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**COMPUTER SIMULATIONS OF A 1/5-SCALE EXPERIMENT OF A MARK I
BOILER WATER REACTOR PRESSURE-SUPPRESSION SYSTEM UNDER
HYPOTHETICAL LOCA CONDITIONS**

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ABSTRACT

We have employed the CHAMP computer code to simulate a plane-geometry cross section of a Mark I boiling water reactor toroidal pressure suppression system air discharge experiment under hypothetical loss-of-coolant accident conditions. We performed the experiments at the Lawrence Livermore Laboratory on a 1/5-scale model of the Peach Bottom Nuclear Power Plant.

INTRODUCTION

One important aspect of the safety of boiling water reactor (BWR) power plants is the structural integrity of the pressure suppression system (PSS) following a hypothetical loss-of-coolant accident (LOCA). The BWR Mark I PSS consists of a drywell surrounding the nuclear reactor and an external toroidal wetwell connected to the drywell by eight vent pipes. The toroidal wetwell, approximately half-filled with water, provides a heat sink to condense primary coolant released during a LOCA. A LOCA is simulated by rupturing a line and discharging primary coolant into the drywell. If a recirculation line is ruptured, some fraction (about one-third of the water in the pipe) flashes to steam as it enters the low-pressure region in the drywell. Air initially inside the drywell followed by steam is channeled from the drywell through vent pipes into a toroidal ringheader and finally through partially submerged downcomers into the pool of water in the wetwell. Figure 1 is a cross section of the flow path.

As the drywell pressurizes, the gas forces the water out of the downcomers, forming bubbles. The hydrodynamic phenomena result in a peak download on the torus at about the time of vent clearing and as bubbles begin to form. As the bubbles grow, they generate an upload that peaks at about the time of surface breakthrough and ringheader impact.

Fig. 1. Cross section of the 1/5-scale pressure suppression experimental apparatus.

Since the peak download and peak upload occur within a fraction of a second after initiation of the hypothetical LOCA, no steam has reached the wetwell. Thus it is adequate to model these loads using only an air discharge.

Under auspices of the U. S. Nuclear Regulatory Commission (NSR), the Physics Department H-Division, Lawrence Livermore Laboratory (LLL), is currently developing and verifying computer simulation programs that will produce a best-estimate code for BWR PSS containment analysis. The principal goals are to provide¹:

- Numerical simulations of air venting into water for three particular cases that abstractly model the Mark I and Mark III type pressure suppression systems.
- A documented computational tool or tools to model fluid dynamics in venting to a BWR pressure suppression pool.

To gain some insight into the dominant hydrodynamics phenomena associated with the peak download and the peak upload, we have used the CHAMP finite difference program² to simulate a portion of an experiment on a 1/5-scale model of the Peach Bottom Nuclear Power Plant.³

COMPUTER SIMULATIONS

The results of three CHAMP simulations of a plane cross section of the 1/5-scale experiment will be given.

Comparison with Test 1.3.1

Figure 2 shows the toroidal cross section with two downcomers and the finite difference mesh for the water region. The vent pipe and ring header are not included in the simulation. The air (bubble)/water surface is driven with a temporal pressure distribution obtained from downcomer pressure measurements taken near the ring header in test 1.3.1.⁴ The water and ullage air regions are solved numerically by the finite difference method.

The ullage air is very coarsely zoned, and to speed up the calculations we used a highly scaled bulk modulus⁵ ($K/1000$) for the water. This reduced sound speed allows only about ten transits from the bottom of the downcomer to the bottom of the torus during vent clearing. Hence we expect signals not only to arrive late but also to be somewhat dispersed.

Fig. 2. CHAMP interfaces and finite difference mesh for test 1.3.1.

Figure 3, from Ref. 6, shows measured pressure data. In Fig. 4 we compare experiment and calculation. The vent clearing occurs at about 3.115 s and, as expected, the computed signal is somewhat late and dispersed. The general agreement is reasonable in light of relatively crude zoning and the scaled bulk modulus.

Figure 5, from Ref. 4, shows the measured load both from the load cells and from a pressure integration. In Fig. 6 we compare the calculation with the experimental pressure integration values normalized to a unit thickness of the torus. Again, except for timing difference, there is qualitative agreement in shape and magnitude. Experimentally, the initial ringheader impact occurs at about 3.16 s (Ref. 7) whereas the calculation would indicate impact at about 3.175 s. Further discussion of ringheader impact will follow in the next section.

Figure 7 shows the bubble and ullage air/water surface configurations at 221.6 ms after initiation. The coarseness of zoning prevents the water from flowing over the tops of the downcomer as rapidly as one would expect. The water velocity vectors are also shown on a scale of $0.5 \text{ cm/ms} = 5 \text{ cm}$.

Ringheader Impact Calculations

We performed the remaining two calculations to obtain information on the ringheader impact and its effect on the upload. To accommodate the coarseness of zoning and to alleviate the problem of water flowing over the top of the downcomer, the downcomers were submerged an additional 10 cm. This submergence means that the clearing process and bubble growth has to push an additional 10 cm of water upward against the ullage pressure and the force due to gravity. The measured ringheader pressure should be increased accordingly; however, we chose to use the drywell temporal pressure distribution to avoid the modeling problems. The drywell pressure does not exhibit the drop after vent clearing that we observed in the downcomer measurements; this reflects the effects of the orifice as well as possibly some choked flow.

Figure 8 shows the initial configuration of interfaces as well as the computational mesh for the water. The remainder of the calculation is the same as in the previous case.

In this case, the vent also clears at about 140 ms and ringheader impact occurs at 214.1 ms. Figures 9 and 10 show the configuration and flow

Fig. 3. Unfiltered pressure data in the drywell and the 90-degree toroidal wetwell sector for a nominal test (test 1.3.1).

Fig. 4. Computed and measured pressures at torus bottom and temporal pressure used for bubble driving condition.

Fig. 5. Variation of the 90-degree toroidal wetwell response determined by external load cells (curve A) and the hydrodynamic vertical-load function determined by pressure integration (curve B) (test 1.3.1). Because the data are a computer-generated line, the scale is indicated in English units.

Fig. 6. Measured load on the torus from pressure integration normalized to unit thickness compared with computed load.

Fig. 7. Interfaces and water velocity vector at $t = 3.227$ seconds.

Fig. 8. CHAMP interfaces and finite difference mesh for ringheader impact of test 1.3.1.

Fig. 9. Interfaces and water velocity vector at $t = 214$ ms.

Fig. 10. Interfaces and water velocity vector at $t = 280$ ms.

field at initial impact and at 280 ms. Figure 11 shows the configuration without ringheader at 280 ms.

Figure 12 shows the pressures computed at the tank bottom both with and without ringheader. These pressures are essentially the same. We note that, in contrast to Fig. 3, there is no dip in pressure after the bubble growth begins.

Figure 13 shows the loads on the system both with and without ringheader impact. We note that the loads indicate an additional up force from 214 ms to about 250 ms.

Returning to Figs. 5 and 6 with regard to the up and down loads on the system, we can begin to understand some of the related hydrodynamic phenomena. The initial peak down load occurs just after vent clearing and appears to be the result of the jet-slug decay as discussed by Kang.⁸ The double peak down load is probably a combination of a "spring-mass" effect and possible choking of air flow through the orifice, vent pipe, and ringheader into the downcomers. This aspect will require further study.

The sharp upload indicated by the load cells at 3.175 s but absent from the pressure integration measurement is probably due to initial ringheader impact. The duration and magnitude are roughly comparable to the calculation. The upload occurring from about 3.2 to 3.26 s appears to be the result of pressurizing the torus air space before bubble breakthrough.

CONCLUSION

The logic of the CHAMP computer code allows simulation of the LLL 1/5-scale experiment in a qualitatively agreeable manner. However, several aspects of the simulation need better modeling, e.g., the temporal pressure applied to the bubble is experimentally measured and can define a simulation. However, if the timing of vent clearing does not agree exactly with experiment, then the timing for the pressure drop is not correct for simulating the exact experiment. One should model the downcomer, vent pipes, orifice, and ringheader perhaps as a "lumped parameter" differential equation using Bernoulli's equation. This modeling will require several iterations to obtain accuracy.

Since each of the reported calculations requires about 10 min of CDC 7600 time, it is extremely expensive to consider doing many iterations.

Fig. 11. Interfaces and water velocity vector at $t = 280$ ms.

Fig. 12. Driving pressure and computed pressure at the bottom of the torus.

Fig. 13. Load on the torus with and without ringheader impact.

Note that if we were to use the true bulk modulus of water, the calculations would require about 30 times as much (300 min) computer time, certainly a prohibitive amount for modeling studies in an iterative manner.

The future effort will be to use an incompressible solution method in the water. Such a method in the CHAMP code would produce a highly versatile simulation method where Eulerian compressible and/or incompressible fluids could readily couple to structures calculations formulated in the Lagrangian mode.

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