MAIN STEAM LINE BREAK ANALYSIS OF A VVER-440 REACTOR USING THE COUPLED THERMOHYDRAULICS SYSTEM/3D-NEUTRON KINETICS CODE DYN3D/ATHLET IN COMBINATION WITH THE CFD CODE CFX-4

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ABSTRACT

The coupled thermohydraulic system/3D-neutron kinetic code complex DYN3D/ATHLET was applied to an asymmetric main steam line break (MSLB) analysis for the Russian VVER-440 type reactor. Such type of MSLB accidents cause an asymmetrical overcooling of the reactor. In this case the coolant mixing inside the reactor pressure vessel (RPV) has an important influence on the behaviour of the reactor. The code DYN3D includes a special model for the mixing of coolant from different primary loops in the lower plenum of VVER-440 type reactors which can be used in the coupled code, too. This model is based on the analytical solution of the Navier-Stokes equations in the potential flow approximation in 2-dimensional cylindrical geometry and the diffusion equation for heat transport or soluble poison. The model is validated against experimental results from a 1:5 VVER-440 flow model with air and experimental data from VVERs with all main coolant pumps (MCP) working. Using this model for the coolant mixing in the MSLB analysis, recriticality of the scramed reactor was predicted. If homogeneous coolant mixing is assumed, no recriticality will be obtained.

The stationary three-dimensional flow distribution in the downcomer and the lower plenum of a VVER-440/V-230 reactor was calculated with a CFD code (CFX-4). For this calculation the RPV from the cold legs inlets, the downcomer, the lower plenum and the lower core support plate was nodalized in detail. The comparison with experimental data and the above mentioned analytical mixing model showed a good agreement for near-nominal conditions (all MCPs are running). However, the comparison between the CFD-results and the analytical model revealed differences for MSLB conditions. After shutdown of the MCPs, natural convection established in the primary circuit. The mass flow rate of the affected by the MSLB loop is approximately twice the value of one of the other loops, a redistribution of the flow below the inlet nozzle of the
affected loop is observed. For this reason the temperature field at the core entry cross section has two equal minima next to the position of the concerned inlet nozzle. The temperature distribution obtained by the analytical model has one minimum, just near to the position of this inlet nozzle. The shape of the temperature distribution for MSLB conditions is practically the same like in nominal conditions. The extension of this sector due to the increased mass flow is properly considered by the model.

The core inlet temperature distribution obtained by means of CFX-4 was used to estimate the reactivity effect in the MSLB analysis.

1. INTRODUCTION

Complex computer codes modeling the whole reactor system including 3D neutron kinetics in combination with advanced thermohydraulics plant models become more and more important for the safety assessment of nuclear reactors. Such codes only are capable of estimating the feedback effects in a realistic way, for instance in reactivity initiated accidents with strongly asymmetric neutron flux distribution in the core caused by a perturbation in one of the primary circuit loops. At Forschungszentrum Rossendorf (FZR), Institute of Safety Research, both the hexagonal and the Cartesian versions of the 3-dimensional neutron kinetics code DYN3D were coupled with the advanced thermohydraulics system code ATHLET (Grundmann, 1995).

The 3-dimensional reactor core model DYN3D (Grundmann, 1996) has been developed at FZR to improve the simulation of reactivity initiated accidents, where space-dependent effects in the reactor core are relevant. The neutron flux distribution is calculated using different nodal expansion methods for the hexagonal and for the square fuel assembly geometry. The neutron diffusion equations are solved for two energy groups. Steady state and transient behaviour can be calculated. The code comprises a thermohydraulics model of the core, a fuel rod model describing the thermo-mechanical behaviour of the fuel and cladding and a heat transfer regime map ranging from one-phase liquid flow to superheated steam. The code allows the estimation of safety relevant parameters like critical heat flux ratio, maximum temperatures or cladding oxide layer thickness due to metal-water interaction in the high temperature range.

ATHLET (Burwell, 1989) is a thermohydraulics system code, developed by the Gesellschaft für Anlagen- und Reaktorsicherheit (Germany). It can be applied to the whole spectrum of operational and accident transients, from small leaks up to large breaks of coolant loops at both PWRs and BWRs. The code includes basic modules for thermohydraulics, heat transfer and heat conduction, neutron kinetics (point kinetics and 1D neutron kinetics) and reactor control simulation.

Safety analyses for accidents, where an asymmetrical perturbation of the reactor core is expected, are the main application fields of the coupled codes. These are, e. g. steam line breaks or boron dilution transients. Since a 1D- and a 3D-code thermohydraulics are coupled, there is a need for an interface between the different spatial resolutions. This interface links the parameters of the single loops with the parameters at the core inlet simulating the mixing inside the RPV and therefore should offer an efficient model for the description of temperature and boron concentration distribution at the core inlet.
In the past, an analytical model for the description of coolant mixing in the RPV of VVER-440 reactors based on the analytical solution of the Navier-Stokes equations in the potential flow approximation has been developed to replace the non-conservative approach of homogeneous mixing inside the RPV. This model is included in the coupled code DYN3D/ATHLET.

Another way is the use of the results of computational fluid dynamics (CFD) calculations. The 3D flow distribution in the downcomer and the lower plenum can be calculated. At present, the direct coupling of the CFD and the thermohydraulics system codes is impossible due to the high demands on computation time in the CFD-calculations. Therefore, in the current paper an off-line coupling approach is applied.

In section 2 a MSLB analysis of the VVER-440 is described. In section 3, features of the CFD-code CFX-4 are shortly described. In section 4 the 3D flow distribution in the downcomer and the lower plenum of the reactor is calculated by means of CFX-4 for operational conditions. The CFX-calculations are compared with the experimental data and the analytical mixing model. This section also contains an analogous calculation for MSLB conditions including the comparison with the analytical mixing model. The provided by CFX-4 temperature core inlet distribution is used in section 5 for an improved safety analysis of the MSLB.

2. MSLB ANALYSIS BY MEANS OF DYN3D/ATHLET

2.1 Scenario and Assumptions

A MSLB accident provokes deep overcooling of the core. This overcooling results in the most severe consequences when the moderator temperature reactivity coefficient (MTC) is strongly negative and when fuel and coolant have the same temperature. In this case no heat is stored in the fuel elements. Considering these facts a MSLB at the end of cycle (EOC) under hot zero power (HZP) conditions (low fuel temperature) was selected for the analysis.

The MSLB analysis presented here concerns the Russian type reactor VVER-440. The VVER-440 is a six loop 1375MWth pressurized water reactor. In the current paper, the V-230 design version of the VVER-440 is considered. An analogous MSLB analysis for the second VVER-440 design V-213 has been presented by Kliem (1997). The main difference between these two design types related to the MSLB analysis is the elliptical sieve plate in the lower plenum for additional flow smoothing in the V-213, which does not exist in the V-230 design version. This sieve plate influences the coolant mixing in the lower plenum.

The corresponding burn-up distribution was determined by a DYN3D burn-up calculation.

The MSLB is postulated as a double ended break (DEB) of the main steam line (MSL) downstream the steamgenerator (SG) in front of the steam isolation valve (SIV). The diameter of the MSL is 0.425m.

The MSLB accident was modeled according to the following scenario:
t=0s  Sudden and complete DEB of the MSL.
The pressure decreases rapidly in all SG, because they are connected through the
main steam collector (MSCOL).
t=1.3s  The velocity of pressure decrease in the MSCOL reaches the critical value of
0.05MPa/s.
t=6.3s  With a delay time of 5s, the SIV in all MSL start to close. Closing of the SIVs
causes the shutdown of the MCP in the corresponding loop. Closing of more than
3 SIVs causes the reactor scram. All withdrawn control rods are immediately
inserted into the core, the most efficient control rod excepted, which is assumed to
stuck at fully withdrawn position.
During the transient the primary pressure reaches the actuation point of the High
Pressure Injection System (HPIS). But in the calculation the failure of the HPIS is
postulated to aggravate the accident.

The first calculation was based on the assumption of homogeneous coolant
mixing in the lower plenum.

2.2 Accident Progression

At the secondary side the
MSCOL and the intact SG's were
isolated from the leak by closing
all SIV. Then the pressure further
decreases only in the leaking SG.
The secondary side temperature of
the broken loop decreases together
with the pressure along the
saturation line. This temperature
decrease leads to an increasing
heat flux from the primary to the
secondary side (Fig. 1) and causes
a temperature decrease in the
corresponding primary loop of
about 100K (Fig. 2). Due to this
temperature decrease the core inlet
temperature decreases, too, from
260°C to 223°C at the end of the
investigated time interval (300s
after the break). This temperature
drop leads to a positive reactivity
insertion into the core. This
reactivity effect does not
compensate the scram reactivity.
Thus, the reactor remains
subcritical. After MCP coastdown,
natural convection develops in the primary circuit. Due to the temperature difference in the loops the mass flow rates are also different. The mass flow in the broken loop is about two times higher than the value of one intact loop.

2.3 Variation of Mixing Conditions in the Lower Plenum

Obviously the distribution of coolant temperature at the core inlet will have an important influence on core behaviour.

To study this effect additional calculations with modified assumptions concerning the coolant mixing in the lower plenum were performed. In the second calculation the coolant mixing was treated by means of the analytical mixing model for VVER-440 included in the code DYN3D. This special model for the mixing of coolant from different primary loops in the downcomer and lower plenum of VVER-440 type reactors was developed by Dräger (1987). It is based on the analytical solution of the Navier-Stokes equations in the potential flow approximation for a 2D flow in the downcomer. The velocity gradient in the radial direction was neglected. In the lower control rod chamber a parallel flow with constant velocity was assumed.

The flow field in the lower plenum, where the coolant changes its flow direction is controlled by a downcomer outlet boundary condition, i.e. there is no modeling of the flow field in this part. With this approximation of the velocity field the diffusion equation for the temperature is solved. The solution is presented as a closed analytical expression based on series of orthogonal eigen-functions. The turbulence was taken into account by constant scalar turbulent Peclet numbers defined individually for the downcomer and the lower control rod chamber. The turbulent Peclet numbers describe the intensity of turbulent diffusion. Dräger has found that in the case of highly turbulent flow the mixing can be well described by choosing values for these two Peclet numbers on the basis of experimental data. By these values one is able to generalize the mixing, i.e. they are insensitive against changes of the operation mode of the reactor (e.g. different situations of disturbed reactor inlet temperatures, mass flow rates of running pumps etc.) in case of operating MCPs.

In order to validate the analytical mixing model, measured values from an air operated 1:5 scaled VVER-440 model were used. Temperature measurements were taken at the end of the

Fig. 3 Temperature Distribution in the calculated by the Mixing Model (before Recriticality)
downcomer and at the inlet of the reactor core. Further, the model was validated against measured operational data from NPP with VVER-440 (Dräger, 1987).

The temperature distribution obtained with this mixing model is demonstrated in Fig. 3. The overcooling effect is rather non-uniformly distributed over the core cross section. A minimum of the temperature can be clearly identified at the azimuthal position of the affected loop. For conservative assumptions, the sticking control rod was supposed to be located in the same sector of the core. Thus, the superposition of overcooling and stuck rod causes strongly asymmetric neutron flux and power distribution (Fig. 4). Due to these effects, the positive reactivity insertion caused by the coolant temperature decrease compensates the scram reactivity at t=145s. Recriticality of the shut down reactor is reached. At that time the cold leg temperature is minimum, later the positive reactivity insertion is stopped and the power level is stabilized by Doppler feedback.

In the third calculation coolant mixing in the lower plenum was inhibited at all. Each loop was connected to a particular sector of the core. The recriticality effect is much more developed in this calculation, where the absence of any coolant mixing in the downcomer and the lower plenum was presumed. In this case, the mutual amplification of reactivity effects caused by overcooling and stick of control rod is stronger due to the more asymmetric temperature distribution. Scram reactivity is compensated already at t=81s. After reaching recriticality, the coolant temperature drop is continued leading to further reactivity insertion. Thus, the maximum power is higher than in the second case (see Tab. 1). But it should be noted that unrealistic assumptions concerning coolant mixing were made leading to an excess of conservatism.

**Table 1** Maximum Fission Power in the different calculations

<table>
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<tr>
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<th>Homogeneous Mixing</th>
<th>Analytical Mixing Model</th>
<th>No Mixing</th>
</tr>
</thead>
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<tr>
<td>Maximum Fission Power reached</td>
<td>-</td>
<td>5</td>
<td>18</td>
</tr>
<tr>
<td>during the transient (MW)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

![Fig. 4](image) Normalized Power Distribution in the Calculation with the Mixing Model (after Recriticality)
3. ASSUMPTIONS FOR CFD-CALCULATIONS

3.1 View of the software package CFX 4.2

CFX is a finite volumes program (CFX-Manual, 1997) that offers the following options:

- Block structured discretization grids
- Solution of the Navier-Stokes-Equations for steady and unsteady flows for compressible and incompressible fluids
- Applicability for laminary and turbulent flows (different models of turbulence)
- Modelling of heat transfers
- Treatment of porous media with volumetric body forces

3.2 Model assumptions, geometry preparation and grid generation

An incompressible fluid was assumed for the coolant flow in pressurized water reactors. The turbulence was modeled using the Standard $k$-$\varepsilon$ approximation. The calculations were done on a SGI Origin 200 (1 GB RAM, 4x R10000 180 Mhz, 64 Bit CPU) workstation platform. For the calculations, a grid model of the VVER-440 RPV has been developed (see Fig. 5). The parameters of the discretization are compiled in Table 2.

In order to receive an optimal net griding for the later flow simulation one must consider the following items: Checking grid number in special regions to minimize numerical diffusion, refinement of the griding in fields with strong changes of the dependent variables, adaptation of the griding to estimated flow lines, generation of nets as orthogonal as possible (angle >20°).

![Fig. 5 Grid Model the VVER-440](image)

**Table 2: Discretizations of the Reactor Type VVER-440**

<table>
<thead>
<tr>
<th></th>
<th>PWR</th>
<th>No. of Blocks</th>
<th>No. of Patches</th>
<th>No. of Grid cells</th>
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</thead>
<tbody>
<tr>
<td>VVER-440</td>
<td>236</td>
<td>912</td>
<td>159800</td>
<td></td>
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</table>

(7)
3.3 Boundary conditions and the modeling of the perforated plate (VVER-440)

Inlet boundary conditions with given velocity and temperature were set at the inlet nozzles. The outlet boundary conditions were set to pressure controlled at the core inlet. In the case of the VVER-440 / V-230 a control rod chamber exists below the core, which is separated from the lower plenum by a sieve plate. It was not possible to simulate the whole core with the fuel elements, control elements etc. The sieve plate is modeled as a porous region with a certain degree of porosity.

The porosity value $\gamma$ for perforated plates is determined by relating the area of orifices to the total area of the sieve plate. The body forces $B$ are added to the momentum equation. To take into account distributed friction losses, the momentum equation is written as:

$$\frac{\partial \rho u_t}{\partial t} + \nabla (\rho u_t \otimes u_t) = B + \nabla \sigma \quad (1)$$

$$B = B_F - (R_c + R_f) v \quad (2)$$

The speed-factor $R_f$ (kg/m$^4$) can be used to calculate a flow resistance depending on the local velocity according to second order law. The following relation between the speed-factor $R_f$ and the flow resistance coefficient $\zeta$ is valid:

$$R_f = \zeta \frac{A \rho}{V^2} \quad (3)$$

Measured values for the flow resistance $\zeta$ were used to calculate the speed-factor $R_f$ at the perforated plate of the VVER-440.

4. RESULTS OF THE CFD-CALCULATIONS

4.1 Flow field in the VVER-440

The CFD-calculations of the downcomer and lower plenum of the VVER-440 / V-230 widely confirmed the validity of the analytical mixing model of Dräger, (1987) (see (8))
section 2). The flow field in the downcomer is shown in Fig. 7 at steady state conditions. While in Western type reactors (PWR Konvoi) recirculation areas exist below the inlet nozzles, almost no vortices are found in the VVER-440. The velocity field is nearly parallel in the downcomer what confirms the applicability of the potential flow approximation. This is a special feature of VVER-440 type reactors which is due to inlet/outlet nozzles construction, downcomer geometry and high number (6) of loops. However, a maximum velocity exists on azimutal positions between the inlet nozzles. In Fig. 8 the velocity at azimutal positions at the end of the downcomer at the VVER-440 is shown.

**Fig. 7** Flow Field in the Downcomer of the VVER-440 at Nominal Conditions (Steady State)

In the lower plenum of the VVER-440, large vortices exist (Fig 9). The perforated plate is controlling the size and location of the vortices and therefore also the mixing of the coolant. The maximum velocity at the core inlet is situated at the outer core radius.

**Fig. 8** Velocity Distribution at the End of the Downcomer
4.2 Comparison of the CFD results with measurements and the analytical model

Fig. 9 Temperature Distribution in the Downcomer and Flow Field in the Lower Plenum at Nominal Conditions (Steady State)

Fig. 10 Scaled Temperature Distribution at the Core Inlet (CFX, Analytical Model)
To compare the measurements, the analytical model and numerical simulations with CFX results an experiment at the scaled air operated model of the VVER-440 at TH Zittau (Dräger, 1987) was considered. All loops were in steady state operation, one of the six loops was operating at lower temperature.

Fig. 10 shows the scaled temperature distribution at the core inlet of the VVER-440. At nominal conditions the numerical simulation using CFX is similar to the analytical model based on the potential theory. In Fig. 11 the temperature distribution at the downcomer outlet is shown. There is almost no mixing in the downcomer flow field. That means a relatively sharp sector of cold water is located below the inlet nozzle.

Fig. 12 shows the scaled temperature distribution over the core diameter. A comparison between CFD-calculation, measurement and analytical model shows a good agreement. The CFD-calculation gives the lowest mixing rate, which can be seen from the greater difference between maximum and minimum scaled temperatures. However, sector formation can be clearly seen in all models. The lowest mixing rate is situated near the core wall with the value 30%.

![Fig. 11 Scaled Temperature Distribution at the End of the Downcomer](image1)

![Fig. 12 Scaled Temperature Distribution at the Core Inlet over the Core Diameter](image2)
4.3 Relevance of the coolant mixing for the main steam line break analysis

The measurements and numerical simulations in section 4.2 at normal operating conditions have shown, that the coolant from different loops is not mixed completely in the downcomer and lower plenum before entering the reactor core. This causes an asymmetry of the coolant temperature in the core.

The simulation of the realistic moderator temperature distributions in the core is of special importance if the transient behaviour of the reactor is significantly determined by reactivity feedback. As shown in section 2 the recriticality of the scramed reactor is strongly affected by the coolant mixing description and therefore by the temperature distribution at the core inlet.

Results of the coupled code DYN3D/ATHLET were used as inlet boundary conditions at the inlet nozzles for the CFD calculation (Tab. 3). To compare the temperature distribution at the core inlet calculated by the analytical mixing model and by the numerical simulation with CFX, temperatures of the coolant at the inlet of each fuel assembly were used.

Table 3 Boundary Conditions for the CFD Calculation at the Inlet Nozzles of the Reactor

<table>
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<tr>
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<th>broken loop 1</th>
<th>intact loops 2-6</th>
</tr>
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<tr>
<td>temperature / K</td>
<td>434.92</td>
<td>521.55</td>
</tr>
<tr>
<td>velocity / m/s</td>
<td>1.508</td>
<td>1.065</td>
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</table>

In Fig. 2 (section 2), the temperature in the broken loop and in the intact loops is shown. To compare the mixing calculated by CFD and by the analytical model it was necessary to have more or less steady state conditions. This is the case at about 150s after start of the MSLB-transient. The temperature and flow field in the reactor vessel show no significant changes in time.

Fig. 13 Velocity distribution at the core inlet of the VVER-440
The temperature distributions from the analytical model and the CFX calculations are shown in Fig. 14 and Fig. 15. Due to the potential flow approach in the analytical mixing model, the temperature distribution at the core inlet obtained from this model is similar to the temperature distribution in the case of nominal conditions. From Fig. 13 can be seen, that there is a minimum of the coolant velocity below the inlet nozzle of the overcooled loop with higher mass flow rate and there are two maxima at both sides of this minimum. This effect indicates the existence of velocity components in azimuthal direction around the core baffle. The division of the flow into two parts moving around the baffle leads to temperature distribution at the end of the downcomer, which has two minima along the perimeter instead of one obtained strongly below the nozzle from the analytical model. In radial direction, the zone of lower temperature is situated closer to the periphery (Fig. 14).

**Fig. 14** Temperature Distribution at the Core Inlet

**Fig. 15** Temperature Distribution at the Core Inlet calculated with the Analytical Model and CFD Simulations (Overcooled Loop at the Arrow Position)
Although mixing is considerably enhanced in the lower plenum and the control rod chamber above the sieve plate, the temperature distribution stretched in azimuthal direction can still be seen at the core inlet (Fig. 15).

The influence of the different temperature distributions on the reactor safety which result from the potential flow mixing model and the CFD simulation is assessed in the next section.

5. USE OF THE CFX-RESULTS FOR THE MSLB

As described in section 4, the CFX-calculation provides a temperature distribution at the core inlet different from the distribution calculated by means of the analytical mixing model. The question is, how to assess the consequences of the different temperature distributions on the reactor safety. Because at present a direct coupling of the codes is impossible, as pointed out in section 1, another way for the use of the results of the CFX-calculation should be found. The stand-alone version of the code DYN3D allows stationary calculations with any given temperature distribution at the core inlet. So, it was decided, to carry out two stationary calculations. The first calculation was made with the temperature distribution calculated by the analytical mixing model. In the second calculation the temperature distribution provided by the CFX-calculation was used. The temperature distributions are based on the cold leg parameter at t=150s. This is near to the time of recriticality in the calculation with the coupled code DYN3D/ATHLET using the analytical mixing model (section 2). The comparison of the two calculations shows, that the positive static reactivity insertion in the calculation with the temperature distribution from the CFX-calculation is about 800pcm lower than in the calculation with the analytical mixing model. This value can be used as a qualitative assessment of the reactor behaviour during the MSLB: The consequences would be milder. But this is not an answer to the question: Can the recriticality be avoided during the transient? It should be kept in mind, that the CFX-calculation is a stationary calculation for one certain point in time. Only a direct coupling during the whole transient of all codes can model all effects in a right way. This must include the coolant mixing in the upper plenum of the RPV, too.

6. CONCLUSIONS

In this paper a MSLB analysis for the VVER-440/V-230 is presented. Different options for coolant mixing conditions inside the RPV were applied. The results show the importance of these conditions. The conservatism of the approach of no mixing inside the RPV was reduced by using an analytical mixing model, developed for the downcomer and the lower plenum of the VVER-440 reactors. The maximum fission power reached after recriticality is about three times smaller.

The stationary 3D-flow field in the downcomer and the lower plenum of the VVER-440/V-230 was calculated using the CFD-code CFX-4. The comparison with the analytical mixing model shows a good agreement for near-operational conditions. For MSLB conditions, the provided temperature distributions at the core inlet are different.
The stationary temperature distribution of the CFX-calculation was used to assess the reactivity insertion into the reactor. It was shown, that the conservatism can be further reduced.

In future, the development of a mixing model based on transient CFX-calculations is planned.

**NOMENCLATURE**

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<td>m/s</td>
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