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ANALYSIS OF THE RS16B EXPERIMENT ON FLUID-STRUCTURE INTERACTIONS DURING PWR BLOWDOWN

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Summary

For analysis of fluid-structure interactions during blowdown of a pressurized water reactor (PWR) the code FLUX2 has been developed. This code is based on a three-dimensional compressible potential flow model and a linear elastic structural model. For assessment of the validity of the code the computed results are compared with the measurements in the RS16B experiment (case DWR5) at Battelle (Frankfurt, 1977).

In the experiment a sudden depressurization of a vessel (height 11.2 m, diameter 0.8 m) with internal structures is studied under PWR conditions. The initial pressure is 14.2 MPa, saturation pressure is 6.4 MPa. Of particular interest are the loadings on the core barrel. The core barrel wall is relatively thin (8 mm) in the upper third while thicker (18 mm) in the lower two thirds.

In FLUX2, bulk friction is included in form of a drag force proportional to the local fluid velocity with a constant friction coefficient. Its magnitude had to be taken relatively large; otherwise the pressure oscillations are larger than found experimentally. The speed of sound is assumed to be a constant as it is appropriate for sub-cooled water. At the break, where two-phase flow appears, the pressure is prescribed to drop linearly from the initial value to saturation pressure within the experimentally found break time of 1 ms. The upper thin part of the core barrel is represented by the shell model CYLDY2 whereas the lower part is treated as a rigid body like the mass ring in CYLDY2.

Measured and computed pressure, strain, and mass flux values are compared. The measured and computed pressure-wave travel-times agree very well. For some positions these travel times can be explained only by accounting for the core-barrel deformations. Also, the pressure wave passing through little holes in the upper flange ("bypass") has a remarkable effect equal in experiments and computations. The measured pressure drop at the opening shows for a period of about 1 ms an undershoot below saturation pressure but otherwise confirms the assumed boundary condition. The absolute differences between measured and computed pressure values is less than 1 MPa. The qualitative agreement of the time functions is even better. From the strain gauges a pronounced ovalizing azimuthal bending oscillation can be identified with a frequency of 77 ± 5 Hz. For this mode a natural eigenfrequency of 74 Hz has been computed using an incompressible code version (FLUX1). The computed mass flux is about 18 % smaller than the measured value.

Overall the agreement between experimental and computed results indicates the general correctness of FLUX2 and supports the used model simplifications.

1. Introduction

For analysis of fluid-structure interactions during blowdown of a pressurized water reactor (PWR) the code FLUX2 [1] has been developed. This code is based on a three-dimensional compressible potential flow model. This model allows for rather short computation times. Support for the validity of this model is provided in this paper by comparison of FLUX2 results with the RS16B experiment (case DWR5) at Battelle [2]. In the experiment a sudden depressurization of a vessel (height 11.2 m, diameter 0.8 m) with internal structures is studied under PWR conditions. Of particular interest are the loadings on the core-barrel.

The same experiment has been used for assessment of the codes WHAM and LECK (neglecting fluid-structural coupling) [2] and for the coupled analysis code DAISY [3].

2. The Model

A short summary of the FLUX2-method is given elsewhere at this conference [4]. Here only those aspects which are peculiar to this computation are described.

In the experiment, the main internal structure is the core-barrel (diameter 0.713 m, length 7.39 m) which is composed of several cylindrical parts. The upper third is relatively thin (8 mm) while the rest is considerably thicker (18 mm). The upper third is treated as a linear-elastic shell which is clamped at the upper flange. The rest is modeled as a rigid cylinder which is attached to the shell part and free to oscillate in the beam mode. The structures inside the core barrel and the upper plenum are neglected. This model can be analyzed by means of the CYLDY2 model [5] included in FLUX 2. For the calculations, 70 structural modes are used. Damping is included in terms of a 1 % critical damping ratio for each structural mode.

In the fluid, friction is accounted for by means of a force $-\varkappa \underline{u}$ per unit volume where $\underline{u}$ is the local velocity and $\varkappa$ a constant empirical coefficient. This is consistent with a potential flow model since this force is irrotational. Friction appears to be important in the blowdown nozzle. Using a pipe friction coefficient f_d and the maximum velocity $u_{max} = [2(p_0-p_1)/\rho]^{1/2}$ (initial pressure p_0 = 14.2 MPa, saturation pressure p_1 = 6.419 MPa, fluid density ρ = 762.5 kg/m^3) one obtains the estimate $\varkappa = f_d\, u_{max} / (4R_s)$ (blowdown pipe radius R_s = 71.5 mm). For the friction coefficient an unexpected high value of f_d = 0.25 was found to be necessary for good agreement with the experimental results, see below.

At the end of the blowdown-pipe (length 0.35 m), the pressure is prescribed to drop linearily within 1 ms from p_0 to p_1 and kept constant thereafter. The speed of sound is a = 1070 m/s.

The fluid in the vessel is resolved by 4 radial, 45 axial grid cells, and 9 azimuthal cosine modes and by 10 grid cells in the pipe. A time step of Δt = 0.2 ms is used and the integration proceeds over 400 time steps. The required computer time is 40 Min. IBM 370/168.

Two main cases have been investigated. In case "R2" the coupled problem is analyzed. In case "RE" the influence of the structural motion on the fluid is neglected, this is the "decoupled" analysis. For further details see [1].

3. Results

The qualitative behaviour of the structural motions and the pressure field can be deduced from Figs. 1 and 2. We note the rather local structural deformation of the core barrel near the nozzle at early times which has an obvious effect on the pressure distribution inside the core barrel at t = 2ms. It is interesting to see the relatively large effect of a small bypass (cross section area 3.9 % of the horizontal downcomer cross section) at times $\gtrsim$ 6 ms.

The computed lowest eigenfrequency of the structure including the virtual fluid mass [1] is 4.1 HZ (21 Hz in vacuum) in the beam mode. The second mode with 44.2 Hz (93 Hz in vacuum) is a tipping motion of the lower core barrel part ("rigid"). Due to its higher eigenfrequency this tipping motion dominates at early times.

In Figs. 3 - 6 computed and measured pressure results are compared. The transducer positions are numbered as in [2]. The measured pressure at pos. 99 (Fig. 3) near the break shows an undershoot below saturation pressure for about 1 ms which cannot be resolved by the present model but this does not seem to significantly affect the subsequent results. The pressure-wave travel-time in the downcomer can be clearly detected from Fig. 3 and explained in terms of the nominal speed of sound a = 1070 m/s of the fluid. One might have expected a smaller effective speed of sound a ' = 829 m/s if the structural response would be mainly in the breathing mode [6]. However this mode seems to be of minor importance.

Fig. 4 shows a similar comparison for a longer period. The behaviour at pos. 105 shows that the bypass effect is fairly well described by the present potential flow model. At time $t > 40$ ms the pressure in the vessel falls below the local saturation pressure in the computations because two-phase effects are not included in the present model. Some differences for pos. 90 appear at time $t \approx 10$ ms. For this value better agreement has been obtained by Grillenberger [3]. It was tried to get better agreement by adjusting the fluid friction parameter f_d and the structural damping ratio. Whereas 1 % structural damping has negligible effect, the result is very sensitive to fluid friction as can be seen from Fig. 5. Damping has qualitively a similar effect as the fluid-structural coupling. Thus the discrepancies might be a consequence of a too stiff structural model, in particular with respect to the lower part of the core barrel.

The fluid friction has also a large effect on the resultant mass flow rate at the nozzle. The computed maximum value is 800 kg/s, the measured is 974 kg/s. The general agreement between the computed and measured pressure reductions in the vessel, however, support the smaller computed value. Without friction the maximum mass flow rate is 1350 kg/s. The effect of the core barrel motion on the mass flow rate is less than 5 %.

In Fig. 6 further effects of fluid-structural coupling are visible. At pos. 106 the structural flexibility causes an increased pressure reduction. As a consequence of the structural motion the pressure at pos. 88 is affected much earlier than to be expected from the travel time B. Again, the computation seems to underestimate the structural effect.

Larger effects of the fluid-structure coupling than on the pressure are to be expected on the resultant structural deformations and stresses [1]. Without coupling the stresses are about 50 % larger than with coupling (140 MPa). The difference in magnitude, however does not grow as dramatically as found in case of the HDR [4]. One reason is the structural damping included in this computation. More important is a different ratio of structural eigenfrequencies (which are very high in this case) to pressure-wave frequencies so that resonance does not play such an important role as in case of a decoupled analysis for the HDR. The maximum stress appears at $t \approx 10$ ms, i.e. in the subcooled period of the blowdown.

The measured strain signals show a pronounced ovalizing oscillation. The measured ovalization frequency of 77 ± 5 Hz, see Fig. 7, coincides well with the corresponding eigenfrequency of 74 Hz as computed for incompressible fluid [1]. The computed dynamical signal itself does not agree as well with the measured one because of certain model deficiencies of CYLDY2 [1] which will be overcome in the near future by an improved structural model [4].

4. Conclusions

In spite of its rather slim geometry, the RS16 B / DWR5 experiment gives important data for assessment of coupled fluid-structure analysis codes. More data on the structural motion would be necessary in order to verify the structural model, however. The overall agreement between the measured values and the results computed with the FLUX2 code is good. Several results like pressure wave travel times, pressure magnitude and strain results have been explained by the coupled fluid-structure analysis. The maximum stresses appear in the subcooled period of the blowdown. In this period a potential flow model including bulk friction with constant speed of sound has been shown to be appropriate.

References

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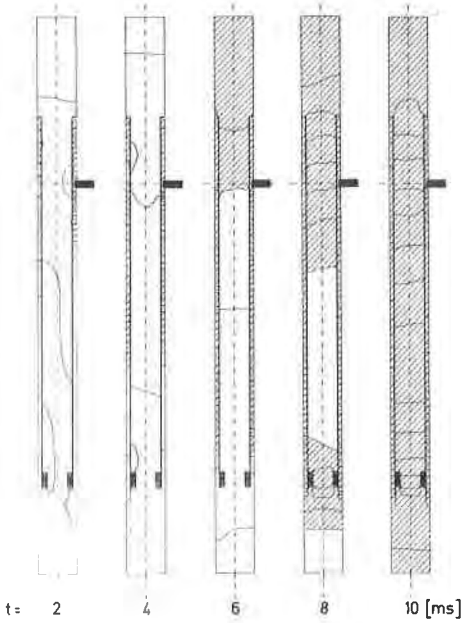


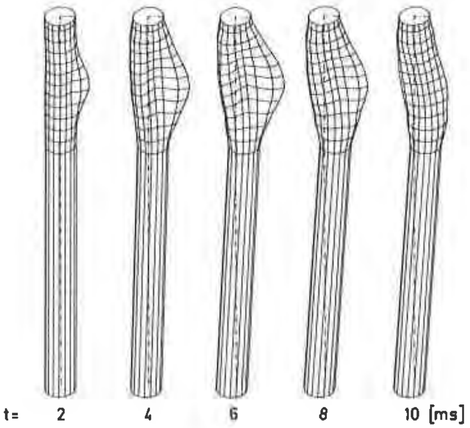


Fig. 1
Computed pressure distribution at subsequent times. Plotted are isobars with 1 bar difference. In the shaded regions the pressure is reduced by 2 bars below the initial value (case R2).

Fig. 2
Computed core barrel deflections (300 times enlarged) at subsequent times (case R2).

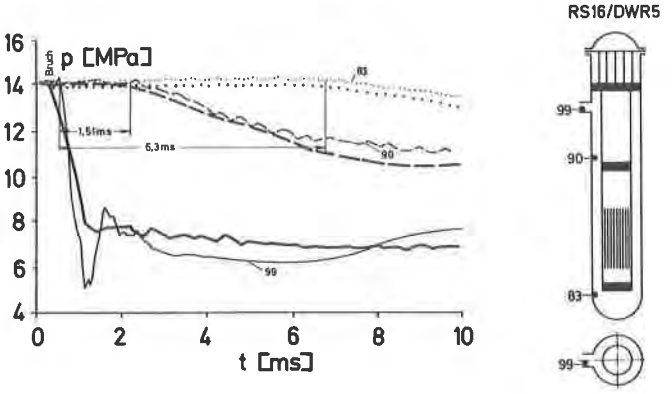


Fig. 3 Measured (thin) and computed (thick) pressure versus time in the nozzle and downcomer with spreading times indicated.

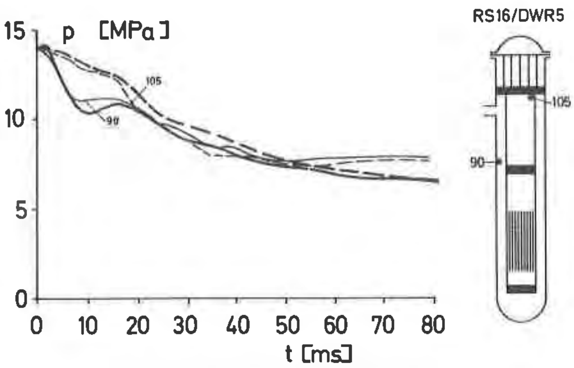


Fig.4

"Long"-time pressure versus time
(measured: thin, computed: thick curves.)

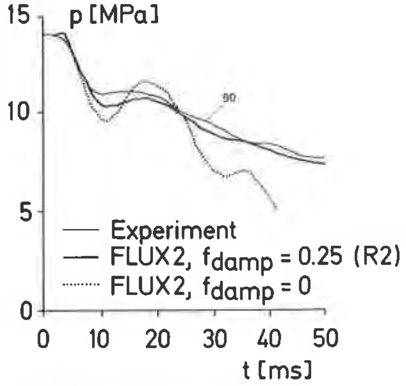


Fig.5

Effect of damping on the pressure.

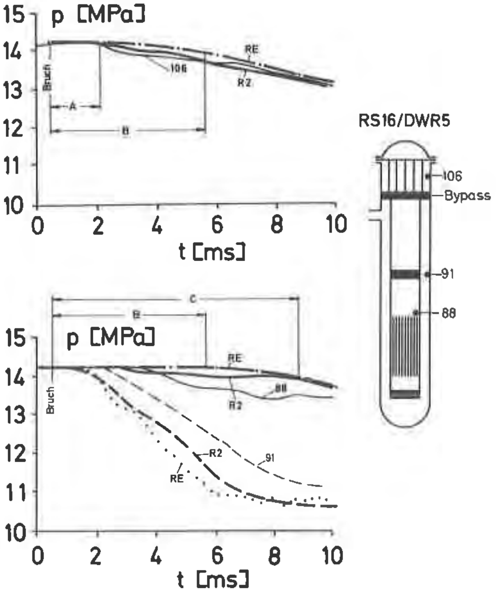


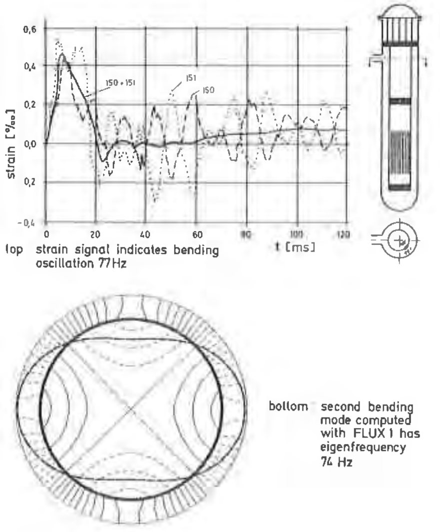
Fig.6

Effect of fluid-structure coupling on pressure (measured: thin curves, coupled analysis: R2, decoupled analysis: RE).

A: travel time nozzle to 106 via bypass

B: travel time nozzle to 88 via lower plenum

C: travel time nozzle to 106 via lower plenum



top strain signal indicates bending oscillation 77Hz

bottom second bending mode computed with FLUX 1 has eigenfrequency 74 Hz

Fig.7

Measured strain rate [2] showing an ovalizing bending oscillation and the corresponding eigensolution (150: inner, 151: outer, 150+151: mean azimuthal strain).