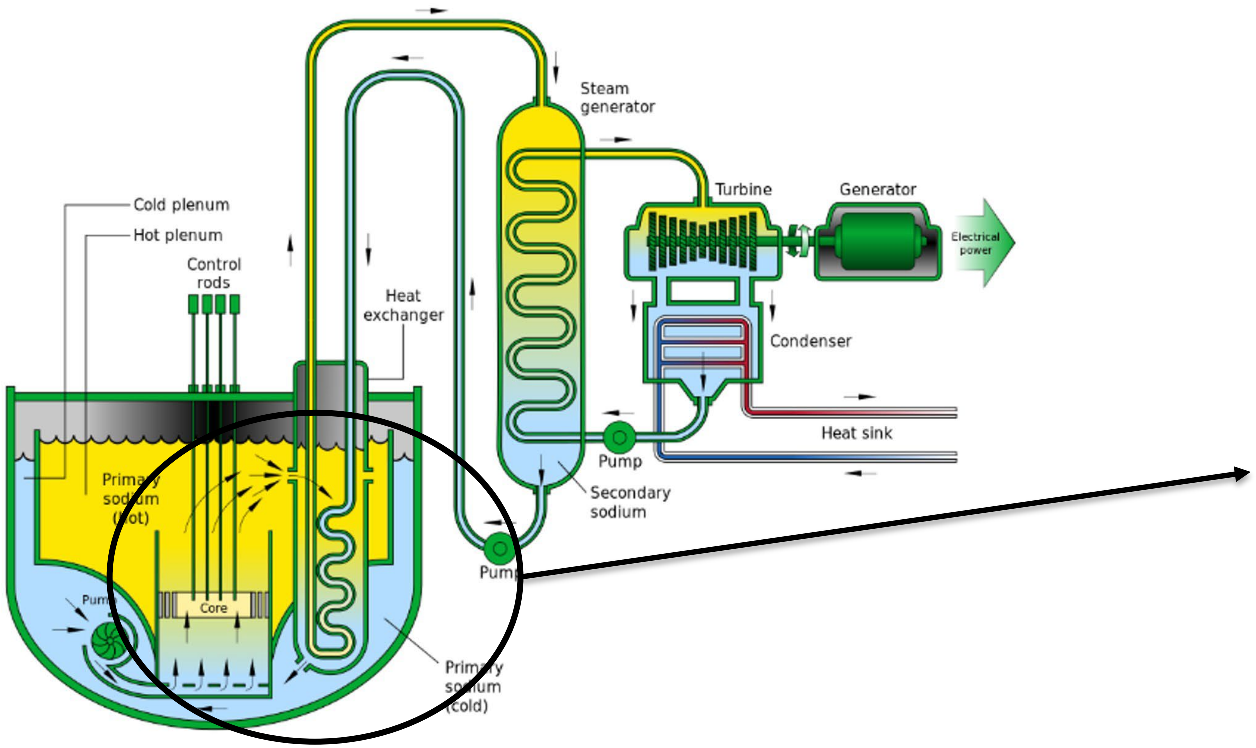
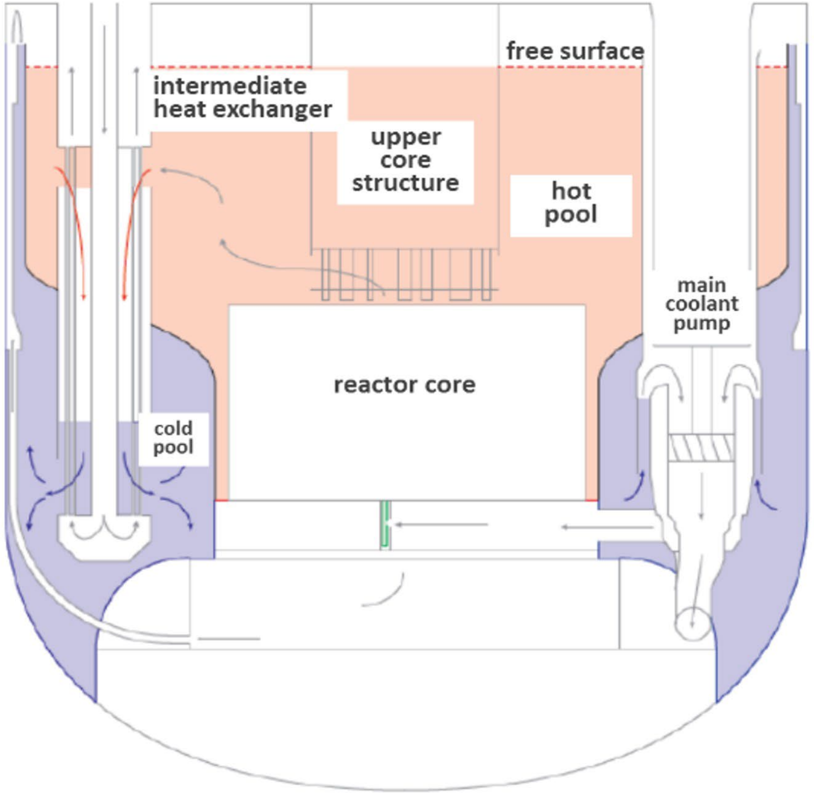
French SFR Problem: ASTRID Project

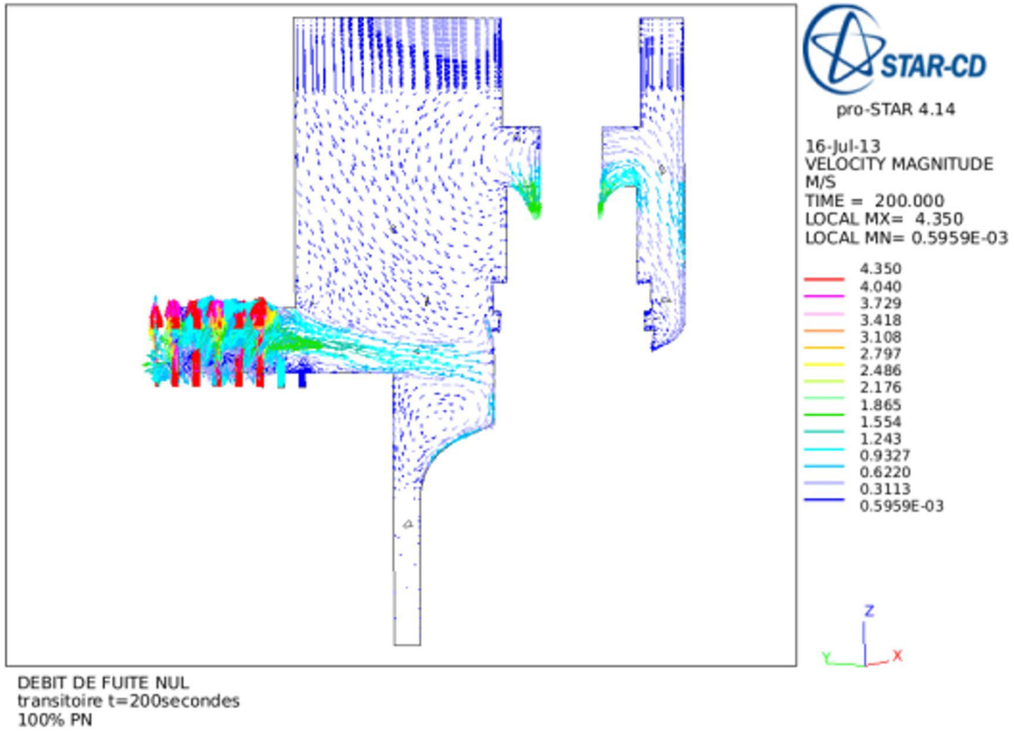
- Hot plenum thermo-hydraulic

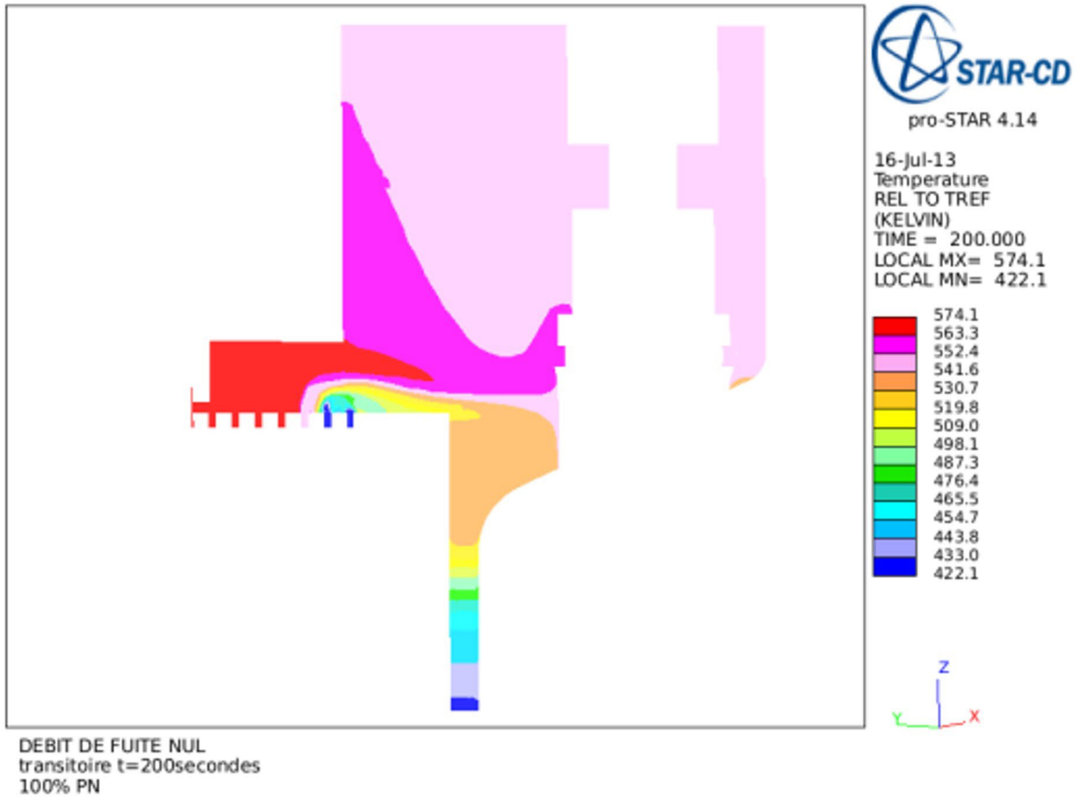




French SFR Problem: ASTRID Project

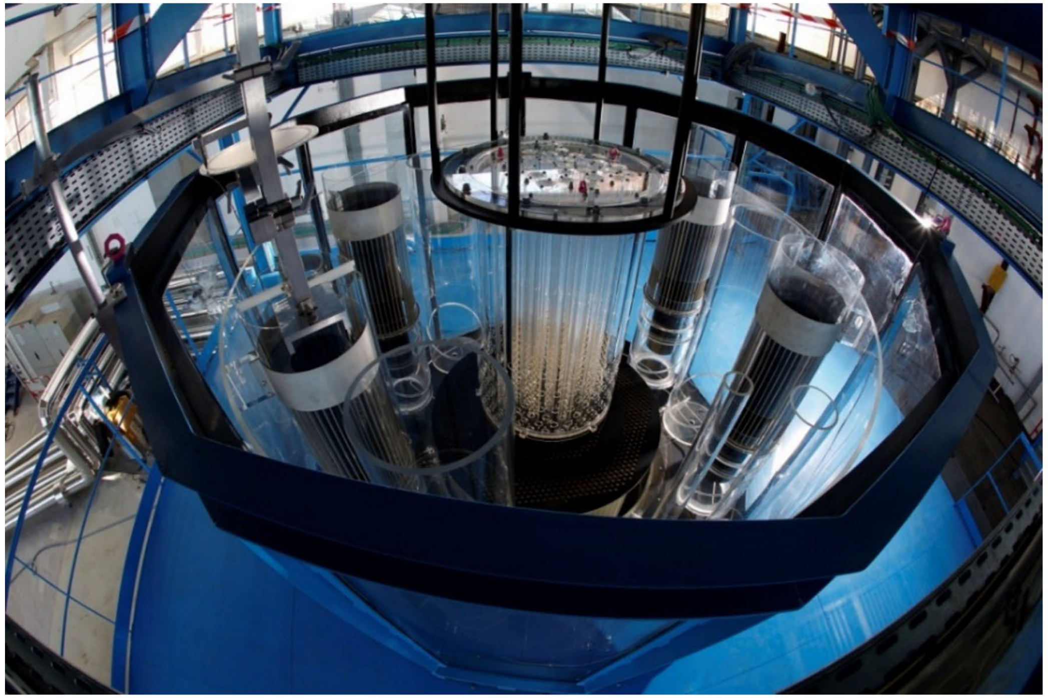
- Numerical simulation: velocity profiles and temperature (Areva, 2013)

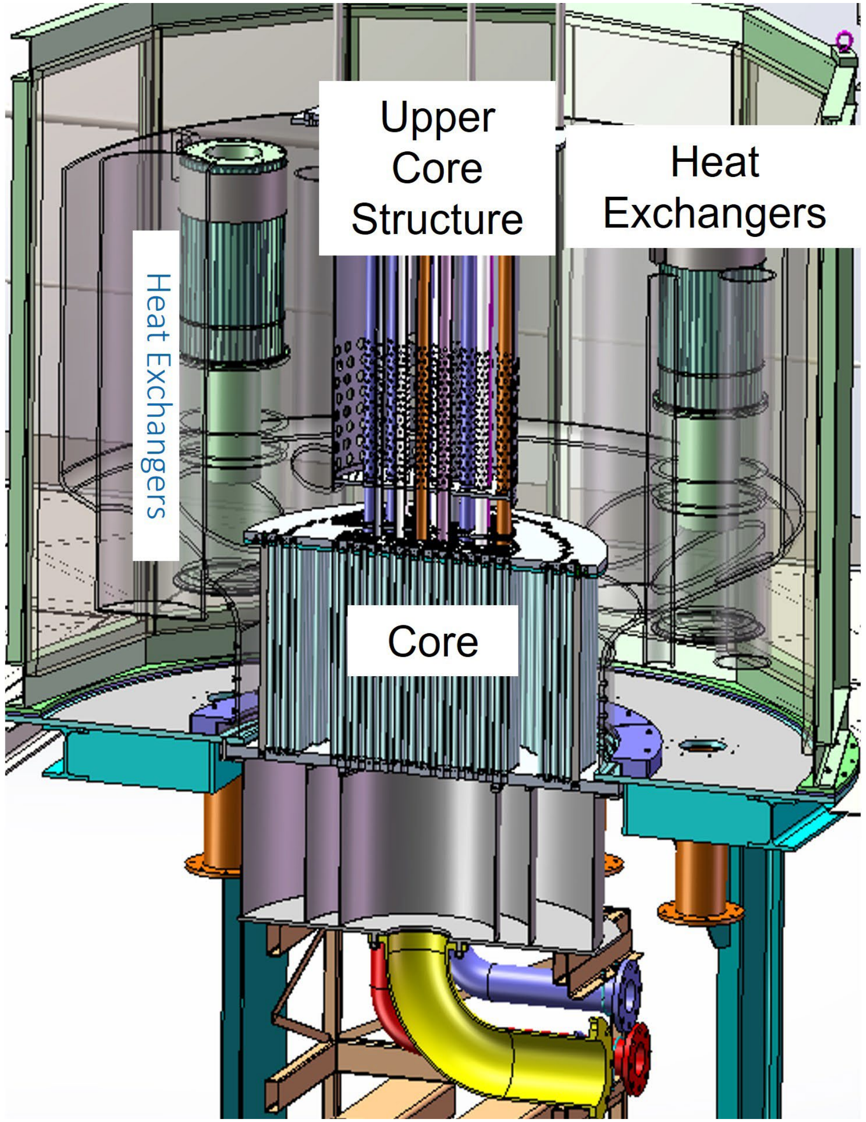




French SFR Problem: MICAS

- Scale 1:6 of the hot plenum
- Homothetic transformation (linear scaling)



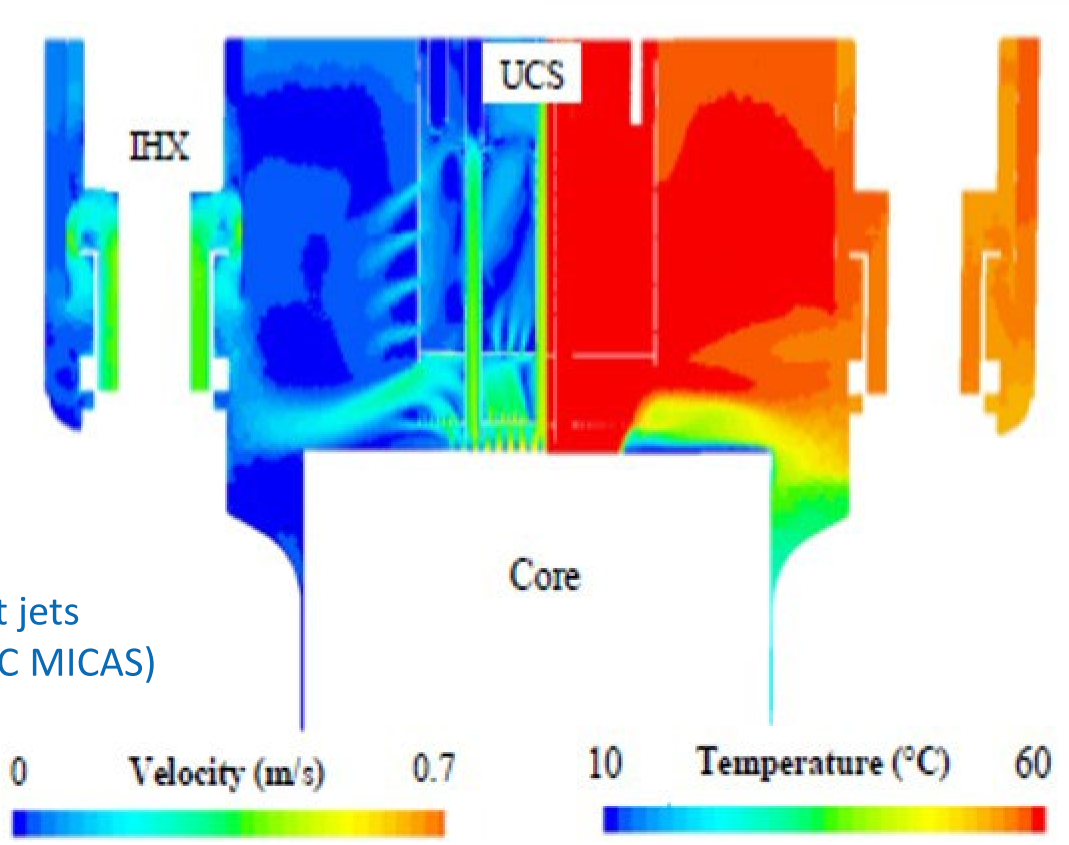


French SFR Problem: Core Jets

Colder environment in the Upper Plenum
(550°C ASTRID – 57°C MICAS)

Out of core: 288 hot jets
(575°C ASTRID - 60°C MICAS)

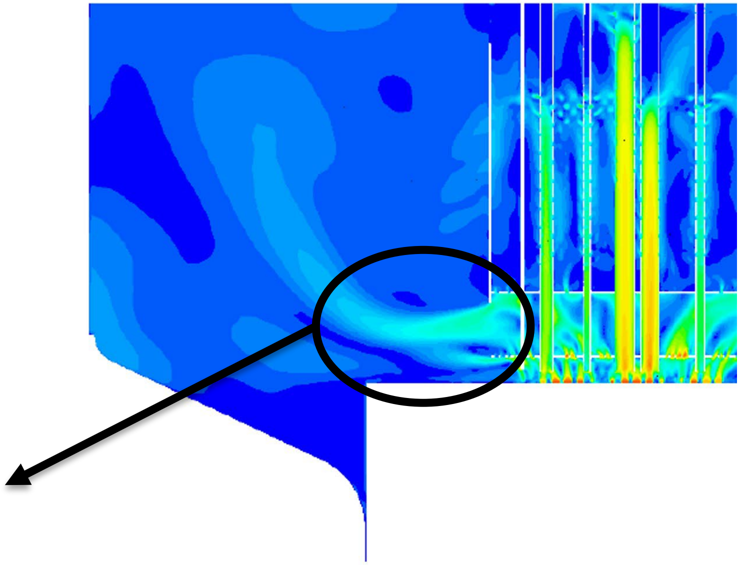
Cold jets
(400°C ASTRID – 10°C MICAS)

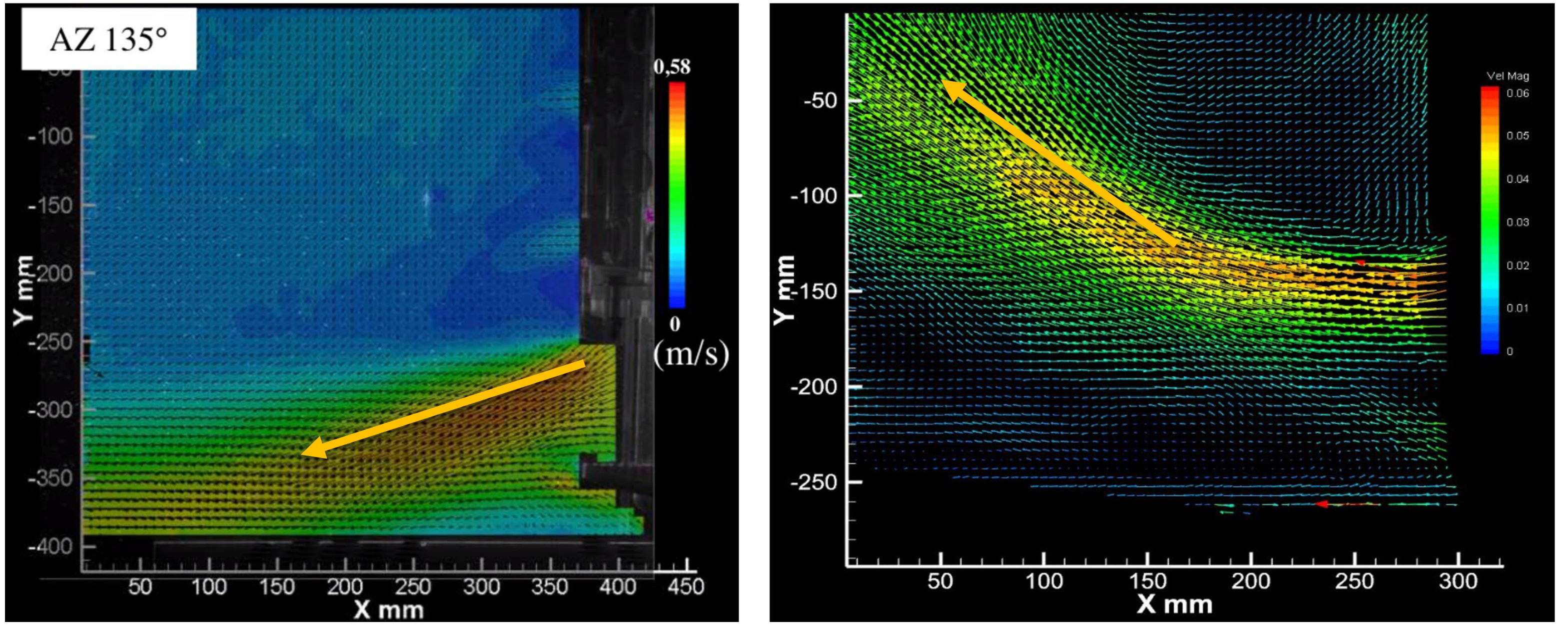


Velocity (left) and temperature (right) fields in the MICAS mock-up (StarCCM)

French SFR Problem: Core Jets

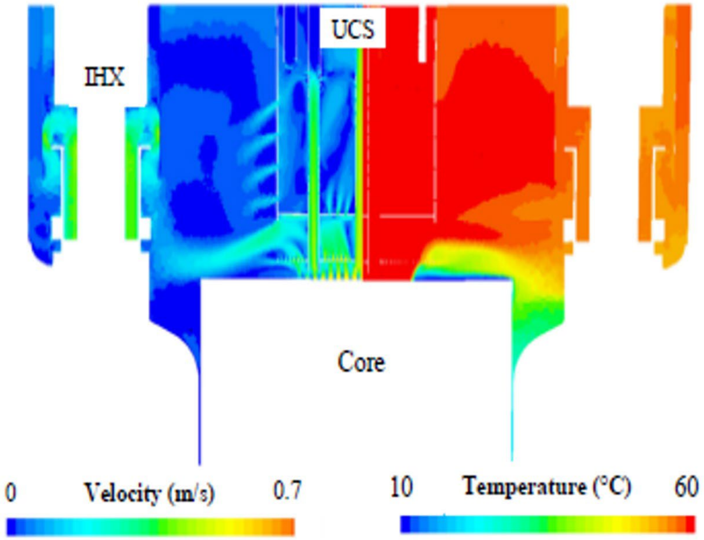
- Low power operating conditions: Rise of the radial jet



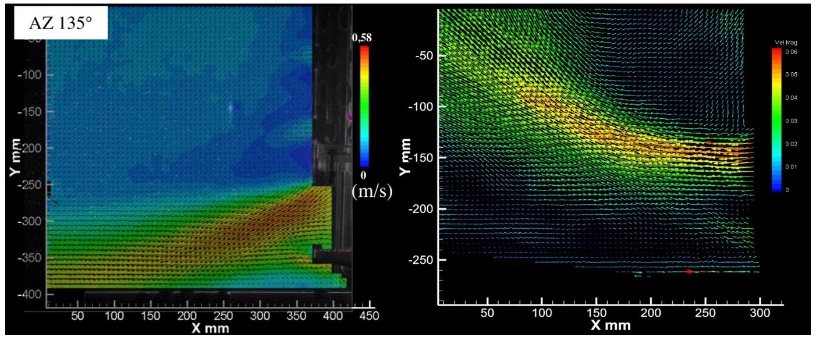


PIV experimental results on MICAS

French SFR Problem: Core Jets



- Consequences:
  - Flow pattern modified
  - Thermal oscillations
  - Thermal stress of the components



- Problem:
  - Issue: Under which conditions does the jet rise ?
  - Transposition from MICAS to ASTRID

→ **Scale effect analysis**

→ **Experimental approach**

Scale Effects: Methods

Scale Effects: Similarity

- Scale model $1{:}\lambda$ completely similar to real-world prototype if it satisfies three criteria (Heller, 2012):
  - Geometric similarity
    - Similar in shape
    - Length, area and volume evolve with λ, λ^2 and λ^3 respectively
  - Kinematic similarity
    - Similarity of motion
    - Constant ratio of time, velocity, acceleration …
  - Dynamic similarity
    - Identical force ratio ⇒ Not **all** force ratio can be preserved

⤷ Dominant force ratio is selected
Others are neglected ⇒ **Scale effects if not negligible**

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Scale Effects: Scaling Techniques

- Target the phenomena at both local and system level
- Local:
  - Dimensional analysis (empirical approach)
    - Correlation and models to derivate similarity parameters
    - Estimation of distortions
  - Dimensionless governing equations (mechanistic approach)
    - Simplify governing equations
    - Comparison of non-dimensional terms between model and prototype
- System:
  - Scaling laws from governing equations
  - Phenomena and process identified and ranked in a PIRT

Dimensional Analysis: Vaschy-Buckingham Theorem

- Simple and direct manner for the formulation of criteria for dynamic similarity
- Physical problem:
  - n independent parameters
  - r reference dimensions (time, temperature, mass, length, …)

⇨ $n - r$ independent dimensionless parameters (geometrical and force ratio)

- Relative importance of dimensionless numbers unknown:
  - Arbitrariness in determining similitude conditions
  - Strongly criticized when $n - r > 6$

Dimensional Analysis: Governing Equations

- Conservation equations:
  - Mass conservation
  - Momentum conservation
  - Energy conservation

$$\frac{\partial U^*}{\partial z^*} + \frac{1}{r^*}\frac{\partial}{\partial r^*}(r^* V^*) = 0$$

- Relative importance of all terms

$$U^*\frac{\partial U^*}{\partial z^*} + V^*\frac{\partial U^*}{\partial r^*} = -\frac{1}{\rho^*}\frac{\partial Eu}{\partial z^*} + \frac{1}{Re}\cdot\frac{1}{r^*}\cdot\frac{\partial}{\partial r^*}\left\{r^*\frac{\partial U^*}{\partial r^*}\right\} - \frac{1}{Fr^2} + \frac{1}{Fr_D^2}$$

- Comparison of force ratio from a scale to another

- Geometric parameters not taken in account

$$\left(U^*\frac{\partial T^*}{\partial z^*} + \frac{V^*}{r^*}\frac{\partial T^*}{\partial r^*}\right) = \frac{1}{Re}\frac{1}{Pr}\frac{1}{r^*}\frac{\partial}{\partial r^*}\left(r^*\frac{\partial T^*}{\partial r^*}\right)$$

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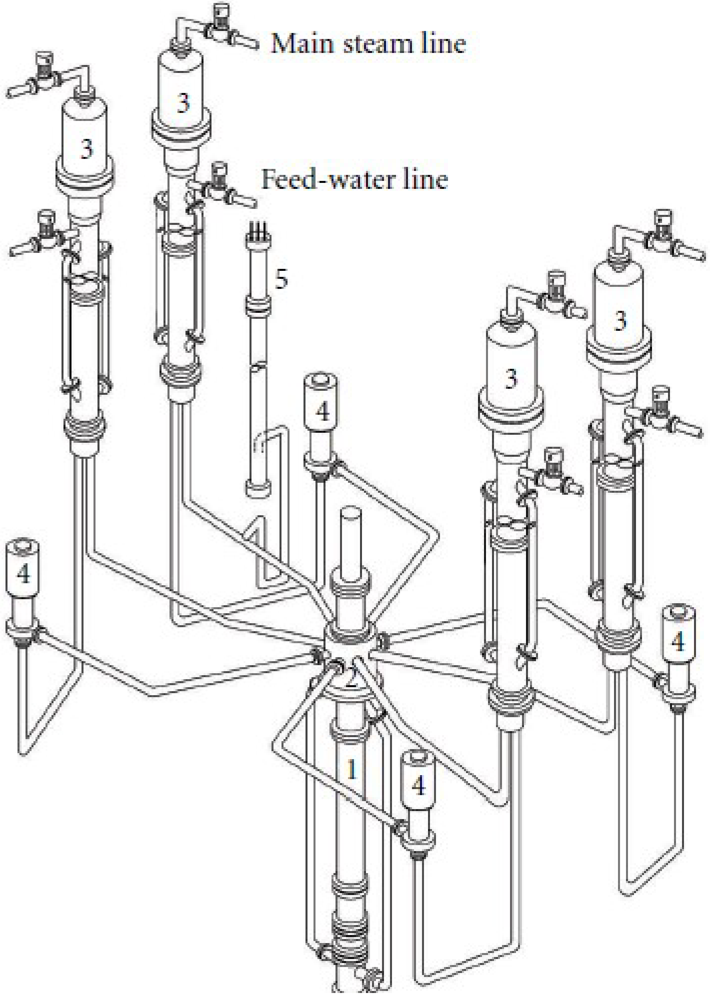
Scale Effects: Scaling Technique Examples

- Linear scaling
  - Same aspect ratio and velocity
  - Can excessively distort gravity effects
- Power-to-Volume scaling (ex: PKL)
  - Conserves time and heat flux
  - No distortion of gravity effects
  - Suitable for accident
  - Other distortions
    - Excessive heat stored in structure
    - Higher heat loss



PKL test facility in Erlangen, Germany
Umminger et al (2011)

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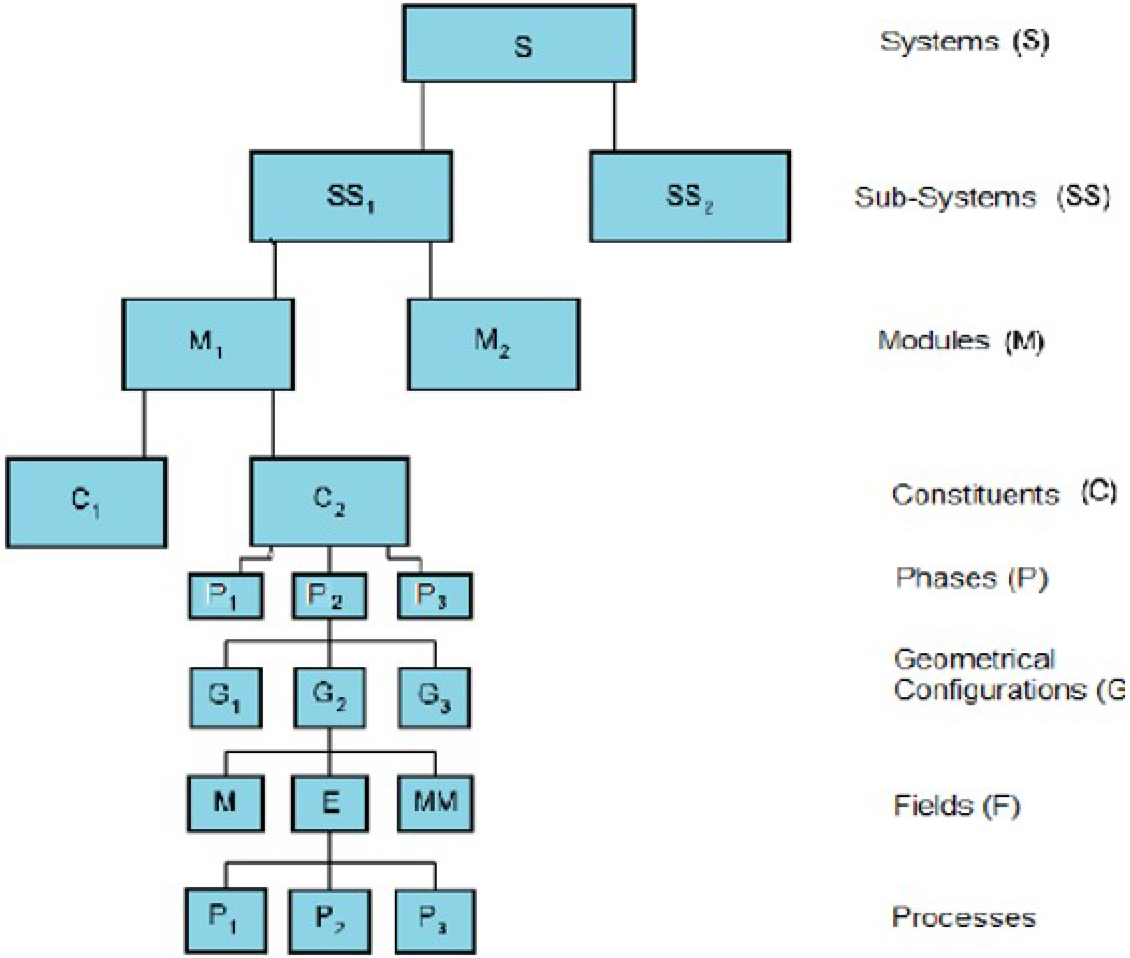
Scale Effects: Scaling Technique Examples

- Hierarchical 2-Tiered Scaling (H2TS)
  - System decomposition
  - Scale identification
    - Volume fraction
    - Spatial scale
    - Temporal scale
  - Top-down analysis
    - Scaling hierarchy
    - Conservation equations
  - Bottom-up analysis
    - Scaling criteria
    - Time constant



H2TS
Zuber et al

Scale Effects: Scaling Technique Examples

- Fractional Scaling Analysis (FSA)
  - Based on “fractional analysis” (Kline, 1986)
  - Analytical approach for complex problems such as economy or ecology
  - Variables influenced by:
    - Convection
    - Diffusion
    - Wave propagation
- Dynamical System Scaling (DSS)
  - Recent innovative approach
  - Address time-dependency of scaling distortion

Experimental Approach for Scale Effects Determination in French SFR

Experimental Approach: General Methodology

- Dimensional analysis
  - Vaschy-Buckingham theorem
  - Dimensionless equations
- Calibration
  - Scale 1 prototype data available
  - If deviation: correction or estimation
- Scale series
  - 3 similar models at different scale
  - Biggest scale = reference scale
  - Quantification of scale effects

General understanding

↓

No ASTRID data available

↓

MICAS = reference scale

↓

Need 2 new mock-ups

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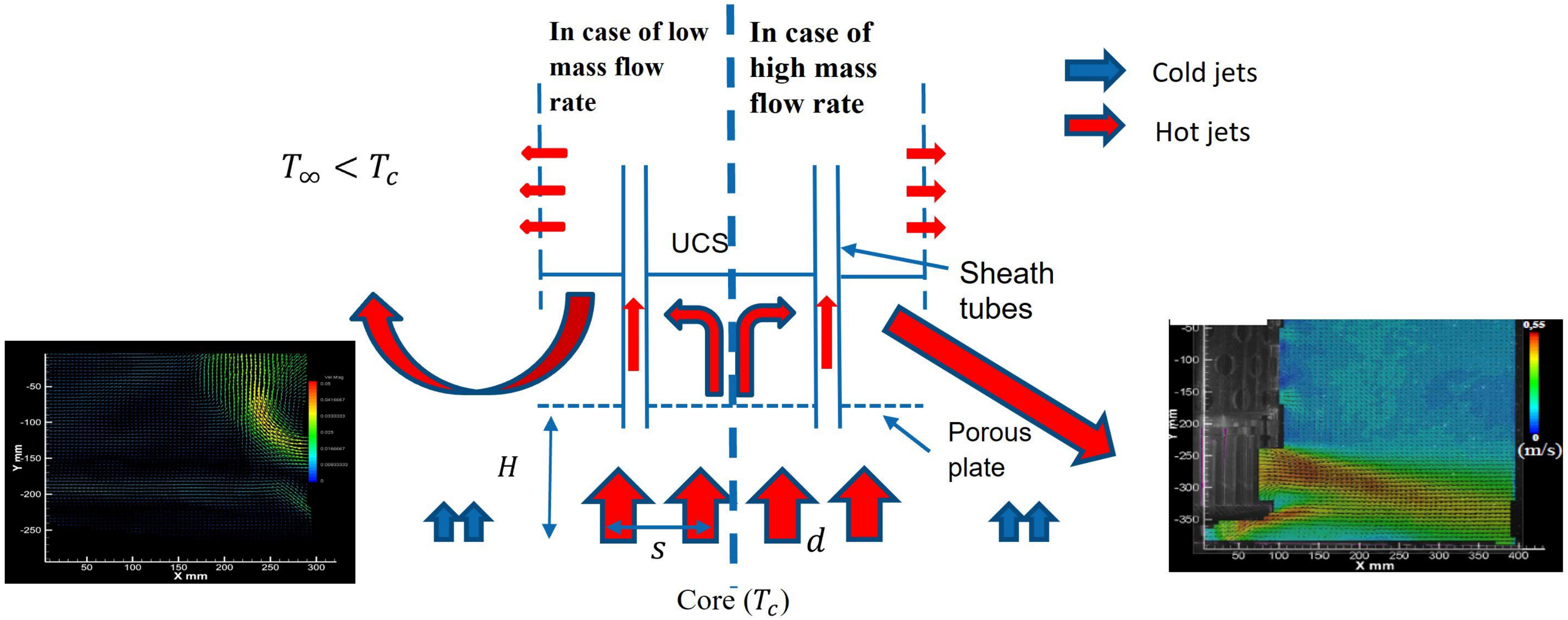
Experimental Approach: Vaschy-Buckingham Theorem



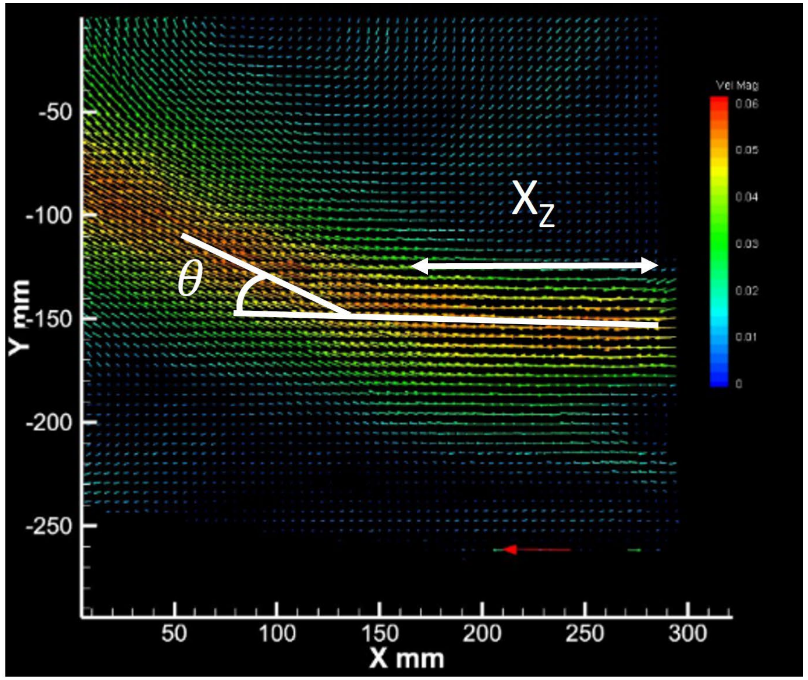
List of the governing parameters

Dimensionless numbers

$\pi_1 = \frac{H}{L}$	$\pi_2 = \frac{p}{\rho.u^2} = Eu$	$\pi_3 = \frac{\eta}{\rho.u.L} = \frac{1}{Re}$
$\pi_4 = \frac{g.L}{u^2} = \frac{1}{Fr^2}$	$\pi_5 = \frac{T - T_\infty}{T_c - T_\infty}$	$\pi_6 = \beta(T_c - T_\infty)$
$\pi_7 = \frac{\alpha}{u.L} = \frac{1}{Pe}$	$\pi_8 = \frac{\rho_\infty - \rho}{\rho_\infty}$	$\pi_9 = \frac{s}{L}$

Experimental Approach: Dimensionless NS Equation

- Vaschy-Buckingham theorem:
  - Expert-dependent on the parameters choice
  - Arbitrariness in the similitude conditions
  - Strongly criticized if n > 6
- Dimensionless Navier-Stokes Equation
  - Stationary
  - Boussinesq approximation



$$\begin{cases} U^*\dfrac{\partial U^*}{\partial z^*} + V^*\dfrac{\partial U^*}{\partial r^*} = \boxed{\dfrac{1}{Re}}\left\{\dfrac{\partial}{r^*\partial r^*}\left(r^*\dfrac{\partial U^*}{\partial r^*}\right) + \dfrac{\partial^2 U^*}{\partial z^{*2}}\right\} - \boxed{\left(\dfrac{1}{Fr^2} + \dfrac{1}{Fr_D^2}\right)}\cos(\theta) \\ U^*\dfrac{\partial V^*}{\partial z^*} + V^*\dfrac{\partial V^*}{\partial r^*} = \boxed{\dfrac{1}{Re}}\left\{\dfrac{\partial}{r^*\partial r^*}\left(r^*\dfrac{\partial V^*}{\partial r^*}\right) + \dfrac{\partial^2 V^*}{\partial z^{*2}}\right\} - \boxed{\left(\dfrac{1}{Fr^2} + \dfrac{1}{Fr_D^2}\right)}\sin(\theta) \end{cases}$$

Viscosity

Buoyancy

$$Re = \frac{\rho\, u_0\, d}{\eta}$$

$$Fr = \frac{u_0}{\sqrt{gd}}$$

$$Fr_D = \frac{u_0}{\sqrt{(\Delta\rho/\rho)gd}}$$

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Experimental Approach: Dominant Dimensionless Number

$\pi_1 = \frac{H}{L}$	$\pi_2 = \frac{p}{\rho . u^2} = Eu$	$\pi_3 = \frac{\eta}{\rho . u . L} = \frac{1}{Re}$
$\pi_4 = \frac{g . L}{u^2} = \frac{1}{Fr^2}$	$\pi_5 = \frac{T - T_\infty}{T_c - T_\infty}$	$\pi_6 = \beta (T_c - T_\infty)$
$\pi_7 = \frac{\alpha}{u . L} = \frac{1}{Pe}$	$\pi_8 = \frac{\rho_\infty - \rho}{\rho_\infty}$	$\pi_9 = \frac{S}{L}$

$$\begin{cases} U^* \frac{\partial U^*}{\partial z^*} + V^* \frac{\partial U^*}{\partial r^*} = \frac{1}{Re} \left\{ \frac{\partial}{r^* \partial r^*} \left(r^* \frac{\partial U^*}{\partial r^*} \right) + \frac{\partial^2 U^*}{\partial z^{*2}} \right\} - \left(\frac{1}{Fr^2} + \frac{1}{Fr_D^2} \right) \cos(\theta) \\ U^* \frac{\partial V^*}{\partial z^*} + V^* \frac{\partial V^*}{\partial r^*} = \frac{1}{Re} \left\{ \frac{\partial}{r^* \partial r^*} \left(r^* \frac{\partial V^*}{\partial r^*} \right) + \frac{\partial^2 V^*}{\partial z^{*2}} \right\} - \left(\frac{1}{Fr^2} + \frac{1}{Fr_D^2} \right) \sin(\theta) \end{cases}$$

Assumption:
Rise of the jet owing to buoyancy effects

⇩

Densimetric Froude number as scaling parameter

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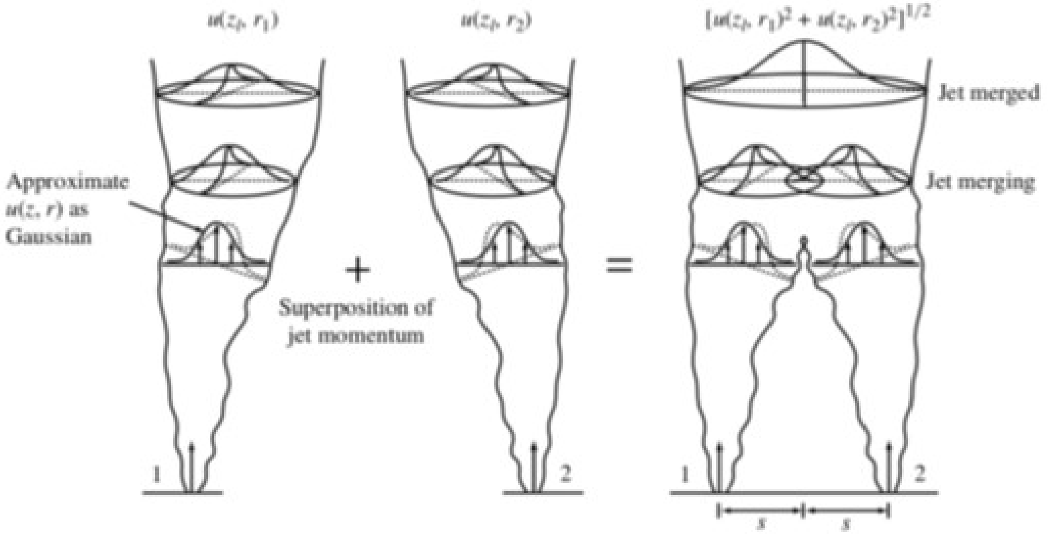
Mock-up Design: 2 Different Scales

- Maximum scale:
  - Material limitation (Mass flow rate = $15\ m^3.h^{-1}$)
  - Maximum facility size = 1:2,5 of MICAS

Leads to **laminar** jets

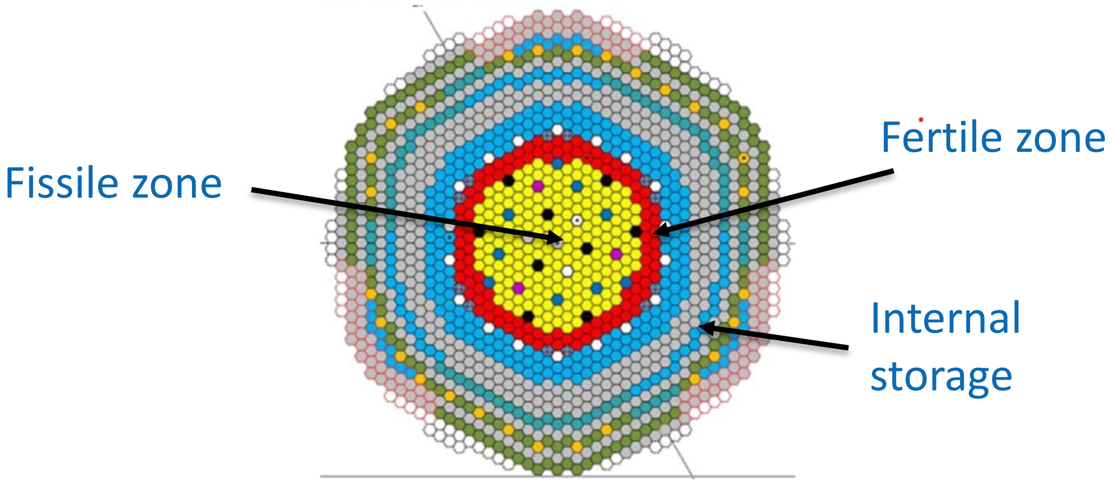
- Solution:
  - Reduction of jet number
  - Increase of each jet diameter
  - Study of jets merging (Lai et al, 2012)

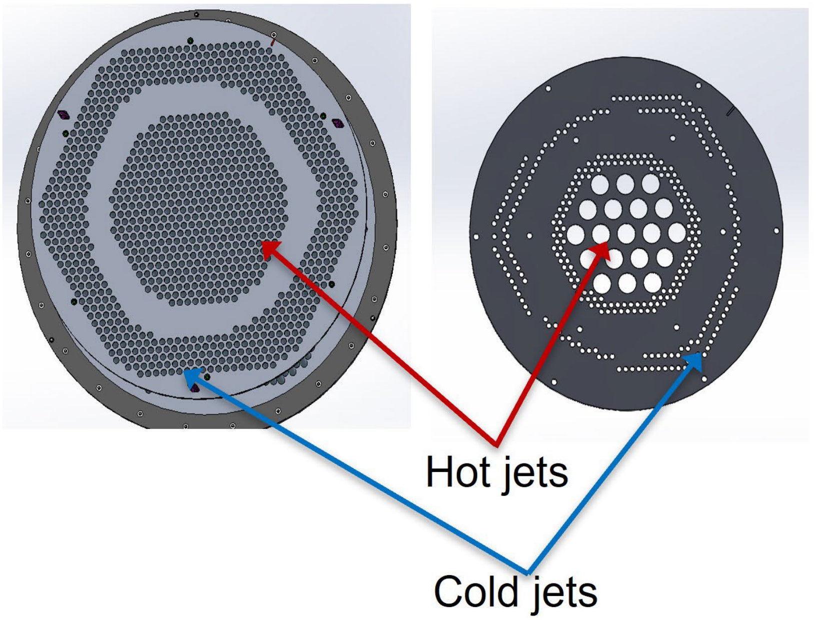


Mock-up Design: Core Exit

- Design of the core exit:
  - Distortion of hot jets
  - Cold jets: flowing ones only

- Minimum scale:
  - Ensure turbulence on the range of study
  - Minimum scale = 1:4 of MICAS





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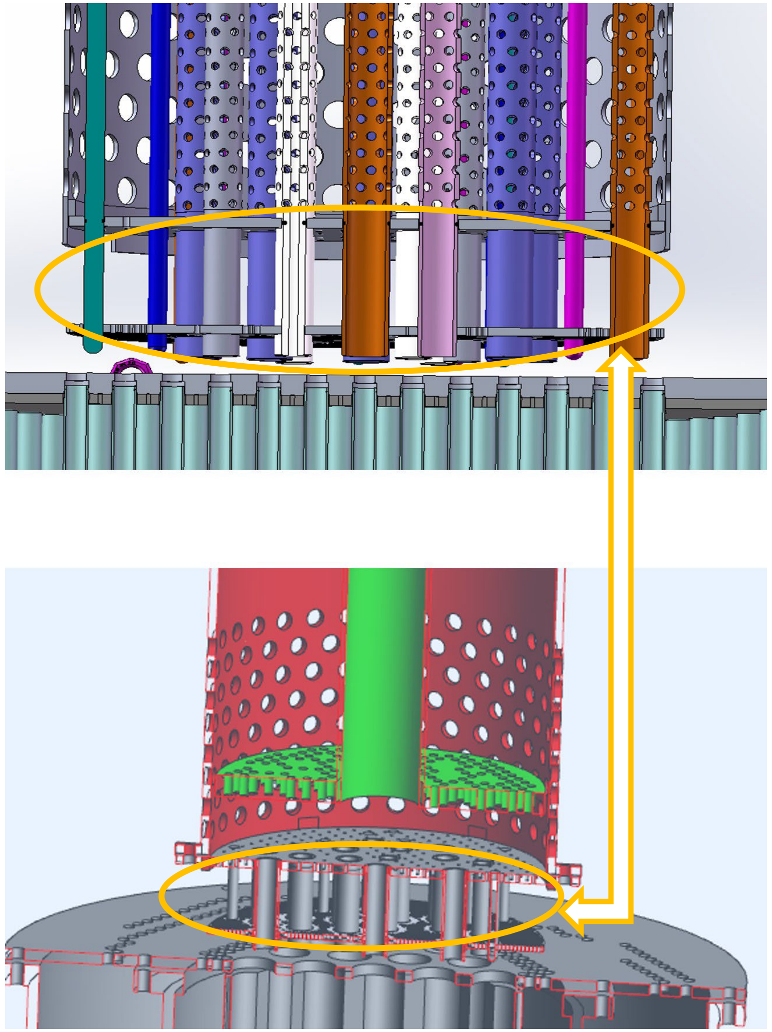
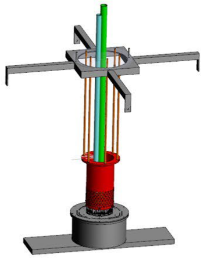
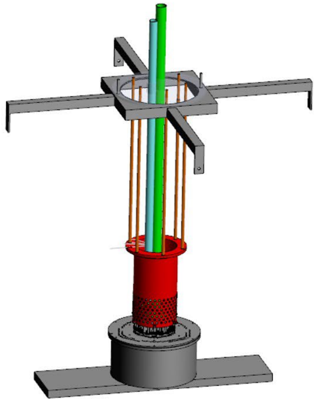
Mock-up Design: Sheath Tubes

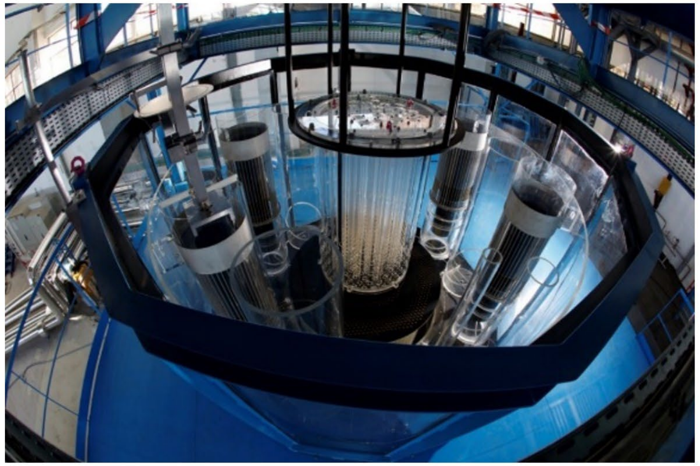
- MICAS:
  - Perforated tubes inside the UCS
  - Non-linear loss of pressure coefficient
- Small scale mock-up:
  - Reproduction under the UCS
  - Adjustable piston inside UCS
- Interest:
  - Influence on rise of the jet
  - Validity domain

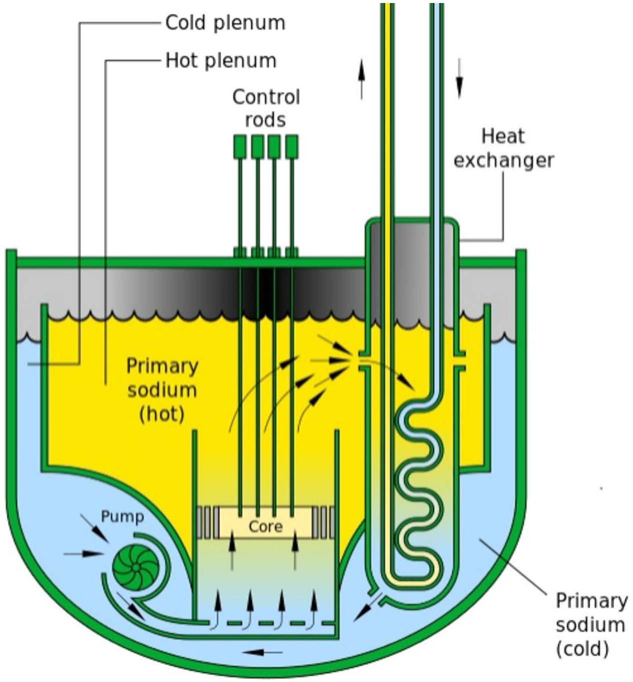


Mock-up Design: MOJIT-Eau



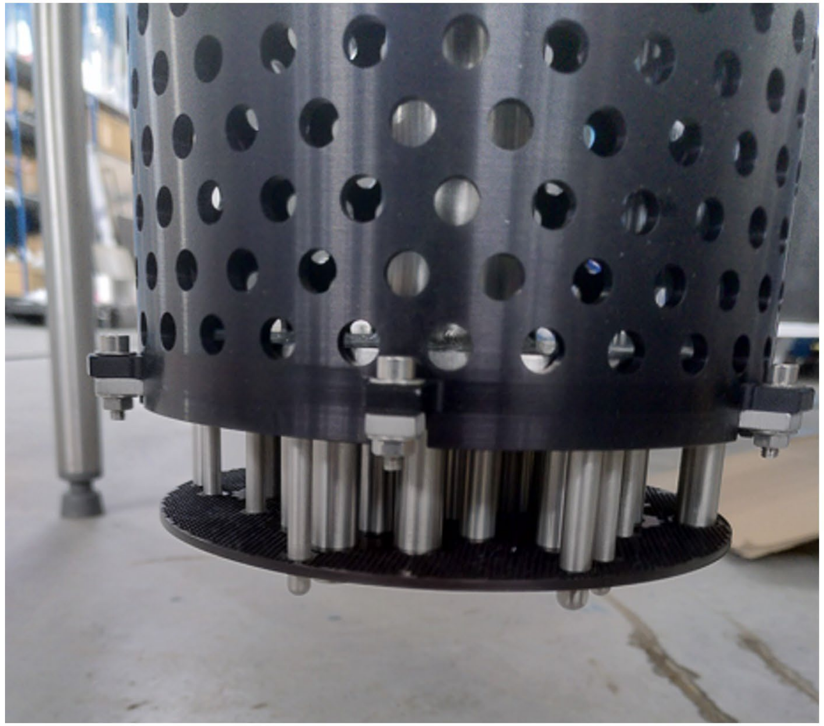






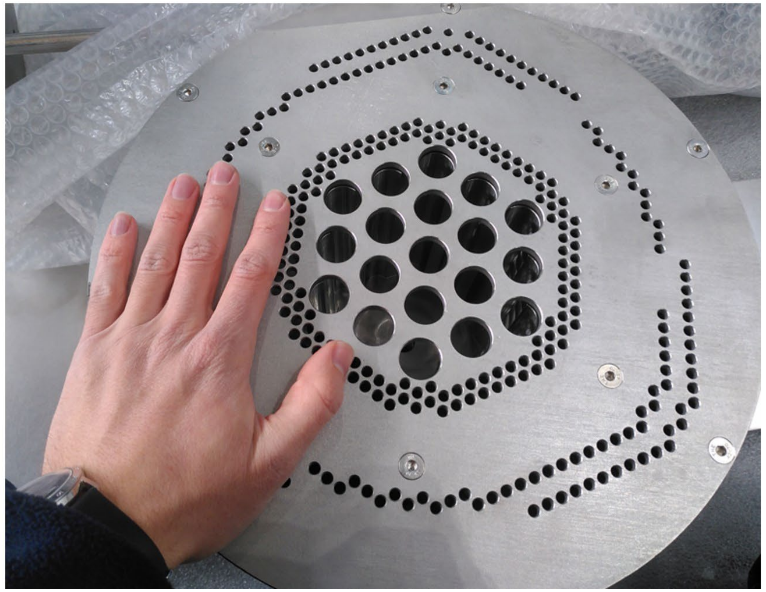
Scale: 1:4 1:2,5 1 (Reference) 6

Mock-up Design: MOJIT-Eau



Upper Core Structure

Core jets



Porous plate

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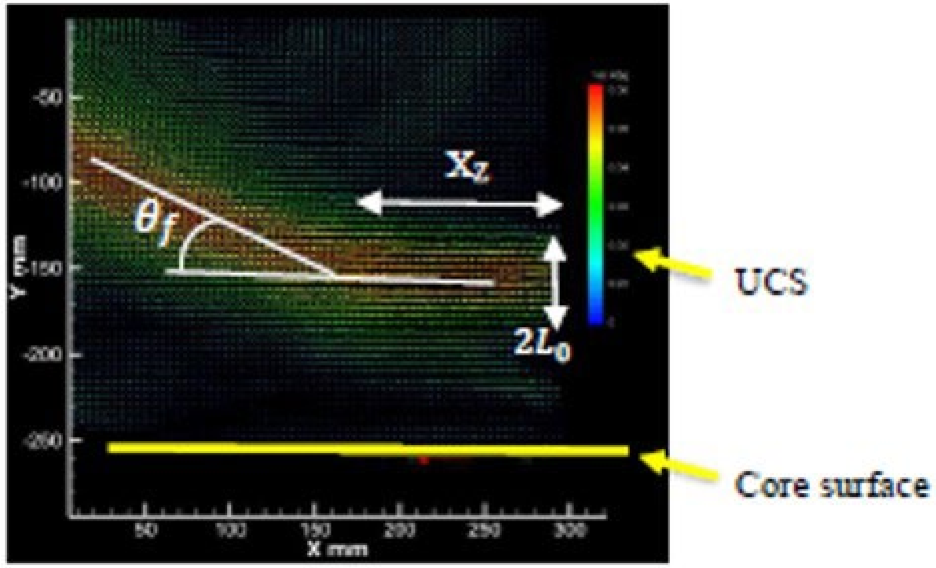
"Full" Scale Experimental Results

"Full" Scale Results: Rise / Drop of a Jet

- Rise of a jet: 3 parameters
  - Half-width L_0
  - Distance from exit to rise / drop X_Z
  - Final angle θ_f

- X_Z relation known: $\frac{X_Z}{L_0\, Fr_D} = K(\theta_0)$

  Papakonstantis et al (2011)



Convention:
$\theta_f > 0$ Jet downward
$\theta_f < 0$ Jet upward

⇨ **Focus on the final angle θ_f**

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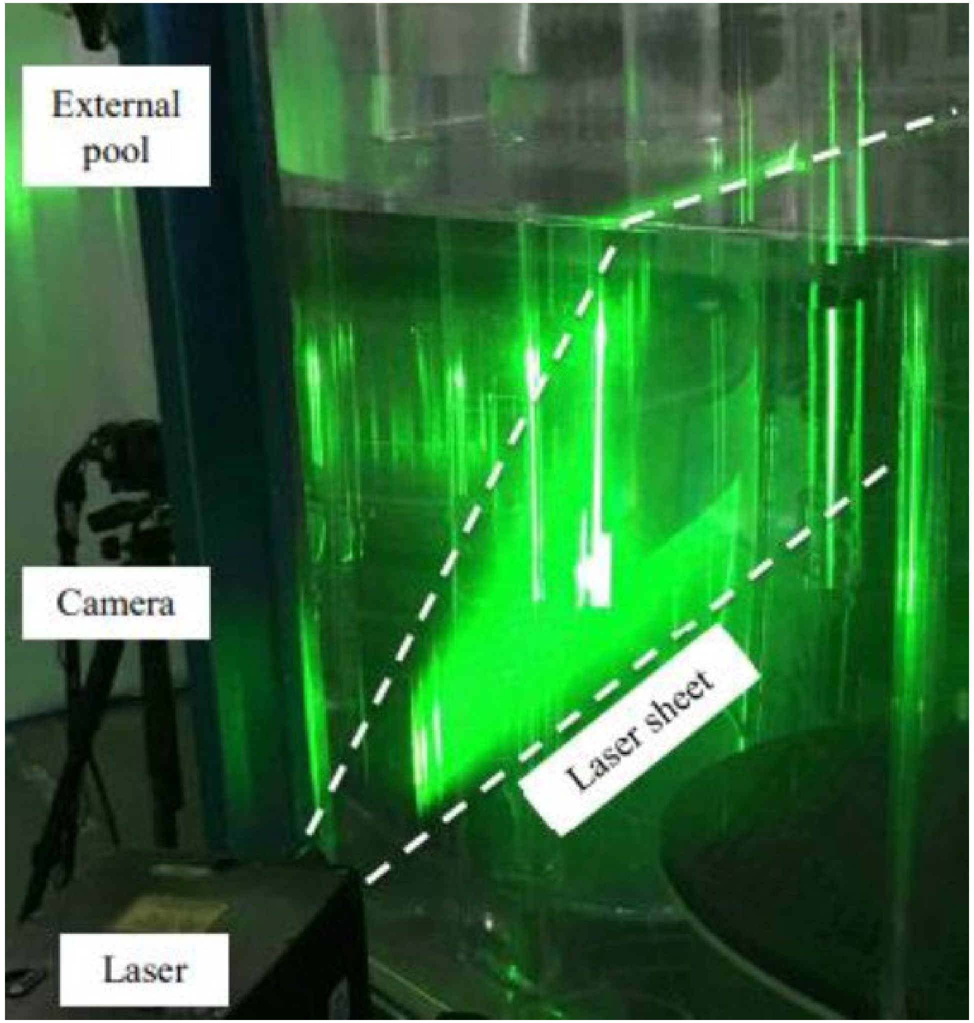
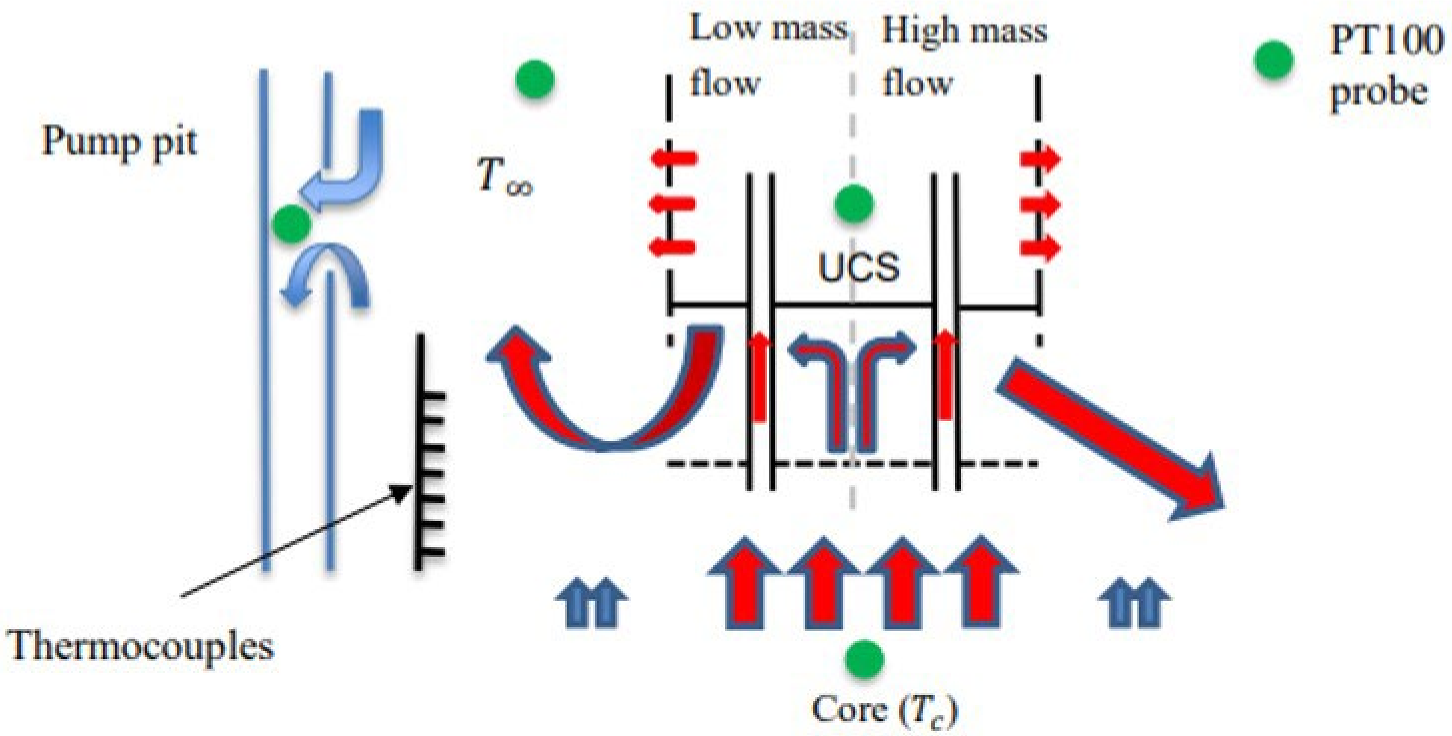
“Full” Scale Results: Instrumental Setup

- Velocity measurement:
  - Particle Image Velocimetry (PIV)
  - Nylon particles (4µm – 1000 $kg.m^{-3}$)
  - 4 MPixels CCD camera
- Stationary fields:
  - 150 averaged images (i.e. 10s acquisition)
  - INSIGHT 4G
- Output:
  - Final angle θ_f
  - Jet half-width L_0
  - Radial jet velocity



“Full” Scale Results: Instrumental Setup

- Temperature measurements:
  - PT100 probes ($\pm 0{,}1°C$)
  - Thermocouples ($\pm 1°C$)
- Zones:
  - Core outlet, UCS and environment
  - From core to UCS (stratification)
- Output:
  - Jet temperature
  - Environment temperature
  - Flow stabilization (thermocouples)



"Full" Scale Results: Experimental Conditions

- Identical flow repartition in the core:
  - 95% hot jets
  - 5% cold jets
- Fr_D conservation at core exit

$$Fr_D = \frac{u_0}{\sqrt{(\Delta\rho/\rho_\infty)\, g\, d}}.$$

- Fr_D variation: change in mass flow rate

	Experimental conditions	
	ASTRID (nominal)	MICAS (20% to 100% of nominal condition)
T_c (°C)	~570	~55
$T_c - T_\infty$ (°C)	~25	1,2 to 4,4
Q_c $(m^3.h^{-1})$	~32 214	32 to 165
Fr_D	~ 3 to 27	

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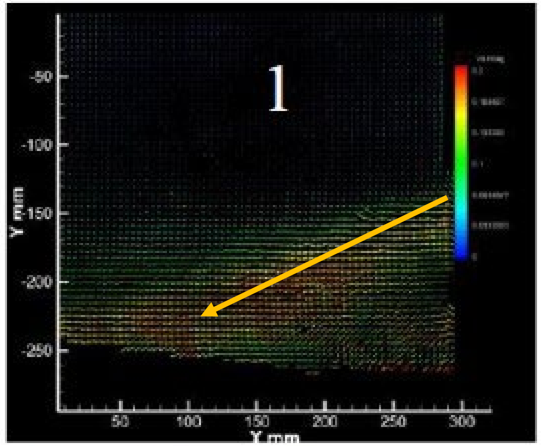
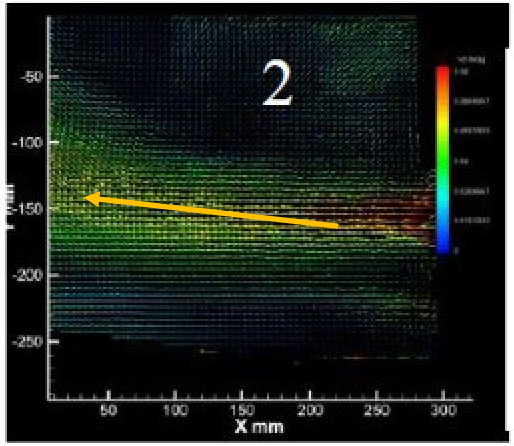
“Full” Scale Results

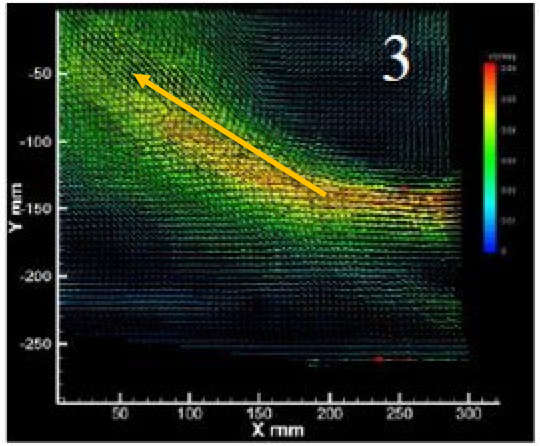
$Q = 151\, m^3.h^{-1}$
$T_{Jet} - T_{\infty} = 2.2°C$
$\theta_f = 21°$
$Fr = 0.93$
$Fr_D = 41$

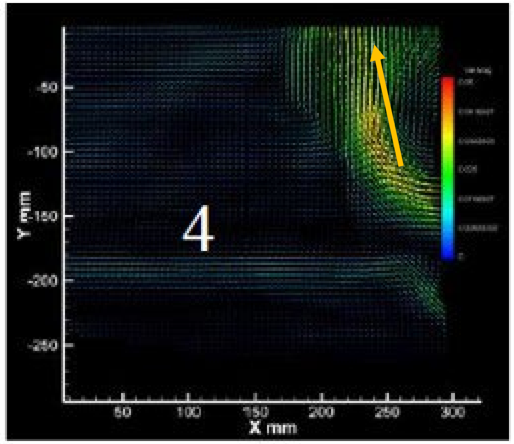




$Q = 50\, m^3.h^{-1}$
$T_{Jet} - T_{\infty} = 1.5°C$
$\theta_f = -12°$
$Fr = 0.62$
$Fr_D = 16$

$Q = 36\, m^3.h^{-1}$
$T_{Jet} - T_{\infty} = 2.1°C$
$\theta_f = -32°$
$Fr = 0.22$
$Fr_D = 9.8$





$Q = 43\, m^3.h^{-1}$
$T_{Jet} - T_{\infty} = 4.4°C$
$\theta_f = -65°$
$Fr = 0.26$
$Fr_D = 7.6$

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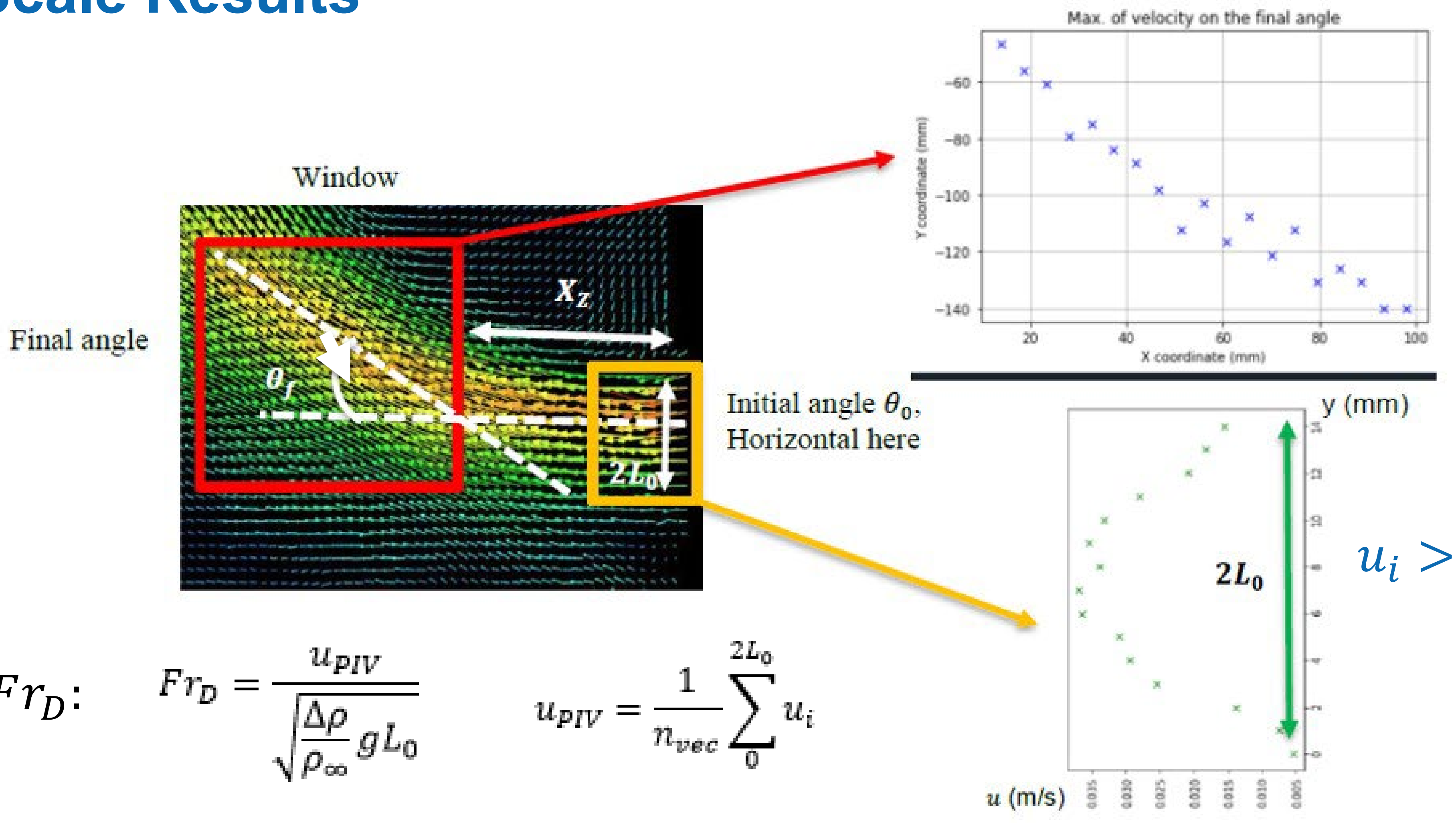
"Full" Scale Results



$u_i > 0.1\, u_{max}$

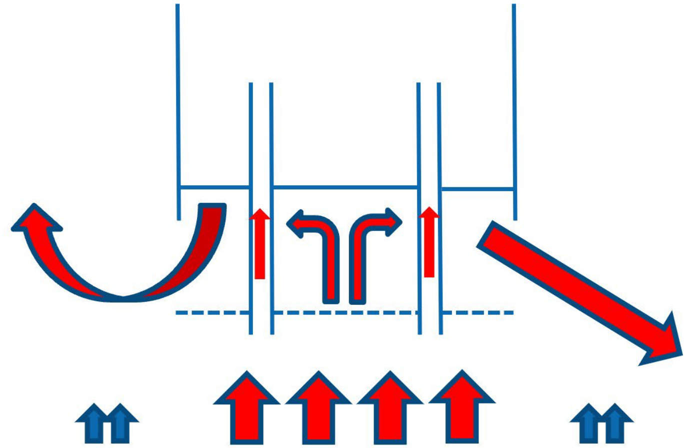
Radial jet Fr_D:

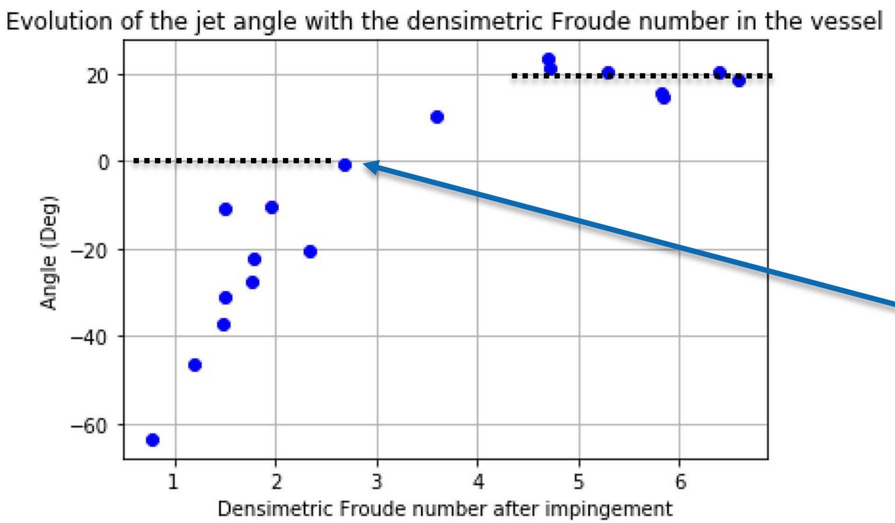
$$Fr_D = \frac{u_{PIV}}{\sqrt{\frac{\Delta\rho}{\rho_\infty} g L_0}}$$

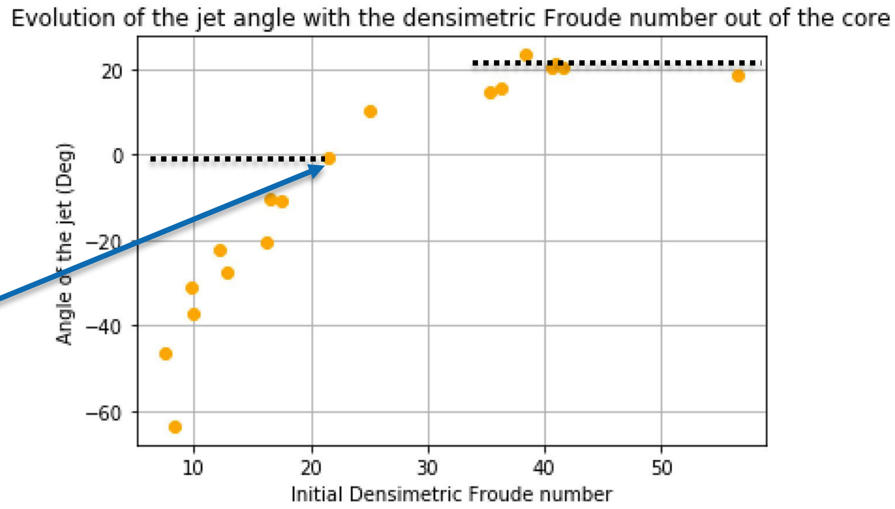
$$u_{PIV} = \frac{1}{n_{vec}} \sum_{0}^{2L_0} u_i$$

"Full" Scale Results

- Fr_D in two zones:
  - Core exit (inlet conditions)
  - Radial jet (after impingement)







Critical Fr_D:
Value when $\theta_f = 0°$

Similar behaviour:
Linear evolution of θ_f with Fr_D
Constant angle (20°) for high Fr_D

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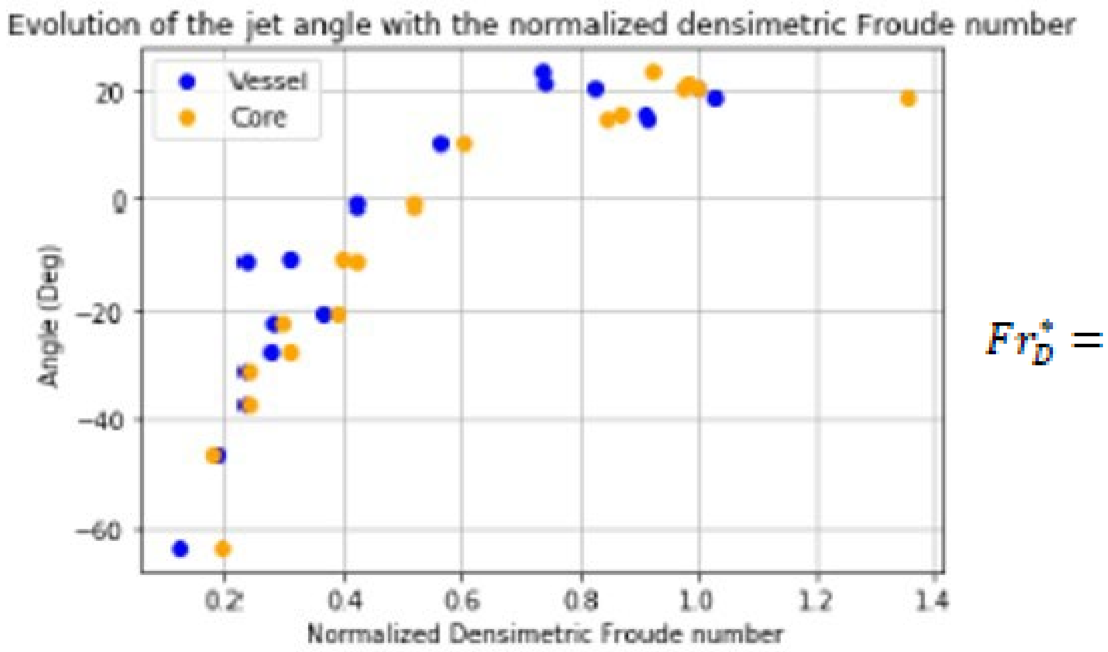
“Full” Scale Results

- Normalization by nominal Fr_D at nominal conditions
- No influence from non-linear phenomena under UCS ?

After normalization:
288 impinging jets = 1 free radial jet ?

Exact transformation from core to radial jet ?



$$Fr_D^* = \frac{Fr_D}{Fr_{D\,100\%}}$$

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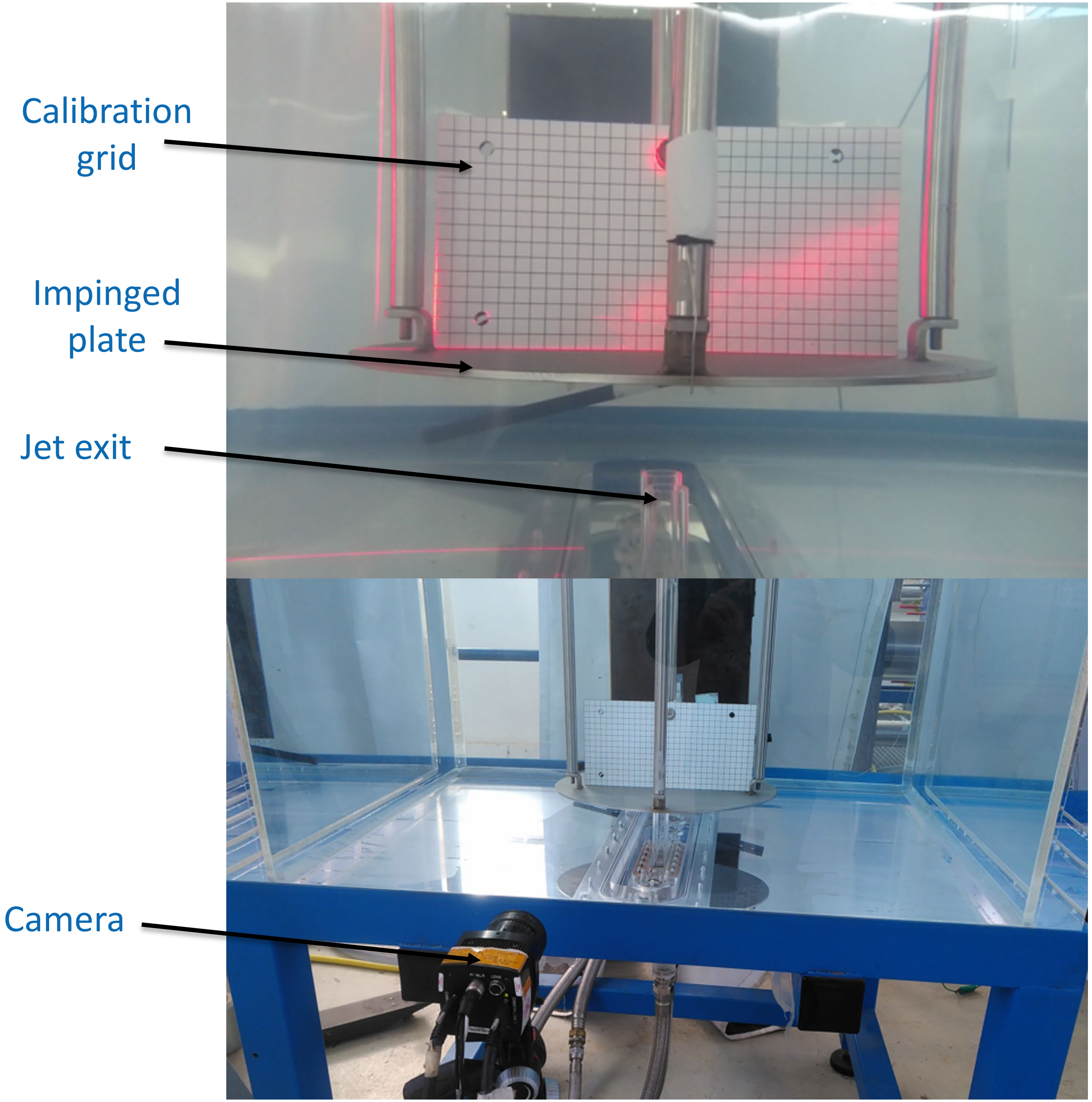
Next Step:
Ongoing and Future Studies

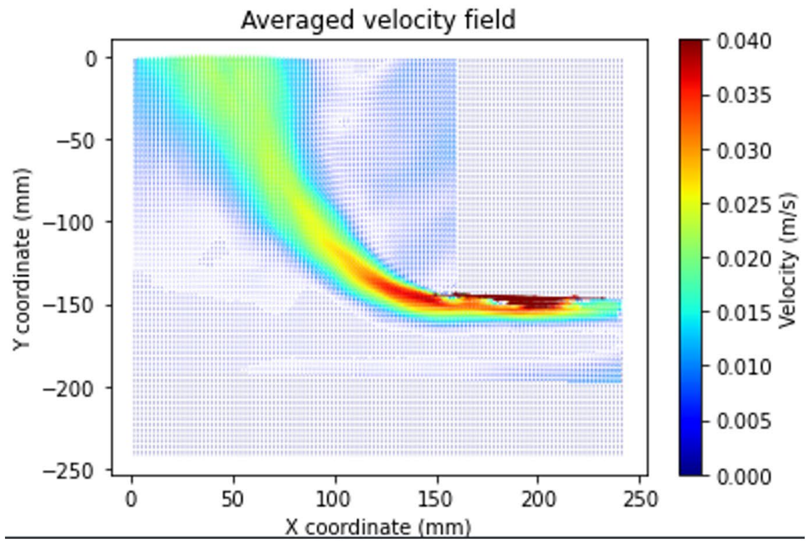
Next Step: PIGNIA

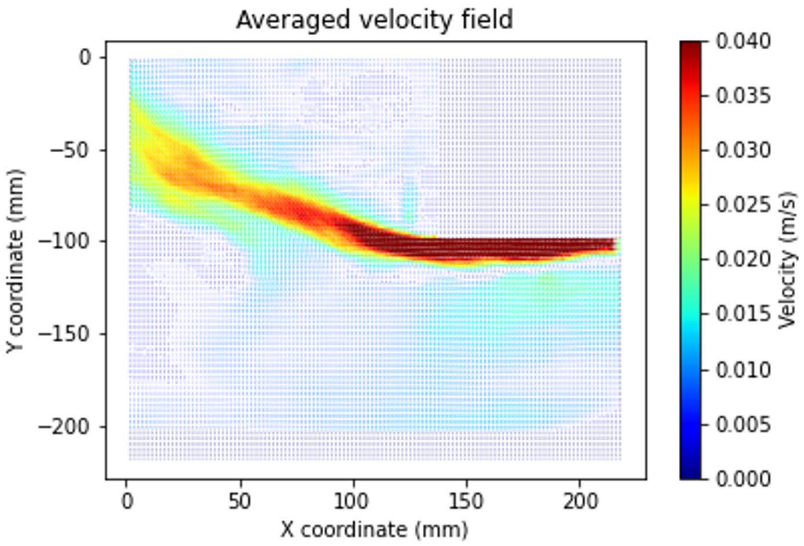
- PIGNIA setup:
  - Oversimplification
  - Single jet impinging flat plate
- Phenomenology:
  - $\theta_f = f(Fr_D)$
  - Influence of H/d
  - Relation jet exit / radial jet

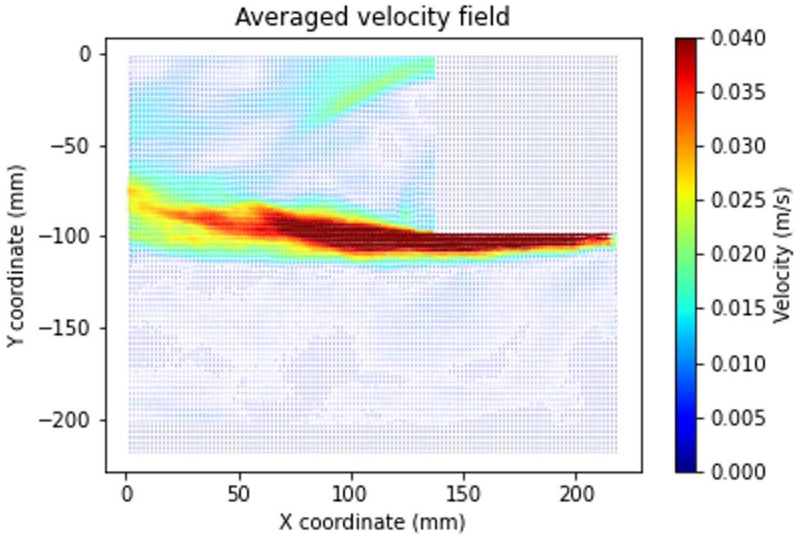


Next Step: PIGNIA

- Preliminary PIV results:







High Fr_D:
PIGNIA: $\theta_f \rightarrow 0$
MICAS: $\theta_f \rightarrow 20°$

⇨ Geometrical influence

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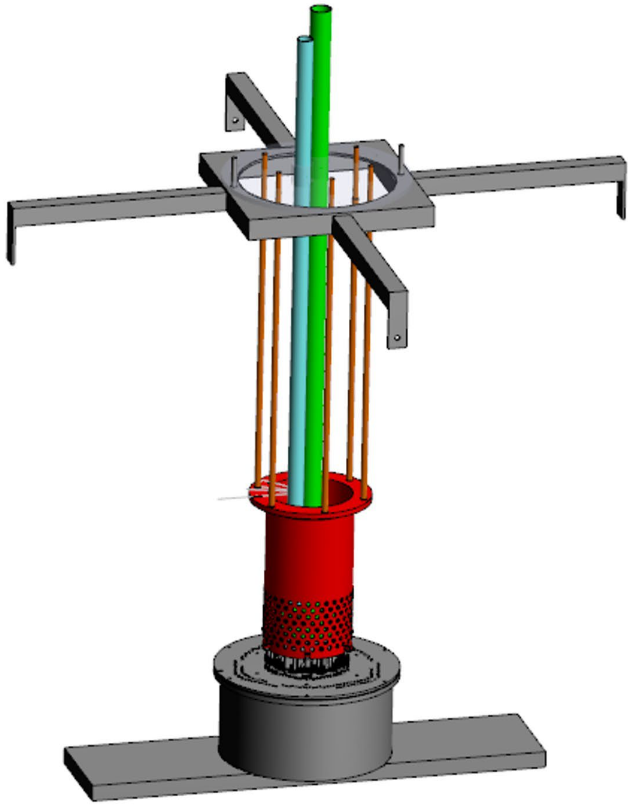
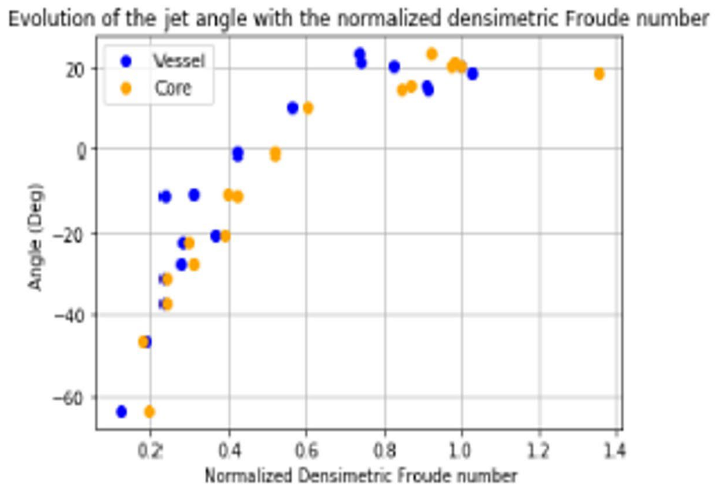
Next Step: MOJIT-Eau

- Experimental campaign incoming



- Comparison with MICAS results:
  - Critical Fr_D for which $\theta_f = 0°$
  - Slope of $\theta_f = f(Fr_D)$ for low Fr_D
  - Constant angle for high Fr_D



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Conclusion

Conclusion: How to Conclude ?

If no scale effects:

- Identical results between MICAS and lower scales MOJIT-Eau
  - Same critical Fr_D ($\theta_f = 0°$)
  - Same slope of $\theta_f = f(Fr_D)$ for low Fr_D
  - Same constant angle for high Fr_D

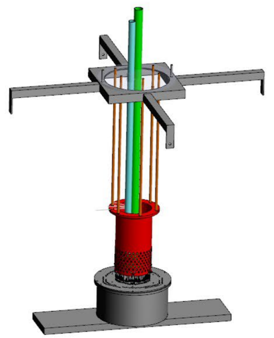
Conservation of Fr_D ensure the similarity of the flow

If scale effects:

- Differences on one (or more) item:
  - Is the difference linear with the scale factor ?
  - How does this difference evolves with other dimensionless numbers ? (Re, Eu, H/d, …)

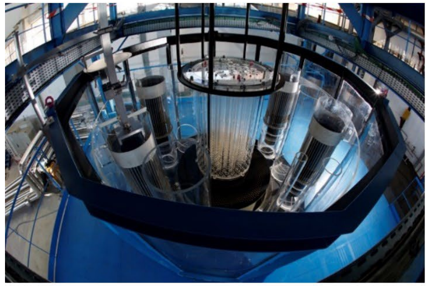
Conservation of Fr_D **only** doesn't ensure the similarity of the flow

Conclusion

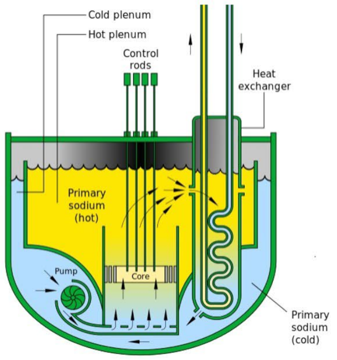


- All experiment on mock-up **may** lead to scale effects compared to prototype

- Different ways to avoid scale effects
  - Complex approach for transient and/or two-phase flow phenomena
  - Scaling techniques for Integral Effect Tests and calibration with scale 1 results
  - Dimensional analysis and scale series for experimental determination



- Ongoing study:
  - Scale series with MICAS and scaled 1:2,5 and 1:4 MOJIT-Eau mock-up
  - Dependence on the jet angle with the densimetric Froude number
  - Phenomenological study on oversimplified mock-up



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Thanks for your attention !

Upcoming Webinars

Date	Title	Presenter
19 April 2022	GIF/IAEA joint Webinar: Role of Nuclear Energy in Reducing CO_2 Emissions	Dr. Bragg Sitton, INL, Mr. Wei Huang, IAEA Ms. Diane Cameron, NEA
11 May 2022	Development of Nanosized Carbide Dispersed Advanced Radiation Resistant Austenitic Stainless Steel (ARES) for Generation IV Systems	Mr. Jiho Shin, KAIST, Republic of Korea
15 June 2022	Nuclear Waste Management Strategy for Molten Salt Reactor Systems	Dr. John Vienna & Dr. Brian Riley, PNNL, USA