Long-Term Fluid-Dynamic Aspects of the HDR-RPV-I Experiment V 31.1 and Comparison with Post-Test Computation by the DRUFAN-02-Code

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Abstract

The HDR-RPV-I Experiment V31.1 was a replication of V31 experiment and was chosen to be the reference test for pretest calculations of the HDR-RPV-I experiment. It simulates a cold leg break of intermediate size of a lage PWR. Analysis efforts of V31.1 in the past were concentrated on the short term period, where the major dynamical fluid-structure interaction occur. However, besides the dynamical fluid-structure interaction, the test shows interesting phenomena such as pressure undershoot in the vessel and noticeable superheating of steam in the inner region of the core barrel even during blowdown.
An analysis of the whole blowdown phase of the reference test V31.1 has been performed using an advanced best-estimate computer code DRUFAN-02, which is developed at GRS. The code is based on the separate field equations for each mass of steam and liquid and overall field equations for energy and momentum of mixture. The thermodynamic nonequilibrium is controlled by the mass transfer rate between phases, which is calculated by means of correlations for the growth and shrinkage of steam bubbles and liquid droplets, respectively.
The critical discharge mass flow rate is calculated with the one dimensional finite difference model. In the analysis, the mixture level tracking model is used in the inner region of the core barrel and a drift flux model is used at all vertical flow paths. All significant structures are modelled. Very good agreement between measured and calculated results has been obtained during the initial blowdown phase, especially in connection with mass flow rate, density, pressure and temperature behavior at different locations. It has been achieved by modifying the evaporation and condensation models through the assumption that the number density of nucleation for bubbles is a function of void fraction with the minimum number density of $5\times10^6/m^3$ in the vessel. This value is much smaller than that usually used. The calculated results have also shown good agreement with measurements in the whole blowdown phase. The drift flux model plays a significant role in the long term period. The noticeable superheating of steam, as observed, is calculated using small number density of the droplet in the evaporation process. The difference between measured and calculated temperatures in the upperhead may be mainly due to local effects.

1. Introduction

The HDR safety program is to provide experimental data at scales and thermodynamic conditions as close as possible to Light Water Reactor (LWR) systems. These data are used for the assesment of computer codes developed for reactor safety analysis. A part of the HDR project EV 3000 deals with the dynamic behavior and loading of the reactor pressure vessel internals (RPV-I) during blowdown. Three experiments V29.2, V31 and V31.1 were performed during the preliminary phase in 1980. The break size corresponds to intermediate break of actual LWR. Test V31.1 /1/ was a replication of test V31.1 and chosen to be the reference test for pretest calculations of the initial blowdown phase during the first 100 ms. In /2/, there is given a summary of the experimental results of the three experiments during the initial period of blowdown together with the results of pretest calculations. Analysis efforts in the past were concentrated on the short term period of the blowdown, especially on the first 100 ms where the major dynamical fluid structure interaction phenomena occur /3/. Interesting phenomena in the V31.1 test besides dynamical fluid structure interaction are pressure undershoot in the vessel as shown in Fig.1 and noticeable superheating of steam in the inner region of the core barrel during blowdown as shown in Fig.2. An analysis of the whole blowdown phase of the reference test V31.1 has been performed using an advanced best-estimate code DRUFAN-02 /4/ and is presented in this report. The dependence of the bubble number density on void fraction has been introduced to well simulate the pressure undershoot in the vessel. Furthermore, a small value for the liquid droplet number density has been used in the inner region of the core barrel in order to simulate the noticeable superheating of steam due to stored energy in structures during blowdown.

2. Description of the experiment

The HDR pressure vessel and core barrel geometry is shown in Fig.3. The pressure vessel is 10.8 m high and has an internal diameter of 3.185 m. The core barrel is rigidly clamped at its upper flange and carries a mass ring at its lower flange to simulate the core weight. Its dimensions are 7.57 m high and 2.66 m internal diameter. The geometry analogy between HDR and 1300 MW PWR shows that the ratio of the fluid volume is: HDR/PWR =69.7/149 = 1/2.1 /5/. The break nozzle is located at the level of 8.85 m and simulate a cold break in PWR. The distance from the inside surface of the reactor pressure vessel (RPV) up to the location of the inside break disk amounts to 1.37 m. The inside diameter of the break nozzle is 0.2 m. The RPV was filled with subcooled water with temperatures ranging from 308 °C in the upper head to 268 °C in the downcomer at 11 MPa. Then the degree of the subcooling in the downcomer region was 50 °C.

3. Description of the computer code DRUFAN-02

The computer code DRUFAN has been developed at the Gesellschaft fur Reaktorsicherheit GRS) mbH for the analysis of the transient thermal-hydraulic behavior of the primary system of LWRs during the blowdown and the initial phase of refill of a loss of coolant accident /6,7/. DRUFAN-02 is the latest version, which is under development /4/. The code is based on the lumped parameter approach allowing the flexible configuration of control volumes. A one dimensional finite difference model (1D-FDM) is used to calculate the critical discharge mass flow rate in taking account of the influence of the geometry in the neighbourhood of the break plane /8/. The physical model is based on the separate field equations for each mass of steam and liquid and overall field equations for energy and momentum of mixture. The thermodynamic nonequilibrium is controlled by the mass transfer rate between phases, calculated by means of correlations for the growth and shrinkage of steam bubbles and liquid droplets, respectively. In the DRUFAN-02 version, drift flux models and mixture level tracking model are implemented. A heat conductor model is available for simulation of structures, electrical heater rods and fuel rods. For the heat transfer between solid structures and the fluid, a comprehensive package of flow-regime dependent heat transfer and critical heat flux correlations can be used.

4. Models for the experiment analysis

The DRUFAN model of the HDR blowdown system consists of 21 control volumes, 21 flow paths (junctions) and 15 heat conductors as shown in Fig.4. The upper head defined as the part above the upper flange is represented with one control volume. The lower plenum is vertically divided into two volumes to simulate flow stagnation in the lower part of the lower plenum and temperature distribution. The upper plenum and core region, which is defined as the inner region of the core barrel is represented with 6 volumes. The downcomer is also represented with 6 volumes. The break nozzle is divided into 6 volumes to calculate the detailed thermal-hydraulic behavior in it. The mass inventories in lines and loops participating in blowdown are added to the mass in the volumes in the neighbourhood of the lines and loops. A mixture level tracking model is used in control volumes from #1 to #7. A drift flux model is used at all vertical flow paths. The one-dimensional finite difference model is used to calculate the critical discharge mass flow rate at flow path #21. Heat exchange between both sides of the core barrel is calculated through conductors #2 to #7. The heat transfer coefficients on both sides of the heat conductors are calculated using the heat transfer correlations corresponding to the thermal-hydraulic state of the connected fluid volumes. The wall of the RPV is subdivided into 9 heat conductors, where the bottom and the top of the RPV are simulated by plates with equivalent surface area. Heat transfer on the inside surface is dependent on fluid condition of the connected volume.
Heat losses from the outer surface to the surrounding atmosphere are estimated by assuming a heat transfer coefficient between 3 and 6 W/m^2K as in /9/.

The number densities of steam bubbles and liquid droplets play key roles in the mass transfer between two phases, which determines the degree of the thermodynamic nonequilibrium. The physical model used in DRUFAN to calculate the mass transfer rate is described in /6,7/. Based on the analyses of several experiments /10/, the value of $5\times10^{9}/m^{3}$ is recomended for the bubble number density and this is usually used also for the droplet number density /11/. The same order of the bubble number density has been reported to be used. For example, an advanced computer code TRAC-PD2 uses $10^{10}/m^{3}$ as the minimum bubble number density /12/. However, the analysis of the HDR-V31.1 test has led us to modifying the above original model. The best results have been obtained by assuming the bubble number density as a function of void fraction, which is different in the RPV and the break nozzle. An initial value (or minimum value) of $5\times10^{6}/m^{3}$ for the bubble number density N_B is used in the RPV as shown in Fig.5(a). In the break nozzle, the function is given in Fig.5(b) with an initial value of $4\times10^{9}/m^{3}$.

In order to take account of droplet fall-down above mixture level, a small value of droplet number density N_D is used only for evaporation ; $N_D=10^{4}/m^{3}$ for evaporation in volumes #1 to #7, and $N_D=10^{10}/m^{3}$ for all other cases.

The total heat transfer rate between two phases is calculated from $Q_{total}= Q_{bubble}\cdot(1-\gamma) + Q_{droplet}\cdot\gamma$. The value of $(1-\gamma)$ is illustrated in Fig.5(c).

5. Comparison of calculated results with experimental values

In Fig.6, there is shown the good agreement between calculated discharge mass flow rate and that deduced from measurements for the short term period.

The agreement between calculated and measured pressure in the upper head is also very good, as shown in Fig.7. The pressure undershoot is a measure of the degree of thermodynamic nonequilibrium. The undershoot in the discharge mass flow rate in Fig.6 corresponds to the undershoot in the pressure in Fig.7 . The pressure recovery in the upper head after 0.15 s is due to the rapid increase of the steam generation rate at that time. The temperature behavior in the upper head is shown in Fig.8. The measured temperature shows that the fluid in the upper head was subcooled water for about 0.1 s. After a period of superheating, the fluid temperature follows the saturation temperature with some delay but in coincidence with the increase of the steam generation rate. It seems that the thermocouple measured locally a steam temperature which lies between saturation temperature and superheated bulk temperature of the water. The agreement between calculated and experimentally deduced discharge mass flow rate, as observed in the initial blowdown phase in Fig.6, was also obtained in the whole blowdown period as shown in Fig.9. The plateau behavior after 10 s is due to the increase of the void fractions in the differrent control volumes of the break nozzle. In Fig.10, there is shown a good agreement in connection with the pressure behavior in the upper head. It should be noticed that the drift flux model has a significant effect in obtaining the above mentioed agreement in the long term behavior /13/.

In Fig.11, there is shown a good agreenent between the calculated and measured temperature in the lower part of the lower plenum. The temperature behavior in the upper head is shown in Fig.12. Both calculation and measurement indicate superheating of steam phase during blowdown. In the calculation, such a noticeable superheating of steam in the early period (55—140 s) is obtained by using a small number density of droplet for evaporation in the inner region of the core barrel. The difference between the calculated and measured temperature in the upper head may be mainly due to local effects. One main cause may be the fluid flow from the hot water line with 12 m length, which is connected to the upper head. Although the fluid volume of this line is included in the control volume #1, the blowdown behavior of such a long pipe is different from that of the upper head.

6. Conclusions

The analysis of the results of the HDR-V31.1 experiment has shown that the thermodynamic nonequilibrium were dominant during the initial phase of the blowdown. The calculated results shows excellent agreement with the experimenttal results, especially in pressure, discharge mass flow rate, temperature. Such a good agreement has been obtained by introducing void-fraction dependent bubble number densities with minimum number of $5\times10^6/m^3$ in the vessel. This minimum bubble number density is much smaller than usually used. During the whole blowdown phase, experimental results have been well simulated by using the drift flux model implemented in DRUFAN-02. The noticeable superheating of steam during blowdown has been calculated by using a small number density of droplet in the inner region of the core barrel only for evaporation. The difference between calculated and measured superheating of steam may be mainly due to local phenomena.

Acknowledgements

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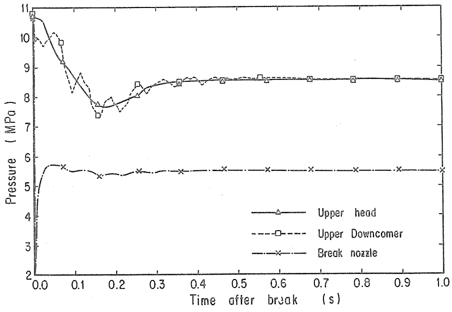

Fig.1 Measured Pressures at Different Locations

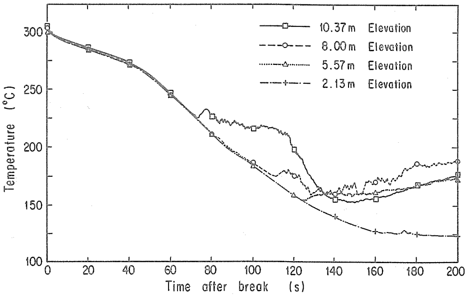

Fig.2 Measured Fluid Temperatures in the Inner Region of the Core Barrel at Different Elevations

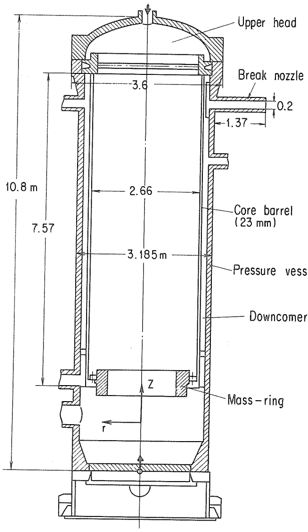

Fig.3 Geometries of HDR Pressure Vessel and Core Barrel

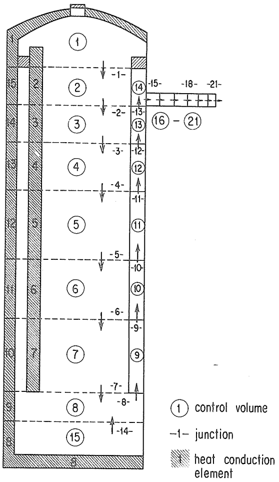

Fig.4 Nodalization Diagram for HDR-V31.1 Experiment Post Test Calculation with DRUFAN-02

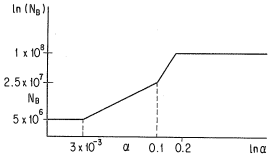

Fig.5(a) Bubble Number Density in the Vessel

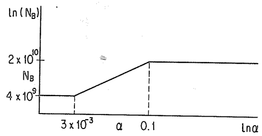

Fig.5(b) Bubble Number Density in the Break Nozzle

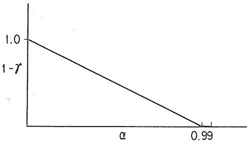

Fig.5(c) Weighting Function for Interpolation between Bubble Heat Transfer and Droplet Heat Transfer

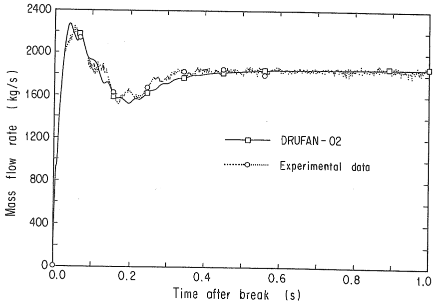

Fig.6 Discharge Mass Flow Rate

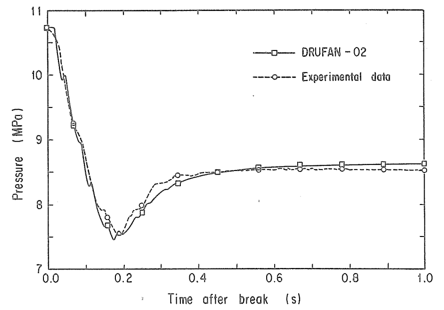

Fig. 7 Pressure in the Upper Head

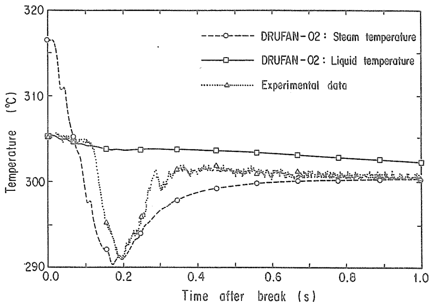

Fig. 8 Fluid Temperature in the Upper Head

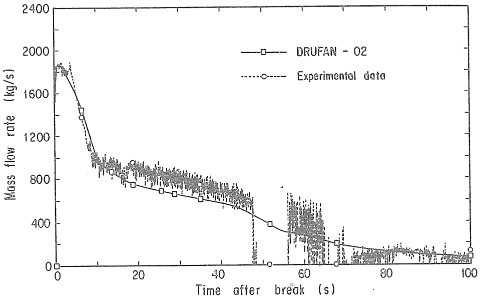

Fig. 9 Discharge Mass Flow Rate

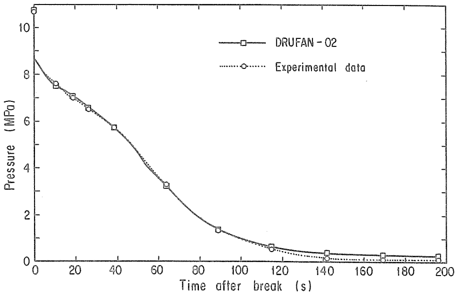

Fig. 10 Pressure in the Upper Head

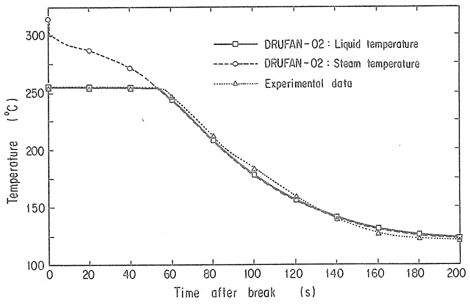

Fig. 11 Fluid Temperature in the Lower Plenum

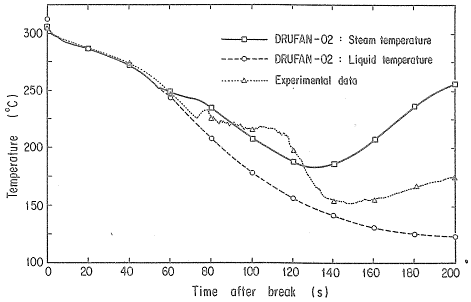

Fig. 12 Fluid Temperature in the Upper Head