Progress in Fluid-Structure Analysis with FLUX for the HDR-RPV-I Blowdown-Experiments

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FLUX is a special purpose code to analyse three-dimensional fluid-structure interactions during the first phase of the blowdown of a pressurized water reactor. It has been used to pre- and postcalculate various blowdown experiments done at the HDR facility. After the first test series (performed in 1980) the code has undergone some extensions and improvements. The present paper describes the main alterations in the code as well as its application to the tests V32 and V33 performed at the HDR in spring 1982.

The main objective of the code extensions was to account for the flexibility of the pressure vessel. This demanded for a coupling procedure which combines the two structural models (core barrel and vessel) to one model. Furthermore, the restriction of the structural model used in FLUX to shells with rigid edges has been released in such a way that it is capable to cover a wide spectrum of boundary conditions including elastic end rings.

Treatment of vessel motion in the fluid-structure interaction algorithm was generally a simple matter of extending the existing coding. In the vicinity of the nozzle, however, a special momentum balance had to be performed in order to avoid large numerical errors.

The improved code has been used for post-test calculations of V31 (to check some input parameters) and for precalculations of the new tests. In computations for V32, a complete set of structural eigensolutions up to eigenfrequencies of 1.500 Hz has been used, which yielded a total of almost 1.000 degrees of freedom. Accordingly, a rather fine fluid discretization with more than 12.000 fluid cells has been employed. This extensive resolution has been chosen in order to do really a "best estimate" calculation. In case of V33, the effect of a reduced break opening area (25%) was investigated.

From the comparisons between measured and computed data a very good agreement has been found, even better than in our precalculations for V31. This holds for both cases, V32 and V33. The largest deviations arise with respect to pressure waves inside the discharge nozzle and with respect to the vessel motion. A comparative evaluation of experimental as well as computational results from V32 and V33 demonstrates that a reduction in the break opening area in the case of a blowdown causes loadings and responses of the pressure vessel internals which are significantly less reduced than the break area.

1. Introduction

FLUX is a special purpose code which has been developed in order to describe the responses of the reactor vessel internals (RPV-I) of a pressurized water reactor (PWR) due to a rapid depressurization and blowdown of the coolant, caused by the postulated rupture of a primary coolant pipe. It analyses the three-dimensional flow regime and accounts for interactions between the fluid and movable parts of the adjacent structures [1].

FLUX is competing with several other codes which have the same purpose [2]. To check the validity of such codes, blowdown and snapback experiments have been performed at the HDR test-facility [3, 4]. The results of FLUX-precalculations for the first blowdown test series (V29.2, V31, V31.1) and for the snapback tests (V59) as compared to the measured data have been reported in Ref. [1]. In the meantime the code has undergone some extensions and improvements. The new version has been used for post-test calculations of V31 (to adjust some input parameters) and for precalculations of the main blowdown test series V32-V34 [4].

Test V34, where the core barrel was loosely supported and motions with impacts arose, is subject to another paper of this conference [5]. The present paper is mainly concerned with the tests V32 (most severe thermodynamical initial conditions) and V33 (break opening area reduced to 25% of the discharge pipe cross section). After a short characterization of the computational model and its enhancements, the precalculated results are compared to the measured data from these experiments.

2. Computational Models Comprehended in FLUX and Their Improvements

FLUX is composed of four principal parts: a structural model (CYLDY3), a nozzle flow model (DRIX-2D), a fluiddynamics and fluid-structure interaction model for the domain inside the vessel (FLUX4), and a procedure for coupling DRIX-2D and FLUX4 ensuring continuity at the interface (DRIFLU). Since the details of these models have been already reported in several papers, only their general properties will be summarized here, and the major alterations will be indicated. A more detailed description of the code enhancements mentioned in this section is given in Ref. [6].

CYLDY3

The structural model CYLDY3 [7] provides the eigensolutions (eigenfrequencies and modal shape functions) of a thin-walled circular cylindrical shell which behaves linear elastically. For this aim, Flügge's homogeneous partial differential equations for such shells are solved by a quasi-analytical approach. Modal mass and stiffness matrices are derived from the eigensolutions in a succeeding step.

In the former version of CYLDY3 as described in [7], the analysis was restricted to shells with rigid edges - either rigidly clamped or attached to a rigid ring. It turned out, however, from the HDR snapback tests V59 [1] that rigid edges might not be a good approximation, even in the case of HDR with its heavy core barrel flanges. Therefore, the shell boundary conditions in CYLDY3 have been reformulated such that they now cover the range from completely free shell ends up to rigid clamping, which are the limiting cases of flexible rings attached to the edges.

These rings are considered to be curved beams with meridional cross sections which do not undergo any deformations. Thus their degrees of freedom are all determined by the axial, azimuthal, and radial displacements and by the meridional slopes of the adjacent shell edges.

With these constraints homogeneous boundary conditions are derived which equilibrate the effective stress resultants in the shell edges to the stiffnes and inertia forces of the rings. The ring stiffness and inertia parameters comprise - besides Young's modulus, Poisson's ratio and the mass density of the ring material - a set of several integrals of geometrical functions over the meridional ring cross sections.

Another extension of the structural model has been stimulated by the significant oscillations of the pressure vessel, which have been found from the analysis of the HDR tests V31 and V31.1 [1]. In the precalculations for these tests the effect of the RPV flexibility had been accounted for only with respect to the speed of pressure wave propagation inside the downcomer, but otherwise the RPV was considered to be rigid. In order to simulate the vessel motions explicitly, the structural model has been expanded by a procedure originally suggested in Ref. [8]. In a first step, the eigensolutions and the modal matrices are determined separately for the vessel and for the core barrel using the existing coding of CYLDY3. Here the core barrel is assumed to be rigidly clamped. Now this clamping is released, i.e., some rigid body motions are superimposed to the core barrel model. Including all degrees of freedom into the kinetic energy and the elastical potential yields - in addition to the already known original modal matrices - some mass and stiffness matrices which relate to the rigid body motions and the interactions of these with the original modes of the core barrel. These expressions are supplemented by kinematical coupling conditions which relate the core barrel displacements to those of the vessel, and by the forces which act between the vessel and the barrel. These forces serve as Lagrangean multipliers. Finally, the application of standard condensation techniques yields the equation of motion for the coupled system in terms of the actually independent degrees of freedom.

The most crucial point in this derivation lies in the evaluation of the energy terms which are strongly influenced by the core barrel model and require more or less tedious integrations of lenthy expressions. The other steps of the transformation may be done in a straight-forward way.

DRIX-2D

DRIX-2D [9] is a code which numerically integrates a four equation model for a water-vapour two-phase mixture in two-dimensional (usually cylindrical) coordinates. The model ensures conservation of mixture and vapour mass, mixture momentum, and mixture energy. Non-equilibrium effects are accounted for with respect to slip between the phases (by a drift flux approximation) and with respect to a delayed phase transition rate, where different parameters are used for evaporation and condensation. Thermal non-equilibrium between the phases cannot be simulated, as only one energy equation is included. In the framework of FLUX, DRIX-2D is used to simulate the two-phase flow regime inside the discharge pipe, including the outflow region.

FLUX4

FLUX4 [6] is the central part of the FLUX model. It describes the flow regime inside the vessel using a three-dimensional compressible potential flow model with a speed of sound which is constant in time. The equations of motion are integrated simultaneously for the fluid and for the structure. Fluid-structure interaction is taken into account by relating the fluid boundary pressure to the normal accelerations and velocities of the structure. The fluid field is discretized by finite Fourier transforms in the azimuthal direction and by finite differences in the r-z-plane. The time integration is performed using the implicit Newmark-β-scheme; the arising large systems of linear equations are directly solved by a fast elliptic solver and using the capacitance matrix technique.

FLUX4 differs from its predecessor FLUX2 [1] mainly with respect to two features: (1) Non-linear supports of the core barrel with gaps and impacts can be treated; this matter is subject to Ref. [5]. (2) Fluid-structure interaction is taken into account not only at the fluid-core barrel interface, but also with respect to the vessel motions. Generally, the existing coding simply had to be extended for this aim. Special attention was necessary, however, near the nozzle, where the vessel reaction force due to the outflow through the nozzle acts in the nozzle area. Since the grid spacing inside the vessel cannot be made much smaller than the nozzle diameter, large finite difference errors could arise. In order to avoid these errors, the reaction force is explicitly determined from a special local momentum balance.

DRIFLU

For the analysis of a blowdown event, the nozzle flow model DRIX-2D has to be coupled to the FLUX4 model. With the already formerly used method [1] the nozzle flow together with a rather crude representation of the vessel volume is analysed by DRIX-2D prior to the FLUX4 calculation, which then uses the pressure history at the nozzle inlet from this precomputation as a time dependent boundary condition. This method, which does not ensure the continuity of mass flow across the model interface and therefore is called the "weak coupling" procedure, does properly work, however, in the most cases.

As an alternative, a "strong coupling" method [6] has been developed. Here, only the nozzle and outflow regions are modelled with DRIX-2D, but the FLUX4 model is somewhat expanded into the nozzle so that the two domains are overlapping. Now the two models are integrated step by step, taking the intermediate result of one model as a boundary condition for the other. The data exchange between the two models is managed by a procedure DRIFLU after each time step. Thus the continuity of pressure, density, and flow velocity over the model interface is enforced.

3. Applications of FLUX to the HDR RPV-I Blowdown Experiments

The improved FLUX model has been checked by postcalculations for the HDR test V31.1. Then FLUX has been employed for precalculations of the tests V32, V33, and V34. In this section first the experiences from the V31-computations will be summarized; thereafter the computational results for V32 and V33 will be reviewed in comparison to the experimental data.

Fig. 1 shows the representation of the HDR vessel and core barrel in the structural model. The darked parts are modelled as cylindrical shells, whereas the dashed regions are mostly considered to be rigid; only in one calculation for V32 (out of two) and in the case of V33 the lower ring at the core barrel was treated as flexible, because the new ring model was not yet ready before.

3.1 Summary of Post-Test Calculations to V31.1

In order to establish some input values of the model as, for example, the required refinement of the discretization, a parametrical study has been performed with FLUX using the measured initial values from the HDR test V31.1. In all cases the "weak coupling" of DRIX-2D and FLUX4 has been applied. Therefore, only one DRIX-2D calculation was necessary. In this calculation the nozzle was represented by 15 axial fluid mesh cells, but only one radial cell. Previous calculations had shown no significant two-dimensional effects, and the quasi one-dimensional model behaves numerically more stable.

Normally a "medium fine" grid in the FLUX4 model was used. It comprised about 4.430 fluid cells inside the vessel and azimuthal Fourier transforms up to order 16. The corresponding structural model comprehended almost 600 degrees of freedom (about 130 originating from the vessel) with eigenfrequencies up to 1.000 Hz.

With this model, the agreement with the experiment has generally been improved in comparison to the precalculations, especially with respect to the structural entities. The measured vessel motions have not been matched in full detail, since obviously the support frame modelling by springs (see Fig. 1) was too stiff; this amounted to an error of about 10% in fundamental frequency and amplitude of the vessel motion, which did not affect, however, the other results very much.

The first variation was addressed to the discretization fineness. A "fine" grid was applied which included more than 12.000 fluid cells, Fourier orders up to 24, and almost 1.000 structural degrees of freedom with eigenfrequencies up to 1.500 Hz. The results turned out to be very similar to those of the preceeding calculation; only the radial displacements of the core barrel in its medium section were improved significantly, but the maximum equivalent von Mises stress dropped merely from 145 MPa to 142 MPa. It was concluded from these findings that normally the "medium fine" grid is satisfactory.

In the second variation the vessel model was replaced by the formerly used rigid boundary in order to test its influence. The effect of the vessel flexibility on the speed of pressure wave propagation inside the downcomer, however, was accounted for like in the precalculations. Surprisingly, besides the vessel motions themselves only small changes of the results have been found. The most significant alterations refer to the displacements of the core barrel (its relative displacements to the vessel wall had been measured), whereas the pressure field as well as the maximum stresses are nearly unaffected. Thus it depends on the special goals of an investigation, whether an explicit vessel model is required or not. In case of a PWR it may be even less important than in the HDR case due to the thicker vessel wall and due to the different support conditions of the vessel.

In a further calculation it was tried to simulate the boiling in the upper plenum which had been observed in V31.1 about 120 ms after blowdown start. For this aim a restart calculation was performed which started 91 ms after blowdown start (the time when the computed pressure in the upper plenum had reached the saturation pressure) and where the speed of sound in the upper plenum had been reduced in order to account for the two-phase mixture. This variation had a distinct effect on the computed pressure field which even surpassed the experimental findings, but its influence on other entities was rather small. It has been concluded from this that the crude approximation of boiling effects which is possible in the framework of FLUX4, is usually not needed.

The last calculation for V31.1 was an indirect check of the nozzle flow model DRIX-2D. Its results had shown pressure waves inside the nozzle which were more distinct and less damped than it could observed from the measurements. Therefore, in the FLUX4 model now the measured pressure history inside the nozzle has been used as a boundary condition instead of the data computed with DRIX-2D. It turned out that only very high frequency effects were reduced, making the pressure history as well as the displacement distribution near the nozzle smoother. This is probably a matter of the finite break opening time which had not been simulated by DRIX-2D. Altogether, this calculation has proved the validity and usefulness of the DRIX-2D model for providing the driving blowdown function for FLUX4.

3.2 Precalculations to V32

The HDR test V32 had been announced as the "German Standard Problem No. 5" which called for "best estimate" predictions of the processes involved in the blowdown. The experimental boundary conditions were similar to those of the V31 series, but the initial subcooling of the water inside the discharge pipe had been increased as much as possible with the existing test facility.

Two precalculations for the first 200 ms of this experiment have been performed with FLUX. They mainly differed with respect to the method used for coupling DRIX-2D and FLUX4 (see Section 2). The first calculation (called "FDS") used the "strong coupling" procedure, whereas in the second one ("FDW") the "weak coupling" was applied as for V31. In view of the best estimate requirement, both calculations used the "fine" grid in FLUX4 and the complete structural model including the vessel. The FDS calculation had to be started several weeks before FDW. Therefore, in FDS the structural model could not yet account for the flexibility of the lower core barrel ring. Finally the two calculations differ in the treatment of boiling in the upper plenum. In FDS it has been ignored, whereas in FDW the above-mentioned approximative approach has been used.

Up to the beginning of boiling inside the vessel (about 120 ms after blowdown start) the results of the two models differ only with respect to the mass flow rate and the pressure values inside the discharge pipe (Fig. 2). Here, the FDS results are closer to the experiment. The pressure field inside the vessel, the pressure differences across the core barrel wall (Fig. 3), and the structural responses (Fig. 4) have been predicted almost identically, and they reproduce the measured time behaviour almost ideally, the amplitudes agreeing within a few percents. The different modelling of the lower core barrel affects merely the amplitudes of the relative displacements between core barrel and vessel (see Fig. 4). The results of FDW with its flexible ring model are a little closer to the experimental data than those of FDS.

This time the crude two-phase model in FDW undervalues the measured pressure increase due to the boiling inside the vessel, and the pressure differences at the core barrel at late times are matched better with FDS which ignores the boiling (see Fig. 3), although here the absolute pressures deviate more from the measurement.

Altogether, it is justified to state that the HDR test V32 has been predicted by both FLUX models, FDS and FDW, qualitatively and quantitatively satisfying.

3.3 Reduced Break Opening Area: V33

The objective of the HDR test V33 was to demonstrate the reduction rate of loadings and strains of the RPV internals due to a reduction of the break opening area in the case of a blowdown. Therefore, an orifice plate has been inserted at the outlet of the discharge pipe, which reduced the outflow area to one quarter of the pipe cross section. The initial conditions equalled those of test V32. The first 100 ms of this experiment have been precalculated with FLUX using the "medium fine" grid in FLUX4 and the weak coupling procedure. The flow through the orifice has been simulated by an actually two-dimensional model in DRIX-2D with four radial meshes inside the nozzle.

The agreement of the computed results with the measurements is almost as good as in the case of V32 (Fig. 5 shows the relative displacements of the core barrel about 1.5 m below the nozzle). Therefore, it is worth while to compare the results of these experiments each to the other in order to evaluate the effect of the reduced outflow area.

A simplified parametrical study with FLUX4 (without DRIX-2D) had indicated that the maximum loadings and responses of the RPV internals are proportional to a power of the break area ratio between one quarter and three quarters in the case of HDR. Thereby, the higher powers relate to global, slowly varying entities such as the displacements of the lower core barrel end or the membrane stress in the barrel due to the bending. The lower powers belong to "local" effects with high frequency variations, as, for instance, displacements and strains of the core barrel in the vicinity of the nozzle.

This estimation has been roughly verified by V32 and V33 for the break area ratio of 25%. Fig. 6 demonstrates that the computational reduction of different entities compares fairly well with the corresponding reduction evaluated from the measurements.

4. Conclusions

The FLUX model has been enhanced to simulate the processes involved in a blowdown event in more detail. From the very satisfactory agreement of the precomputed results for the HDR tests V32 and V33 with the experimental data it is concluded that the present FLUX model is validated, at least for HDR-type configurations of core barrel clamping.

The differences in the results of these two experiments furthermore assess a prediction which was based on FLUX calculations, that the reduction of the break opening area (1) causes essentially less reduction in the loadings and responses of the pressure vessel internals, and (2) affects more the global, low frequency phenomena than local effects connected with high frequency.

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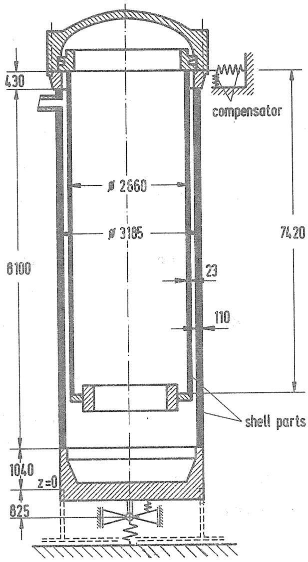

Fig. 1: Structural representation of the HDR pressure vessel and core barrel

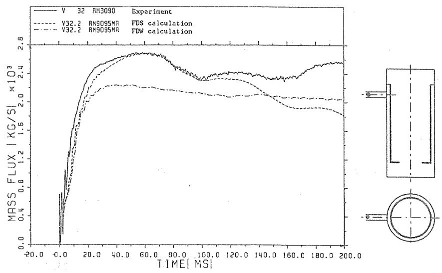

Fig. 2: Mass flow rate through the discharge pipe in case of V32

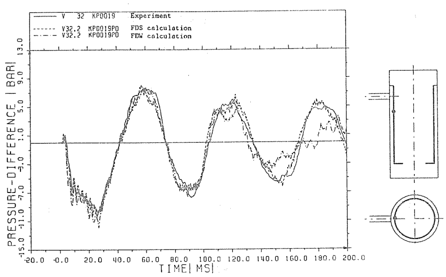

Fig. 3: Pressure difference across the core barrel wall below the nozzle in V32

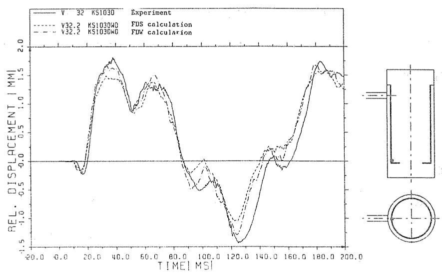

Fig. 4: Radial displacement of the lower core barrel wall in case of V32

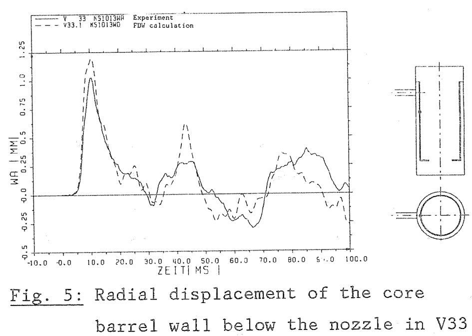

Fig. 5: Radial displacement of the core barrel wall below the nozzle in V33

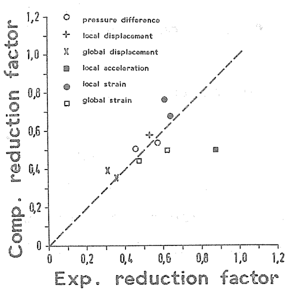

Fig. 6: Reduction of maximum response values from V32 to V33: Computational vs. experimental reduction factors