SUPER PHENIX Reactor Block Thermalhydraulic Behaviour Comparison Between Calculations and Experimental Results

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INTRODUCTION

The design and the thermal stress analysis of the internal structures and vessels of Liquid Metal Fast Breeder Reactors require a thorough knowledge of the thermalhydraulic behaviour of the primary circuit which provides the boundary conditions. This knowledge has to be improved for the future reactor's conception as EFR since they will be more simple to also more compact.

This paper compares the previous calculations to the experimental results obtained during the commissionning tests of the CREYS MALVILLE's plant SUPER PHENIX (Fig. 1).

It is therefore a mean to improve the general understanding of the Primary Circuit behaviour and also to verify the suitability of the design hypothesis.

Problems are not the same for sodium and gas. As examples, the two kind of fluids are investigated here :

- annular spaces in the roof slab,
- hot plenum.

For each subject the phenomena are described and the basic assumptions are recalled.

ANNULAR SPACES IN THE ROOF SLAB

Phenomenon

The primary circuit is closed on the upper part by the roof. This thick structure supports the main components (IHX and primary pumps) and the rotating plugs. The penetrations provide some annular spaces between the roof and the components (see Fig. 2). These gaps are filled with argon which communicates with the argon cover gas above the free surface of sodium.

In case of SPX1, the roof is cold ($T \leqslant 50$ °C) cooled by water circuits, and insulated to prevent large heat losses. For component penetrations the vertical insulation consists of two separated annular gap. One is closed and roof side is insulated with metallic insulator, the other one is open on the hot cover gas plenum (Fig. 2). These annular spaces are submitted to an important axial temperature difference ($\simeq 300$ °C), and this temperature field induces some convective phenomena. In respect to the height/thickness ratio, the flow pattern is organized on cells. This phenomenon called thermosiphon has been observed on the Phenix reactor (1) and studied with numerical tools validated on specifics rigs (2) and (3).

Calculations

The calculation's method is based on an iterative process between two kinds of heat transfer modes :

- thermal calculation. It is a classical calculation involving conduction, radiation, convection

- thermalhydraulic calculation. In this step, convection and mass transfer modes are solved. For this flow calculation the annular space is developped along the circumference considering the weak thickness of the gap with regard to the others dimensions.

The fluid mechanic equation continuity, momentum and energy are solved in this developped space, using :
- vorticity and stream functions (Ω, Ψ),
- Boussinesq approximation,
- a mixing length method for the turbulence model.

Two axisymmetric calculations are performed with THERNOV code (2) coupling thermal and thermalhydraulic process. They provide the velocity and temperature fields for the up and down stream side (Fig. 3).

The most important consequence of such a phenomenon for the components behaviour are the circumferential temperature differences. They are summarized in table 1.

	Circumferential ΔT °C	Cover gas Temperature °C
Heat exchangers	72	500
	42	400
Primary pumps	250	500

The cover gas temperature is a significant parameter for calculation since for IHX's support shell the circumferential temperature difference increases of about 70 % when the cover gas temperature change from 400 °C to 500 °C.

Experimental results

Three penetrations on SUPER PHENIX's plant are provided with great number of thermocouples :
- 2 IHX
- 1 primary pump

35 thermocouples/component.

This instrumentation has shown that the thermosiphons exist on SPX1's penetrations. They are generally stable but sometime their orientation changes owing to the operating conditions. The maximum circumferencial temperature differences are located in the lower part of the penetration. The thermal dissymmetries and the temperature fields in argon and in the structures have been found well calculated.

The measured temperatures have confirmed that components are submitted to azimuthal dissymmetries and that the range is strongly linked to the argon cover gas temperature which has been found close to the expected lower value.

HOT PLENUM

Phenomena

The hot plenum is the link between the core outlet and the Intermediate Heat Exchangers (IHX) inlet. Its functionnal requirements are mainly :
- to insure a good feeding of IHX (no azimuthal dissymmetries of the flow),
- to avoid agitation of the free sodium level (no vortices, no gas entrainment, no vibration of the structures).

To achieve such requirements the sodium going out of the subassemblies is deflected lateraly by the core cover plug shield. This produce recirculations of the sodium above and under the core jet in the plenum. A part of the flow (15 %) enters inside the Above Core Structure (ACS) by the shroud tubes (control rod penetrations) and is mixed to the hot plenum near the ACS's shell. The hot pool is directly submitted to the core outlet transients.

Most of the transients are cold shocks which occur very quickly (7 °C/s) and with a large temperature range (100 to 150 °C). They correspond mainly to the reactor trip. Some of them occur at partial power or with partial primary flow (or primary flow decreasing).
The hot plenum behaviour depends on the relative importance of the inertia and density forces.When buoyancy effects are important, a hot sodium layer appears near the free level, above the IHX inlet, while the cold sodium flows under the IHX windows in a region which becomes cold very quickly. These two regions are separeted by an axial gradient more or less important.
This phenomena is governed by the adimensionnal number of Richardson
$Ri = K \cdot \Delta T / Q^2$, where ΔT is the outlet core temperature decrease, Q the primary flow, K a normed coefficient such as $Ri = 1$ for $\Delta T = 150$ °C and $Q = 1$ (100 % nominal flow).
For low Richardson numbers, this phenomenon also appears inside the ACS. The pression is more important under the ACS so the stratification levels inside the ACS and in the hot pool are not the same.

Calculations

The TRIO computer code (4, 5) solves for incompressible fluids :
- the Navier Stockes equation,
- energy equations,
- momentum equations,

with Boussinesq approximation and a $K - \varepsilon$ turbulence model
The pressure equation is solved implicitly and the other equations are solved explicitly.
In order to predict the conditions of the onset of stratification (particularly important for stress analysis, induce by axial gradient along shells and in IHX bundle) a stratified hot pool model has been developped. The problem was to find a 2D modelisation able to simulate the flow under and inside the ACS which depend in fact of the 3D geometry. For such calculation it is necessary to respect :
- the percentage flow rate inside the ACS,
- the flow distribution along the ACS shell (outlet),
- the velocity profile of the jet under ACS towards the hot plenum,
- the raising speed of the stratified layer.

The turbulent model has been carried out to simulate the motion of the interface affected by the entrainment process. The numerical model has been compared to the reactor test for the most significant transients.
- reactor trip at 80 % Pn (100 % QN)
- reactor trip with simulated loss of station service power at 80 % Pn
- reactor trip at minimal power 23 % Pn.

Steady state results

Results for steady state at 80 % Pn are given on Fig. 4. The two recirculations above and under the core jet are confirmed and the free level velocity is radially inwards. The maximal velocity in the jet is 2.1 m/second.
During steady state partial power conditions, it appeared that the stability of the flow pattern was strongly influenced by buoyancy effect in the plenum. It was necessary to improve the model, in order :
- to simulate the inertia effect and obtain a correct radial velocity profile at the edge of the ACS. The singular pressure drop coefficient has been adjusted from water mock-up test's results, to get the correct velocity profile ;
- to simulate the buoyancy effect particularly to respect mixing conditions between hot and cold sodium outlet subassemblies.

One difficulty was the numerical diffusion which is linked to the space discretization and to the modelling of turbulence. An accurate simulation needs a refine computational grid for local discontinuities as core jet outlet and also an overal meshing for circulation in the plenum.

It is therefore necessary to have an accurate treatment of non-linear advective terms avoiding numerical diffusion.

Transient results

For reactor trip with low Ri number (full flow) the calculation shows that no stratification appears in the hot pool and temperature follow a mixing law.
For reactor trip with Richardson number of about 1.4 the calculation shows a stratification in the hot pool as indicated by Fig. 5. The axial gradient reachs 110 °C/m and the temperature dissymmetry in the IHX inlet is about 65 °C. The hot layer desappear after 20 minutes.

Experimental results

During the commissioning test about 50 transients occured. Some of them where planned and had been previously calculated. The hot plenum is instrumented with 70 thermocouples and with 2 specific instrumented rods (40 thermocouples). One is in the hot plenum, the other inside the ACS (Fig. 6).

Steady state

Visual observation of the free surface level have been performed during isothermal tests. They have shown that no vortices occur for the different operating conditions. The hydraulic measurements such IHX pressure drop (2 m Na) pressure loss in the recovering collector (1.65 m Na) and core pressure drop (4.8 bars) are very close to the predicted values. The good knowledge of the primary circuit hydraulics had been very helpfull to solve the vibration phenomenon that occured in the spill way during the isothermal tests.

Transient conditions

The instrumentation has shown that 3 situations can affect the hot pool :

- low Richardson number ($Ri < 1.3$). The hot pool is not stratified and temperature evolution comply with mixing law with half time response of 80 seconds
- medium Richardson number ($1.3 \leq Ri < 2.7$). In that case the stratification appears in the hot pool but not in the ACS. The axial gradients and the initial position of the interface are consistent with the predicted ones
- high Richardson number ($Ri \geqslant 2.7$). The stratification exists in the hot pool and also in the ACS. It appears in the IHX windows and after 10 minutes it is positionned above the IHX inlet. In the ACS the buoyancy forces are strong enough to block the flow in the shroud tubes.

These results are summarized on Fig. 7 that shows also the good agreement between predicted and experimental results.

CONCLUSION

The thermalhydraulic phenomena occuring in LMFBR plena are complex due to the physical phenomena involved (buoyancy and turbulence in fluids, argon, or sodium). The primary circuit behaviour of the SUPER PHENIX's plant has been studied using a lot of rigs in suitable similarity and also numerical tools.
The results of the commissioning tests of the CREYS MALVILLE's plant show the validity of the methods used. The improvement of the numerical method and of the modelisation will be conducted from the viewpoint of compact and economical design for the next European Fast Breeder Reactor.
The sodium leak on the fuel storage drum of SPX1 will change the internal storage conditions for subassemblies. This event will allow some improvements in the thermalhydraulic knowledge of the primary circuit and in their numerical approach. These improvements will be very helpfull for the design of the future reactor for which internal storage and core flexibility are basic options.

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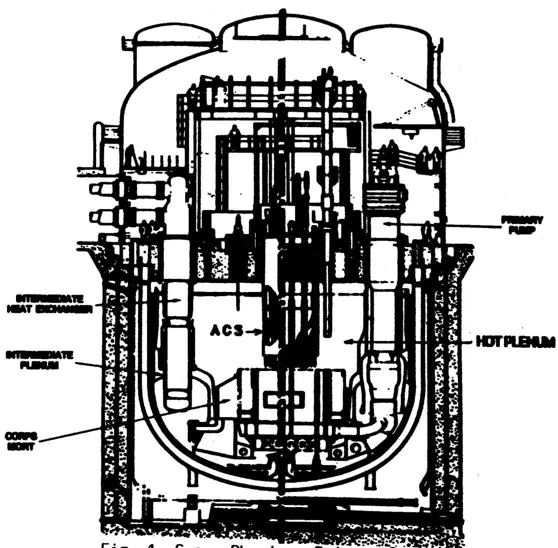

Fig. 1 Super Phenix - Primary Circuit

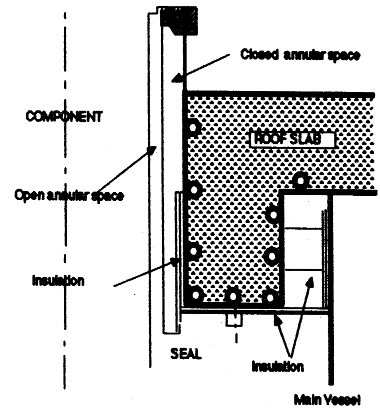

Fig. 2a Super Phenix Component's penetration

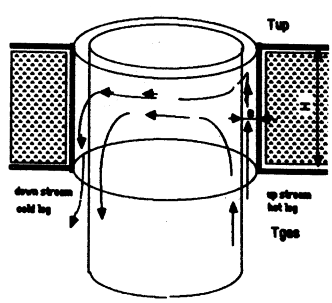

Fig. 2b Convective phenomenon in the annular space

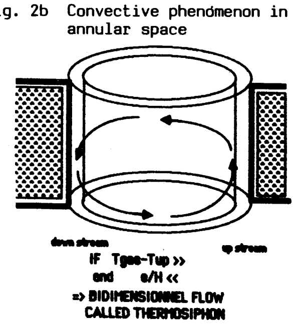

Fig. 2c Convective phenomenon in closed annular space

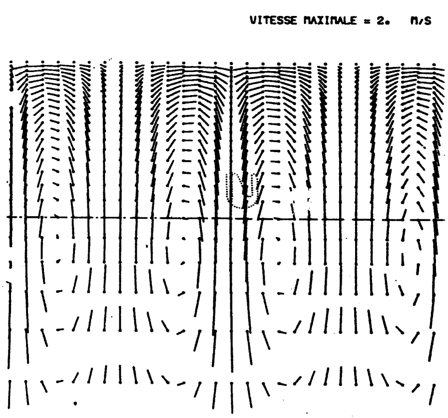

Fig. 3 IHX's penetration velocity field in argon open annular space

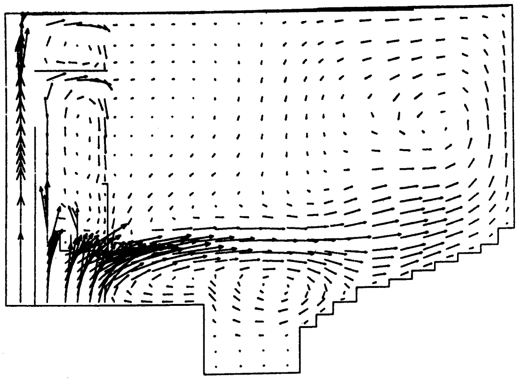

Fig. 4 Reactor trip at 80 % PN - Hot pool - Initial velocity field

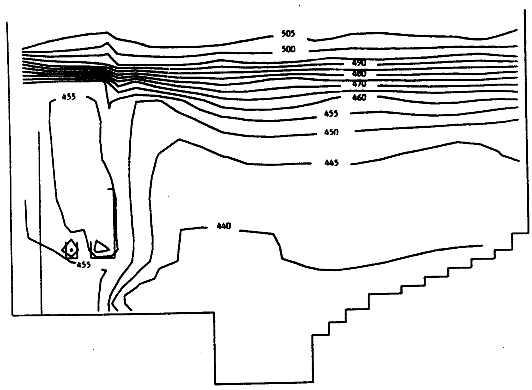

Fig. 5 Isothermal lines after trip (stratification) 840 seconds

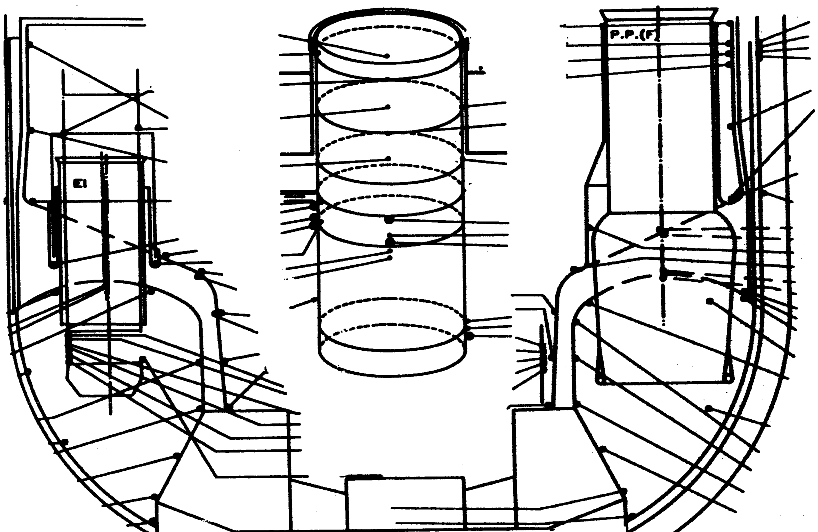

Fig. 6 Super Phenix - Hot pool instrumentation

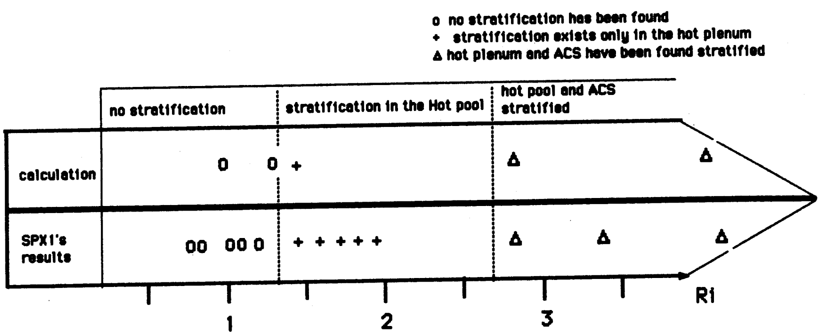

Fig. 7 SUPERPHENIX thermal hydraulic behaviour. Stratification in the hot plenum comparison between calculation and experimental results