Title	Multi-physics modelling of small modular reactors with Serpent 2 and thermal hydraulics solvers
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Citation	4th International Technical Meeting on Small Reactors, 2 - 4 November 2016, Ottawa, Canada, Pages 4.
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4th International Technical Meeting on Small Reactors (ITMSR-4)
Delta Ottawa City Centre Hotel
Ottawa, Ontario, Canada, 2016 November 2-4

MULTI-PHYSICS MODELLING OF SMALL MODULAR REACTORS WITH SERPENT 2 AND THERMAL HYDRAULICS SOLVERS

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ABSTRACT – In this work coupled problems with neutronics and thermal-hydraulics are solved with Serpent 2 Monte Carlo code and thermal hydraulics solvers. The focus is on modelling small modular reactors (SMRs). To demonstrate that a steady state coupled neutronics/thermal hydraulics problem can be solved with the coupled code system, a SMR core in a steady state at full power with multiphase flow will be modelled.

1. Introduction

Recently there has been an increasing interest towards the development of small modular reactors which are advanced reactors with electric power up to 300 MW. This interest is explained by lower financing cost compared to larger reactors and the need to service small electricity grids. SMRs also have shorter construction times and can offer non-electric applications such as desalination and district heating. Even though SMRs have many differences in design and construction compared to traditional larger reactors the physics related to the safe operation of a reactor stay the same. The key difference is the much smaller size of the modelled system.

The accurate modelling of a nuclear reactor is a cumbersome task as considering only the neutronics of the core is not enough due to several important feedback mechanisms. The main focus of this research is on the two-way feedback with thermal hydraulics. In reactor physics, thermal hydraulics is used to solve density and temperature distributions which have major effect on neutron flux distribution and spectrum. An increase in the moderator temperature results in a decrease in moderator density and moderating effectiveness. This in turn hardens the neutron spectrum which is a negative reactivity addition in a thermal reactor. In the fuel the neutron flux is mainly affected by the Doppler broadening of the effective resonance cross sections. As the fuel temperature increases so does the resonance absorption of neutrons. Most SMR designs employ passive safety systems which rely on feedback effects. Therefore it is vital to take the feedback with thermal hydraulics into account when modelling SMRs.

Different approaches exist to solve the coupled problem with neutronics and thermal-hydraulics. The neutronics are typically solved using either multi-group deterministic or continuous energy Monte Carlo methods. Thermal-hydraulics are usually solved using subchannel/channel or computational fluid dynamics (CFD) codes.

In this research the goal is to solve coupled steady state and transient problems with a focus on SMRs. The neutronics are solved with Serpent 2, a Finnish state-of-the-art Monte Carlo neutronics code developed at VTT. Monte Carlo method is the tool of choice for modelling the geometry and interaction physics to within maximum accuracy. The tradeoff is the high computational requirements. Luckily the required calculation time for accurate results depends heavily on the size of the modelled system. The small size of SMR cores makes it possible to do full-core calculations which would be computationally too expensive for larger reactors.

Thermal-hydraulics are solved with the COSY (COmponent/SYstem-scale) thermal-hydraulics tool also developed at VTT. The coolant flow solution is based on a porous-media three-field flow model on unstructured grid. The code also solves axial and radial temperature distributions in the fuel and the cladding using finite volume method as well as the radial expansion of the fuel rods.

The motivation to this research is the fact that an accurate solution of the coupled problem is vital for the safe operation of a nuclear reactor at full power. For example, the fuel temperature must remain within safety limits at all times. Serpent can also be used to calculate the decay heat source term which is important after the reactor has been shut down. The accurate solution obtained using Monte Carlo/thermal hydraulics coupling can be used to assess the fulfilment of the safety limits. It can also be compared to a solution obtained using less accurate methods for example to ensure that the error in the solution of a system scale code is insignificant concerning the safe operation of the reactor.

2. Background

2.1 Serpent 2

Serpent [1] is a Monte Carlo reactor physics code developed at VTT Technical Research Centre of Finland since 2004. The code was originally written for spatial homogenization but has gained many additional features over the years of development. These include a built-in burnup calculation capability and an universal multi-physics interface [2] which allows coupling to external CFD, thermal hydraulics and fuel performance codes. The interface allows the modelling of materials with arbitrarily refined temperature and density distributions supplied by the external solver. Serpent uses several special methods for efficient neutron tracking. These include the Woodcock delta tracking for neutron transport which simplifies the geometry routine and reduces calculation times, and on-the-fly temperature treatment routine based on the Target Motion Sampling (TMS) technique [3] which makes it possible to use materials with high resolution temperature distributions in the problem geometry.

2.2 COSY

COSY is a three-dimensional thermal-hydraulic analysis tool intended for safety analyses of nuclear power plants. The code is able to solve both steady state and transient problems with the aim to capture the large-scale three-dimensional effects on the flow fields. The finite volume method used for the flow solution is based on a porous-medium three-field flow model. The flow equations are solved on an unstructured grid saved in CGNS file format. COSY also solves axial and radial temperature distributions in the fuel and the cladding as well as the radial expansion of the fuel rods. In order to couple COSY with Serpent 2 special input and output routines compatible with Serpent's multi-physics interface have been implemented to COSY.

2.3 Previous coupled thermal hydraulics calculations with Serpent 2

Serpent 2 has been previously coupled internally to the sub-channel code SUBCHANFLOW developed at Karlsruhe Institute of Technology (KIT) in Germany. The coupled code system has been used for example to simulate full PWR core in steady-state [4] and the CZP/HFP states of the SPERT research reactor [5].

In my Master's thesis Serpent 2 was coupled externally with a CFD solver from the OpenFOAM toolbox [6]. The coupling was tested by modelling a mock-up 5x5 fuel assembly cooled with water in a steady state condition at full power. The flow was modelled as single phase and the effects of boiling were neglected. Solving the coolant flow in full core calculations with CFD is currently not possible as it is computationally too expensive.

The development to couple Serpent 2 with COSY was started in September 2015. The first step was to write a subroutine that converts the CGNS-mesh used in COSY flow solution to the OpenFOAM mesh format which is used in the Serpent multi-physics interface. After that output routines were implemented in order to write coolant density and temperature fields as OpenFOAM field files. Finally, output routines for the fuel and cladding temperature distributions were implemented to COSY as well as an input routine to update the power distribution in COSY based on Serpent output.

The Serpent/COSY-coupling has been tested by modelling a mock-up SMR core in a steady state at hot full power with single phase flow. Core specifications were based on publicly available data from the NuScale SMR design. The test calculation converged without problems and the coupling routines worked as intended.

3. Current coupled calculations and expected results

A SMR core in a steady state at full power with multiphase flow will be modelled. Core specifications will be based on a real SMR design if possible. Otherwise a mock-up SMR core will be modelled. The idea is to demonstrate that a steady state coupled neutronics/thermal hydraulics problem can be solved using the Serpent-COSY coupling and assess the computational cost of the solution. Detailed temperature and density distributions acquired from the coupled calculation can be used in assessing relevant safety parameters. In addition, a separate Monte Carlo simulation can be run with the final temperature and density distributions to study key parameters such as effective multiplication factor with high accuracy.

The obvious next step is to move to coupled transient problems by making use of the transient capabilities of Serpent 2 that are currently under development [7]. As transient simulations with Monte Carlo method are even more time consuming than the steady state simulations, the applicability of the Monte Carlo method to SMR full-core transient modeling remains to be seen.

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