ANALYSIS OF THE OECD MSLB BENCHMARK USING THE COUPLED CODE DYN3D/ATHLET

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1. Introduction

3D neutron kinetics core models have been coupled to advanced thermohydraulics system codes. These coupled codes can be used for the analysis of the whole reactor system. A benchmark task to compare different coupled codes for reactors with quadratic fuel assembly cross section geometry was defined by the Pennsylvania State University (PSU) under the auspices of the OECD/NEA [1]. The reference problem chosen for this benchmark is a main steam line break (MSLB) at end of cycle (EOC) and full power conditions. It is based on real plant design and operational data for the TMI-1 nuclear power plant. TMI-1 is a two-loop B&W designed plant with once-through-steamgenerators.

For the calculation of this benchmark, performed in the Institute of Safety Research of the Forschungszentrum Rossendorf the 3D neutron kinetics core model DYN3D [2] coupled to the thermohydraulics system code ATHLET [3] was used. The coupling was accomplished in an external way, where the core is completely modeled by DYN3D including the thermohydraulics [4].

The core was modeled with one node per assembly in radial and 28 layers in axial direction. The cross section library was provided by the PSU. This library covers only the moderator density range from 641.4 kg/m^3 up to 810.1 kg/m^3. In case of exceeding this range which occurs during the transient, the boundary values have to be taken. In spite of the calculations, submitted for code comparison within the benchmark work, where this approach was realized, in the calculations presented here an extrapolation of the cross section data beyond the highest density value is applied. It allows a more realistic comparison with the point kinetics analysis being a part of this benchmark where the feedback is described by reactivity coefficients.

For the modeling of the remaining plant components, an exisiting ATHLET input data deck for the TMI-2 plant was modified and extended. The extension concerns especially the secondary side, where the two main steam lines of the steamgenerator (SG) affected by the leak were modeled in detail.

The degree of mixing of coolant from different loops inside the reactor pressure vessel (RPV) is considered by a mixing ratio, which is based on mixing tests carried out at a similar power plant. These tests define the degree of mixing that occurs within the RPV as a ratio of the difference in hot leg temperatures to the difference in cold leg temperatures:

$$\text{Ratio} = (T_{hot}(\text{intact})-T_{hot}(\text{broken}))/(T_{cold}(\text{intact})-T_{cold}(\text{broken}))$$

The ratio was chosen to be equal to 0.5. 20 % of the heat is exchanged in the lower plenum and 80 % in the upper plenum.

The application of this mixing formula requires a full splitting of the two loops of the reactor not only outside but also inside the RPV. In the upper head, cross connections between the two loops were introduced to keep the loop pressures in balance. The desired amount of flow mixing is obtained by energy exchange between the two control volumes in the lower and in the upper plenum, respectively. As a more detailed mixing model does not exist it is assumed, that one half of the fuel assemblies is supplied by the coolant with the lower temperature (mainly from the broken loop) and the other one by the coolant with the higher temperature.

2. Accident progression and results

The transient is initiated by a sudden rupture of one main steam line upstream of the main steam isolation valve. Therefore, the affected SG cannot be isolated from the leak and so the rapid pressure decrease leads to an increasing heat transfer to the secondary side and to an overcooling of the corresponding part of the primary circuit. Due to the strong negative moderator temperature coefficient, the overcooling causes a core power rise. The high neutron flux scram set point of 114% is reached 4.99 s after the leak opening. An asymmetrical stuck rod is assumed for the scram. After the scram, the overcooling continues.

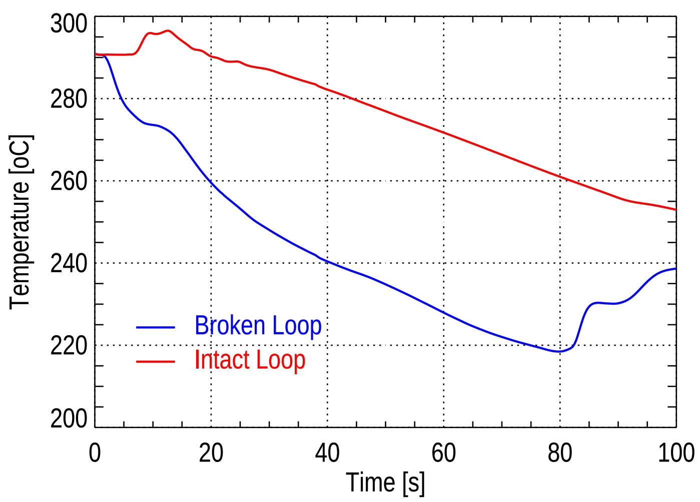

Fig. 1: Cold leg temperatures in the basic calculation

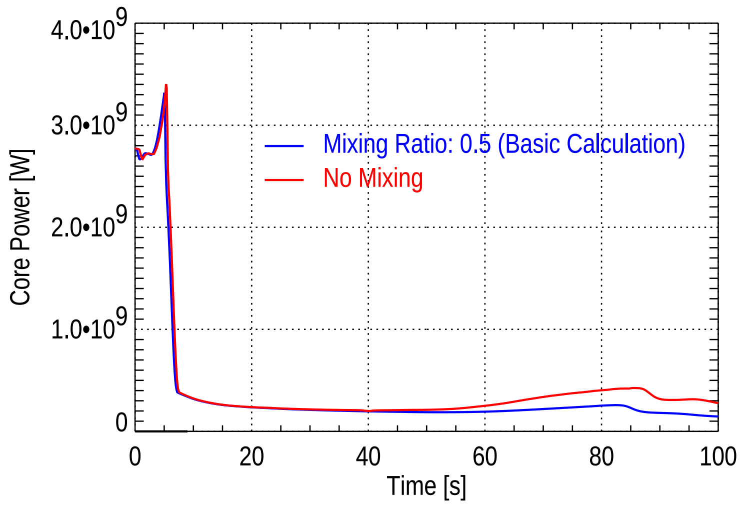

Fig. 2: Core power in the different DYN3D/ATHLET calculations

Fig. 1 shows the temperature in the cold leg of both loops. The temperature difference between the two cold legs rises up to 40 K. In the intact loop, a reverse heat transfer from the secondary to the primary circuit occurs. This hotter coolant is than partly mixed (according to the mixing ratio) with the coolant of the loop with the affected SG. Together with the decay heat, this leads to a rise of the temperature difference to about 18 K between cold and hot leg in this loop. The overcooling in the SG of this loop is higher than the sum of the decay heat and the reversal heat transfer. Therefore the core inlet temperature for both sectors decreases continuously. This overcooling leads to a compensation of the negative reactivity inserted by the scram. From t = 50 s on, the reactor power begins to rise (basic calculation in fig. 2). The reactor returned to power. At about t = 80 s, the affected SG becomes emptied. The heat transfer and the corresponding overcooling are suddenly stopped. The power rise is stopped, too. The maximum power reached during this second power rise corresponds to about 9 % of the nominal power.

3. Influence of the coolant mixing on the core behaviour

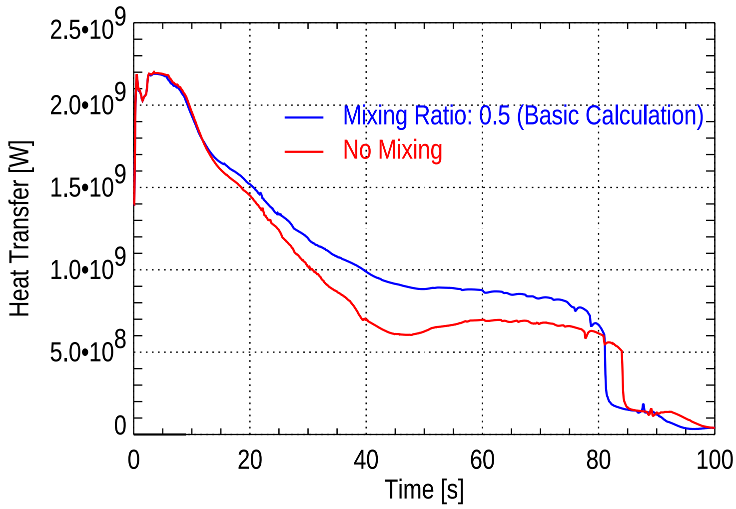

Fig. 3: Heat transfer in the affected SG in the different calculations

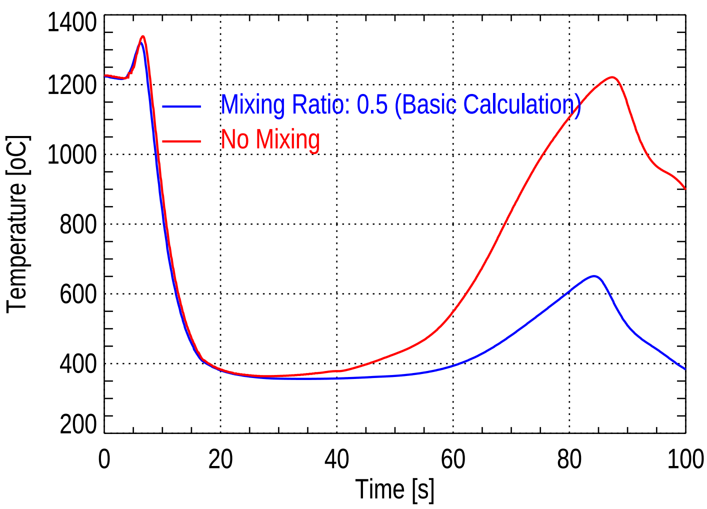

Fig. 4: Maximum fuel temperature in the different DYN3D/ATHLET calculations

To assess the influence of the mixing, sensitivity studies were carried out, where the mixing inside the RPV was inhibited at all. In the absence of mixing, the temperature difference between cold and hot leg of the affected loop is only caused by the decay heat. Therefore, the heat transfer to the secondary side in the affected loop is smaller than in the basic calculation (fig. 3). That means, that the global overcooling of the reactor is smaller, too! On the other hand, the coolant of the affected loop enters only the corresponding half of the core, where the stuck rod is located. This leads to a higher core power rise (about 15 %) than in the basic calculation (fig. 2). Although the heat transfer in the affected SG is lower than in the basic calculation, the coolant at the entry of the affected core half has a lower temperature due to the exclusion of mixing. This is the reason for the higher energy release in the core, especially in the affected region. It can be seen in the maximum fuel temperature which reached a value of about 1200 ^{o}C. This is nearly the same temperature as in the steady state (fig. 4). In the basic calculation, only a value of about 650 ^{o}C was reached.

The main goal of the OECD MSLB Benchmark is the validation of coupled 3D neutron kinetics/ thermohydraulics codes. However in the first phase of the benchmark, a point kinetics calculation had to be carried out using coefficients derived from 3D nodal core calculations with the same cross section data, provided for the calculation presented above. Special attention was

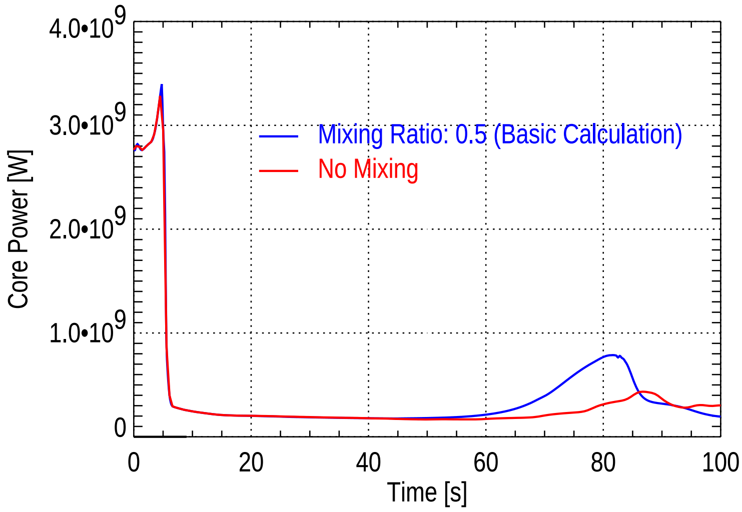

Fig. 5: Core Power in the different point kinetics calculations

paid to make both calculations comparable. The thermohydraulics parameter in the coupled and the point kinetics calculations behave very similar, but the power in the point kinetics calculation (28% of the nominal power) is about three time higher than that of the coupled calculation (fig. 5). The maximum fuel temperature reached during the point kinetics calculation is less than 400 °C. This is mainly due to the fact, that the asymmetric power distribution in the core is not considered in this calculation. The comparison of these two calculations demonstrates the superiority of the coupled 3D neutron kinetics/thermohydraulics plant model. The variation of the mixing in a sensitivity calculation with the point kinetics model shows a lower power peak (fig. 5). This is due to the fact, that the core power is calculated using only the core averaged moderator temperature value. The spatial distribution of the core inlet temperature has no influence on the feedback. Therefore, the smaller heat transfer in the calculation without mixing is responsible for the lower power peak.

As can be seen, the changes of the coolant mixing conditions inside the RPV have an opposite effect on the power behaviour in the coupled 3D neutron kinetics/thermohydraulics and the point kinetics calculations.

References

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