Scale Effects and Thermal-Hydraulics: Application to French SFR

Mr. Benjamin Jourdy
CEA, France
23 March 2022
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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 $10^4L^2$, volume $10^6L$

  Surface / Volume 100 times lower for elephant

  Mouse has to eat 100 times more than an elephant (relative to weight) to maintain body temperature
Gas entrainment criterion
Image from Guenadou et al (ICMF 2019)
Study from Eguchi et al (1994)

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

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Scale effect analysis

Experimental approach
Scale Effects: Methods
Scale Effects: Similarity

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

\[ \text{Dominant force ratio is selected} \]
\[ \text{Others are neglected} \]

\[ \text{Scale effects if not negligible} \]
Scale Effects: Scaling Techniques

- Target the phenomena at both local and system level
- **Local:**
  - Dimensional analysis (empirical approach)
    - Correlation and models to derive 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

- Relative importance of all terms

- Comparison of force ratio from a scale to another

- Geometric parameters not taken in account
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)
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
**Experimental Approach: Vaschy-Buckingham Theorem**

List of the governing parameters

Dimensionless numbers

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Equation</th>
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</tr>
</thead>
<tbody>
<tr>
<td>$\pi_1$</td>
<td>$\frac{H}{L}$</td>
<td>$\pi_2$</td>
<td>$\frac{p}{\rho \cdot u^2} = Eu$</td>
<td>$\pi_3$</td>
<td>$\frac{\eta}{\rho \cdot u \cdot L} = \frac{1}{Re}$</td>
</tr>
<tr>
<td>$\pi_4$</td>
<td>$\frac{g \cdot L}{u^2} = \frac{1}{Fr^2}$</td>
<td>$\pi_5$</td>
<td>$\frac{T - T_{\infty}}{T_c - T_{\infty}}$</td>
<td>$\pi_6$</td>
<td>$\beta(T_c - T_{\infty})$</td>
</tr>
<tr>
<td>$\pi_7$</td>
<td>$\frac{\alpha}{u \cdot L} = \frac{1}{Pe}$</td>
<td>$\pi_8$</td>
<td>$\frac{\rho_{\infty} - \rho}{\rho_{\infty}}$</td>
<td>$\pi_9$</td>
<td>$\frac{s}{L}$</td>
</tr>
</tbody>
</table>
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

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

\[Re = \frac{\rho u_0 d}{\eta}\]
\[Fr = \frac{u_0}{\sqrt{gd}}\]
\[Fr_D = \frac{u_0}{\sqrt{(\Delta \rho/\rho)gd}}\]
Experimental Approach: Dominant Dimensionless Number

<table>
<thead>
<tr>
<th>$\pi_1 = \frac{H}{L}$</th>
<th>$\pi_2 = \frac{p}{\rho . u^2} = Eu$</th>
<th>$\pi_3 = \frac{\eta}{\rho . u . L} = \frac{1}{Re}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\pi_4 = \frac{g . L}{u^2} = \frac{1}{Fr^2}$</td>
<td>$\pi_5 = \frac{T - T_\infty}{T_c - T_\infty}$</td>
<td>$\pi_6 = \beta(T_c - T_\infty)$</td>
</tr>
<tr>
<td>$\pi_7 = \frac{\alpha}{u . L} = \frac{1}{Pe}$</td>
<td>$\pi_8 = \frac{\rho_{\infty} - \rho}{\rho_{\infty}}$</td>
<td>$\pi_9 = \frac{s}{L}$</td>
</tr>
</tbody>
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Assumption:
Rise of the jet owing to buoyancy effects

Densimetric Froude number as scaling parameter
Mock-up Design: 2 Different Scales

- Maximum scale:
  - Material limitation (Mass flow rate = $15 \, m^3 \cdot h^{-1}$)
  - Maximum facility size = 1:2.5 of MICAS

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

Leads to **laminar jets**
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
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)
Mock-up Design: MOJIT-Eau

Upper Core Structure

Core jets

Porous plate
"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 $\theta_f$

• $X_Z$ relation known:
  \[
  \frac{X_Z}{L_0 F_{rD}} = K(\theta_0)
  \]

Papakonstantis et al (2011)

Focus on the final angle $\theta_f$

Convention:
$\theta_f > 0$ Jet downward
$\theta_f < 0$ Jet upward
“Full” Scale Results: Instrumental Setup

• Velocity measurement:
  – Particle Image Velocimetry (PIV)
  – Nylon particles (4µm – 1000 $k g m^{-3}$)
  – 4 MPixels CCD camera

• Stationary fields:
  – 150 averaged images (i.e. 10s acquisition)
  – INSIGHT 4G

• Output:
  – Final angle $\theta_f$
  – Jet half-width $L_0$
  – Radial jet velocity
“Full” Scale Results: Instrumental Setup

• Temperature measurements:
  – PT100 probes (±0.1°C)
  – Thermocouples (±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
- $Fr_D$ variation: change in mass flow rate

$$Fr_D = \frac{u_0}{\sqrt{(\Delta \rho/\rho_\infty)} g d}.$$
“Full” Scale Results

1. \(Q = 151 \text{ m}^3 \cdot \text{h}^{-1}\)
   \(T_{\text{jet}} - T_{\infty} = 2.2\degree C\)
   \(\theta_f = 21\degree\)
   \(Fr = 0.93\)
   \(Fr_D = 41\)

2. \(Q = 50 \text{ m}^3 \cdot \text{h}^{-1}\)
   \(T_{\text{jet}} - T_{\infty} = 1.5\degree C\)
   \(\theta_f = -12\degree\)
   \(Fr = 0.62\)
   \(Fr_D = 16\)

3. \(Q = 36 \text{ m}^3 \cdot \text{h}^{-1}\)
   \(T_{\text{jet}} - T_{\infty} = 2.1\degree C\)
   \(\theta_f = -32\degree\)
   \(Fr = 0.22\)
   \(Fr_D = 9.8\)

4. \(Q = 43 \text{ m}^3 \cdot \text{h}^{-1}\)
   \(T_{\text{jet}} - T_{\infty} = 4.4\degree C\)
   \(\theta_f = -65\degree\)
   \(Fr = 0.26\)
   \(Fr_D = 7.6\)
Radial jet $F_{r_D}$:

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

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

$u_i > 0.1 u_{max}$
"Full" Scale Results

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

Critical $Fr_D$:
Value when $\theta_f = 0^\circ$

Similar behaviour:
Linear evolution of $\theta_f$ with $Fr_D$
Constant angle (20°) for high $Fr_D$
“Full” Scale Results

- Normalization by nominal $F_{rD}$ 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?
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: $\theta_f \rightarrow 20^\circ$

Geometrical influence
Next Step: MOJIT-Eau

- Experimental campaign incoming

- Comparison with MICAS results:
  - Critical $Fr_D$ for which $\theta_f = 0^\circ$
  - Slope of $\theta_f = f(Fr_D)$ for low $Fr_D$
  - Constant angle for high $Fr_D$
Conclusion
Conclusion: How to Conclude?

If no scale effects:

- Identical results between MICAS and lower scales MOJIT-Eau
  - Same critical $Fr_D (\theta_f = 0^\circ)$
  - 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 evolve 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
References

- Nuclear Energy Agency, « A state-of-the-art report on scaling in system thermal-hydraulics applications to nuclear reactor safety and design », 2017
- Papakonstantis et al, « Inclined negatively buoyant jets 1: geometrical characteristics », *Journal of Hydraulic Research*, vol.49, n°1, p.3-12, 2011
Thanks for your attention!
# Upcoming Webinars

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<th>Title</th>
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<td>19 April 2022</td>
<td>GIF/IAEA joint Webinar: Role of Nuclear Energy in Reducing CO$_2$ Emissions</td>
<td>Dr. Bragg Sitton, INL, Mr. Wei Huang, IAEA Ms. Diane Cameron, NEA</td>
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<td>11 May 2022</td>
<td>Development of Nanosized Carbide Dispersed Advanced Radiation Resistant Austenitic Stainless Steel (ARES) for Generation IV Systems</td>
<td>Mr. Jiho Shin, KAIST, Republic of Korea</td>
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<td>15 June 2022</td>
<td>Nuclear Waste Management Strategy for Molten Salt Reactor Systems</td>
<td>Dr. John Vienna &amp; Dr. Brian Riley, PNNL, USA</td>
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