Development of coupled neutronics/thermal–hydraulics test case for HPLWR

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Abstract. The High-Performance Light Water Reactor (HPLWR) is the European concept of a supercritical water reactor (SCWR) which is one of the most promising and innovative designs of the Generation IV nuclear reactor concepts. The thermal–hydraulics behavior of supercritical water is significantly different from water at sub-critical pressure because of the difference in the specific heat value. Coupled analysis of HPLWR assembly neutronics and thermal–hydraulics has become important because of the strong influence of the water density on the neutron spectrum and power distribution. Programs MCU (Monte-Carlo Universal) and ATHLET (Analysis of Thermal-hydraulics of Leaks and Transients) were used for better estimation of power and temperature distribution in HPLWR assembly.

1. Introduction

Supercritical water-cooled reactor (SCWR) is the nuclear reactor using supercritical pressure water as coolant. The SCWR is considered as one of the most promising Generation IV reactors because of its simplicity, high thermal efficiency, and nearly fifty years of industrial experience from thermal-power stations with a supercritical water cycle [1]. Based on existing designs, they can be divided into two main categories of the conceptual designs of SCWRs: (1) pressure vessel concepts being studied mostly in Japan and European Union are analogous to conventional LWRs, and (2) pressure tube or channels containing fuel bundles concepts being focusing in Canada and Russia are analogous to conventional CANDU and RBMK nuclear reactors.

High Performance Light Water Reactor (HPLWR) is the European conceptual design of the SCWR. Distinction between the HPLWR and the LWRs is that the HPLWRs use supercritical pressure water (25 MPa) with very high water temperature increase in outlet (500°C) from inlet (280°C), so that some components of LWRs are not required anymore, for example, steam separators and dryers in BWR; steam generators and pressurizer in the PWR.

In the papers [2], [3], [4] several designs for the SCWR assemblies based on square and hexagonal geometry were proposed. Several partners of the HPLWR project [12] studied the hexagonal assembly design [2] and concluded that the hexagonal assembly design has the major weaknesses: the under-moderation, which causes reactivity swing; the high enrichment; and three different enrichment fuel pins within the subassembly making a complicated mechanical structure.
Design of a square assembly containing a central moderator box and two rows of fuel rods being proposed in [4] was proved that this design compared with an hexagonal assembly with one and two rows of fuel rods is better for minimizing the structural material, for optimizing the moderator to fuel and for achieving a more uniform radial power distribution in a cross section of the assembly [12]. The design concept will be described in more detail further.

Neutronics/thermal–hydraulics coupling schemes having been developed sparingly for HPLWR were introduced in [13] and [14]. For the same input parameters calculations give similar results to these schemes. It is necessary to extend development of neutronics/thermal–hydraulics coupling schemes to predict basic reactor physics design parameters for HPLWRs. In this work a coupling scheme MCU/ATHLET for prediction of the power and temperature distribution of HPLWR fuel assembly was developed. The square assembly as described in [4] is considered. The principal aim of this study is to consider the temperature distribution, the pin power distribution, the maximum power peaking factor of HPLWR fuel assembly obtained by MCU/ATHLET.

2. Fuel assembly design

HPLWR assembly selected in the current analysis is the square fuel assembly with two rows of fuel rods and a central moderator box as described in [4]. The assembly consists of 40 fuel rods of 8mm outer diameter and a single central water box replacing 9 fuel rods (table 3, Figure 2). Because HPLWR reactor core consist of three regions evaporator, first superheater, second superheater with 52 clusters (the cluster is comprising nine fuel assemblies in a 3×3 arrangement) for each region as shown in fig 1. So that we will consider assembly model in three regions with 3 different temperature ranges (Figure 3; tables 1, 2). Due to the strong variation of coolant density along active core height, assembly is divided in 10 axial layers identified as locations 1, 2, 3, 4, 5, 6, 7, 8, 9, 10 respectively (table 3; Figure 4).

### Table 1. Temperature-density distribution of coolant in three regions: evaporator, first superheater, second superheater.

| Axial layer | Lower Position, cm | Evaporator T, °K, ρ, (g/cm³) | First superheater T, °K, ρ, (g/cm³) | Second superheater T, °K, ρ, g/cm³ |
|-------------|--------------------|-------------------------------|------------------------------------|---------------------------------|
| 1           | 0                  | 583.0, 0.724092               | 706.0, 0.12383                     | 706.0, 0.12383                  |
| 2           | 42                 | 591.9, 0.705878               | 701.2, 0.12479                     | 713.4, 0.11779                  |
| 3           | 84                 | 600.8, 0.686021               | 696.4, 0.13121                     | 720.9, 0.11173                  |
| 4           | 126                | 609.7, 0.66406                | 691.7, 0.13652                     | 728.3, 0.11083                  |
| 5           | 168                | 618.6, 0.639275               | 686.9, 0.14076                     | 735.8, 0.10233                  |
| 6           | 210                | 627.4, 0.610422               | 682.1, 0.14666                     | 743.2, 0.09787                  |
| 7           | 252                | 636.3, 0.574954               | 677.3, 0.15652                     | 750.7, 0.09340                  |
| 8           | 294                | 645.2, 0.526317               | 672.6, 0.17089                     | 758.1, 0.08893                  |
| 9           | 336                | 654.1, 0.428571               | 667.8, 0.19126                     | 765.6, 0.08447                  |
| 10          | 378                | 663.0, 0.235714               | 663.0, 0.23571                     | 773.0, 0.08000                  |
Figure 1. Arrangement of evaporator, first superheater, second superheater and assembly clusters in the HPLWR three-pass core [5].

Figure 2. Cross sections of HPLWR assembly.

Thermal hydraulics characteristics are described in table 3, in first iteration of MCU calculation the fuel temperature was constant given 1227 \(^\circ\)K and moderator temperature out of assembly – the outlet temperature of the moderator box about 633 \(^\circ\)K. Because of symmetry of assembly, so that we only calculate one eighth of assembly (rods 3, 4, 5, 6, 8, 9, 10).
Table 2. Temperature-density distribution of moderator and fuel claddings in three regions: evaporator, first superheater, second superheater.

| Axial layer | Moderator | Evaporator | First superheater | Second superheater | Fuel cladding temperature |
|-------------|-----------|------------|-------------------|--------------------|--------------------------|
|             | T, °K     | T, °K      | T, °K             | T, °K              |                          |
| 1           | 633.0     | 593.0      | 716.0             | 716.0              |                          |
| 2           | 626.9     | 601.9      | 711.2             | 723.4              |                          |
| 3           | 620.8     | 610.8      | 706.4             | 730.9              |                          |
| 4           | 614.7     | 619.7      | 701.7             | 738.3              |                          |
| 5           | 608.6     | 628.6      | 696.9             | 745.8              |                          |
| 6           | 602.4     | 637.4      | 692.1             | 753.2              |                          |
| 7           | 596.3     | 646.3      | 687.3             | 760.7              |                          |
| 8           | 590.2     | 655.2      | 682.6             | 768.1              |                          |
| 9           | 584.1     | 664.1      | 677.8             | 775.6              |                          |
| 10          | 578.0     | 673.0      | 673.0             | 783.0              |                          |

Table 3. HPLWR fuel Assembly design data [6].

| Assembly design data                              | Value       | Units |
|---------------------------------------------------|-------------|-------|
| Fuel active length                                | 420         | cm    |
| Inlet temperature                                | 280         | °C    |
| Outlet temperature                               | 500         | °C    |
| Fuel pin diameter                                 | 0.69        | cm    |
| Outer cladding diameter                           | 0.8         | cm    |
| Cladding thickness                                | 0.05        | cm    |
| Pitch of fuel rods                                | 0.92        | cm    |
| Water box side length                             | 2.69        | cm    |
| Water box side length thickness                   | 0.2         | cm    |
| Outer side length box of assembly                 | 7.05        | cm    |
| Length box of assembly                            | 0.3         | cm    |
| ½ gap around the assembly                         | 0.5         | cm    |
| Fuel                                              | UO₂         | (-)   |
| Enrichment                                        | 5, 6, 5.5   | %     |
| Density                                           | 10.15       | g/cm³ |
| First fuel temperature                            | 1227        | °K    |
| Cladding and structural material                  | SS347       | (-)   |
| Density                                           | 8.027       | cm    |
| Burnable absorber material                        | Gd2O3       | (-)   |
| Enrichment                                        | 2           | %     |
| Fluid pressure                                    | 25          | MPa   |
| Flow direction in water boxes                     | downwards   | (-)   |
| Coolant direction in Evaporator                   | upwards     | (-)   |
| Coolant direction in first superheater            | downwards   | (-)   |
| Coolant direction in second superheater           | upwards     | (-)   |
| Average core power density                        | 57.3        | MW/m³ |
| Average coolant mass flux                         | 1600        | kg/m²s|
3. Brief description of MCU and ATHLET codes

The codes used for calculating power and temperature distribution of HPLWR in this work were MCU and ATHLET.

MCU (Monte Carlo Universal) is a neutronics code based on numerical Monte Carlo method which simulates the transport of neutrons, gamma rays and electrons with different energies. The code takes into account the effects of the continuous changes in the particle energy in collisions, as well as a continuous or step-energy dependence of the cross sections. The MCU accuracy is determined primarily using evaluated nuclear data libraries. MCU system allows to calculate the real geometry and material composition of the complex at various temperatures. It contains module sections for recalculating cross sections in the thermalization and resolved resonance regions, depending on the temperature of the material (using the Breit-Wigner formalism or Adler-Adler). It can be used for multi-processor calculations. [7]

Thermal-hydraulic system code ATHLET (Analysis of Thermal-Hydraulics of Leaks and Transients) developed Gesellschaft für Anlagen- und Reaktorsicherheit (GRS mbH) and was originally intended for the analysis of the entire spectrum of leaks and transients in PWRs and BWRs. However, experience has shown that ATHLET is applicable for western reactor designs as well as for Russian VVER and RBMK reactors. ATHLET consists of several modules that allow to describe the various phenomena in the operation of a light water reactor: thermo-fluid dynamics (TFD); heat transfer and heat conduction (HECU); neutron-kinetics (NEUKIN) for describing the point and the one-dimensional kinetics; module for operation of the equipment (GCSM) and a module for the numerical integration of FEBE for implementation the fully implicit scheme. Other independent modules (three-dimensional neutron kinetics, describe the behavior of containment, etc.) can be connected through the main interface.

The TFD – the fundament module that is based on the use of substantially five equations (equations of conservation of mass and energy for the liquid and vapor phase separately and the general equation for the angular momentum of mixture with drift flow) or six equations (equations of conservation of mass, energy, and pulse for the liquid and vapor in the description of the two-fluid model) with a wide range of closing relations. In addition, the module allows to simulate the behavior of non-condensable gases, nitrogen dissolution and describe the boron transport system. Reactor coolant system is modeled by a compound of basic thermodynamic objects (TFO), where the detail of modeling of the studied installation is limited, in principle, only the possibility of computing - the amount of memory and speed. In addition, TFD module is capable for specific descriptions of transverse coolant flow in system of related parallel channels. [8]

A flowchart describing the coupling process between neutron and thermal hydraulic codes MCU/ATHLET is shown on Figure 3. Nomenclature: TFi - fuel temperatures [°K], TCi - cladding temperatures [°K], TMi - moderator temperatures [°K], TMbi - moderator’s box temperatures [°K], TCoi - coolant temperatures [°K], TABi - assembly’s box temperatures [°K], TOMi - moderator temperatures out of assembly [°K], ρMi - moderator density in moderator’s box [g/cm³], ρOMi - moderator density out of assembly box [g/cm³], ρCoi - coolant densities [g/cm³], Qi - local power [KWt], i - layer subscripts.

Coolant flow scheme in ATHLET for HPLWR thermal hydraulics analysis is shown on Figure 4. The coupling procedure carries on until a reasonably converged power profile is achieved. Difference in local powers less than 0.5% in two successive iterations is applied to dampen out the fluctuations and get a converged profile more quickly.
Figure 3. MCU/ATHLET flowchart.

Figure 4. Coolant flow scheme.
4. Preliminary results

The results of neutron calculations in the first iteration are shown in Table 4, Figures 5, 6, 7, and 8. The value of infinite multiplication factor of assembly in evaporator is greater than that in first superheater and second superheater as shown in Table 4. This is explained by smaller coolant temperature and density in evaporator as compared to that in first superheater and second superheater. This also indicates that the coolant temperature coefficient of reactivity is negative.

| Assembly in:     | K infinite | Std.Dev. |
|------------------|------------|----------|
| Evaporator       | 1.115      | 0.000498 |
| First superheater| 1.082      | 0.000504 |
| Second superheater| 1.078    | 0.000463 |

Table 4. The infinite neutron multiplication factor of assembly in three region.

Figure 5. Assembly liner power along active height in three regions.

Figure 6. Liner power of rods along active height in evaporator region.

Figure 7. Liner power of rods along active height in first superheater region.

Figure 8. Liner power of rods along active height in second superheater region.
5. Conclusions
The coupled scheme MCU/ATHLET has been developed for analysis of HPLWR reactor behavior. Code MCU were used to calculate the power distribution in HPLWR assembly which is put into ATHLET input file to obtain the corresponding thermal–hydraulic parameters. The obtained thermal–hydraulic parameters are used to generate a new MCU input file for the next calculation. This procedure is repeated until the convergence is achieved.

Three types of HPLWR assembly were calculated with MCU code. The results indicate that in fuel rods with gadolinium (Figure 7-9, rod 10) axial power distribution is closer to uniform and has smaller average power value than in other types of fuel rods.

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