COUPLED NEUTRONICS – THERMAL HYDRAULICS ANALYSIS OF SCWRs

Ph.D. thesis

Tibor Reiss

Supervisors:
Sándor Fehér, Ph.D.
Prof. Gyula Csom, D.Sc.

MŰEGYETEM 1782

Budapest University of Technology and Economics
Institute of Nuclear Techniques
2011

Research context

The Generation IV International Forum is the most significant program regarding the future of nuclear energy. During a thorough selection process, which major criteria were sustainability, safety and reliability, proliferation resistance and physical protection, the forum chose six reactor concepts for further R&D ([GIF2002]). These are: the Gas Cooled Fast Reactor (GFR), the Lead Cooled Fast Reactor (LFR), the Sodium Cooled Fast Reactor (SFR), the Molten Salt Reactor (MSR), the Supercritical Water Cooled Reactor (SCWR) and the Very High Temperature Reactor (VHTR).

The SCWR is a high-temperature, high-pressure light water cooled reactor ([Fischer2009]) operating above the critical point of the water (374 °C, 22,1 MPa). It combines the advantages of today's Light Water Reactors and supercritical pressure fossil fired power plants (e.g. compared to the Pressurized Water Reactors it has higher plant efficiency, lower coolant inventory and under normal operating conditions there is no boiling crisis). The SCWRs also have disadvantages (e.g. due to the once-through cycle the coolant is in direct touch with the turbine; due to the smaller coolant inventory, the dry out of the core progresses faster), but with proper design these can be mitigated or fully eliminated. Based on the setup of the core the SCWR can have a fast or a thermal neutron spectrum.

SCWRs were already investigated in the 1950's and '60's ([Oka2000]). There was little interest for them in the '70s and '80s, but they became the focus of attention again in the '90s. New Japanese ([Oka1998]) and Russian ([Silin1993]) concepts were developed: at the University of Tokyo both a thermal and a fast option were analyzed, parallel to this the Russian Kurchatov Institute designed the B-500 SKDI. These results encouraged other countries to develop their own concepts:

- in Europe, a consortium was formed to design the High Performance Light Water Reactor (HPLWR, [Schulenberg2007]);
- between 2001 and 2004, the USA made a feasibility study of the SCWR ([MacDonald2004]);
- the Republoc of Korea started their research in 2002 ([Bae2007]);
- and eventually, in the case of the Canadian CANDU, developing a supercritical pressure version is obvious ([Torgerson2006]).

In a typical SCWR the coolant, supercritical pressure water, has two functions in the core: cooling of the fuel assemblies and slowing down (moderation) of the neutrons. While passing through the core, during a heat-up of about 220°C (from 280°C to 500°C), the density of the water changes approximately by an order of magnitude (from 0.77 g/cm^3 to 0.08 g/cm^3, although without phase transition). This means that the system exhibits local temperature, density and power oscillations. These phenomena are increased by the pseudocritical transition (a dramatic, but continuous change in the physical properties between 372 and 392°C, [Pioro2007]) of the water.

In the Institute of Nuclear Techniques (NTI), BME the research corresponding to SCWRs started in 2005 mainly in the fields of reactor physics and thermal hydraulics. The NTI joined the HPLWR Phase 2 project (which started in 2006 under the European 6th Framework Programme).

Goals

From the above it follows that coupled neutronics – thermal hydraulics calculations are necessary to examine SCWRs. The first goal was to develop such a program system which is capable of determining the stationary state (temperature and power distribution) of any SCWR – e.g. the European three-pass HPWLR – including burnup calculations. During the work it was evident that an enormous number of calculations was required, thus I searched for methods which allowed the fast and efficient calculation even of large models, e.g. full cores.

The active height of most of the SCWRs is over 4.0 m, thus they are susceptible to spatial xenon oscillations ([Csom2005]). This effect, combined with the density and power oscillations mentioned above, can lead to dynamic processes which can differ significantly from that observed in today’s reactors. After some modifications to the above program system my goal was to also examine these phenomena.

In order to mitigate the consequences from the large density (and moderation) decrease of the coolant, several solutions have been proposed, e.g. the HPLWR uses so called moderator boxes ([Hofmeister2007]). These in turn result in quite complicated coolant flow paths compared to today’s commercial light water reactors. With simplicity in mind, I set the goal to design a SCWR assembly which features a simple coolant flow path and additionally has a much better fuel utilization than the present concepts.

Methods of analysis

During my research I used a self-developed coupled neutronics – thermal hydraulics program system. The basic idea was to determine the steady-state solution of the temperature and power distribution at each burnup step, since the time scale of the burnup is much larger than the residence time of the coolant in the core. Next, a depletion step with appropriate length follows which changes the material composition of the system. This results in the change of the microscopic cross sections, thus also the power distribution. Hence, a new steady-state solution has to be determined. The process is repeated until the desired burnup is achieved.

I placed great emphasis on modularity which allowed me to solve several different problems fast and efficiently. The two main modules were the neutronics and the thermal hydraulics. Inside of the neutronics module, I used mainly the MCNP ([Briesmeister2000]) for the detailed three-dimensional calculations, whereas for larger models I utilized the SCALE code package ([ORNL2009]). For the latter I developed a cross section homogenization process which significantly reduced the required computational time. Inside of the thermal hydraulics module, I used a single channel code based on the energy and mass conservation equations.

Xenon oscillations can be thought of as special burnup calculations since the material composition changes as well. However, due to the short half-life of the isotopes (^{135}I, ^{135}Xe) in the xenon decay chain, the concentration changes of other isotopes can be neglected. Thus, I also implemented the differential equations required for the calculation of xenon oscillations into the program system.

References

[Bae2007] Bae K-M., Joo H-K., Bae Y-Y. (2007), *Conceptual design of a 1400MWe Supercritical Water Cooled Reactor core with a cruciform type U/Zr solid moderator,* Proceedings of ICAPP ’07, Nice, May 13-18

[Briesmeister2000] Briesmeister J.F. (2000), *MCNPTM – a general Monte Carlo n-particle transport code*, LA-13709-M

[Csom2005] Csom Gy. (2005), *Atomerőművek üzemtana II/1. kötet*, Műegyetemi Kiadó

[Fischer2009] Fischer K., Schulenberg T., Laurien E. (2009), *Design of a supercritical water-cooled reactor with three-pass core arrangement*, Nucl. Eng. Des. 239, pp. 800-812.

[GIF2002] Generation IV International Forum (2002), *A technology roadmap for Generation IV nuclear energy systems*

[Hofmeister2007] Hofmeister J., Waata C., Starflinger J., Schulenberg T. (2007), *Fuel assembly design study for a reactor with supercritical water*, Nucl. Eng. Des. 237, pp. 1513-1521.

[MacDonald2004] MacDonald P., Buongiorno J., Sterbentz J.W., Davis C., Witt R. (2004), *Feasibility study of Supercritical Water Cooled Reactors for electric power production*, Final Report, INEEL/EXT-04-02530

[Oka1998] Oka Y., Koshizuka S. (1998), *Conceptual design study of advanced power reactors*, Prog. Nucl. Energy 32, pp. 163-177.

[Oka2000] Oka Y. (2000), *Review of high temperature water and steam cooled reactor concepts*, 1st International Symposium on Supercritical Water-cooled Reactors, Tokyo, November 6-9

[ORNL2009] Oak Ridge National Laboratory (2009), *SCALE: A modular code system for performing standardized computer analyses for licensing evaluation*, ORNL/TM-2005/39, Version 6, Vols. I-III

[Pioro2007] Pioro I.L, Duffey R.B. (2007), *Heat transfer and hydraulic resistance at supercritical pressures in power-engineering applications*, ASME Press

[Schulenberg2007] Schulenberg T., Starflinger J. (2007), *Core design concepts for the High Performance Light Water Reactors*, Nuclear Engineering and Technology 39, pp. 249-256.

[Silin1993] Silin V. A., Voznesensky V.A., Afrov A.M. (1993), *The Light Water Integral Reactor with natural circulation of the coolant at supercritical pressure B-500 SKDI,* Nucl. Eng. Des. 144, pp. 327-336.

[Torgerson 2006] Torgerson D.F., Basma A., Shalaby A., Simon Pang (2006), *CANDU technology for Generation III+ and IV reactors,* Nucl. Eng. Des. 236, pp. 1565-1572.

New scientific results

1. **Thesis:** I developed a modular coupled neutronics – thermal hydraulics (CNT) program system which is capable of analyzing SCWRs. I used both deterministic (SCALE6.0) and Monte Carlo (MCNP) codes for the neutronics part of the program system. I developed a cross section homogenization method for the calculations based on SCALE, because the methods used for calculation of conventional light water reactors did not reproduce the neutron flux spectrum correctly. I implemented the method into the CNT program system which made the optimization and burnup calculations (a special case of which is the xenon oscillation) of SCWR zones quite fast. [1] [3] [4] [6]

2. **Thesis:** By determining the approximate migration length in the one-pass and three-pass SCWR cores (PWR-SC and HPLWR) and by comparing these values to the geometrical dimensions of the cores, I showed that - in a first order - these reactors are stable against xenon oscillations. With detailed calculations I first demonstrated that the negative reactivity feedback from the fuel temperature (Doppler effect) is the dominant effect in the stabilization of the HPLWR reactor. On the other hand, the large density change of the coolant and the corresponding increase in the migration length, which are both the effects of the strong heat-up of the coolant, play only a secondary role. I proved that reactors with $(Th\text{-}^{233}U)O_2$ instead of UO_2 as fuel are more stable against xenon oscillations, which is due to the more favorable yield ratio of the relevant fission products (^{135}I and ^{135}Xe). [4]

3. **Thesis:** I carried out coupled neutronics – thermal hydraulics calculations on a one-pass SCWR assembly with UO_2 as fuel and $ZrH_{1.6}$ as extra moderator. I compensated the axial density drop of the coolant and the corresponding decrease in moderation, both of which are typical for SCWRs, by gradually replacing several of the fuel pins with ZrH rods. I determined the optimal configuration of a fresh core consisting of the above assemblies while minimizing the radial and axial power peaking. After performing a burnup calculation for the full core, I pointed out the weak points of the design and proposed solutions to tackle them. [2] [3]

4. **Thesis:** I first examined the neutronic properties of a SCWR assembly with $(Th\text{-}^{233}U)O_2$ as fuel, which primary goal was to prove that with such a reactor it is possible to achieve breeding of the fissile material while the reactivity is positive. In order to reach a long enough fuel cycle and a high enough conversion ratio, I showed that a two-pass assembly configuration is necessary. Thus, I optimized the pitch, diameter and fuel enrichment of the different regions of the assembly. Through two-dimensional calculations I established the optimal dimensions of the assembly. [5]

5. **Thesis:** I carried out three-dimensional coupled neutronics – thermal hydraulics calculations on the two-pass, optimized, (Th-^{233}U)O_2-fueled SCWR assembly. After analyzing the results, I came to the conclusion that the (Th-^{233}U)O_2 is the natural fuel of the SCWRs, which main proof is that there is no need for extra moderator in the two-pass assembly configuration. After optimizing the fuel enrichment and the amount of burnable poison, I showed that the system is self-sustaining up to the burnup of about 40.0 MWday/kg considering the fissile material. I determined the reactivity coefficients as well which proved that such a SCWR is an inherently safe reactor. [1] [5]

List of publications

Journal papers (English)

[1] Reiss T., Fehér S., Czifrus Sz. (2008), *Coupled neutronics and thermohydraulics calculations with burn-up for HPLWRs*, Prog. Nucl. Energy 50, pp. 52-61.

[2] Reiss T., Csom Gy., Fehér S., Czifrus Sz. (2010), *The Simplified Supercritical Water-Cooled Reactor (SSCWR), a new SCWR design*, Prog. Nucl. Energy 52, pp. 177-189.

[3] Reiss T., Csom Gy., Fehér S., Czifrus Sz., Szieberth M. (2010), *Full-core SSCWR calculations applying a fast computational method*, Prog. Nucl. Energy 52, pp. 767-776.

[4] Reiss T., Fehér S., Czifrus Sz. (2011), *Xenon oscillations in SCWRs*, Prog. Nucl. Energy 53, pp. 457-462.

[5] Reiss T., Csom Gy., Fehér S., Czifrus Sz. (revision submitted to journal on June 23, 2011), *Thorium as an alternative fuel for SCWRs*, Ann. Nucl. Energy

Journal papers (Hungarian)

[6] Reiss T., Czifrus Sz., Fehér S. (2008), *A HPLWR tanulmányozásához használt csatolt neutronfizikai-termohidraulikai programrendszer továbbfejlesztése*, NUKLEON I/1.

[7] Reiss T., Horváth D., Fehér S., Czifrus Sz. (2007), *Csatolt neutronfizikai-termohidraulikai számítások a HPLWR reaktor axiális teljesítmény-eloszlásának meghatározására*, Magyar Energetika 2007/5.

Conferences

[8] Reiss T., Horváth D., Fehér S., Czifrus Sz. (2006), *Csatolt neutronfizikai-termohidraulikai számítások a HPLWR reaktor axiális teljesítmény-eloszlásának meghatározására*, 5th Symposium of Nuclear Techniques, Paks, November 30 - December 1

[9] Reiss T., Dr. Czifrus Sz., Dr. Fehér S. (2007), *Coupled neutronics and thermohydraulics analysis for the optimization of the axial enrichment profile of HPLWRs*, International Youth Conference on Energetics, Budapest, Mai 31 - June 2

[10] Reiss T., Fehér S., Czifrus Sz. (2007), *A HPLWR tanulmányozásához használt csatolt neutronfizikai-termohidraulikai programrendszer továbbfejlesztése*, 6th Symposium of Nuclear Techniques, Budapest, November 29-30

[11] Reiss T. (2008), *A coupled neutronics-thermohydraulic program system for steady state analysis of HPLWRs*, International Students´ Workshop on High Performance Light Water Reactors, Karlsruhe, March 31 - April 3

[12] Reiss T., Fehér S., Czifrus Sz. (2009), *Calculation of xenon-oscillations in the HPLWR*, 4th International Symposium on Supercritical Water-Cooled Reactors, Heidelberg, March 8-11

[13] Reiss T., Fehér S., Czifrus Sz. (2009), *Calculation of xenon-oscillations in the HPLWR*, ICAPP'09, Tokyo, Mai 10-14

[14] Reiss T. (2010), *Coupled neutronics – thermal-hydraulics programs for SCWRs*, 4th ENEN PhD Event 2010 (European Nuclear Conference 2010), Barcelona, June 2

Other

[15] Presentations for and contribution to the HPLWR Phase 2 projec, Contract number: FI6O-036230

[16] Presentations for and contribution to the NUKENERG NAP project, Contract number: DMFB00719/2005

[17] Author, co-author in BME-NTI research reports: 372/2006, 439/2008, 449/2008, 495/2009, 541/2010.

Acknowledgement

I would like to thank my supervisors, Sándor Fehér and Gyula Csom for their guidance, helpful advices and the joint work. I thank Szabolcs Czifrus the support and the review.