Investigation of the Dynamic Behaviour of Molten Salt Reactors

PhD thesis summary

Kópházi József

Supervisor:
Fehér Sándor, PhD

BME
Institute of Nuclear Techniques
2010

Background

The world's increasing demand on energy and the economical and environmental issues related with the electric energy production have launched a nuclear renaissance during the recent years. The future development put forward the two challenges the nuclear industry has to face: the transmutation of long-lived waste and the breeding of fissionable material.

The molten salt reactor seems to be a promising tool to solve both problems. In these reactors the fuel is dissolved in some molten salt and is circulated in the primary circuit. In the case of thermal reactors, the reactor vessel contains graphite as well, and the fuel flows in the channels machined into the graphite slabs. Since the fuel is in fluid form, fuel pin and assembly fabrication is unnecessary and the fuel is directly accessible for reprocessing. This gives molten salt reactors transmutational and breeding potential inconceivable in other reactors.

Investigation of the dynamic behaviour is one of the main research topics concerning molten salt reactors. The short-time behaviour of these reactors is fundamentally dissimilar to that of the traditional solid fuel reactors. First, due to the flow of the fuel, delayed neutron precursors drift away from the site of the fission event and decay at a different location. This will influence the kinetic behaviour of the reactor since the neutron importance at the location the delayed neutrons are born is different from that at the location of the fission. This results in a loss of reactivity and effective delayed neutron fraction as well. On the other hand, most of the fission heat is deposited directly into fuel while the rest of the heat is deposited in the moderator and is transferred to the fuel by heat conduction. Moreover, the moderator represents a thermal connection between fuel channels.

Current physical models and reactor analysis tools are not fully capable for taking into account the peculiarities of the molten salt reactors. This is mainly because no molten salt reactors have been operated by today, except an experimental reactor, which existed at the late 60's in the United States (Molten Salt Reactor Experiment – MSRE) and an abandoned military project. Due to the renewed interest, in recent years papers have been published describing newly developed calculational schemes. Most of these are based on one dimensional and point kinetic equations, some

lack the proper modelling of heat transfer between channels and graphite and all of them neglect the connection between channels.

Goals

The primary goal of my thesis was to develop and implement a three-dimensional, time dependent, coupled reactor physics – thermal hydraulics calculational scheme for channel type molten salt reactors. The scheme was intended to be able to take into account the time dependence of the shape of the precursor concentrations, describe the feedback effects, and pay respect to the effects of the neutron and photon heating deposited in the moderator and the connection between fuel channels represented by the heat conductivity of the moderator. I also intended to carry out calculations for some typical molten salt related transients and investigate the responsibility of the convective mixing of the fuel for the discrepancy between the results of earlier models and experimental data regarding the oscillations of the reactor power. Finally, I planned to develop a Mote Carlo based method to determine the reactivity loss due to the circulation of the fuel in the primary loop.

Methods

The core of the calculational scheme is based on the coupling of a reactor physics and a thermal hydraulics module. The top level of the neutronics module consists of the well known diffusion equation extended by a streaming term describing the flow of the fuel and the precursor nuclei. The neutron diffusion equation is solved in three dimensions while the convection of the precursors is described in one dimension in each channel. In order to maintain the required accuracy and avoid numerical instabilities, the convection term was spatially discretized using a TVD (Total Variation Diminishing) scheme. Lower levels of the neutronics module is based on the well known and long time ago implemented procedures (discrete ordinate equations, Nordheim integrals, etc). The thermal module is made up of coupling the three dimensional heat conduction equation describing the moderator and the convection equations describing each fuel channel. In order to avoid instabilities, time dependent equations were discretized using the implicit Euler method. The resulting algebraic systems of equations were solved using various

combinations of the conjugate gradient and Gauss Seidel method and power iterations.

A simplified model consisting of a point kinetic model for reactor power and 1D convection equation for precursor densities was applied to investigate the reactivity oscillations. The turbulent dispersion was estimated using a semi-empirical correlation obtained from the literature. To calculate the reactivity loss by Monte Carlo method, the traditional Monte Carlo neutron transport scheme was expanded by taking into account the precursor nuclei as particles described by their own transport and scattering kernels.

Theses

1. I have developed a three-dimensional coupled reactor physics and thermal hydraulics scheme for static and dynamic analysis of channelled molten salt reactors. The neutron diffusion system of equations was extended by the streaming of the delayed neutron precursors and was implemented in the DALTON code. The thermal model of the reactor includes the calculation of every channel of the reactor. Thermal connection between channels is represented by the heat conduction of the graphite moderator. A parametric cross section library was set up containing the group constants obtained from cell calculations. Using the code described above I have created a model of the MSRE. The model was validated using the results of the feedback measurements and natural circulation experiment of the MSRE. [K1,K2,K3]
2. Using the implemented code I have determined the time-dependency of the reactor power during a channel blocking incident and the dependence of the sustained reactor power on the level of the blockage. I have shown that the maximum temperature of the fuel remains well below the critical temperature damaging the reactor vessel (~ 1400 K), even in case of significant reduction (80%) of the mass flow rate at the affected channels. Furthermore, I have shown that after the sudden unblocking of the channels the reactor power sharply increases and temporarily can double within a few seconds. [K1]
3. I have investigated the effect of the convective mixing occurring in the primary circuit on the kinetics of the reactor using a simplified model. The point kinetic equation was applied for the reactor power and the 1D convection-dispersion equations for the precursor densities. I determined that, while the effect of the convective mixing in the pipes of the primary circuit on the behaviour of the reactor is negligible, the mixing phenomena occurring in the heat exchanger and the reactor vessel (downcomer, distributor and collector plena) may significantly influence it. [K4,K5]
4. I have developed a Monte Carlo simulation method for determining the reactivity loss due to fuel circulation. The method was implemented in the code MCNP to make it

capable for accounting for the drift of the precursor nuclei and calculate the reactivity loss directly. The reactivity loss of the MSRE was calculated. The results are in good agreement with the measured and analytically estimated values. [K6,K7,K8]

Publications related to the thesis

[K1] J. Kópházi, D. Lathouwers, J. L. Kloosterman; *"Development of a Three-Dimensional Time-Dependent Calculation Scheme for Molten Salt Reactors and Validation of the Measurement Data of the Molten Salt Reactor Experiment*"; Nuclear Science and Engineering; vol. 163, 118-131 (2009)

[K2] J. Kópházi, D. Lathouwers, J. L. Kloosterman, S. Fehér; *"Three-dimensional space and time-dependent analysis of molten salt reactors";* ANS Topical Meeting on Reactor Physics (PHYSOR 2006), Vancouver, Canada (2006).

[K3] Kópházi J., Fehér S., D. Lathouwers, J. L. Kloosterman; *"Sóolvadékos Reaktorok Háromdimenziós Időfüggő Modellezése";* Magyar Energetika, 05/2007, (2007)

[K4] J. Kópházi, G. Légrády, Sz. Czifrus, S. Fehér; *"Effect of Fuel Mixing Phenomena on the Kinetic Behaviour of Molten Salt Reactor"*; Transport Theory and Statistical Physics, vol. 36, 227-239, (2007)

[K5] W. Maschek, A. Stanculescu, ... , J. Kophazi et Al.; *"Advanced Reactor Technology Options for Utilization and Transmutation of Actinides in Spent Nuclear Fuel*"; International Atomic Energy Agency, TECDOC-1626, ISBN 978-92-0-109309-7 (2009)

[K6] J. Kópházi, M. Szieberth, S. Fehér, Gy. Csom, P.F.A. de Leege; *"MCNP based calculation of reactivity loss in circulating fuel reactors"*; Int. Conf. on Nuclear Mathematical and Computational Sciences, Gatlinburg, Tennessee, April 6-11, 2003, on CD-ROM, American Nuclear Society (2003)

[K7] J. Kópházi, M. Szieberth, S. Fehér, Sz. Czifrus, P.F.A. de Leege; *"MCNP based calculation of reactivity loss due to fuel circulation in molten salt reactors"*; 7th International Conference on Nuclear Criticality Safety, October 20-24, 2003, Tokai-Mura, Japan (2003)

[K8] J. Kópházi, M. Szieberth, S. Fehér, Sz. Czifrus, P.F.A. de Leege; *"Monte Carlo calculation of the effects of delayed neutron precursor transport in molten salt reactors"*; Proceedings of the International Conference on The Physics of Fuel Cycles and Advanced Nuclear Systems: Global Developments (PHYSOR 2004); Chicago, Illinois, April 25-29, 2004, on CD-ROM, American Nuclear Society (2004)

Further publications

A. Molten salt reactors

[K9] W. Maschek, A. Stanculescu, ... , J. Kophazi et Al.; *"Report on Intermediate Results of the IAEA CRP on Studies of Advanced Reactor Technology Options for Effective Incineration of Radioactive Waste"*; Energy Conversion and Management, vol. 49, 1810-1819, (2008)

[K10] Kópházi J., Fehér S., D. Lathouwers, J.L. Kloosterman: *„Sóolvadékos reaktorok háromdimenziós időfüggő modellezése"*; V. Nukleáris Technikai Szimpózium, Paks, 2006. november 30 - december 1.; ISBN 978-963-420-916-4, CD-ROM (2007)

[K11] Kópházi J., Szieberth M., Yamaji B.: *„Transzmutációs kutatások VI."*; Kutatás-fejlesztési részjelentés, BME-NTI-407/2007, Budapest, 2007. november (2007)

[K12] Fülöp I, Kópházi J., Szieberth M., Yamaji B., Légrády G., Reiss T., Fehér S.: *„Transzmutációs kutatások III."*; Kutatás-fejlesztési részjelentés, BME-NTI-372/2006, Budapest, 2006. november (2006)

[K13] Yamaji B., Kópházi J., Szieberth M. , Csom Gy., Fehér S.: *„Transzmutációs kutatások II."*; Kutatás-fejlesztési részjelentés, BME-NTI-307/2005, Budapest, 2005. október (2005)

[K14] Kópházi J., Szieberth M., Yamaji B., Fehér S., Csom Gy.: *„Transzmutációs kutatások I."*; Kutatás-fejlesztési részjelentés, BME-NTI-288/2004, Budapest, 2004. november (2004)

[K15] M. Szieberth, J. Kophazi, B. Yamaji, C. le Brun (ed.), A. Nuttin, D. Heuer, L. Mathieu, J. Krepel, R. Koch, R. Vocka, C. Garzenne (ed.), D. Lecarpentier, A. Rineiski, M.

Schikorr, W. Gudpwski, S. Dulla, P. Ravetto, O. Köberl, P. Aujollet, P. Marucci: *"MOST – WP2&3 Reactor Physics Study, Design Review and Nominal Operating Conditions, non Proliferation Issues"*; 1998-2002 (2004)

[K16] M. Delpeche, S. Dulla, C. Garzenne, J. Kophazi, J. Krepel, C. Lebrun, D. Lecarpentier, F. Mattioda, P. Ravetto, A. Rineiski; *"Benchmark of Dynamic Simulation Tools for Molten Salt Reactors*"; Proceedings of the International Conference GLOBAL 2003, New Orleans, p. 2182-2187 (2003)

[K17] Kópházi J., Szieberth M., Fehér S., Czifrus Sz., Csom Gy.: *„Folyékony üzemanyagú reaktorok reaktivitásveszteségének számítása módosított MCNP kóddal"*; MNT II. Nukleáris Technikai Szimpózium 2003, Budapest (BME) 2003. december 4-5. (2003)

B. Incident cleanup in the Paks NPP

[K18] A. Wirth, S. Fehér, J. Kópházi, S. Czifrus: *"Criticality safety analysis of the incident occurred at Paks NPP in 2003*"; Proceedings of the International Conference on Reactor Physics, Nuclear Power: A Sustainable Resource (PHYSOR 2008); Interlaken, Switzerland, September 14-19, 2008 (2008)

[K19] A. Wirth, S. Fehér, J. Kópházi, S. Czifrus: *" Reactor Physics Aspects of the Incident Occurred at Paks NPP in 2003*"; Proceedings of the 2008 International Congress on Advances in Nuclear Power Plants (ICAPP '08); Anaheim, CA USA, June 8-12, 2008 (2008)

[K20] Fehér S., Kópházi J., Szieberth M.: *„A tisztítótartály köré telepített neutrondetektorok jelére alapozott védelmi rendszer vizsgálata"*; Kutatási jelentés, BME-NTI-290/2004, Budapest, 2005. január 18. (2005)

[K21] Fehér S., Kópházi J.: *„A tisztítótartályba telepítendő ideiglenes vészbórozó rendszer hatásosságának vizsgálata"*; Kutatási jelentés, BME-NTI-289/2004, Budapest, 2005. január 5. (2005)

[K22] Fehér S., Kópházi J.: „A tisztítótartályban található fűtőelem-kazetták eltávolítása során használt szerszámok szubkritikussági elemzése"; Kutatási jelentés, BME-NTI-283/2004, Budapest, 2004. október 12. (2004)

[K23] Fehér S., Kópházi J.: „*A tisztítótartály köré telepített neutrondetektorok jele közötti kapcsolat vizsgálata”*; Kutatási jelentés, BME-NTI-297/2004, Budapest, 2004. augusztus 5. (2004)

[K24] Fehér S., Kópházi J., Czifrus Sz., Berki T.: „*A tisztítótartályban található sérült üzemanyag részletes háromdimenziós reaktorfizikai modellezése”*; Kutatási jelentés, BME-NTI-281/2004, Budapest, 2004. május 20. (2004)

[K25] Szatmáry Z., Fehér S., Csom Gy., Kópházi J., Czifrus Sz.: „*A 2. blokki meghibásodott tisztítóberendezés reaktivitására vonatkozó számítások”*; Kutatási jelentés, BME-NTI-274/2003, Budapest, 2003. december (2003)

[K26] Fehér S., Kópházi J., Czifrus Sz., Csom Gy.: „*A 2. blokki tisztítótartályra vonatkozó kritikussági számítások normál és sérült geometria mellett”*; Kutatási jelentés, BME NTI-267/2003, Budapest, 2003. május 6. (2003)

C. SPN detectors

[K27] S. Fehér, J. Kópházi, G. Pór, Sz. Czifrus, P.F.A. de Leege: *”Development of an MCNP-based calculational model for segmented type self-powered neutron detectors”*; Proceedings of the International Conference on the New Frontiers of Nuclear Technology: Reactor Physics, Safety and High-Performance Computing (PHYSOR 2002), ISBN 0-89448-672-1, October 7-10, 2002, Seoul, Korea, (2002)

[K28] Fehér S., Kópházi J., Czifrus Sz., Pór G.: „*Elektronemissziós neutrondetektorok működésének elemzése Monte Carlo modellszámítások és mérési eredmények összevetésével”*; MNT Nukleáris Technikai Szimpózium 2002, Budapest (BME) 2002. október 3-4. (2002)

[K29] Fehér S., Pór G., Kópházi J., Czifrus Sz.: „*Béta-emissziós neutrondetektorok működésének modellezése a mért jelek feldolgozásának és metrológiájának javítására”*; Kutatási jelentés, OAH/NBI-ABA-28/01, p. 95. BME-NTI-257/2002, 2002. január 31. (2002)

[K30] J. Kópházi, Sz. Czifrus, S. Fehér, G. Pór: *”Measuring Delayed Part of the Current of a Self-Powered Neutron Detector and Comparison with Calculations”*; *Proceedings*

of the International Conference on Nuclear Energy in Central Europe 2001, September 10-13, 2001, Portoroz, Slovenia (2001)