NEUTRONIC AND THERMAL-HYDRAULIC MODELLING OF HIGH PERFORMANCE LIGHT WATER REACTOR

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Introduction

In EU, the use of supercritical-pressure water as coolant in a light water reactor is studied under the name High Performance Light Water Reactor (HPLWR). During the “HPLWR2” project, the technological feasibility of the concept is examined using various analysis methods.

In a HPLWR core the temperature of the coolant increases from 280 ºC to 500 ºC. Consequently, the large decrease of coolant density induces a strong coupling between neutronics and thermal-hydraulics. Because of this, coupled codes are required for conducting analysis of transients with large spatial variations in thermal-hydraulic or neutronic properties. In addition, the three pass core design can only be modelled using a three-dimensional code for core calculation. At the Technical Research Centre of Finland (VTT), an advanced three dimensional nodal code TRAB-3D was selected for calculating neutronics. It is internally coupled to a system code SMABRE for thermal-hydraulics. This paper outlines the modifications made on SMABRE to extend its functionality to supercritical pressures and presents the current state of the HPLWR model for TRAB-3D/SMABRE.

Parametrized two-group cross-sections for a HPLWR fuel assembly generated with MULTICELL deterministic transport code and a subroutine for handling the cross-sections was received from KFKI Atomic Energy Research Institute [1]. Group constants for HPLWR were also generated using a new Monte Carlo code, PSG, developed at VTT. Comparison of the group constants is presented together with multiplication factors calculated with MCNP4C.

Codes and models

TRAB-3D [2] is a stand-alone core dynamics code for a square geometry, which is actively applied to transient and accident analysis of BWRs and PWRs at VTT. The code has been validated against international benchmarks and actual measured data from real plant transients. TRAB-3D includes 3D neutronics and thermal-hydraulics models for core calculation as well as a 1D model for BRW's pressure vessel and cycle. The parametrized cross-sections from KFKI and the subroutine for handling them were implemented to TRAB-3D for modelling HPLWR.

1D thermal-hydraulic system code, SMABRE [3], contains a five-equation two-phase thermal-hydraulic model, using the drift-flux model for phase separation. SMABRE has a point kinetics model for independent calculation. The functionality of SMABRE was extended to supercritical pressures by creating a fictional two-phase zone to the supercritical pressure regime. This 200 kJ/kg broad region is located along the pseudo-critical line and void fraction changes from zero to one as increasing water temperature passes the region. New material functions have been generated covering pressures from 0.001 MPa to 100 MPa.

There are two options for the coupling of TRAB-3D/SMABRE, a parallel coupling scheme and an internal coupling scheme. The internal coupling scheme increases the flexibility of the code compared to the parallel coupling scheme and allows for example reversed flow in the core. With the internal coupling scheme, TRAB-3D calculates only neutronics and SMABRE handles the thermal-hydraulic calculation of the whole cooling circuit including core. Heat transfer and fuel temperature feedback for neutronics can be optionally selected to be based on either TRAB-3D or SMABRE. TRAB-3D and SMABRE require separate inputs.

Input models were made for TRAB-3D and SMABRE according to the latest design of HPLWR. The core model for TRAB-3D includes 1404 fuel elements (one per fuel assembly) and 156 flow channels (one per fuel assembly cluster). In addition, one moderator channel is modelled for each cluster. Feedback phenomena from moderator water are not taken into account at this stage and therefore a constant density value is set for the moderator. The plant model for SMABRE includes pressure vessel internals and an approximate model of the steam cycle. The model consists of 101 nodes, 104 junctions and 152 heat slabs. The nodalization is shown in Figure 1. The core is divided into three radial sections according to the three pass core design and it is modelled with three core channels each attached to one moderator channel. Axially the core is divided into 20 nodes. The gap water is modelled with one node. With the internal coupling the SMABRE code nodalization is divided to match the radial nodalization of TRAB-3D flow channels, as depicted in Figure 2. The moderator channels are also divided.

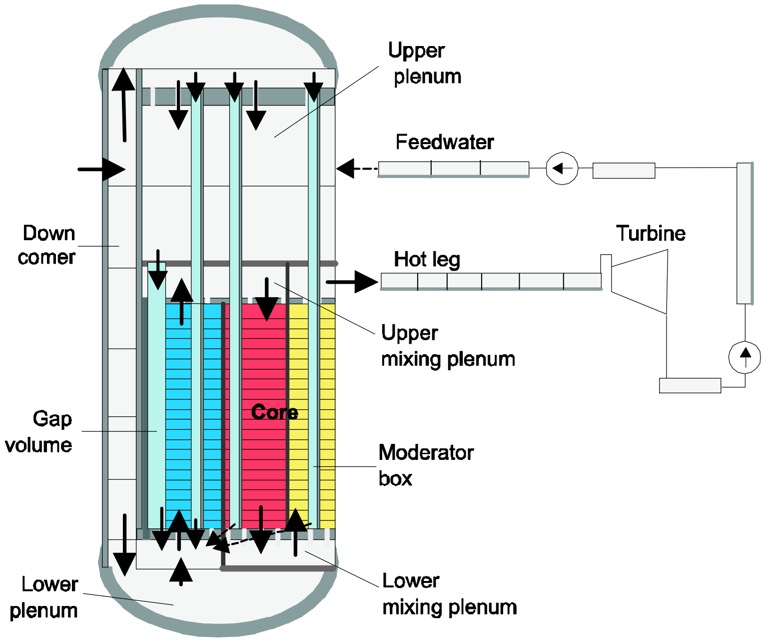

Figure 1. Nodalization of the HPLWR plant model for SMABRE.

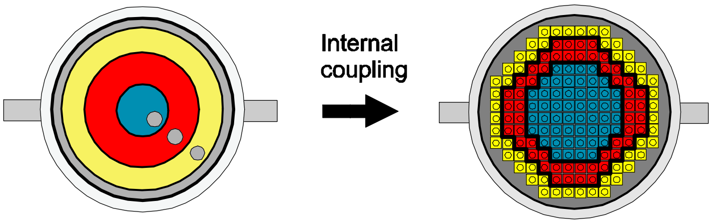

Figure 2. Radial nodalization of the HPLWR core channels in independent SMABRE calculations and with internal coupling to TRAB-3D.

PSG (Probabilistic Scattering Game) [4] is a new Monte Carlo neutron transport code developed especially for reactor physics calculations, which makes it run faster than general-purpose Monte Carlo transport codes. PSG is capable of generating all group constants required for few-group nodal simulator calculations. PSG has been validated against MCNP4C and CASMO-4E codes by comparing LWR lattice calculations. At the moment, PSG is not able to perform burn-up calculations, which restricts its applications. This together with a Monte Carlo specific leakage model, are the most important areas of development for PSG.

An input model was made for PSG according to the latest HPLWR core design. The input model is based on a MCNP input received from KFKI-AEKI. The rounded corners and material details of the moderator and assembly box walls were handled by adjusting the dimensions and material composition of angular boxes. Although this kind of simplification of the geometry is not necessary for PSG due to predefined assembly geometry description, it eases the comparison to MCNP calculations. For the fuel rods, 6 % basic and 5 % corner pin enrichment was used.

Results

The Edwards-O'Brien [5] experiments compose of fluid depressurization experiments on a horizontal pipe. In the modified tests the blowdown of a 4.096 m long pipe with an inside diameter of 0.0762 m is studied. A break, with an area 87% of the cross-section of the pipe, opens at 0 s and the pressure at the break decreases from the initial value, 25.0 MPa, to 0.1 MPa in 0.001 s. Three cases are defined with initial temperatures of 580 K (test01), 700 K (test02) and 780 K (test03). The SMABRE model for the test cases consists of 20 nodes of equal size. The pressures and void fractions calculated for the three supercritical are shown in Figure 3. The results are from the so called GS-5 point which is located in the middle of the eight node from the closed end of the pipe.

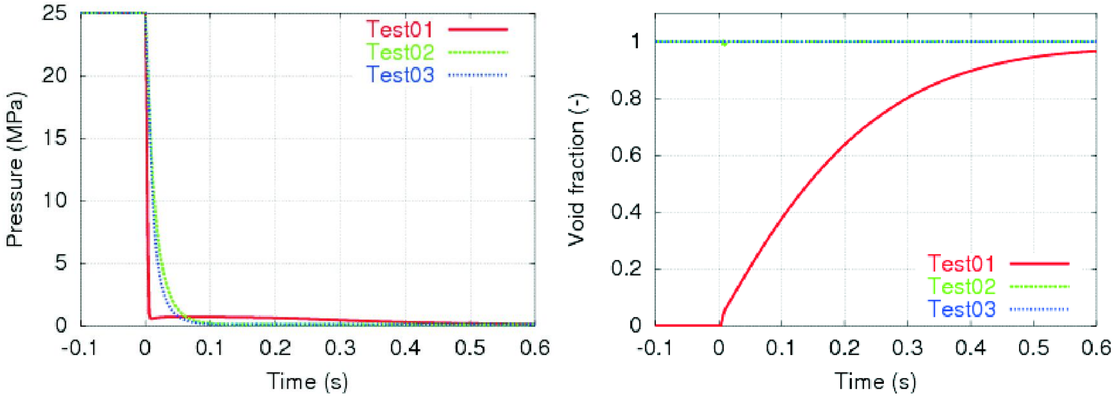

Figure 3. Pressure and void fraction in the Edwards-O'Brien test cases calculated with SMABRE.

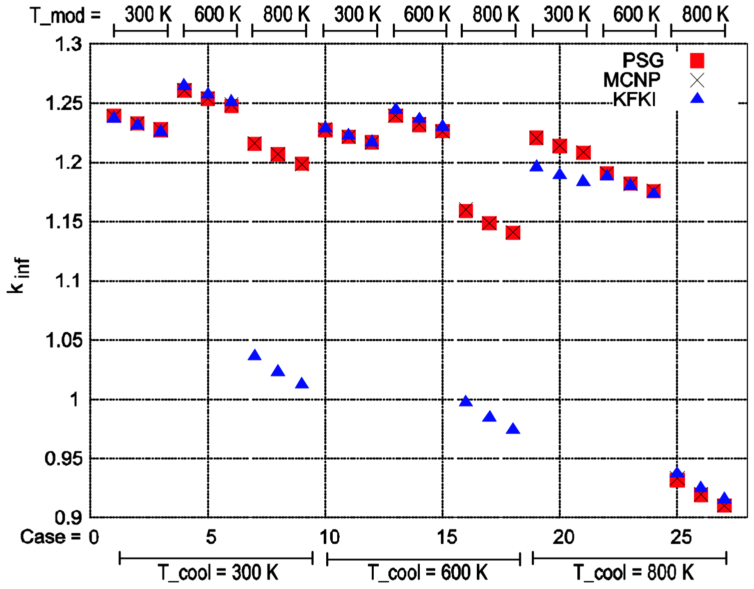

Figure 4. Multiplication factors calculated with PSG and MCNP4C compared to values from the KFKI parametrized cross-sections.

Table 1. Comparison of two-group constants for case 14.

Parameter	PSG	KFKI	Difference	Rel.diff. (%)
k_{inf}	1.2319 (0.00029)	1.2363	0.0044	0.357
$\Sigma_{a,1}$	0.008734 (0.00062)	0.008592	0.0001427	1.634
$\Sigma_{a,2}$	0.09335 (0.00053)	0.09001	0.003342	3.580
$\nu\Sigma_{f,1}$	0.007146 (0.00069)	0.007126	2.031E-05	0.284
$\nu\Sigma_{f,2}$	0.1365 (0.00073)	0.1312	0.005365	3.929
$\Sigma_{r,1\rightarrow 2}$	0.01587 (0.00050)	0.01582	4.82E-05	0.304
D_1	1.4508 (0.00086)	1.4009	0.04988	3.438
D_2	0.3628 (0.00106)	0.3427	0.02001	5.519
$1/v_1$	5.819E-08 (0.00059)	5.250E-08	5.691E-09	9.781
$1/v_2$	2.347E-06 (0.00021)	2.359E-06	1.247E-08	0.531

27 cases were defined for the cross-section calculations with varying coolant temperature (300 K, 600 K, 800 K), moderator temperature (300 K, 600 K, 800 K) and fuel temperature (600 K, 900 K, 1200 K). The temperature of the moderator in moderator boxes and in the gaps between fuel assemblies is kept the same. Reference values for group constants were generated using the parameterized cross-sections from KFKI.

Multiplication factors were also calculated with MCNP4C. 100 inactive and 500 active cycles of 5,000 source neutrons were used in the PSG and MCNP calculations. Multiplication factors calculated with PSG compared to values from MCNP and the parameterized cross-sections are shown in Figure 4. For each combination of coolant and moderator temperatures, the fuel temperature is given values 600K, 900K and 1200K, in this order.

Case No. 14 best represents the nominal conditions in a HPLWR core with coolant temperature 600 K, moderator temperature 600 K and fuel temperature 900 K. Two-group constants generated with PSG and the KFKI cross-section library are shown in Table 1 together with the absolute and relative differences of the results.

Discussion

Calculation of the Edwards-O'Brien blowdown test shows that SMABRE is capable of modelling the transition from supercritical to subcritical pressures. The results can be enhanced by refining of the flashing correlation and the handling of the convection term of moment in SMABRE.

A preliminary thermal-hydraulic steady-state for the HPLWR plant model has been achieved with SMABRE and it will be tuned in the near future. The next step is to make the final enhancements for the internal coupling of TRAB-3D/SMABRE before starting the coupled calculations. During the "HPLWR2" project, the final goal is to perform control rod ejection analysis on HPLWR using TRAB-3D/SMABRE.

The comparison of the multiplication factors shows satisfying consistency. Differences in the multiplication factor calculated with PSG and MCNP vary from 0.0% (case 11) to 0.16% (case 25) with an average of 0.04%. The differences are within the standard deviations. Some of the cases are not physically realistic in the HPLWR core. In cases 7-8 and 16-18 the moderator temperature is higher than the coolant temperature. In cases 19-21 the moderator is 500 K cooler than the coolant. Excluding these cases which are clearly out of the range of validity for the KFKI parametrized cross-sections, the differences between PSG and KFKI results vary from 0.004% (case 12) to 0.59% (case 26), with an average of 0.27%.

Comparison of the two-group constants calculated with PSG and the parameterized cross-sections shows that the differences are mostly the order of a few per cent, which is a typical result when comparing a Monte Carlo code and a deterministic code.

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