Advanced Coupling methodology for Thermal-hydraulic calculations

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Abstract

The purpose of this paper is to describe in a first part a coupling methodology between two codes in order to describe global thermal-hydraulic behavior inside a sodium-cooled fast reactor. A CFD code (STAR-CCM+) is used for the modelling of primary circuit, while a system code (CATHARE) is used for the modelling of specifics area in primary circuit (core structures and primary pumps) and the modelling of secondary circuits. The main advantage of this method is the computation of the whole primary loop while representing accurately complex 3D phenomena like thermal stratification onset or unsymmetrical mixture in plena.

The second part of the paper presents thermal-hydraulics results obtained with this coupling tool in case of two reactor design sizing transients: a station-blackout transient in which primary and secondary loops are operated in natural circulation, and a loss of one secondary loop which exhibits thermal mixing phenomena in primary pools.

Key Words: sodium fast reactor, thermal-hydraulic, CFD, coupling methodology

1. Introduction

In the frame of the Generation IV reactor deployment, a 600MWe sodium-cooled fast reactor prototype named ASTRID (Advanced Sodium Technological Reactor for Industrial Demonstration) is currently under development. The main purpose of this prototype is to demonstrate the safety and the operation of 4th generation SFRs on an industrial scale (see [2] and [3]).

In a post-Fukushima context, the reactor ability to remove heat decay without active system is a strong requirement of ASTRID design. In order to demonstrate the ability of the reactor to rely on passive system and natural behaviour to remove decay heat, appropriate engineering tool must be implemented.

The 3D character of the flow inside the primary loop and the complexity of physical phenomena encountered call for a predictive approach with a CFD tool (see [1]). In addition, for certain accidental transients, reactor behaviour depends on many systems and requires a computation of the entire nuclear island over a large period of time, which needs an adapted system tool.

In order to conjugate the advantages of these different approaches, a coupling methodology has been developed and improved by AREVA NP (see [4], [5], [6]).

This paper presents this methodology and its application in the frame of ASTRID project to calculate reactor behaviour for two sizing transients: a station black-out event in which primary and secondary circuits are operated in natural circulation, and a loss of one secondary loop event in which thermal mixing phenomena in primary pools are preponderant on the structures and components thermal loads.

2. ASTRID design overview

ASTRID prototype is a pool-type sodium fast reactor, like previously-constructed sodium fast reactors in France: PHENIX and SUPERPHENIX. Primary circuit with sodium cooling is integrated in one vessel (main vessel) in the reactor block.

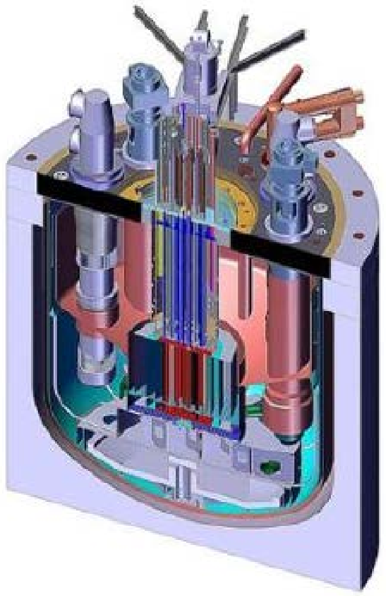


FIG. 1. ASTRID reactor block.

Primary circuit includes the core, three primary pumps (PP) and four intermediate heat exchangers (IHX). The hot pool contains hot sodium flowing from the core outlet to the IHXs inlet windows. The cold pool contains cold sodium flowing from the IHX outlet to PP inlet, then to core inlet. Hot and cold pools are separated by an inner vessel.

Each IHX is associated with a secondary loop which includes electromagnetic pump and sodium-gas heat exchanger or steam generators. The tertiary circuit includes gas power conversion system (reference design) or steam-water power conversion system (alternative design).

The core includes about 300 fuel subassemblies containing the fissile material. A large thickness of lateral neutron shielding surrounds the core area. The core reaction is managed by about twenty control rods.

Each subassembly is delimited by a hexagonal wrapper tube and it contains 217 pins separated by spacer wires. Subassemblies are inserted in spikes of the diagrid in which the PP outlet flow is collected thanks to diagrid-pump connection.

The decay heat can be removed by two in-vessel Decay Heat Removal (DHR) systems (two trains by system) and one reactor vessel DHR system. The two sodium-sodium Decay Heat eXchangers (DHX) of passive DHR system are located in the hot pool. The two sodium-sodium DHX of active DHR system are located in the cold pool.

3. Calculation methodology of reactor global thermal-hydraulic behaviour

As a first step, circuits and components that are relevant to studied physics situations are to be identified. Usually, ASTRID transients require taking into account the primary circuit and the secondary loops. For each of them, a physical phenomena analysis enables to choose the more accurate and efficient code to use: system or CFD.

The coupling methodology allows to assemble all separate models to describe the whole nuclear-island thermal-hydraulic.

a. STAR-CCM+ primary circuit modelling

A CFD modelling has to be used for the primary circuit. Indeed, for many investigated transients, non-symmetric behaviour of sodium is expected in ASTRID big collectors, as well as thermal stratifications.

A RANS model (K-$\mathcal{E}$ realizable) is used to model turbulence.

The 360° CFD model includes hot and cold collectors, and all the main components (FIG. 2.): core, above-core-structure, intermediate heat exchangers, primary pumps, decay heat-removal exchangers. It is made of 8 million of polyhedral cells.

Porous media are used to describe complex zones such as IHX, primary pumps and fuel subassemblies.

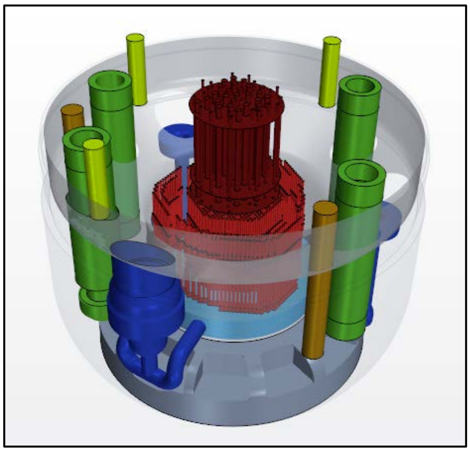


FIG. 2. CFD primary circuit model

b. CATHARE modelling

CATHARE is the CEA developed reference system code for ASTRID. It has available module to compute primary-pumps shaft rotation (including hydraulic and mechanical friction), which is mandatory in case of loss of primary pumps. Thus, a basic **CATHARE pump model** is built and will complete the CFD primary circuit model.

CATHARE also has available modules to compute core fuel thermo-mechanics (including fuel conductivity). An additional **CATHARE core model** is developed and will complete the CFD primary circuit model. Fuel assemblies are distributed in 35 groups, each group bringing together assemblies that have similar power and similar inlet flow-rate. A 1-D axial description of these 35 groups constitutes the CATHARE model.

For many transients that are to be studied, physical phenomena in secondary loops are expected to remain 1-D. As separate secondary loops may behave differently (e.g. in case of single secondary loop failure), the four loops are modelled separately. Each loop model contains around 400 cells, and includes IHX tubes, one SG or one sodium-gas heat exchanger, and electro-magnetic pump.

Finally, CATHARE is used to model the passive DHR system. Indeed, this system is based on a natural convection sodium circuit that connects the primary circuit to a heat removal air circuit.

c. Coupling methodology

All the individual circuits can be connected thanks to the coupling methodology, as illustrated on FIG. 3. Coupling interfaces performing CATHARE/CFD connections are independent and can be plugged in or unplugged at any time during the calculation, which provides a high flexibility to the whole model.

Each interface includes a time-processing tool that manages both codes time-progressions.

The different types of coupling interfaces available are illustrated hereafter.

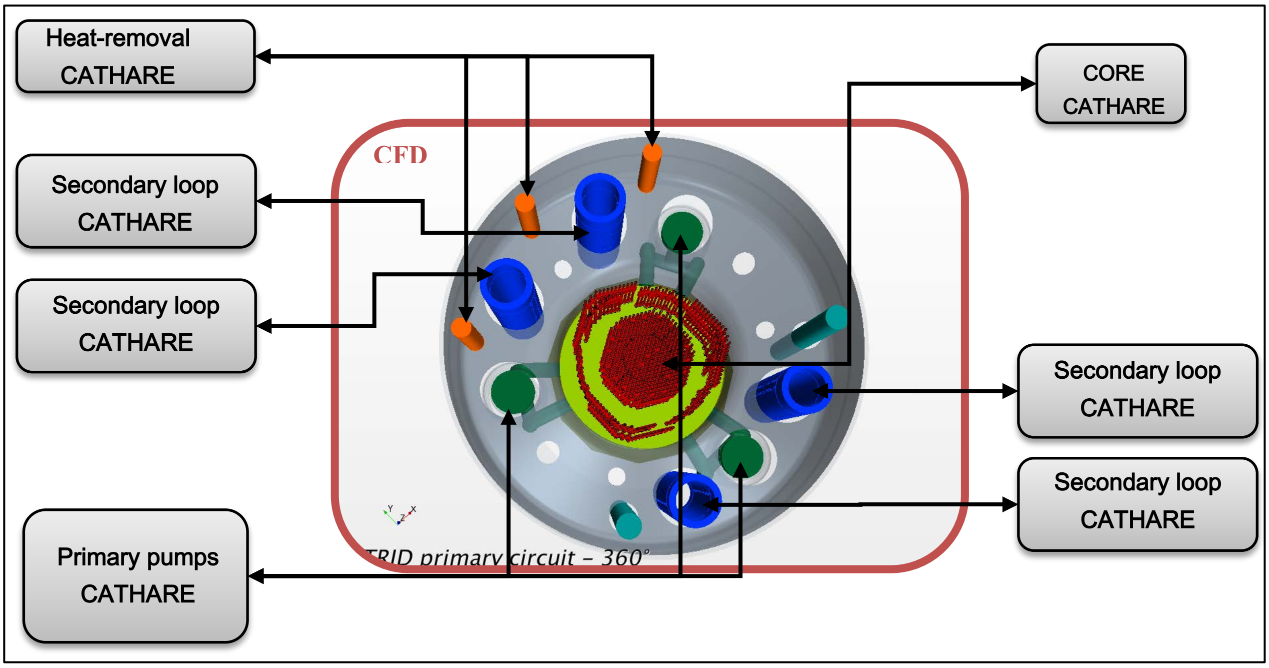


FIG. 3. : ASTRID whole-model coupling-interfaces schema

Non-recovering coupling-interfaces to connect two circuits through a heat exchanger:

This type of interface is used to connect the primary circuit to the secondary loops. Indeed, modelled domains are perfectly separated in the intermediate heat exchangers (IHX): primary sodium outside the tubes belongs to CFD primary-circuit model, while secondary sodium inside the tubes and tubes themselves belong to the secondary-loop CATHARE model. Thus, the interface between codes is precisely located on the external wall of tubes.

Information such as temperature, velocity and exchanged-power at this location are permanently exchanged between the two codes through the coupling interface.

The same type of interface is used to connect the decay heat removal system with the primary circuit trough the decay heat removal exchanger (DHX).

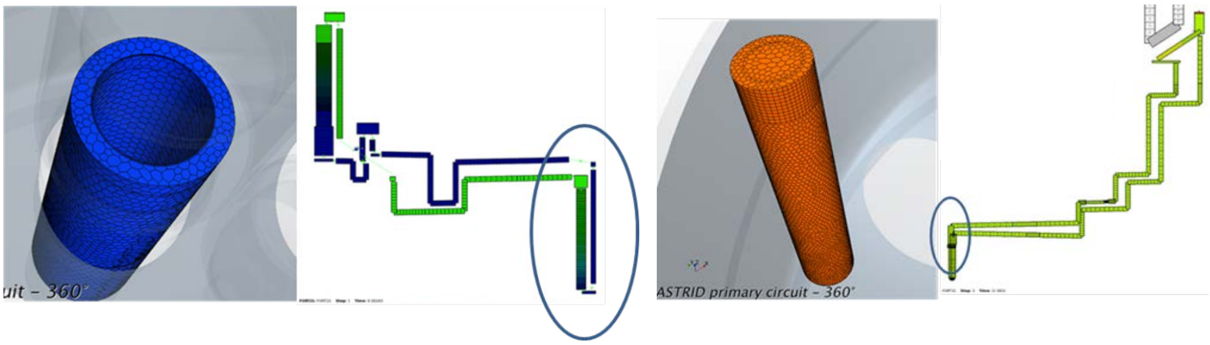


FIG. 4. : coupling-interface connecting CFD and CATHARE inside IHX (left) and DHX (righ)

Recovering interfaces for additional specific modelling:

This type of interface is used to connect the CFD primary circuit to the CATHARE pump module. The velocity-field calculated by CFD model is reproduced in the CATHARE model, in order to obtain the pump elevation, which is given back to CFD as a porous momentum source or sink.

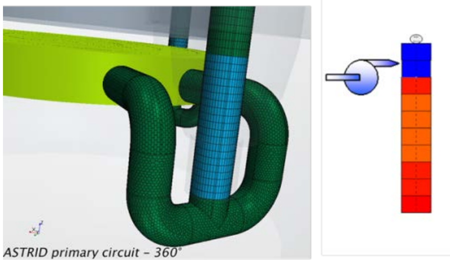


FIG. 5. : coupling interface connecting CFD and CATHARE for primary pump modelling

This type of interface is also used to connect the CFD primary circuit to the CATHARE core module. Again, velocity & temperature fields calculated by CFD model are reproduced in the CATHARE model, in order to obtain the fuel delivered power that is given back to CFD as a volumetric heat source.

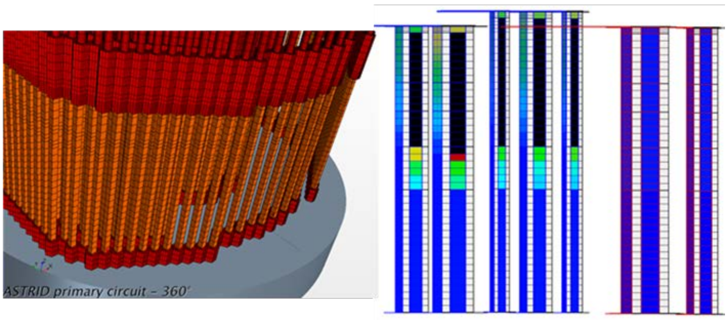


FIG. 6. : coupling interface connectiong CFD and CATHARE for core modelling

4. Sizing transients calculation and thermal-hydraulics results

a. Station Black-Out transient

The Station Black-Out event is a sizing transient for ASTRID safety demonstration. It has a direct impact on plant design and DHR system architecture.

This accidental transient is characterized by the Loss Of Offsite Power (LOOP) and the loss of emergency power supply. It leads to the loss of all active system:

- Loss of primary pump on its inertia (auxiliary engine are not available)
- Loss of intermediate loop and power conversion system heat removal capability
- Active in-vessel DHR system are not available

In this case, the reactor shutdown is induced by reduction of primary flow. The opening of passive in-vessel DHR system air damper, to remove core decay heat, is managed by core outlet temperature increase in the beginning of the transient.

During the entire transient, passive in-vessel DHR system is the only DHR system available to remove the core decay heat. Indeed, reactor vessel DHR system is not sufficiently efficient in this case. Because of the safety analysis rules (single aggravating failure criterion), one passive in-vessel DHR train failure is considered in the analysis.

The reactor is placed in passive operation in which reactor safety needs to be demonstrated. Core decay heat is to be removed by generalized natural circulation of primary sodium maintained by natural circulation in secondary and tertiary loops of the passive DHR system.

This situation requires the implementation of a coupled method for computation because of complex physical phenomena in primary circuit. The reduction of primary flow leads to thermal stratification establishment in hot and cold pools which have an impact on the resulting level of primary natural circulation flowrate. In addition, the heat removal performance of the passive DHR system depends on the temperature close to the DHX in hot pool.

The calculation has been performed for several hours of physical time to simulate the two phases of the transient:

- The onset of natural circulation within the primary loop and the transition from the nominal state,
- The decay heat removal by passive DHX in hot pool process within established generalized natural circulation.

Concerning the onset of primary natural convection, the reduction of primary flow leads to the reactor shutdown which induces a cold thermal shock in the core. In the same time, the loss of heat removal by intermediate loop leads to accumulate hot sodium in IHX primary side as indicated on the figure below:

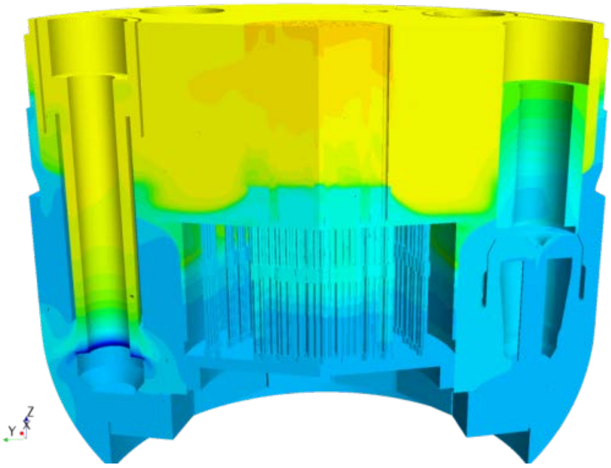


FIG. 7. : Station Black-Out – Temperature field – Illustration of cold shock in core and hot sodium accumulation in IHX

Before the stop of primary pumps, the thermal inertia of the secondary loops is sufficient to allow the cooling of the primary sodium in IHX (see figure below):

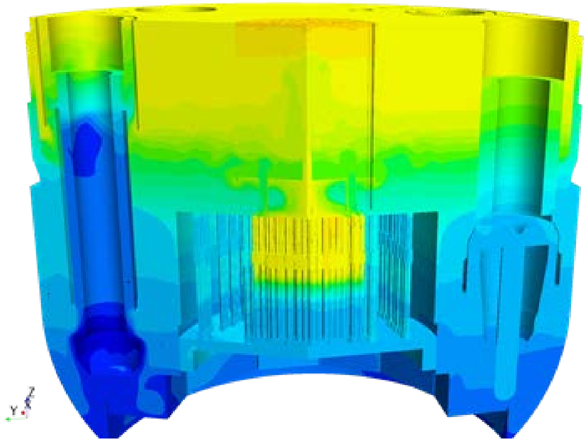
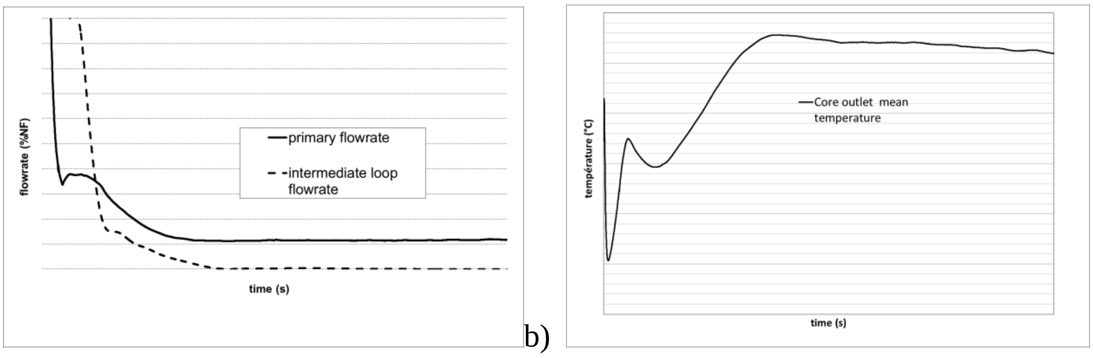


FIG. 8. : Station Black-Out – Temperature field – Primary sodium in IHX cooled by intermediate loop inertia

The cooling of sodium in IHX improves the primary flowrate intensity by natural circulation in the beginning of transient. Then, all the cold sodium volume available in secondary loop is used, which leads to cancel the secondary flowrate and to reduce the primary flowrate intensity. The core outlet temperature increases in consequently.



a) b)

FIG. 9. : Station Black-Out – Flowrates and temperature evolution during the first thousands of seconds of the onset of natural circulation

The onset of natural circulation in case of Station Black-Out is fast enough to prevent any damageable temperature rise inside the core .Figure 9 illustrates (on the left) that primary flowrates never reaches 0 as intermediate-loop flowrate does. It induces design requirements on secondary loop in terms of cold sodium volume and axial position of heat exchangers.

Concerning the decay heat removal process, passive DHX located in hot pool allows to maintain a generalized natural circulation in the plant during the entire transient and ensures thermal loads of structures and components compatibles with the criteria.

b. Loss of one secondary loop transient

Another transient category requiring the use of a coupled method for computation is the dissymmetrical transients. As a matter of fact, during these accidental or incidental situations, only some of the loops of the plants are affected. As a result, some mixing can take place inside the reactor vessel, which has a consequence on the way the transient affects the different loops.

Among this category the transients related to the loss of one secondary loop have been studied, as they can have a direct impact on primary loop sizing.

The transient studied is related to the sudden, immediate loss of an electromechanical secondary pump. These devices do not have mechanical inertia, so the loss of momentum at the secondary side is very sharp.

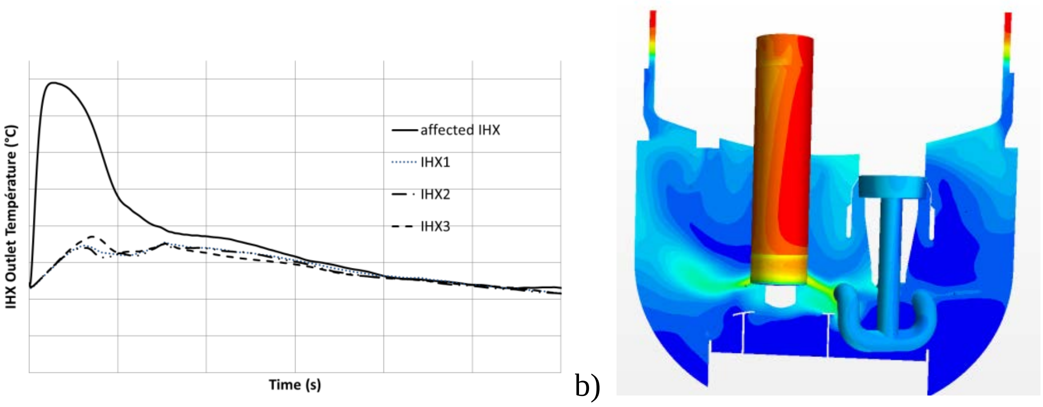
The consequences of this initiator are:

- Reactor shutdown
- Primary flowrate is maintained
- Secondary flowrate is decreased to 25 % in the unaffected loops (it gets down to natural convection in the affected loop)
- Tertiary flowrate is decreased to 20% in all the loops.

As a consequence of the sharp decrease of secondary flowrate in the affected loop, the efficiency of the affected intermediate heat exchanger is strongly decreased and there is a hot shock at the outlet of this heat exchanger.

Results obtained are of two kind:

- Some curves can be plotted showing local parameters such as for instance the maximal temperature at the outlet of the various intermediate heat exchangers (FIG. 10.a)
- Some thermal fields can be plotted at given times to show the area of influence of the hot shock (FIG. 10.b)



a) b)

FIG. 10. : example of results obtained – reference configuration

As the CFD computation includes the representation of the mechanical structures, the impact of this transient on the mechanical parts can also be quantified, see figure 11 below :

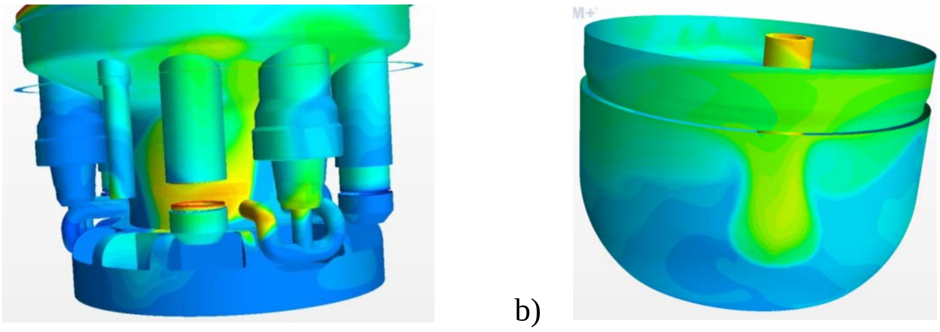


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FIG. 11. : impact of the hot shock (thermal field) on structures

The first conclusion of this study is that, in the reference configuration, some effect of the hot shock of temperature (temperature gradient inducing mechanical stress) can be seen on the cold structures, mainly the PP-diagrid connection, which is a very sensitive equipment and the main reactor vessel.

The effect of this thermal loading in terms of damage to the structure is being assessed. Note that the fact that this computation methodology provides 3D temperature fields enables to perform easily, at design stage, 3D mechanical stress analyses, which tends to limit excessive penalization of the damage and will provide a more realistic view of the impact of the loadings.

5. Conclusion

In order to study the behaviour of ASTRID plant in various situations involving both complex phenomena and a large number of systems, a coupling methodology between CFD and system codes has been applied to ASTRID design studies.

This methodology relies on CFD code STAR-CCM+ and system code CATHARE, which are both commonly used for design studies of ASTRID and has the following advantages:

- Applicability of all the validation work performed for both codes
- Usability of available data and work already performed with any of these codes
- Traceability of the information exchanged by the code, possibility to check the conservation of energy through sum checks between the codes
- Independence of the time steps used for both codes
- No exchange of mass between both codes : better convergence and stability.

This method is deployed at an industrial scale and now serves as reference for ASTRID studies requiring investigating 3D phenomena such as mixing or flowrate repartition on a large scale.

Two applications have been presented:

- Regarding the onset of natural convection within the primary loop, this engineering methodology enables to demonstrate that, provided the thermal inertia of the secondary loop can be credited, the onset of natural convection is fast enough to prevent any damageable temperature rise inside the core. This positive conclusion also enables to specify design constraints on the secondary loop in order to be in a good position to achieve this on the final design.
- Regarding the dissymmetrical transients, the computation has quantified the mixing inside the vessel and enables to use realistic (but conservative) data for the sizing

The future work will be oriented toward validation:

- A lot has been already done by AREVA NP to perform physical validation of both codes
- Some work has been achieved in order to address V&V of the coupling methodology
- Nevertheless, a proper benchmark between a fully coupled computation and a test remains to be performed. The CEA data on end of life test of PHENIX plant will be used at this end.

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