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Scale Effects Methodology for Buoyant Impinging Jets in Sodium Fast Reactors

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ABSTRACT

The CEA is involved in the development of 4th generation sodium-cooled fast reactors for which specific codes were developed. However, they need to be validated using experimental results obtained on relevant mock-ups. Due to the complexity of building a full-sized prototype in the nuclear field, most of the experiments are performed on reduced-sized models but it may lead to scale effects. We have to ensure that the validation carried out at small scale is effective at the reactor one. A critical issue in SFR reactor is the rising of the jets outgoing the core at low operating power: this phenomenon induces thermal fluctuations in the vessel, leading to thermal fatigue of the components. Therefore, this scale effect study is focused on the behaviour of the jets.

Previous studies on this issue were performed on a 1:6 scaled mock-up representative of a SFR's hot plenum named MICAS. Theoretical study, thanks to the Vaschy-Buckingham theorem and dimensionless Navier-Stokes equation under Boussinesq's approximation, led to relevant dimensionless numbers such as the densimetric Froude number and the Euler number.

The scale effect methodology based on the scale series is detailed, using MICAS as a reference scale. A new experimental mock-up called MOJIT-Eau has been designed to be representative of the smaller scales: this mock-up can be modified to allow scale effects investigation from 1:4 to 1:2.5 of MICAS's scale, and allows a phenomena investigation to quantify the influence of the complex geometry on the raise of the jets. Due to the size reduction, some geometrical distortions were made in order to ensure the turbulence of the flow. Other distortion devices were also designed to quantify the relative influence of the Euler number compared to the densimetric Froude number. This work is a preliminary study for a later experimental investigation with numerical comparison.

This mock-up is built in a transparent polymer vessel to carry out optical measurements as laser velocimetry. Temperature fields are measured with optical fibre and PT100 probes in the vessel.

1 INTRODUCTION

Nuclear energy is a sustainable and carbon-free way to produce electricity. The energetic density of nuclear energy allows an important production of electricity in a smaller surface area compared to other low-carbon emission power plant like solar panels or wind turbines. However, in order to use the wide spread uranium 238 isotope instead of the uranium 235 currently used in Gen II and Gen III reactor types, CEA is involved in the development of GEN IV sodium fast reactors (SFR).

These reactors are under pre-conception study, to improve both design and safety margins by means of numerical simulation. These numerical codes need experimental validations: to do so, thermal-hydraulic experiments are performed at the CEA Cadarache site on a 1:6 small-scaled mock-up named MICAS, using water instead of sodium as simulant fluid.

However, as no experimental results are available at scale 1, results on MICAS may be subjected to scale effects. To confirm the representativeness of MICAS experiments compared to scale 1:1 prototype, a scale effects analysis is under study.

The first part of this article presents both reactor and mock-up facilities, and the phenomena under scale effects study. The second part is devoted to the methodology of this scale study. Then, the last part presents a new mock-up downsized from MICAS to achieve this scale effects methodology.

2 ASTRID REACTOR & MICAS FACILITY

2.1 ASTRID & MICAS Overviews

ASTRID (Advanced Sodium Technological Reactor for Industrial Demonstration) is the French technological demonstrator reactor project prior to the industrial deployment of 4th generation sodium fast reactors (SFR) [1]. This project aims at demonstrating the technical options chosen and at giving an idea of the operating costs. Its power was 600 MWe. Unfortunately, the reactor's project was temporarily stopped in 2019. At that time, efforts were being made to build a numerical model of the reactor, implying a strong validation of numerical codes.

The MICAS facility is a 1:6th sized mock-up representing the hot plenum of the ASTRID reactor, based in Cadarache, South of France [2]. The scale was chosen to be a compromise between the overall size and the detail of the geometry of the vessel. Its dimensions are about 2.5 m in diameter and 1.7 m in height. A cut view of both ASTRID and MICAS is presented in Figure 1.

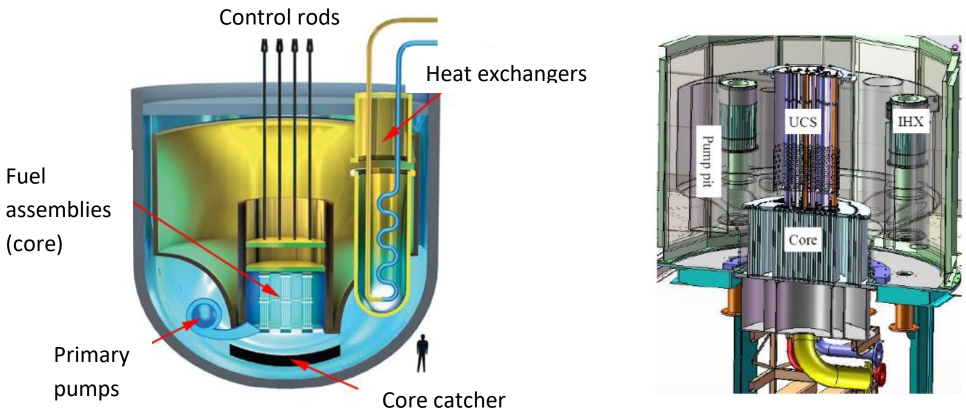

Figure 1: Cut views of ASTRID (left) and MICAS (right)

2.2 Phenomenon of interest

Out of the core, 288 hot jets (575°C in ASTRID, 55°C in MICAS) are impinging the Upper Core Structure (UCS). Part of the water (around 15% [3]) flows through the UCS and exits around the sheath tubes. The UCS forces the jets to merge and cause a radial deviation of the flow. Then, the unique radial jet spreads into the plenum where the temperature is lower: this temperature difference is around 25°C in ASTRID and 2°C in MICAS.

In the plenum, the temperature differences between the jet and the environment leads to buoyancy effects that can, if buoyancy becomes predominant over inertia, cause the rise of this unique jet. This phenomenon, shown in Figure 2, is still under study.

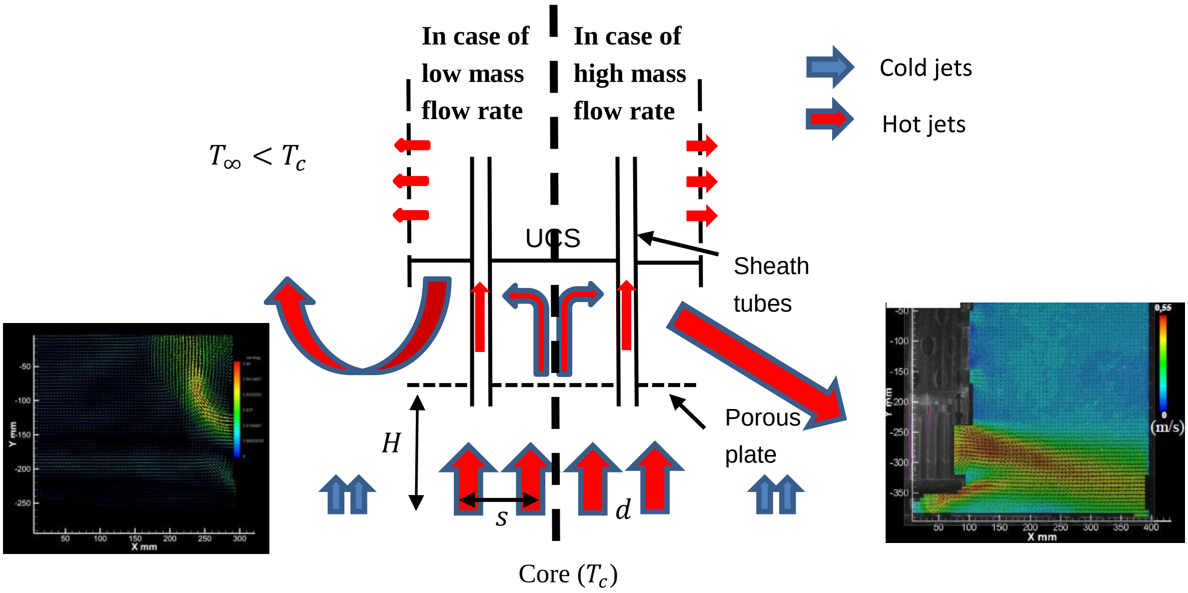

Figure 2: Schema of the flow path above the core in ASTRID and MICAS in two different cases of flow rates and associated experimental results (velocity vectors coloured according to velocity scale)

3 SCALE EFFECTS & JETS THEORY

In order to investigate scale effects, between ASTRID and MICAS, on the raise of the jets after impingement on the UCS, a new mock-up representative of the phenomena has to be conceived based on a particular theory and methodology.

3.1 Scale effects methodology

To investigate scale effects in thermal-hydraulics, different approaches for model-prototype similitude are possible. If the set of equations describing the phenomena are well known, an analysis is possible by comparing governing dimensionless numbers values between model and prototype [4].

When the governing equation or the studied phenomena are not known, the Vaschy-Buckingham theorem [5] can be applied in order to determine dimensionless numbers that should be conserved between model-prototype scales: this analysis leads to arbitrariness in determining the condition of similitude, as this theorem does not give a hierarchy between each dimensionless numbers linked to the phenomenon.

When experimental results from the prototype are already available, an experimental calibration can be achieved if the parameters under similarity agree well between the model and the prototype: deviation in the results between two scales helps quantifying and correcting scale effects.

In our case, no data on the ASTRID reactor are available. Thus, in this study, the methodology to assess scale effects is based on the scale series methodology [4] where the higher scale model (MICAS in our case) is used as a reference instead of the prototype. And two scale-reduced mock-ups have to be considered in order to determine and quantify scale effects.

3.2 Vaschy-Buckingham & dimensionless equations

The Vaschy-Buckingham theorem, applied to this jet issue in MICAS facility, gives the dimensionless π-groups shown in Table 1.

Table 1: π-groups derived from Vaschy-Buckingham theorem

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

As the Vaschy-Buckingham theorem does not give a hierarchy between the different π-groups, we use the non-dimensional governing equations of the axisymmetric jets (known as the conservation equations) under the Boussinesq approximation to determine the most influential π-groups. We assume axisymmetric incompressible steady jets in cylindrical coordinates where the velocity vector in the (r, z) coordinate system is defined as $\vec{u} = U\,\vec{e_z} + V\,\vec{e_r}$, z and r being the axial and radial coordinates of the jets respectively. The scaling parameters are chosen as U_0, the average axial velocity at the jet exit, d the jet diameter, $T_c - T_\infty$ the temperature differences between the outlet jets and the environment, and ρ_∞ the environment density. The notation X^* means the non-dimensional variable X.

Mass conservation equation:

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

Momentum conservation equation:

$$\begin{cases} U^*\frac{\partial U^*}{\partial z^*} + V^*\frac{\partial U^*}{\partial r^*} = -\frac{1}{\rho^*}\frac{\partial Eu}{\partial z^*} + \frac{1}{Re}\left\{\frac{\partial}{r^*\partial r^*}\left(r^*\,\frac{\partial U^*}{\partial r^*}\right) + \frac{\partial^2 U^*}{\partial z^{*2}}\right\} - \frac{1}{Fr^2} + \frac{1}{Fr_D^2} \\ U^*\frac{\partial V^*}{\partial z^*} + V^*\frac{\partial V^*}{\partial r^*} = -\frac{1}{\rho^*}\frac{\partial Eu}{\partial r^*} + \frac{1}{Re}\left\{\frac{\partial}{r^*\partial r^*}\left(r^*\,\frac{\partial V^*}{\partial r^*}\right) + \frac{\partial^2 V^*}{\partial z^{*2}}\right\} \end{cases} \tag{2}$$

The momentum equations as written in equation (2) are valid for a single jet: in the zone under the UCS where the jet is diffusing on the z axis with an homogeneous temperature, the Froude and densimetric Froude number terms can be neglected, as well as the r-axis equation. In the vessel after impingement, the Euler terms (π_2 in Table 1) can be neglected as pressure variations are negligible in a free jet. Re referred to the Reynolds number, defined as π_3 in Table 1.

Energy conservation:

$$\left(U^* \frac{\partial T^*}{\partial z^*} + \frac{V^*}{r^*}\frac{\partial T^*}{\partial r^*}\right) = \frac{1}{Re}\,\frac{1}{Pr}\,\frac{1}{r^*}\frac{\partial}{\partial r^*}\left(r^*\,\frac{\partial T^*}{\partial r^*}\right) \tag{3}$$

In order to study scale effects on the raise of this jet, we choose, as a dimensionless number parameter to transpose results from one scale to another, the densimetric Froude number, defined by equation (4):

$$Fr_D = \frac{U_0}{\sqrt{(\Delta\rho/\rho_\infty)\ g\ d}}\ , \tag{4}$$

where U_0 is the inlet velocity of a jet, $\Delta\rho = \rho_\infty - \rho_c$ is the density difference between the jets and the environment in the vessel, g the gravity acceleration and d a jet's diameter at the core exit. This dimensionless number, build from π_4 and π_8, is commonly used as a parameter for buoyant jets studies [6]–[8].

4 THE MOJIT-EAU MOCK-UP

As presented in sec. 3.1, three facilities at different scales are needed in order to investigate scale effects. As MICAS is our reference scale, we need two other smaller representative experimental facilities.

4.1 Design of the MOJIT-Eau mock-up

The aim of this mock-up is to allow investigations at two different scales using a single facility. The scales chosen are 1:2.5 and 1:4 of the MICAS mock-up as they are the best compromise between material limitations (pumps, water storage) and physical limitations in order to ensure the fully-turbulence of the jets at these small scales. The components can easily be removed and replaced to change from a scale to another. The vessel is 1x1x1 m^3. Some geometrical distortions have been made in order to find a compromise between material and physical limitations. Each distortion has been studied to justify its no-influence on the rise of the jet in the upper plenum.

4.2 Geometrical distortions

4.2.1 Core exit

From the ASTRID reactor to the MICAS facility, a constant geometric transformation (constant length reduction) was applied, even if some geometrical simplifications were made.

From MICAS to MOJIT-Eau facilities, the same transformation is not possible as, in MOJIT-Eau, the reduced scale involves reduced velocity and non-turbulent outgoing jets, whereas jets are turbulent in MICAS and ASTRID. In order to keep turbulent jets, a geometrical distortion has been made at the core outlet. The number of hot jets in this zone has been reduced (Figure 3), increasing their diameter and leading to fully turbulent jets (Re > 3000), as the velocity and volumetric flow rate are imposed by the densimetric Froude similarity. To keep the dimensionless number $\pi_1 = \frac{H}{d}$ constant, the nozzle-to-plate distance has also been increased. The dynamic interaction between jets has been studied [9] to ensure that reducing the number of jets would not change the behaviour of the jets after their impingement on the UCS. We found that the chosen nozzle-to-plate distance allows jets to merge before impinging the UCS plate. As the hot jets in MICAS are merged before their impingement, we assume that the global system behaviour is not compromised by reducing the number of hot jets.

As cold jets temperature cannot be constant between MICAS (7°C) and MOJIT-Eau (ambient temperature, ~20°C), flow conditions are calculated to keep the same temperature differences between hot jets and ambient temperature in the vessel. Only the flowing jets holes have been reproduced on MOJIT-Eau as shown in Figure 3, as not every jet hole in MICAS presents a flow rate.

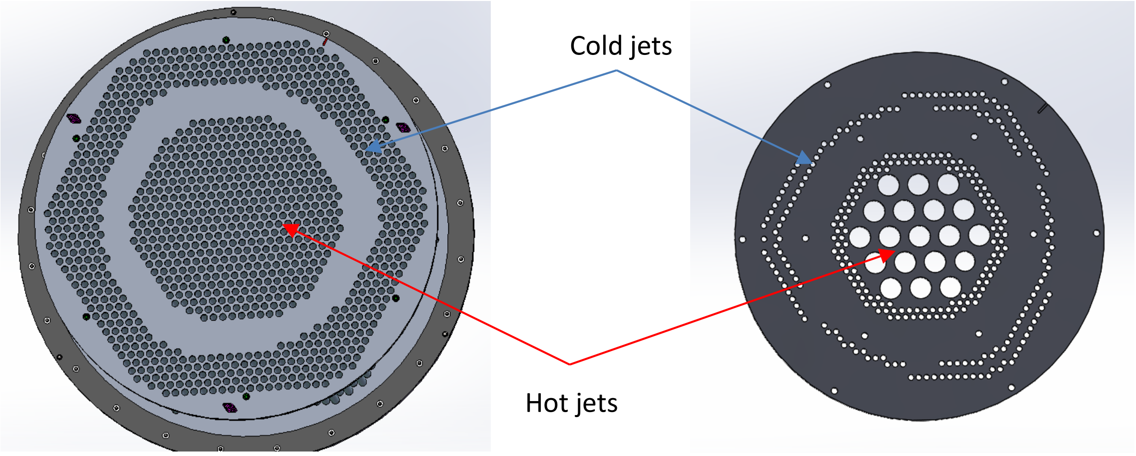

Figure 3: Layout of jets in MICAS (left) and MOJIT-Eau (right)

4.2.2 Upper Core Structure

Around 15% of the flow goes in the UCS through the sheath tubes, and then spreads in the plenum by exiting the UCS thanks to holes inside the structure. The geometry of these tubes is difficult to reproduce at lower scale.

The sheath tubes inside the UCS have been removed and replaced by a piston as shown in Figure 4. This new geometry allows a control of the pressure losses induced by these tubes and thus of the flow rate going inside the UCS. Pressure losses being related to the Euler number, this modification allows a direct visualisation of its influence on the rise of the jet.

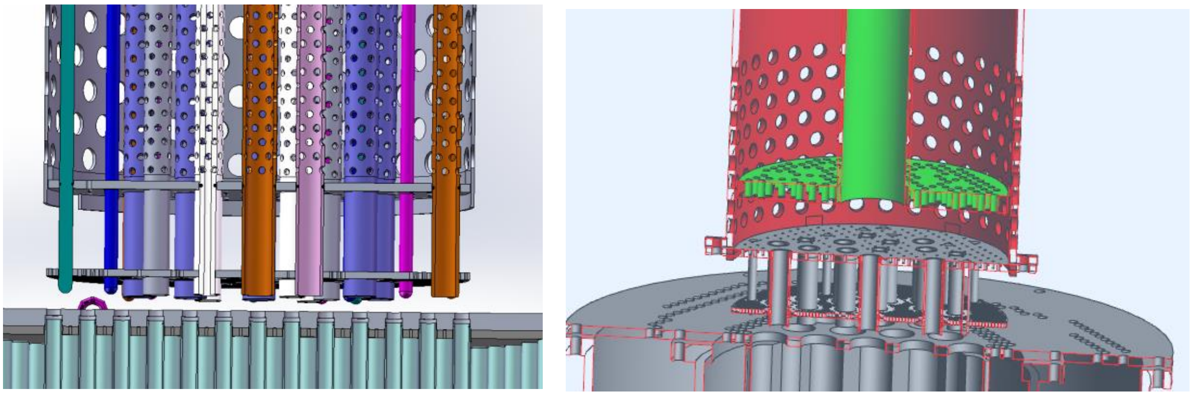

Figure 4: Cut views of the UCS in MICAS (left) and MOJIT-Eau (right)

Hence, the facility features are summed-up in Table 2. As we can see, the geometrical distortion allows a fully turbulent flow even at the 1:4 scale of MICAS. These conditions are given at the outlet of the core at nominal operating conditions with a densimetric Froude number similarity from a scale to another.

Table 2: Main characteristics and experimental conditions at different scales

Scale	**1 (MICAS)**	**1:2.5**	**1:4**
Jet number	288	19	19
Jets diameter (mm)	21	33	20
Jets velocity (m/s)	0.477	0.302	0.238
Hot flow rate (m^3/h)	170	17.7	5.1
Cold flow rate (m^3/h)	7.8	1.2	0.3
Hot T° (°C)	52	52	52
Cold T° (°C)	7	≈ 20	≈ 20
Re (per core jet)	18 691	18 576	8 900

5 CONCLUSION

The MOJIT-Eau mock-up has been designed to study scale effects on the hot jet behaviour in the upper plenum of a SFR reactor. A first mock-up, the MICAS facility, was built in order to study the raise of this jet at low power when the buoyancy effects become predominant on the jet inertia. The MOJIT-Eau mock-up is a reduced-scale facility of MICAS at 1:2.5 and 1:4th with some geometrical modifications in order to ensure the fully turbulence of the jets outgoing from the core.

The methodology to investigate scale effects is based on the Scale Series methodology on the densimetric Froude number. If the similarity is reached, we should observe a raise of the jets for the same critical densimetric Froude number at each scale, leading to the conclusion that there are no or negligible scale effects. Otherwise, further investigations will be made depending on the obtained critical densimetric Froude number's variation.

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NOMENCLATURE

d	Jets diameter $[m]$
g	Gravity acceleration $[m.s^{-2}]$
g'	Reduced gravity $[m.s^{-2}]$
H	Nozzle-to-plate distance $[m]$
L	Characteristic length scale $[m]$
p	Static pressure $[Pa]$
Q	Mass flow $[m^3.s^{-1}]$
r	Radial jet coordinate
S_{jet}	Exit surface of a jet $[m]$
s	Inter-jets distance $[m]$
T	Temperature $[°C]$
U	Axial velocity $[m.s^{-1}]$
u	Velocity $[m.s^{-1}]$
V	Radial velocity $[m.s^{-1}]$

Dimensionless numbers:

Greek symbols:

α	Thermal diffusivity coefficient $[m^2.s^{-1}]$
β	Thermal expansion coefficient $[K^{-1}]$
η	Dynamic viscosity $[kg.m^{-1}.s^{-1}]$
ρ	Density of the jets $[kg.m^{-3}]$

Subscripts:

∞	Ambient environment
c	Core
0	Initial condition

Acronyms:

ASTRID:	**A**dvanced **S**odium **T**echnological **R**eactor for **I**ndustrial **D**emonstration

Eu	Euler number
Fr	Froude number
Fr_D	Densimetric Froude number
Pe	Peclet number
Pr	Prandtl number
Re	Reynolds number

CEA:	**C**ommissariat aux **E**nergies **A**tomiques et aux **E**nergies **A**lternatives
IHX:	**I**nternal **H**eat E**x**changer
MICAS:	**M**aquette **I**nstrumentée du **C**ollecteur **C**haud d'**AS**TRID
MOJIT-Eau	**M**ise en **Œ**uvre de **J**ets **I**mpactant pour **T**ransposition en **Eau**
SFR:	**S**odium **F**ast **R**eactors
UCS:	**U**pper **C**ore **S**tructure

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