Sensitivity Analyses of the Peach Bottom Turbine Trip 2 Experiment

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ABSTRACT

In the light of the sustained development in computer technology, the possibilities for code calculations in predicting more realistic transient scenarios in nuclear power plants have been enlarged substantially. Therefore, it becomes feasible to perform ‘Best-estimate’ simulations through the incorporation of three-dimensional modeling of reactor core into system codes. This method is particularly suited for complex transients that involve strong feedback effects between thermal-hydraulics and kinetics as well as to transient involving local asymmetric effects.

The Peach bottom turbine trip test is characterized by a prompt core power excursion followed by a self limiting power behavior. To emphasize and understand the feedback mechanisms involved during this transient, a series of sensitivity analyses were carried out. This should allow the characterization of discrepancies between measured and calculated trends and assess the impact of the thermal-hydraulic and kinetic response of the used models. On the whole, the data comparison revealed a close dependency of the power excursion with the core feedback mechanisms. Thus for a better best estimate simulation of the transient, both of the thermal-hydraulic and the kinetic models should be made more accurate.

1 INTRODUCTION

Nowadays, it becomes feasible to perform ‘Best-estimate’ safety analysis simulations through the incorporation of three-dimensional modeling of reactor core into system codes. This method is particularly suited for complex transients that involve strong feedback effects between thermal-hydraulics and kinetics. In the current framework, the Peach Bottom Turbine Trip (PB-TT) [1] transient test number 2 is selected owing to fact that it involves a rapid positive reactivity addition resulting from core-plant interactions. The test is characterized by a prompt excursion. After a while due to prompt compensating Doppler effect as well as the contribution of the moderator gamma heating effect the power trend exhibits a deceleration and a self-limiting behavior. Shortly after, the delayed feedback due to the release of the excursion energy into the coolant and the control rods insertion introduces larger negative reactivity and accordingly the power course is stopped. A numerical simulation of such mechanisms was performed using the coupled thermal-hydraulic system code RELAP5/Mod3.3 [2] and the 3D neutronics code PARCS/2.3 [3]. A sensitivity study have been carried out in order to identify the most influent parameters that govern the transient behavior. The considered cases showed that the self-limiting power amplitude as predicted by the coupled code calculation is due to delayed feedback mechanisms whereas the experimental data shows that the power quenching before the Scram is governed by the prompt feedback effects.
2 TEST DESCRIPTION

The experiment was carried out by manually (tripping the turbine) closing the Turbine Stop Valve (TSV) at an operating prescribed power level equal to 61.65% of its nominal value [4]. As a result, a pressure wave is generated in the main steam piping and propagates at sound velocity with relatively little attenuation into the reactor core. The pressure wave reaches the core zone following two different paths: through the steam separator filled with a mixture of water and steam and through the vessel downcomer filled with water. This double effect results in dramatic changes of the core void inventory. The inherent feedback of the core makes the reactor power to exhibit a rapid exponential rise. Few milliseconds after the TSV closure, the Bypass Valve (BPV) is opened automatically to reduce the pressure rise in the steam line. The TSV signal that activates the reactor scram initiation was intentionally delayed to allow a relative neutron flux effect to take place in the core. The scram signal is set to 95% of the nominal power with a delay time of 0.12 s.

3 CALCULATION TOOLS

In the current framework a parallel processing for coupling 3-D kinetics PARCS code with RELAP5 system code is used. This allows the codes to be run separately and exchange data during the calculation. The coupling process consists in performing calculations to evaluate the thermal-hydraulic parameters evolution using the REALP5 modules and the kinetic solution is obtained using the PARCS solver. The PARCS code reads the fuel and coolant temperature, coolant density from the RELAP5 interface to estimate the feedbacks that affect the instantaneous neutron flux value. In the same way the RELAP5 code performs its calculations using as input the time-space dependent core power from the PARCS interface.

4 SENSITIVITY ANALYSIS

In an attempt to qualify and identify the degree of dependence of the key transient parameters that govern the transient course, and the discrepancies between the coupled code calculations and the experimental results, a series of sensitivity analyses have been carried out. These cases emphasize only the code models response since it was not possible in this framework to generate other cross section tables rather than the used one or to modify the thermal-hydraulic closure relations. Since the main difference between the experiment and the coupled code calculations is about the self-limiting power behavior [5] prediction, the base case for this series of analyses is a Turbine Trip without Scram. Through the considered cases, the positive and negative prompt and delayed feedback responses are assessed.

Table 1: Sensitive cases and their relative investigated feedback

<table>
<thead>
<tr>
<th>Reactivity Evolution Phases</th>
<th>Case Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>Prompt positive reactivity insertion</td>
<td>Case-8, Case-9</td>
</tr>
<tr>
<td>Prompt negative reactivity Doppler Feedback</td>
<td>Case-1, Case-2</td>
</tr>
<tr>
<td>Prompt negative reactivity Moderator gamma heating Feedback</td>
<td>Case-5, Case-6, Case-7</td>
</tr>
<tr>
<td>Delayed Negative reactivity Moderator Feedback</td>
<td>Case-3, Case-4</td>
</tr>
</tbody>
</table>
In the following, results relative to power self-limiting course for all the considered cases are commented according to the nature of the investigated feedback. The main results of the sensitive study are outlined in Table 2, whereas the power and reactivity evolution are shown in Fig. 1 and 2, respectively.
Case 1: For the first sensitive case, the power behaviour is shown in Fig. 1. The power peak is slightly lower than the base case (370% of nominal power) due to a weaker Doppler feedback effect. In this case, the delayed feedback effect occurs slightly sooner due to smaller heat transfer core constant. This explains the time of the power excursion peak point which occurs at 0.825 s.

Case 2: The effect of reduced gap conductivity on the power course is a self-limiting power peak lower than the base case (330 % of its nominal value). This lower power peak is due to higher (prompt) fuel Doppler temperature feedback effect. In fact, as can be seen in Table 2, the amount of inserted reactivity is lower than the base case. However the self-limiting behaviour occurs at the same time as the base case.

Case 3: By considering a larger fuel heat capacity, the peak power reaches (444% of its nominal value) since more heat is accumulated into the fuel. This effect delays the release of the power burst in the coolant and consequently void reformation is also delayed. However, the self-limiting peak power time occurrence, as outlined in Table 2, is delayed in comparison with the base case by only 0.01 s.

Case 4: The effect of reduced fuel heat capacity on the power transient course is a power peak of 270% of its nominal value. This reduced value is due a smaller value of the core thermal constant and consequently faster transfer of the heat to the coolant. In this case, the self-limiting peak power time occurrence is anticipated by 0.02s.

Case 5: The direct gamma heating of the moderator is an important prompt feedback effect. The calculations results show that the direct gamma heating in the coolant inside the fuel element is surprisingly insignificant even though stronger feedback effect is involved. Indeed, the total prompt effect, due to reduced Doppler and higher gamma heating, is practically unchanged. The self-limiting peak power of about 393% is again due to the delayed feedback effect.

Case 6: In an attempt to emphasize the effect of the prompt gamma heating of the moderator, it is assumed in this case that all the heat is generated into the fuel and no prompt coolant feedback is considered. The power course is more or less like the precedent cases with a peak slightly lower than the base case (372% of its nominal value) due to stronger Doppler effect. Any way the self-limiting behaviour remain unchanged also in this case and occurs at 0.835s.

Case 7: This case is interesting since it does not consider the direct gamma heating of the coolant in the core coolant bypass; the total power is released in the coolant contained inside the fuel assembly. The prompt coolant feedback is located entirely in the fuel assembly. This explains the lower value of the power peak (374% of its nominal value). It should be noticed that even in this case the power self-limiting take place at the same time as the precedent cases and the system response is governed by the delayed feedback effects.

Case 8: A more realistic 3 D power distribution is simulated using a 77 channels model instead of 33. This configuration gives a more symmetric steady state power (as shown in Fig. 3) and void distribution. The power course trend did not change significantly; a little bit higher peak power is observed (403 % of its nominal value). A higher reactivity insertion rate is observed due to higher pressure wave amplitude (more void collapsing). But on the whole the self limiting behavior occurs at the same time as in the other cases.

Case 9: In this case, only one channel is involved in the thermal-hydraulic calculations. The steady state 2D mean power distribution, as shown in Fig. 4, is not symmetric as in the former case (77 channels). In this case, due to a uniform core void distribution, the rate of void collapsing which is lower than the base case and consequently lower positive reactivity is inserted into the system. This leads to a power self-limiting peak of (365% of its nominal value). The power peak occurs approximately at the same time as in the other cases.
Figure 3: Steady state mean core power distribution using 77 channels nodalisation

Figure 4: Steady state mean core power distribution using single channel model
According to the main results of the sensitive study outlined in Table 2 the following conclusion can be derived:

- The global effect of the delayed negative feedback time response, in all the considered case, is constant and equal to 0.55 s (=0.83-0.28). The experimental value of this constant should be of the same order of magnitude as the calculated one. Then it is concluded that unlike the experiment, where the self-limiting behavior is governed by the prompt feedback response, the coupled code calculation predicts a power self-limiting due mainly to delayed moderator feedback contribution (after the release of the excursion energy into the coolant).
- The effect of the gamma heating is overshadowed by a high value of the calculated void constant time generation or underestimated feedback coefficient since no significant effect is observed when varying this parameter.

Table 2: Considered cases for the sensitivity analyses

<table>
<thead>
<tr>
<th>Case Number</th>
<th>Altered Problem Conditions</th>
<th>ATWS</th>
<th>Amplitude of Pressure wave (MPa)</th>
<th>Relative Peak Power (%)</th>
<th>Maximal inserted Reactivity ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base Case</td>
<td>-</td>
<td>yes</td>
<td>0.298 (0.785)</td>
<td>392.8 (0.830)</td>
<td>0.824 (0.785)</td>
</tr>
<tr>
<td>Case-1</td>
<td>Gap conductivity raised by 20%</td>
<td>yes</td>
<td>0.299 (0.79)</td>
<td>370.2 (0.825)</td>
<td>0.814 (0.780)</td>
</tr>
<tr>
<td>Case-2</td>
<td>Gap conductivity reduced by 20%</td>
<td>yes</td>
<td>0.276 (0.77)</td>
<td>330.0 (0.830)</td>
<td>0.788 (0.785)</td>
</tr>
<tr>
<td>Case-3</td>
<td>Fuel heat capacity raised by 20%</td>
<td>yes</td>
<td>0.297 (0.785)</td>
<td>444.4 (0.835)</td>
<td>0.843 (0.785)</td>
</tr>
<tr>
<td>Case-4</td>
<td>Fuel heat capacity reduced by 20%</td>
<td>yes</td>
<td>0.277 (0.775)</td>
<td>270.36 (0.810)</td>
<td>0.747 (0.770)</td>
</tr>
<tr>
<td>Case-5</td>
<td>4% of Direct gamma heating</td>
<td>yes</td>
<td>0.298 (0.785)</td>
<td>393.1 (0.830)</td>
<td>0.824 (0.785)</td>
</tr>
<tr>
<td>Case-6</td>
<td>No Direct gamma heating</td>
<td>yes</td>
<td>0.293 (0.785)</td>
<td>372.6 (0.835)</td>
<td>0.814 (0.79)</td>
</tr>
<tr>
<td>Case-7</td>
<td>No Bypass Direct gamma heating</td>
<td>yes</td>
<td>0.294 (0.785)</td>
<td>374.4 (0.835)</td>
<td>0.815 (0.785)</td>
</tr>
<tr>
<td>Case-8</td>
<td>77 Channels</td>
<td>yes</td>
<td>0.301 (0.785)</td>
<td>403.6 (0.835)</td>
<td>0.828 (0.790)</td>
</tr>
<tr>
<td>Case-9</td>
<td>1 Channel</td>
<td>yes</td>
<td>0.298 (0.785)</td>
<td>365.83 (0.835)</td>
<td>0.812 (0.795)</td>
</tr>
</tbody>
</table>

* Quantities between brackets indicate the time occurrence of the corresponding event.
5 CONCLUSION

The global aim of the present work is to assess the coupled code calculations in simulating realistically complex transient in Nuclear Power Plants. In this framework, the Peach Bottom 2 Turbine Trip test has been considered. The test is characterized by a rapid positive reactivity addition into the core caused by sudden core pressurization, followed by a self-limiting power course due to compensated inherent reactivity mechanisms. In order to simulate and identify the dominant parameters that govern the dynamic behavior of the test, the coupling code technique using the system code RELAP5/mod3.3 and the 3D neutronic code PARCS were considered. The Turbine Trip test was revealed to be very sensitive to the feedback modeling and the impact of the steam bypass opening on the pressure wave amplitude during the transient. In fact, small errors in estimating the dynamic evolution of a predominant parameter result in a ‘coarse’ prediction of the phenomenon. For this purpose, sensitivity studies have been carried out in order to identify the most influent parameters that govern the transient behavior. The considered cases revealed that:

- The self-limiting power amplitude as predicted by the coupled code calculation is due to delayed feedback mechanisms since the global system negative feedback time response is more or less constant. On the other hand, the experimental data shows that the power excursion and quenching is governed by the prompt void feedback effects.
- The large calculated void formation and collapsing time response or the feedback coefficient calculated form the cross section lookup table fail to reproduce the experimental power excursion and quenching response.

Thus, to better match the experiment phenomenology, improvements of the used analytical approach should take into account the following items:

- A more refined cross section table should be studied to evaluate the impact of this modeling parameter.
- A better modeling of the prompt void feedback as well as the impact of the valve opening and closure on the rapid variation of local parameters should be taken into account in the RELAP5 constitutive models.

On the whole, more efforts and further experimental data should be investigated including the other two turbine trip tests in order to identify the inaccuracy and limitations of the coupled code calculations.

REFERENCES