NUMERICAL ANALYSIS OF CORE THERMAL-HYDRAULIC FOR SODIUM-COOLED FAST REACTORS

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ABSTRACT

The paper presents the numerical analysis of core thermal hydraulics performed by CEA for Sodium-cooled Fast Reactors (SFR). This core thermal-hydraulic analysis is performed at three scales:

- Individual sub-assemblies, characterized by its triangular-lattice pin bundle with helical spacer wires:
  In the 1980s, a specific subchannel scale model for SFR-type subassemblies was developed at CEA. In 2008, this model was re-implemented in the Trio_U CFD code, under the name Trio_U MC (Core Model), for use in design studies. Besides this subchannel model, refined CFD models of the sub-assembly were also developed. Some examples (sodium or clad temperature inside the bundle) are presented.

- Complete core:
  The nominal thermal-hydraulic behavior of the complete core must be optimized for specific objectives, such as obtaining a required mean outlet core temperature while keeping the maximum cladding temperature within a given limit: in practice, this is achieved by allocating the fuel sub-assemblies among a number of flow-rate zones. The paper describes the methodology to determine the number and flow zones allocation and the corresponding mass flow rates with Trio_U MC, as well as the associated optimization process. This whole-core subchannel model can also be used to determine the peak cladding temperature reached during transients.

- The whole core, with sub-assemblies, inter-wrapper gaps and the hot pool plenum.
  A model for the interaction of the core sub-assemblies with the adjoining inter-wrapper gaps and with the hot pool plenum has been developed at CEA. Known as Trio_U MC2, it consists in a code coupling of Trio_U MC with a Trio_U CFD domain representing the inter-wrapper gaps and hot pool plenum. This model can be used to determine hex-can temperatures in the nominal state; it addition, it can also be used to predict the effect of inter-wrapper flows on decay heat removal during loss-of-flow accidental transients.

KEYWORDS

SFR, thermal-hydraulic, code, Trio_U MC2

1. INTRODUCTION

Thermal hydraulics is recognized as a key scientific subject in the development of Sodium Fast Reactors (SFR). In most cases, SFR cores are composed of hexagonal sub-assemblies with triangular-lattice wire-wrapped rod bundles: a thorough understanding of their thermal-hydraulic behavior is essential to SFR development.

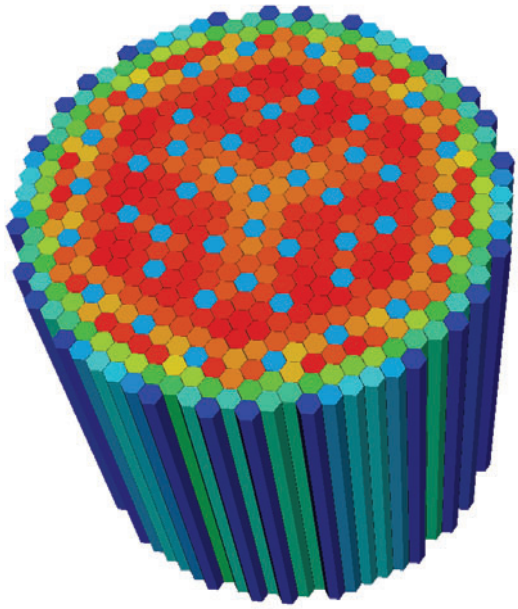


Fig. 1 SFR core view

Numerical analysis of core thermal hydraulics is required for design and safety purposes. Permanent calculations for nominal and partial operating conditions and transient calculations for accidental conditions must be considered.

Numerical analyses are performed at three scales:

- the individual fuel sub-assembly ("S/A"), characterized by a triangular-lattice pin bundle with helical spacer wires enclosed in a hexagonal wrapper tube ("hexcan");
- the complete core, consisting in around 300 S/As;
- the whole core, with S/As and inter-wrappers gaps, as well as the hot pool plenum.

The main parameters to be evaluated in the thermal-hydraulic studies are the pressure, temperature and velocity distributions in the sub-assembly that helps to determine the following quantities:

- the clad temperature and especially its maximum over the core;
- the temperature gradients and the maximum temperature of the liquid sodium coolant;
- the hexagonal can temperatures (for thermo-mechanical analysis);
- the mass flow rate for each fuel S/A;
- the total sub-assembly pressure drop including the lower and upper regions of the S/As.

2. INDIVIDUAL FUEL SUB-ASSEMBLY THERMAL HYDRAULICS

2.1 Numerical Analysis Needs

The fuel sub-assembly consists in a hexagonal duct wall wrapped around the fuel pins (Fig. 2). The cylindrical fuel pins are arranged in a triangular lattice: they are separated from each other by helical wrapper wires called spacer wires.

This geometry presents a higher flow area at the periphery of the bundle than at its center: because this disparity, nominal regimes in SFR sub-assemblies typically exhibit strong temperature gradients (around 60/70 °C in nominal operation). These gradients are in turn strongly affected by the flow deviations induced by the helical wrapping of the wire spacers: these induced transverse flows induce momentum and temperature mixing effects far stronger than those resulting from molecular and turbulent diffusion.

Taking these effects into account in the computation of sodium and pin cladding temperatures while retaining a reasonable computational cost requires a modelization scale intermediate between the system scale (in which the S/As are represented by 1D sections) and the CFD scale (where the detailed geometry of the pins and wire-wrappers would be modelled). An intuitive choice for this scale is the subchannel scale, where each interstitial sodium flow area between the pins is represented by a single radial mesh.

As shown on Fig. 2, the SFR sub-assembly geometry results in three types of subchannel meshes: triangular (type 1 - red) in most of the bundle, rectangular (type 2 – blue) along the hexagonal can, and corner (type 3 - green). Such a meshing does not allow for a direct representation of the wire-wrappers: hence, their effects must be taken into account through the use of dedicated correlations.

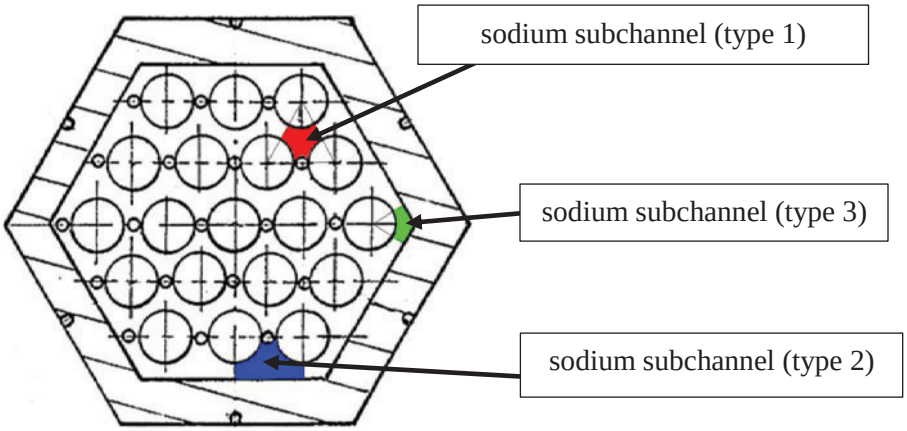


Fig. 2 SFR S/A schematic view with its different sodium subchannels

2.2 Trio_U MC Application in Trio_U Code

2.2.1 Development and validation

SFR subchannel codes such as TASNA [1], THERNAT [2] and CADET [3] have been under development at CEA in the 1970s and 1980s in the framework of PHENIX and SUPERPHENIX design studies. More recently, ASTRID design studies have required the development of subchannel models in a modern computing environment: in 2008, the CADET subchannel models were thus coded within the Trio_U CFD code [4] under the name Trio_U MC (“Modèle Cœur”, or “Core Model”).

The initial capabilities of Trio_U MC were adapted for its use as a tool for core design studies. The code features a fast solution method suitable for the calculation of forced and mixed-convection steady states with strong axial flows. In these conditions, radial pressure gradients can be neglected and a marching-type solution method can be adopted [5], leading to fast computation times: around 20s on a single core for a whole-core steady-state calculation.

More recently, Trio_U MC has been extended in order to compute local pin cladding temperatures during accidental transients such as protected and unprotected loss-flows and pump-to-diagrid pipe breaks. This required the addition of a new, slower solution method, suitable for the calculation of transient and natural-convection conditions, as well as two-phase conditions : to that end, the code now includes a six-equation, semi-implicit staggered-grid solution method similar to those used in the 3D modules of system codes such as RELAP, TRACE or CATHARE [6] (Fig. 3).

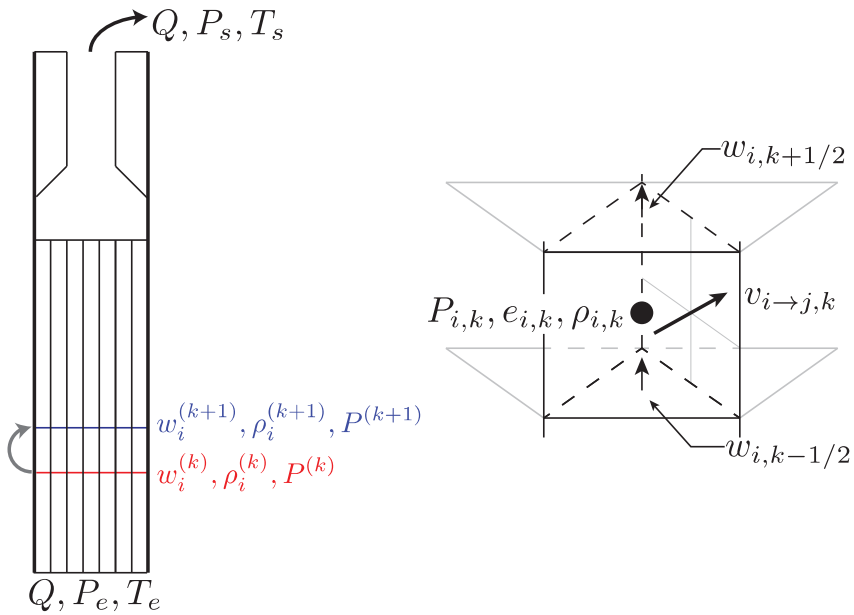


Fig. 3 Solution methods used in Trio_U MC: marching resolution for steady-states in forced/mixed convection (left), semi-implicit staggered-grid resolution for two-phase, transient and natural-convection conditions (right).

At the subchannel scale, correlations must be introduced to take into account the pressure drops and the mixing effects induced by the spacer wires. The following choices were made in Trio_U MC:

1. for mixing effects, the Cheng-Todreas correlations [7] were chosen over alternate correlations derived from the CADET code [3]. The possibility to include a more refined model such as the Distributed Resistance Model [8] is under discussion;
2. for pressure drops, the Cheng-Todreas detailed correlation [7] was chosen for its good performance and its ability to supply the pressure drops of individual subchannels. However, because of the large uncertainties associated with such correlations (~15%), it is expected that final reactor calculations will use an experimental correlation obtained on an 1:1 scale hydraulic model of the ASTRID S/A.

These choices were obtained by evaluation on the code's validation database, which currently includes 75 tests performed on 6 in-sodium experiments with 37 to 91-pin bundles with pitch-to-diameter ratio P/D

such $1.05 \leq P/D \leq 1.2$. An example validation calculation on a CEA 91-pin test section [9] is shown in Figure 4.

In two-phase situations, the 6-equations model chosen for Trio_U MC requires the introduction of several additional correlations for mass, momentum and energy exchanges between the two phases and between each phase and the wall. Initially, correlations from the SABENA code [10] were chosen because of the good performance. More details on the two-phase development and validation of Trio_U MC are available in [11].

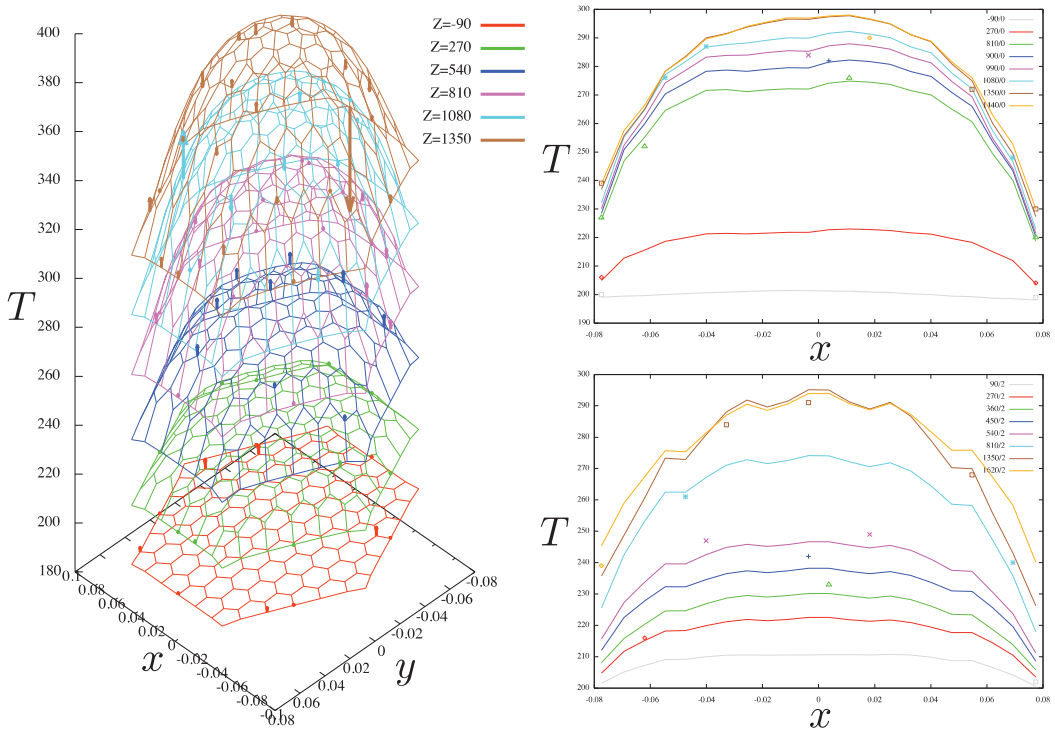


Fig. 4 Trio_U MC calculation of a 91-pin CEA sodium test section. The 3D plot (left) allows checking for global agreement between the code's predictions for subchannel temperatures at each level (meshes) and experimental thermocouples (arrows represent the difference from code result to experimental points). The 2D slices on the right allow for a detailed comparison (code results are represented by lines and experimental data by points).

Reactor calculations performed with Trio_U MC usually involve subchannel-scale calculations of the complete core: an example mesh is shown on Fig. 5. In the nominal state, calculations with the marching-type resolution (see fig. 3) are performed in order to determine how the total core flow must be split among S/As to satisfy maximum cladding temperature criteria : to that end, the code includes heuristic algorithms for allocating the S/As between a reduced number of flow zones (see §3).

Accidental calculations (transient, two-phase, natural convection) are also performed at the complete-core scale with the semi-implicit method (fig. 3). To that end, the code was parallelized, with a limit of 1 core per S/A. Thanks to this development; loss-of-flow transient calculation can typically be performed in a few hours on around 150 CPUs.

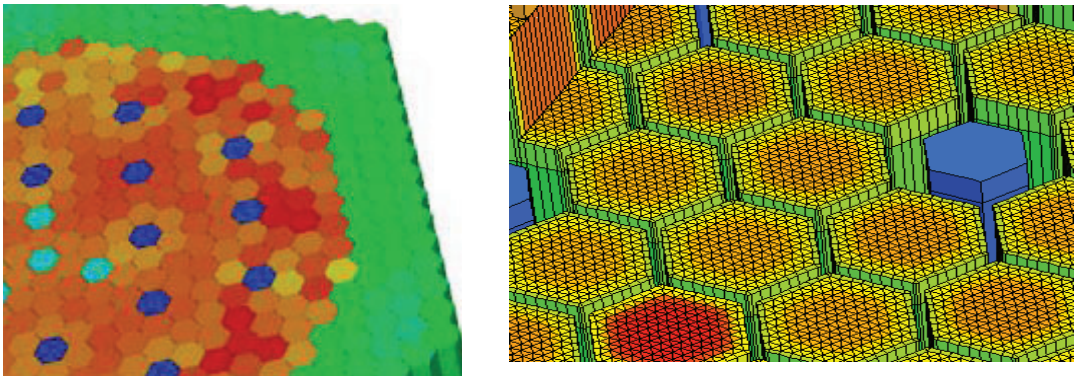
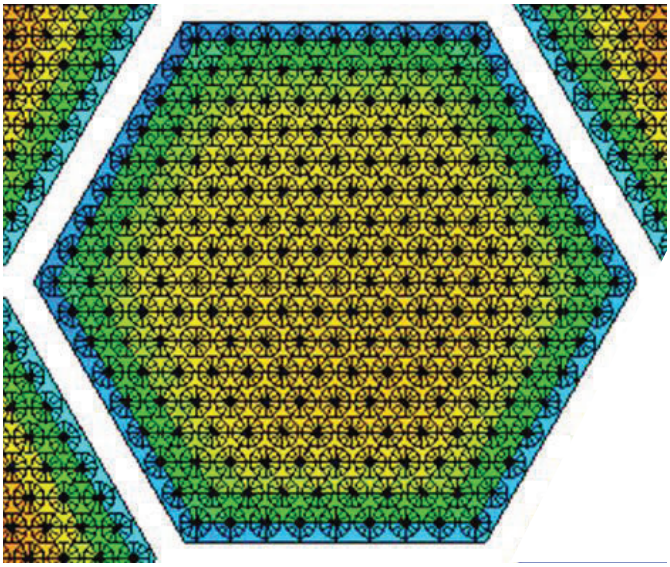


Fig. 5 Trio_U MC application – Modelling type

2.2.2 Example reactor results

An example of a Trio_U MC computation for an SFR fuel S/As (in nominal working operation) is shown in Fig. 6:

- The higher flow sections on the edge on the bundle (subchannel type 2 on Fig. 2) lead to higher cooling in the first peripheral pin row (blue color): this effect is spread by wire spacer mixing to the second and third rows (green color). Hence, they exhibit lower outer temperatures than the mean over the S/A (550 °C).
- Other rows (yellow-orange) are at least as hot as the mean S/A temperature (550°C); the hottest sodium subchannels (central part) correspond to sub-assembly thermal-hydraulic "hot spots".



In operating conditions, sodium temperature heterogeneities calculated by the code in a S/As at bundle outlet are the following:

- about 30 °C between the central sodium hot subchannels (580 °C) and the sodium mean temperature (550°C);
- about 80 °C for the sodium radial gradient temperature (580°C to 500°C).

The radial temperature distribution (sodium and pin clad) exhibits the same 1/12 symmetry as the S/As geometry, except in the presence of an asymmetrical power distribution (such as on the edge of the core.

Fig. 6 SFR fuel S/As – Temperature radial distribution

The knowledge of thermal-hydraulic fields within each sub-assembly is also necessary in incidental and accidental transient scenarios. In transients where local core effects have no feed-back on the global behavior of the reactor, a system (CATHARE) or coupled system CFD/CATHARE/Trio_U) calculation is used to obtain the evolution of core power, core inlet temperature, and core flow over the transient [12]: then, these calculation results are used as input data to a Trio_U MC calculation to obtain the local

sodium and cladding temperatures during the transient. The transients studied and the relevant computational schemes are described in [13]

2.3 CFD Code

2.3.1 Presentation

Besides the subchannel model used for design phase, it has nowadays become possible to use a refined CFD model of the SFR fuel S/As to obtain reference thermal-hydraulic behavior and detailed data. Such computations provide direct information on the flow field, with the effect of helical wires and the influence of the hexagonal wrapper tube.

The difficulty of a refined CFD simulation arises from the complex geometry of SFR fuel S/As, which requires a large number of mesh cells for the fluid domain and hence long computational times. Because the Trio_U CFD code only allows for tetrahedral meshes, Trio_U calculations on SFR subassemblies have a high computational cost : hence, the industrial CFD code STAR-CCM+ is often used instead for these calculations, as its hexahedral volume cells allows for lowering the number of cells, thus reducing this CPU cost.

First computations with STAR-CCM+ are based on a very detailed meshing of the flow field around the pin bundle [14]; the mesh generation is based on a specific multi-block elliptic meshing technique. As a first step, the S/As is sub-divided into axial slices in order to perform a 2D meshing of the region comprised between the external contour of the pins and the hexagonal wrapper tube (Fig. 7).

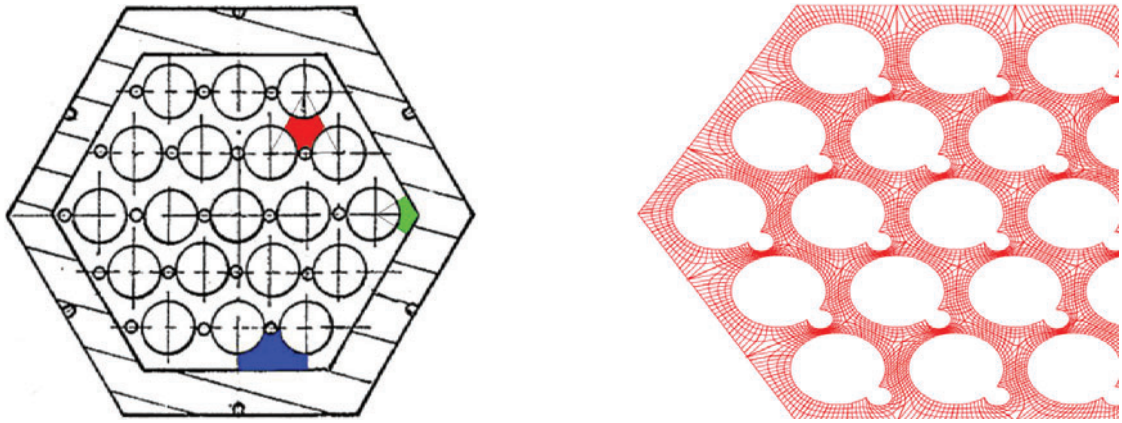


Fig. 7 SFR fuel S/As – Detail of the 2D meshing

The S/As meshing is finally built by assembling the 2D meshes. The S/As final 3D mesh contains 150 axial layers, resulting in a mesh with 15 million cells (in comparison with 100 million cells with automatic meshing - Fig. 8). The mesh resolution has been verified by checking the value of non-dimensional distance from wall (y^+). It gives an idea that the first point after the wall is placed correctly to have physical value of the velocity and wall shear stress.

Fig. 8 SFR fuel S/As – 3D CFD meshing of the computational domain

2.3.2 Resolution

Some physical models, in coherency with the meshing, are selected in the commercial CFD code STAR-CCM+:

- the energy equation is not coupled to the momentum equation,
- the resolution of equations is based on the finite volume convection scheme,
- a RANS (Reynolds-Averaged Navier-Stokes) model is selected ; more precisely, the k-ε turbulent model: it consists of an additional turbulent viscosity added to the momentum and energy equations. This turbulent viscosity is calculated thanks to k, the turbulent energy per unit mass and the dissipation per unit mass, ε. Each of these two terms is solution of a transport equation. The wall law model used is the two-layer all y+ treatment.
- to account for the high thermal diffusivity of the liquid sodium in the present analyses, the equation developed by Reynolds is used with values of turbulent Prandtl number $Pr_t \approx 2$.

2.3.3 Boundary conditions

The boundary conditions are defined for the S/As. The power generated by the fuel pin is represented by imposing the heat flux on the pin outer surface. As the heat flux is totally transported by forced convection on the axial direction, the condition of adiabadicity imposed on the hexagonal wrapper tube is justified. For the spacer wire, the adiabatic condition is also set up. The average mass flow rate is imposed at the S/As inlet, to meet the desired sodium average temperature increase of 150°C.

2.3.4 Some results

The sodium coolant mass flow rate is not uniform in the sodium flow subchannels surrounding the fuel pins. As a consequence, there are strong temperature variations around the fuel pins that give rise to local hot spots at locations of deficient coolant supply, such as wake of the spacer wire. Temperature and velocity near outlet region of the rod bundle, around the central zone are shown in Fig. 9. The high radial temperature fluctuations existing around the spacer wire indicate that the spacer wire generates, at the pin contact, local hot spots of a few degrees downstream from the spacer wire.

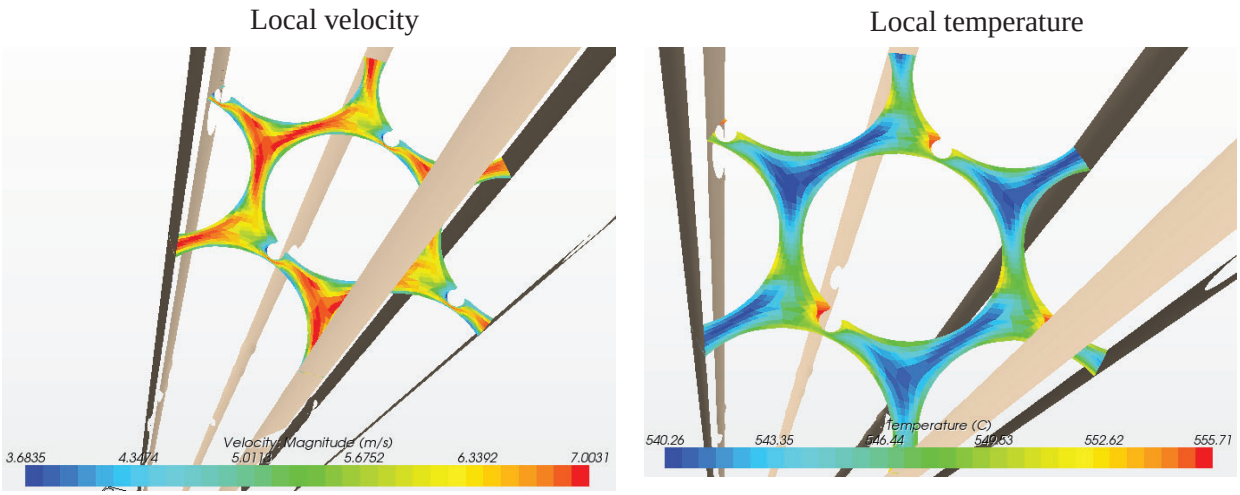


Fig. 9 Local thermal-hydraulic fields

3. CORE STEADY-STATE THERMAL-HYDRAULIC CONDITIONS

3.1 Numerical Analysis Needs

The main objective is to determine for all S/As in the core, their steady-state thermal-hydraulic conditions, with specific objectives, such as the achievement of a target mean outlet core temperature under sodium and pin cladding temperature limitations.

3.2 Flow Rate Management

3.2.1 Total core mass flow rate

SFR total core mass flow rate, Q_TOTAL_CORE, is deduced from mean inlet (for example 400°C) and mean outlet core temperatures (for example hot pool plenum at 550°C), associated to the thermal power of the SFR under consideration (around 1500 MW).

Several percent of Q_TOTAL_CORE, correspond to the by-pass flow Q_LEAKAGE, corresponding to the leakage at the bottom of the sub-assemblies. The rest, Q_S/As, is fed to the S/As by forced convection.

A part of Q_S/As is dedicated to specific S/A families, such as Absorber (ABS), part of the Steel Reflectors (SR), and Internal Storage (IS). For these, flow rates (Q_ABS, Q_SR and Q_IS) are designed, taking into account specific design criteria, especially preservation of maximum cladding temperature within a given limit.

The remain part Q_FUEL can be used to cool the fuel S/As, and is deduced from balance equation:

$$Q\_FUEL = Q\_TOTAL\_CORE - (Q\_ABS + Q\_SR + Q\_IS) - Q\_LEAKAGE \quad (1)$$

3.2.2 Fuel S/As flow rates

From a design point of view, one main target is to obtain fuel S/As outlet temperatures as uniform as possible (in nominal flow condition), in order to optimize the core loading characteristics. As the radial heat power profile is not uniform in the core, the radial distribution of fuel S/As mass flow rates must be

adjusted. For practical reasons, the fuel S/As flow management is done by dividing the fuel S/As between a restricted numbers of flow zones: all the assemblies within a given flow-zone are fitted with a flow restrictor in order to adjust their mass flow rate to a common value. Fuel S/As flow rates determination is performed:

- to respect the equation (1), in order to obtain the required mean outlet core temperature (550°C for example);
- to maintain the hot-spot pin cladding temperature (in all fuel S/As) within a given limit; at present, this considered limit is 620°C (without uncertainties);
- to flatten the S/As mean outlet temperature distribution, T_Out_Na, in order to minimize "Na hot spots"; it is realized by limiting T_Out_Na discrepancies in the core to a limit value of 50°C.

3.3 Using Trio_U MC within an Optimization Process

Determination of flow zone number and corresponding mass flow rate is done with Trio_U MC application. Given the constraints above, numerous fuel S/A flow rate distributions are conceivable (several thousands). Trio_U MC contains a simple heuristic that can compute, given a flow zone number and a target core flow rate, a flow zone distribution minimizing the hot-spot pin cladding temperature while avoiding excessive S/As outlet temperature discrepancies.

Then, an optimization process allows choosing between all these distribution possibilities, the one which:

- maximizes the margin of the core hot-spot pin cladding temperature to the 620°C limit;
- minimizes sodium outlet temperature discrepancies;
- maintains a reduced flow zone number.

3.4 Some Results

For present SFR cores, less than 10 flow zones are sufficient to reach the objectives stated above: in the example of Fig. 10, each color apart from dark-blue (which denotes non-fuel S/As) corresponds to a flow zone.

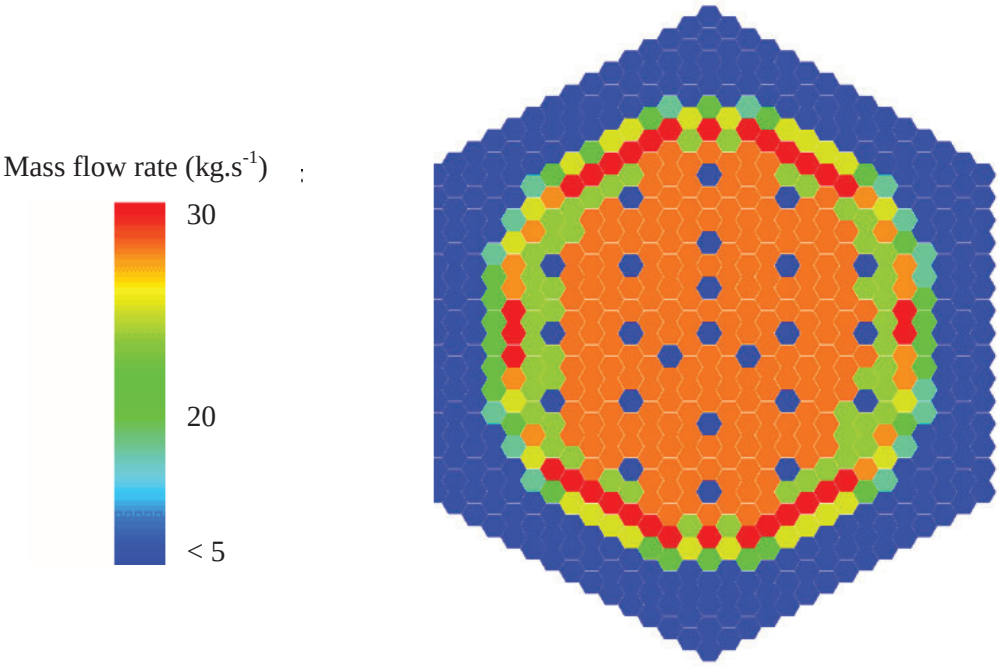


Fig. 10 SFR core – Flow management design example

Once the flow-rate repartition is defined, Trio_U MC allows one to access radial and axial thermal-hydraulic fields at the subchannel level over the whole core: pin temperature examples are shown on Fig. 11, with the coolest temperatures in blue and the highest temperatures in orange/red. As shown, the highest temperatures are usually reached in sub-assemblies with an uneven power distribution.

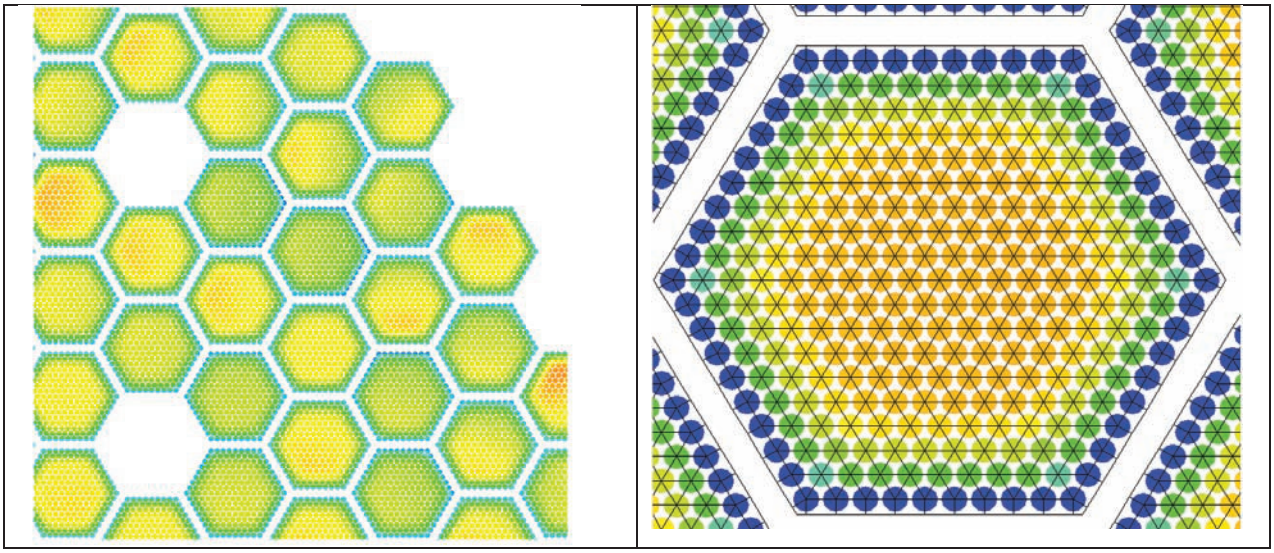


Fig. 11 SFR core – Sodium and pin clad radial temperature distributions

4. HEXCAN TEMPERATURES

4.1 Numerical Analysis Needs

Another design requirement is the knowledge of hexcan temperatures for thermo-mechanical analyses. This information requires a good evaluation of the inter-wrapper flow behavior and the temperature field in this region [4].

The inter-wrapper zone may be fed by a by-pass flow adjusted at the bottom of the S/As: it is also traversed by recirculation loops to and from the hot pool plenum. Due to the radial pressure profile imposed by the Above Core Structure at the core outlet, hot sodium can penetrate downwards from the core outlet region into the inter-wrapper region, and then interact with the (cold) by-pass flow before returning upwards to mix with the main core outlet flow.

Heat transfer with the hexcans, heat transfer with the outer core baffle and buoyancy effects must be taken into account in the inter-wrapper flow analysis.

4.2 MC2 Model in Trio_U Code

The numerical analysis of hexagonal wrapper tube temperatures requires a global core modelling to determine the temperature distributions and the influence of the inter-wrapper flow. To reach this objective, a 3D model of the complete core is used, with the sub-channel model for S/As and a 3D modelling of the other physical components. The Trio_U MC2 code couples:

- the MC application described in §2.2, for each S/A (including its hexcan);
- a 3D Trio_U CFD model of the inter-wrapper zone (Fig. 12 – left) and of the hot pool plenum, with the Above Core Structure (Fig. 12 – right).

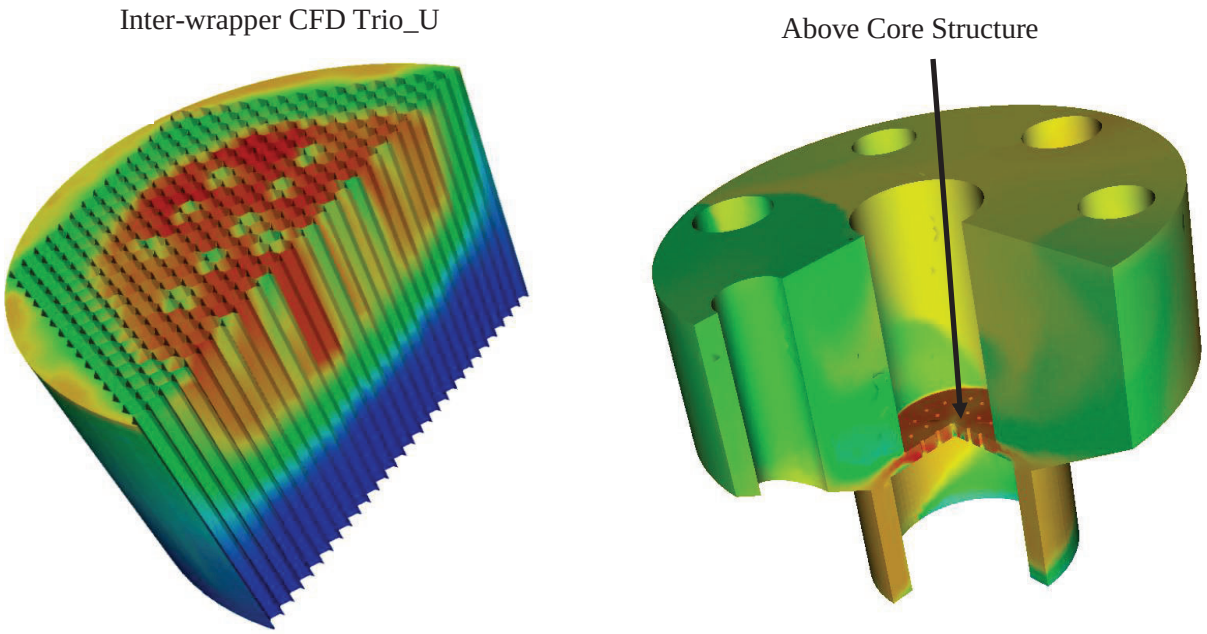


Fig. 12 : Trio_U MC2 code – Thermal-hydraulic modelling

Thus Trio_U MC2 can be used to simulate the local thermal-hydraulic behavior of the inter-wrapper zone under the influence of the complex global flows between the core, the Above Core Structure and the hot pool plenum. An example of Trio_U MC2 computation for present SFR core (in nominal operating operation) is shown in Fig. 13: the different sodium flows in various areas are represented by little black arrows, with corresponding sodium temperature (in color).

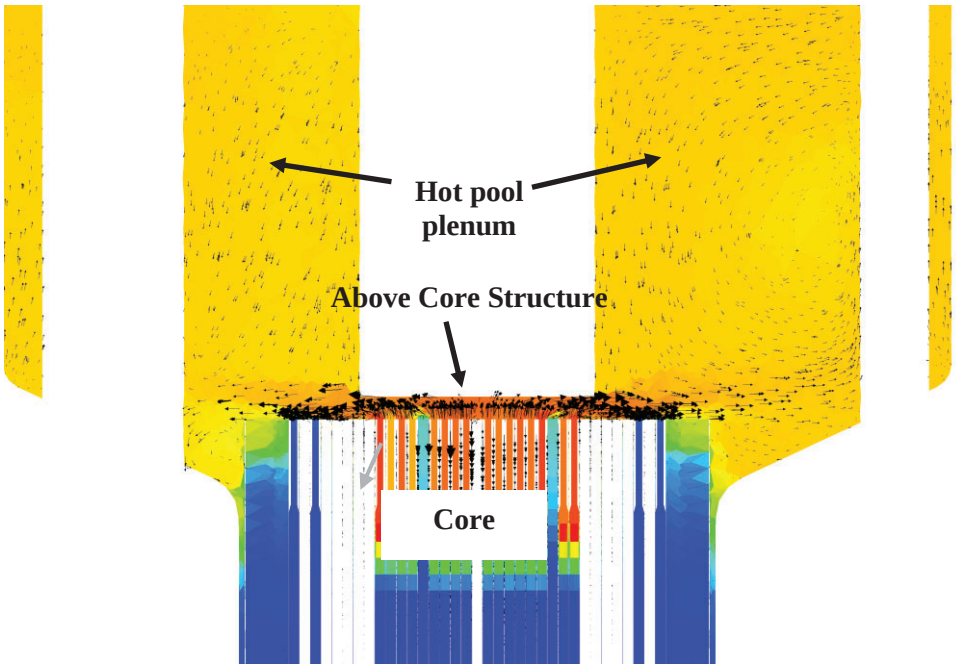


Fig. 13 Trio_U MC2 code – Sodium flow in SFR core

The hexcan temperatures depend on the sodium temperature within the S/As and on those in the corresponding inter-wrapper region; to obtain sufficiently converged results, it is necessary to simulate several hundred physical seconds. In Fig. 14, an example of SFR core radial distribution of hexcan temperatures is shown. These results are then used in the analysis of the static mechanical equilibrium of the core.

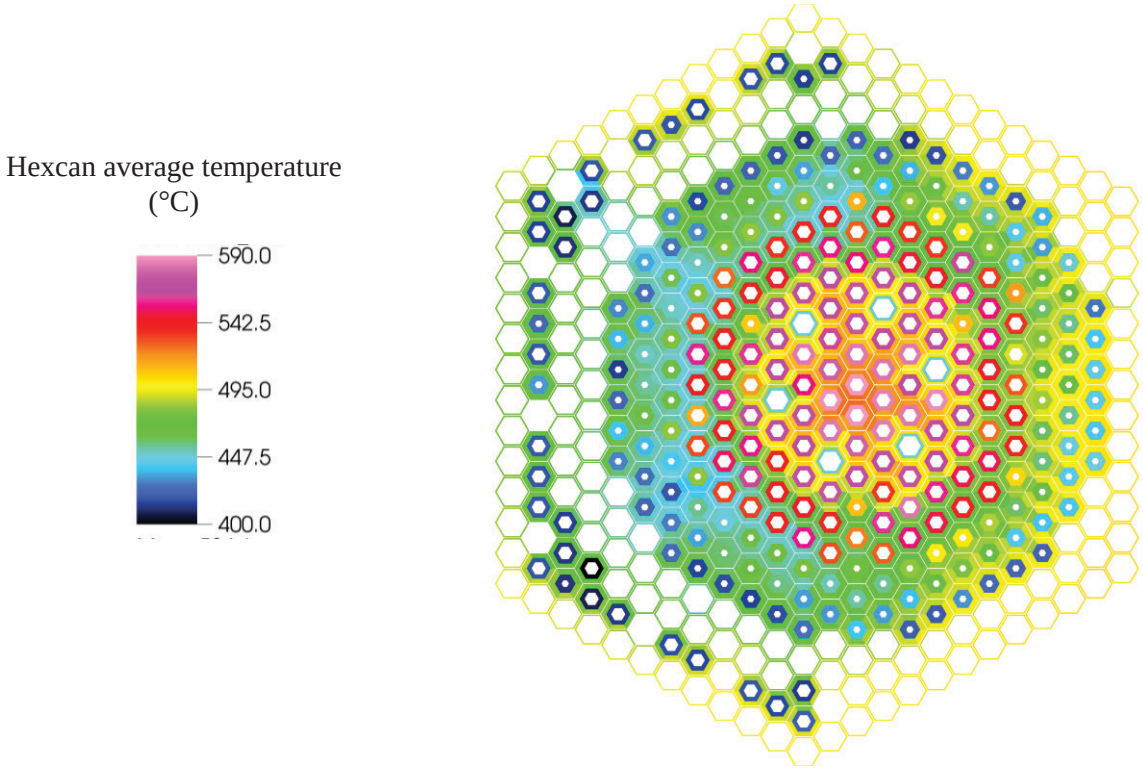


Fig. 14 Trio_U MC2 code – Hexcan radial temperature distribution in SFR core

5. CONCLUSIONS

SFR core thermal-hydraulic analyses lead to:

- the thermal-hydraulic fields in individual fuel S/As, either by a sub-channel approach (implemented in the Trio_U MC code) in order to determine the sodium and cladding temperatures inside the bundle, or by a refined CFD model (implemented in Star-CCM+) in order to compute local sodium flows and to determine the effect of the helical wires;
- the core nominal thermal-hydraulic conditions, which require the determination of the number of flow zones and of their corresponding flow rates (flow rate management) in order to access the radial and axial distributions of each thermal-hydraulic field locally within the core;
- the hexcan temperatures: the "Trio_U MC2" code coupling associates the sub-channel S/As approach (Trio_U MC) and a 3D CFD model (Trio_U) of the inter-wrapper gaps and of the hot pool plenum, with the Above Core Structure.

For each of these items, the CEA relevant numerical tools have been presented as well as some examples of computations. A validation process is currently underway with comparisons of code predictions to measured data, both on out-of-pile experiments and on reactor cases.

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