Hydro Mechanical Analysis of a Primary Pipe (1D) Coupled to a Reactor Vessel (3D) During a Depressurization

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ABSTRACT

It is possible to analyse separately, in 3D, the transitory hydromechnical regimes of the vessel and the pipe respectively. However, the treatment of fluid-structure coupling at the junction, demands the modelisation of the complete system. This paper presents some validation tests and the results of PWR blowdown calculation.

1. INTRODUCTION

For a large, rapid, close-to-the-vessel break of a PWR inlet pipe, anticipated hydrodynamic loads on internal core structure and its supports may be significant during the subcooled portions of an hypothetical loss-of-coolant accident (LOCA). This accident is considered as a reference one.

Early experiments on "reference accident" have started by 1960. These early experiments were mostly devoted to study a two phase critical flow, some others were designed to study the structure behaviour, the choc wave propagation or the influence of the break geometry. Accordingly, these installations are very different in dimensions and in geometries. These experiments were not particularly designed to help in understanding some physics fundamental phenomena, occuring during the blowdown, particularly, the interaction fluid-structure in 3D. Understanding of such interaction needs quite sophisticated codes.

Near 1975, more attention was paid to develop the multi-dimensional codes taking into account the fluid-structure coupling effects. At the beginning of 1980 in Karlsruhe (Germany) blowdown experiments were carried on the HDR reactor, to validate these codes.

PLEXUS is well adapted to such phenomena with fast dynamics. It has been developed at CEA/DEMT France. It treats the problem in mono-bi or tri-dimensions. It uses the finite element method and for time discretisation it uses an explicit algorithm (Ref. 1).

In 3D, its possible to analyse separately, the transitory hydromechnical regimes of the vessel and the pipe respectively. A 3D-1D transition element is used to assure the mechanical and hydraulic continuity by introducing the equations of conservation and of coupling at the junction.

The objective of this paper is to demonstrate how PLEXUS can be employed as a useful tool for blowdown investigations. The fluid is modeled with an homogeneous equilibrium model. The thermal-mechanical nonequilibrium model is actually under development. It will be used for later calculations and comparisons with HDR Test.
2. METHODS

2.1 A 3D-1D transition element

The vessel and the contained fluid are represented by 3D shell elements and solid elements respectively. The fluid-structure coupling is treated by the A.L.E. method (Arbitrary, Lagrange, Euler). The coupling of the fluid movement and the pipe wall, both modelled by 2-node elements, follows also an A.L.E. scheme. These 2-node elements admits 7 d.o.f for each node (1 d.o.f for a movement of fluid, 6 d.o.f for a movement of the pipe wall).

At the junction, a 3D-1D transition elements (see fig. 1 ) assures the mechanical and the hydraulic continuity. It permits also to fulfill the coupling and the mass transfert (Solid element $\rightarrow$ 2-node element).

The relations of coupling are as follows:

- For Mass transfert: (See fig. 2)

$$
\dot{\psi}_c * S_c * \vec{V}_i = \dot{\psi}_t * S_t * U \vec{w} 
$$

(for i = 1 to 4)

where

- $\vec{w}$: Vector director of pipe
- $U$: Velocity component in pipe
- $\dot{\psi}_t$: Density in pipe
- $S_t$: Cross-section area of the pipe
- $\vec{V}_i$: Vector velocity of fluid at node i
- $S_c$: Cross-section area of solid element
- $\dot{\psi}_c$: Density in solid element

so, two conditions are imposed :

- the first one : direction for flow
- the second one : the conservation of Mass flow.

- For Mechanical links :

$$
D_{mk} = d_k \\
\psi_k = \theta_k
$$

where

- $D_{mk}$: Displacement means of shell element in direction k
- $d_k$: Displacement of pipe in direction k
- $\psi_k$: The angle of rotation of shell element round axis k
- $\theta_k$: The angle of rotation of pipe round axis k

As for local three-dimensional effects due to junction, they could be corrected in considering them as a pressure loss, located or distributed.

2.2 Basic equation for fluid Model

In conservation low form, assuming constant flow area for one dimensional model, the mass, momentum and energy equation are:

$$
\frac{\partial \psi}{\partial t} + \frac{\partial \phi}{\partial x} = 0
$$
where \( \psi, \varnothing, \) and \( Q \) are defined as follows:

<table>
<thead>
<tr>
<th></th>
<th>( \psi )</th>
<th>( \varnothing )</th>
<th>( Q )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass</td>
<td>( \varnothing )</td>
<td>( \varnothing \cdot U )</td>
<td>0</td>
</tr>
<tr>
<td>Momentum</td>
<td>( \varnothing \cdot U )</td>
<td>( \varnothing \cdot U^2 + P )</td>
<td>( - \frac{1}{\varnothing \cdot H} \cdot \varnothing \cdot U^2 )</td>
</tr>
<tr>
<td>Energy</td>
<td>( \varnothing \cdot H )</td>
<td>( \varnothing \cdot U \cdot H )</td>
<td>( q + (\frac{\partial P}{\partial t} + U \frac{\partial P}{\partial x}) )</td>
</tr>
</tbody>
</table>

with

\[
\varnothing = \alpha \varnothing_0 + (1 - \alpha) \varnothing_1
\]

\[
H = x \varnothing_0 + (1 - x) \varnothing_1
\]

in the above equations, \( x \) and \( \alpha \) represent the vapor quality and the void fraction, respectively. For \( 0 < x < 1 \) and \( 0 < \alpha < 1 \), the quantities \( \varnothing_0, \varnothing_1, \varnothing_0, H_0, H_1 \) are evaluated as function of pressure on the saturation line. To close the system of equations, the following constitutive relations are required:

- state equation: \( F(\varnothing, P, H) = 0 \)
- \( f = \) friction factor

### 2.3 Application to PWR simplified geometry

In the geometry arrangement for the test, the internal vessel structures of a PWR are represented by an idealized core barrel. This barrel is a cylindrical shell clamped to a rather rigid flange at upper edge and connected with a stiff mass ring, which serves to simulate roughly the mass of PWR core, at the lower edge.

For the reactor, the simplified geometry is shown on the fig.3.

Only half of the reactor geometry is here considered, because of the assumed symmetry with respect to the plane through the vessel and blowdown pipe axes.

For the generation (see fig.4) and visualisation of results the GIBI and ALICE programs are used.

Initial state of the fluid:

- \( P_0 = 91 \text{ bar} \)
- \( T_0 = 273 \text{ °C} \)
- \( \varnothing_0 = 762 \text{ kg/m} \)
- \( C_0 = 812 \text{ m/s} \)
- \( H_0 = 1.2147 \times 10^7 \text{ J/kg} \)

Material data of the core barrel:

- Density \( \varnothing = 7900 \text{ kg/m} \)
- Young's modulus \( E = 1.98 \times 10^4 \text{ N/m} \)
- Poisson's ratio \( \eta = 0.295 \)
- Mass of the ring \( M = 13517 \text{ kg} \)
At the exit of the pipe, the pressure is prescribed to be:

\[ P_{\text{exit}} = P_{\text{sat}}(T_{\text{exit}}) + \left[ P_0 - P_{\text{sat}}(T_{\text{exit}}) \right] \times \exp(-t/\tau) \]

where \( P_{\text{sat}}(T_{\text{exit}}) \) is the pressure of saturation corresponding to the exit temperature.

\( \tau = 0.001 \text{ s} \) is preestimated "break time".

Most calculation were performed for the first 120 ms of the blowdown.

4. RESULTS

Fig. 5 shows sketches of the predicted core barrel deformation at sequence of times; The core barrel movement has been exaggerated in the figures to make the deformation more visible.

Fig. 6 shows the pressure time histories in the downcomer at junction. We can notice that the accoustical phenomenon lasts a little more than that which has been observed in the previous experiments due to an overestimated coefficient pressure loss.

Fig. 7 shows the pressure time histories in the downcomer opposite to and at the level of the blowdown pipe.

Fig. 8 shows the pressure time histories in the inlet of pipe.

Fig. 9 shows the discharge flow rate in the break pipe.

5. CONCLUSION

It is now possible to treat in the same analysis the hydro-mechanical coupled behaviour of the reactor vessel and primary pipes, during a blowdown. The method presented here, is of particular interest for situations where the complex affects related to the fluid come into play.

References:


(2) D. Guildbaud, F. Jeanpierre, R.J. Gibert "A substructure method to compute the 3D fluid-structure interaction during blowdown of the HDR vessel, SMIRT 7, Chicago, 1983.

(3) Wolf, Schumann, Scholl "Experiment and analytical results of coupled fluid-structure interaction during blowdown of the HDR vessel, SMIRT 7, Chicago, 1983.

(4) Ludwig and Schumann "Fluid-structure analysis for the HDR blowdown and Snapback experiments with FLUX", Nuclear Engineering and Design 70, 1982, 321-333.

Fig. 1 Schematic of coupling 3D-1D element

Fig. 2 Schematic of the mass transfer (solid element $\Leftrightarrow$ 2-node element)

Fig. 3 Configuration of HDR pressure vessel and reactor internals.
Fig. 4 Idealized Reactor Vessel geometry considered in FLENS.
Fig. 5 Sketches of the predicted core barrel deformations at sequence of time.
Fig. 6 Pressure-time history in the Downcomer at the blowdown pipe level.

Fig. 7 Pressure-time history in the Downcomer opposite to and at the level of the blowdown pipe.
Fig. 8 Pressure-time history at break and in the inlet of the blowdown pipe

Fig. 9 Transient mass flow in the discharge pipe at the break.
Fig. 10 Pressure-time history in the mid-downcomer under the blowdown pipe.

Fig. 11 History of barrel wall displacement at the blowdown pipe level.