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Neutronic and Thermal-hydraulic Modelling of High Performance Light Water Reactor

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ABSTRACT

High Performance Light Water Reactor (HPLWR), which is studied in EU project “HPLWR2”, uses water at supercritical pressures as coolant and moderator to achieve higher core outlet temperature and thus higher efficiency compared to present reactors. At VTT Technical Research Centre of Finland, functionality of the thermal-hydraulics in the coupled reactor dynamics code TRAB-3D/SMABRE was extended to supercritical pressures for the analyses of HPLWR. Input models for neutronics and thermal-hydraulics were made for TRAB-3D/SMABRE according to the latest HPLWR design. A preliminary analysis was performed in which the capability of SMABRE in the transition from supercritical pressures to subcritical pressures was demonstrated. Parameterized two-group cross sections for TRAB-3D neutronics were received from Hungarian Academy of Sciences KFKI Atomic Energy Research Institute together with a subroutine for handling them. PSG, a new Monte-Carlo transport code developed at VTT, was also used to generate two-group constants for HPLWR and comparisons were made with the KFKI cross sections and MCNP calculations.

1 INTRODUCTION

Supercritical Water-cooled Reactor (SCWR) [1] is one of the six Generation IV reactor concepts, which are selected by the Generation IV International Forum as the most promising future reactor concepts. There are several projects in progress around the world, for example in Japan, Canada, USA, Korea, Russia and Europe, for designing SCWR and for assessing its technological feasibility.

In SCWR water at supercritical pressures (25 MPa) is used as coolant. Supercritical fluid experiences no phase changes, which enhances safety by for example excluding the possibility of a boiling crisis. At supercritical pressures, water has a significantly high heat capacity along the so called pseudocritical line resulting in lower coolant mass flow rate compared to present light water reactors (LWR). The most important consequence of using supercritical water as coolant is that due to no phase change a high outlet temperature of 500 ºC can be reached, which results in higher efficiency (44 %), and the coolant can be circulated directly to the turbines. Besides, a simplified plant is attained since no steam separators or steam generators are required, lower pump power is necessary and the containment building is more compact. Much of the technology for SCWR has already been proven in LWRs and supercritical water-cooled fossil fired power plants (SCFPP). On the other hand, the coolant experiences very high enthalpy rise (almost 2000 kJ/kg) in the core and strong decrease in density (from 750 kg/m^3 to 80 kg/m^3) when the coolant passes the pseudo-critical point and heats up from 280 ºC to 500 ºC. High temperatures and rapidly varying thermal-hydraulic conditions impose challenges to materials selection and core design.

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). The first project, “HPLWR” [2], was carried out in 2000-2002 and the second project, “HPLWR2” [3], started in 2006 and is planned for four years. During the “HPLWR2” project, the technological feasibility of the concept is examined using various analysis methods and research is done also on materials and heat transfer.

The HPLWR concept is based on studies conducted at the University of Tokyo in the 1990s, resulting in a thermal Supercritical Light Water-cooled Reactor (SCLWR) [4] concept. The current HPLWR design, which was frozen for assessment in September 2007, includes a detailed description of the reactor core and a schematic design for the steam cycle.

Based on studies by Hofmeister et al. [5] the HPLWR core consists of square fuel assemblies with 40 fuel rods, which are collected in fuel clusters of 3x3 fuel assemblies (Fig. 1) in order to ease their handling and to enable adopting the control rod drive technology from pressurized water reactors (PWR). Supercritical water is used also as moderator, which is directed downwards through the core ensuring adequate moderation at the top of the core where density of the coolant is low. The moderator water flows in two kinds of channels: moderator channels in the middle of the fuel assemblies and in the gaps between the assemblies. Studies by Waata et al. [6] showed that in order to restrict the cladding temperature to the allowed 620 ºC, fuel enrichment in the corner rods should be one percentage unit lower than in the other rods. Basic enrichment of 6 % and corner rod enrichment of 5 % has been proposed.

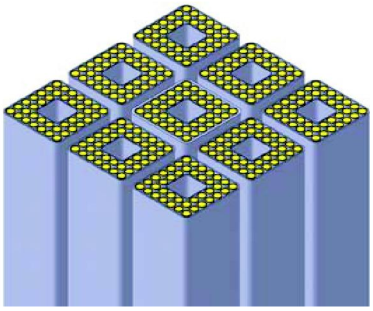

Figure 1. HPLWR fuel assembly cluster with 3x3 fuel assemblies, which consist of 40 fuel rods and a moderator channel in the middle. [7]

To address the challenges brought by the high enthalpy rise of coolant in the core, Schulenberg and Starflinger [8] proposed a three pass core design (Fig. 2) inspired by the three heating stages used in SCFPPs. The coolant is directed through the core three times in radial sections with mixing between to prevent hot spots. The coolant from the downcomer is first mixed in the inner part of the lower mixing chamber with moderator water, which has flown downwards through the core. In the "evaporator" part in the middle of the core coolant is directed upwards through the core. It is mixed in the inner part of the upper mixing chamber before flowing downwards in the "first superheater", mixed again in the outer part of the lower mixing chamber and flown for the third time through the core in the "second superheater". After leaving the core, the coolant is circulated directly to the turbines.

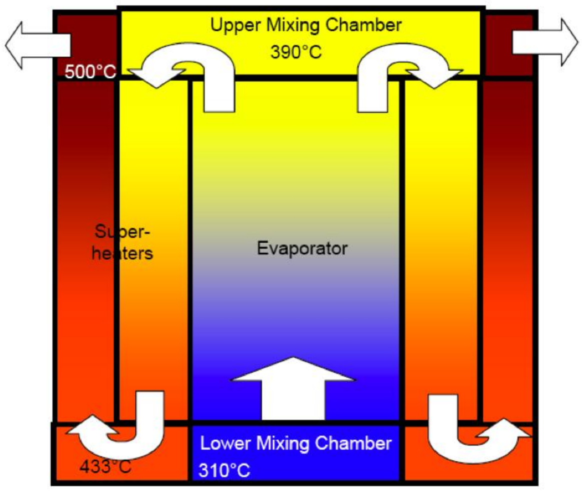

Figure 2. Three pass core design for HPLWR. [8]

In the HPLWR core the large decrease of coolant density induces a strong coupling between neutronics and thermal-hydraulics. Because of this, coupled codes are required for performing 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 neutronics code for core calculations. VTT participates in the "HPLWR2" project by performing coupled transient analysis on HPLWR. At VTT, advanced three dimensional nodal code TRAB-3D [9] was selected for calculating neutronics. It is internally coupled to system code SMABRE [10] 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. Modified Edwards-O'Brien blowdown test cases were calculated to show the capability of SMABRE to handle the transition from supercritical to subcritical pressures.

Parameterized two-group cross sections for a HPLWR fuel assembly and a subroutine for handling the cross sections were received from Hungarian Academy of Sciences KFKI Atomic Energy Research Institute [11]. They are generated with MULTICELL deterministic transport code. The cross sections were implemented in TRAB-3D. For assessing cross sections, group constants for a HPLWR fuel assembly were also generated using a new Monte Carlo code, PSG (Probabilistic Scattering Game) [12], developed at VTT. Comparison of the group constants is presented in this paper together with reference values for infinite multiplication factors calculated with MCNP4C.

2 CODES AND MODELS

2.1 Coupled neutronics and thermal-hydraulics code system TRAB-3D/SMABRE

TRAB-3D is a stand-alone core dynamics code for square lattice geometry and it 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 a 3D neutronics model and in parallel 1D thermal-hydraulic channels for core calculations as well as a 1D model for the BWR's pressure vessel and coolant circuit. The parameterized cross sections from KFKI and the subroutine for handling them were implemented to TRAB-3D for modelling HPLWR.

1D thermal-hydraulic system code, SMABRE, contains a five-equation two-phase thermal-hydraulic model, using the drift-flux model for phase separation. SMABRE has a point kinetics core 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, shown in Fig. 3 [13]. This 200 kJ/kg broad region is located along the pseudo-critical line and void fraction changes from zero to one when water enthalpy increases past the region. New material functions representing the steam tables have been generated covering pressures from 0.001 MPa to 100 MPa. In general, the supercritical pressure region is handled in SMABRE in the same manner as the subcritical two-phase region.

There are two options for the coupling of TRAB-3D/SMABRE, a parallel coupling scheme, where the codes run in parallel and exchange information at the bottom and top of the core and TRAB-3D handles the core calculation, and an internal coupling scheme. With the internal coupling scheme, TRAB-3D calculates only neutronics and SMABRE takes care of the thermal-hydraulics calculation of the whole cooling circuit including the core. The internal coupling scheme increases the flexibility of the code compared to the parallel coupling scheme and allows for example modelling of reversed flow in the core. TRAB-3D and SMABRE require separate inputs. For the modelling of the downward flow of the three pass core of HPLWR, the internal coupling scheme is required.

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 the pressure vessel internals and an approximate model of the steam circuit. The model consists of 101 nodes, 104 junctions and 152 heat slabs. The nodalization is shown in Fig. 4. 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 flow channels in TRAB-3D, as depicted in Fig. 5. The moderator channels are also divided.

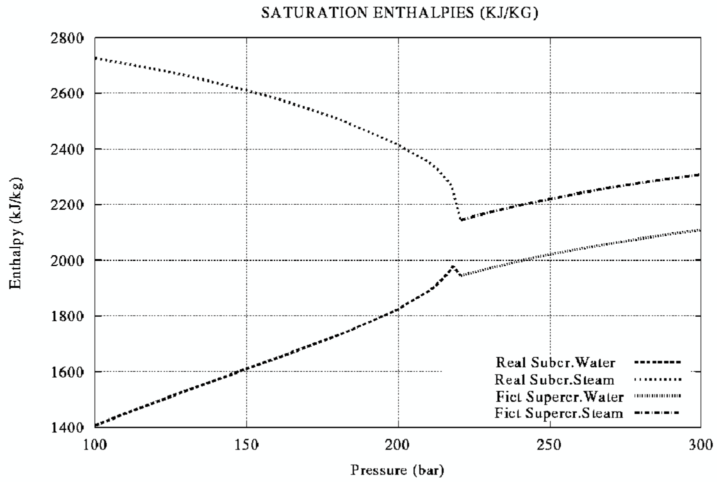

Figure 3. Real and fictive saturation enthalpies of water and steam at subcritical and supercritical pressures in SMABRE. [13]

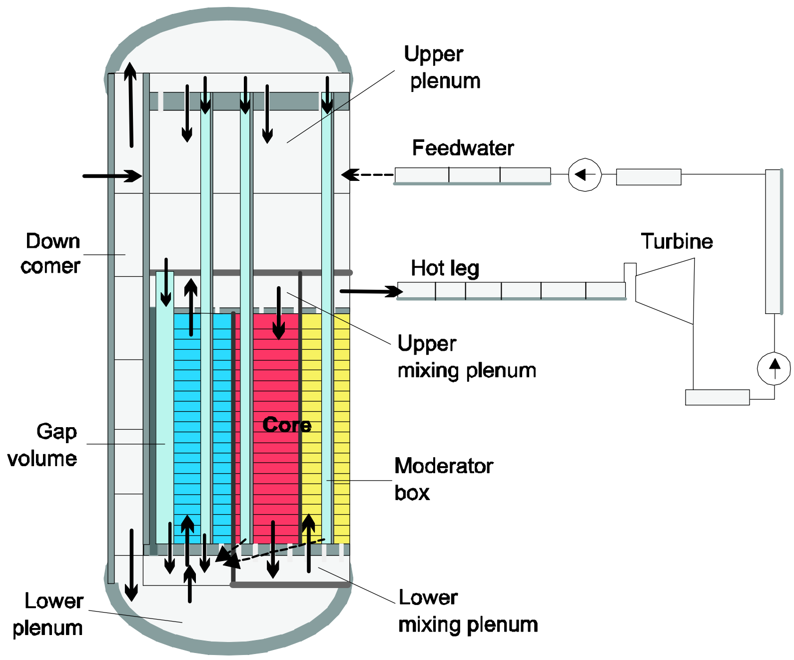

Figure 4. Nodalization of the HPLWR plant model for SMABRE.

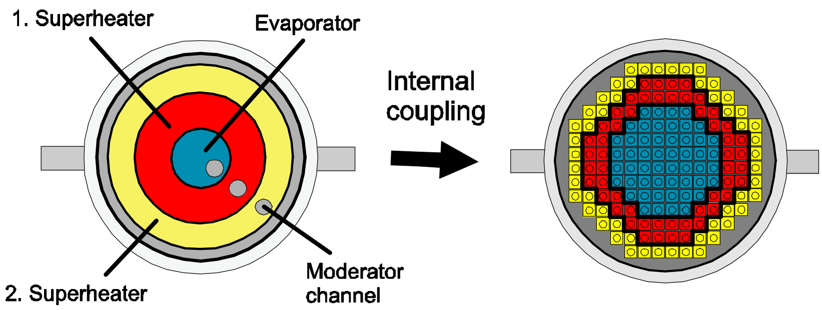

Figure 5. Radial nodalization of the HPLWR core channels in standalone SMABRE calculations and with internal coupling to TRAB-3D.

2.2 Monte Carlo transport code PSG for group constant generation

PSG 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 with good results. During the past year, a new version of PSG was made, for which the source code was completely re-written correcting the programming errors and methodological flaws of the previous code version [14]. In addition, the geometry routine based on the Woodcock delta-tracking method has been changed to a more general approach and the capability to perform fuel depletion calculations has been implemented. All calculations presented in this paper were done using the old version of 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. 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 descriptions, it eases the comparison to MCNP calculations. For the fuel rods, 6 % basic and 5 % corner pin enrichment was used.

3 RESULTS

3.1 Modelling of the supercritical Edwards-O'Brien blowdown test cases with SMABRE

The Edwards-O'Brien tests [15] compose of fluid depressurization experiments on a horizontal pipe. The blowdown of a 4.096 m long pipe with an inside diameter of 0.0762 m was 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 to 0.1 MPa in 0.001 s.

Participants of the "HPLWR2" project defined modified test cases with initial pressure 25.0 MPa to allow comparison between different thermal-hydraulics codes in supercritical pressure conditions. There is no experimental data of the supercritical pressure cases. Three modified cases are defined with initial temperatures of 580 K (test01), 700 K (test02) and 780 K (test03). The SMABRE model consists of 20 nodes of equal size. The break is modelled with valve for which the counter pressure is decreased according to the test definition. The pressures and void fractions calculated with SMABRE for the three supercritical cases are shown in Fig. 6. The results are from the so called GS-5 point which is located in the middle of the eighth node from the closed end of the pipe.

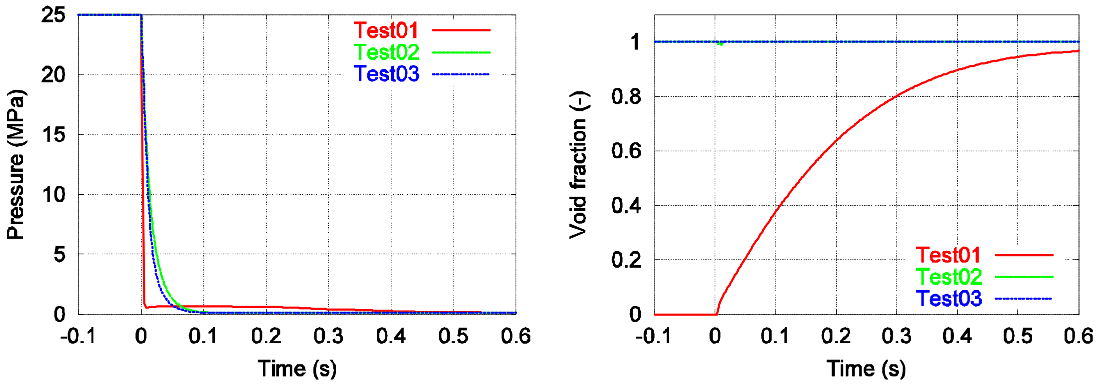

Figure 6.Pressure and void fraction in the supercritical Edwards-O'Brien test cases calculated with SMABRE.

3.2 HPLWR model for TRAB-3D/SMABRE

A functioning thermal-hydraulic steady-state for the HPLWR model has been achieved with SMABRE. Axial cosine distribution is used for power and radially the power profile is flat in each section of the core. 53 % of the power is produced in the evaporator section, 30 % in the first superheater and 17 % in the second superheater. The mass flow and temperature distributions have been tuned according to the specified target values. Calculated and specified steady-state parameters are given in Table 1. Axial distributions for "pseudo" void fraction and mixture temperature in the core are shown in Fig. 7. The order of the core node numbering follows the flow path of the coolant.

Calculations of preliminary transients concerning for example reactor trip and depressurization behaviour have been started with SMABRE and testing with the coupled code with TRAB-3D neutronics is in progress.

Table 1. Calculated steady-state parameters with SMABRE and the target values.

	SMABRE	**Target**
Thermal power (MW)	2245	2245
RPV inlet temperature (ºC)	281	280
Temperature, evaporator outlet (ºC)	388	390
Temperature, 1. superheater outlet (ºC)	435	433
RPV outlet temperature (ºC)	508	500
Pressure RPV outlet MPa	25.0	25.0
Pressure difference, RPV inlet-outlet (MPa)	0.24	-
Mass flow rate, feedwater (kg/s)	1160	1160
Mass flow rate, downcomer (kg/s)	870	870
Mass flow rate, gap volume (kg/s)	195	193
Mass flow rate, mod. channels (kg/s)	95	97

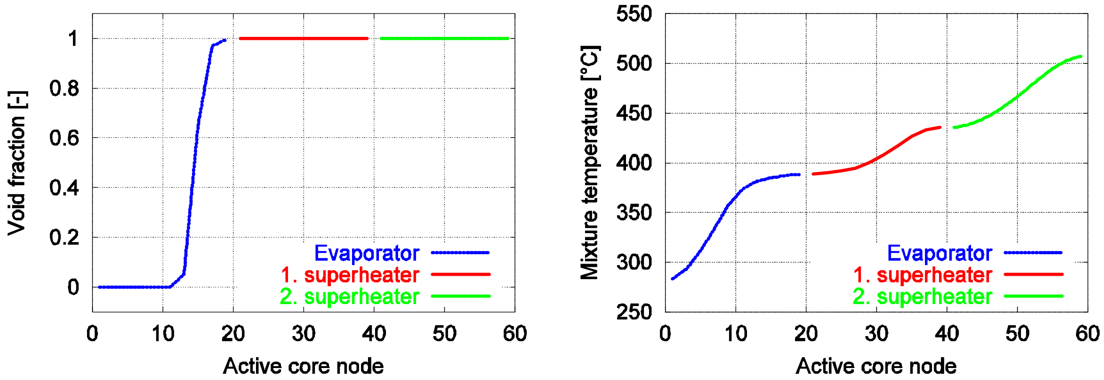

Figure 7. "Pseudo" void fraction and mixture temperature in the HPLWR core calculated with SMABRE.

3.3 Multiplication factors for HPLWR fuel assembly calculated with PSG

For the generation of two-group constants with PSG, 27 cases were defined 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). Temperature of the moderator in the moderator boxes and in the gaps between fuel assemblies is kept equal. The results were compared to 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 from the parameterized cross sections are shown in Fig. 8. For each combination of coolant and moderator temperatures, the fuel temperature has values of 600K, 900K and 1200K, in this order.

Case No. 14 best represents the nominal conditions in the 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 sections are shown in Table 2, together with the absolute and relative differences of the results.

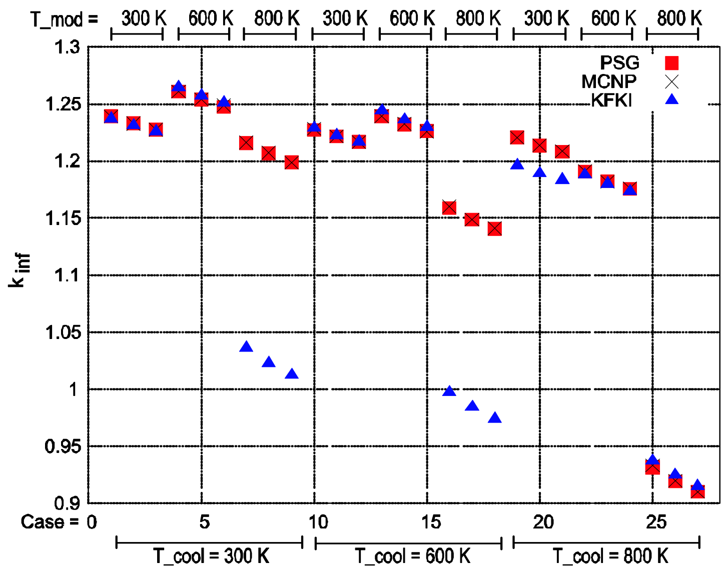

Figure 8. Multiplication factors calculated with PSG and MCNP compared to values from the KFKI parameterized cross sections.

Table 2. Comparison of two-group constants for case 14 (T_{cool} = 600 K*,* T_{mod} = 600 K, T_{fuel} = 900 K) *calculated with PSG and from the parametrized KFKI cross sections.*

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
$\Sigma_{r,12}$	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

4 DISCUSSION AND CONCLUSIONS

The capabilities of the thermal-hydraulics system code SMABRE were extended to supercritical pressures for the modelling of HPLWR within the EU project “HPLWR2”. SMABRE is internally coupled with TRAB-3D for 3D neutronics calculation, which allows for example the calculation of reactivity initiated transients with a varying radial power distribution. Parameterized two-group cross sections for HPLWR fuel assembly have been received from KFKI and they are implemented to TRAB-3D.

Calculation of the Edwards-O’Brien blowdown test shows that SMABRE is capable of modelling the transition from supercritical to subcritical pressures. The results for pressure calculated with SMABRE behave smoother than which is expected for the cases. In general, this is due to the numerical solution procedure of SMABRE. The changes in the Edwards-O’Brien test cases are too fast for the non-iterative solution procedure of SMABRE. SMABRE is not intended for detailed modelling of this kind of rapid phenomena. However, the results can be further enhanced by refining of the flashing correlation and the handling of the convection term of moment in SMABRE. The same test cases have also been calculated with other codes, for example APROS [16], RELAP and CATHARE, but no comparisons have yet been made between the SMABRE results and them.

A thermal-hydraulic steady-state for the HPLWR plant model has been achieved with SMABRE and it has been tuned according to the specified target values. Core mixture temperature distribution in the core shown in Fig. 7. coincides well with the target distribution. Void fraction is a quasi variable in the supercritical pressure reason and the distribution in the core depends on how wide the pseudo-two-phase region has been determined. Preliminary transient calculations have been performed with SMABRE. The next step will be to make the final modification to the internal coupling of TRAB-3D/SMABRE before starting the coupled calculations. During the “HPLWR2” project, the final goal for VTT is to perform control rod ejection transient analysis on HPLWR using TRAB-3D/SMABRE.

In addition to the KFKI cross sections, two-group constants for HPLWR fuel assembly were also generated with PSG, a new Monte Carlo code developed at VTT. The results were compared to the KFKI cross sections and reference calculations were also performed with MCNP.

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 statistical accuracy. 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 parameterized 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 KFKI 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. Large differences were expected in comparing the diffusion coefficients, because there are many definitions for it in the Monte Carlo method and multiple ways of calculating it.

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