Coupling of dynamic Monte Carlo with thermal-hydraulic feedback

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A B S T R A C T

Transient analysis of nuclear reactors is traditionally the domain of deterministic methods, even tough these methods are known to have limitations. With the development of dynamic Monte Carlo and the development of coupled-steady state Monte Carlo calculations the road has been paved to perform transient analysis of high power reactors using Monte Carlo. By this way, it is possible to take into account the thermal-hydraulic feedback, while the neutron transport is modelled in full detail.

In this paper a new method is described, which can perform such stochastic analysis of a transient scenario.

1. Introduction

One of the most important aspects for transient analysis is the thermal-hydraulic feedback. This feedback mechanism is essential for the safe operation of nuclear reactors. For example, when the temperature in a light water reactor increases, the density of the moderator decreases and neutrons will be less moderated, causing, in general, a reactivity decrease. When the reactivity becomes negative, the power produced will be reduced, which lowers the temperature of the reactor. There are many of these feedback mechanisms, some positive and some negative and for the design of a nuclear reactor, it is crucial to take these effects into account. These effects determine the time dependent behaviour of a reactor and therefore the maximum temperatures reached during a transient.

To incorporate these feedback mechanisms into a neutronics calculation, it is common to couple a thermal-hydraulics code to a neutronics code. A thermal-hydraulics code calculates the density profile of the coolant and the temperature profile in the reactor using heat-transfer models and the new material properties are then used for the neutronics calculation. An elaborate description of the methods currently applied can be found in D'Auria et al. (2004).

1.1. Deterministic coupled transient calculations

With the ever increasing computing power, many new developments can be found, which couple a deterministic neutronics solver to a thermal-hydraulics solver. The neutronics solver can be, for example, a nodal code (Vedovi et al., 2004), or, more advanced, use the method of characteristics (Hursin et al., 2011) and these codes can be either internally or externally coupled to the thermal-hydraulics code. The advantage of external coupling is the limited adjustments needed to the codes; they can stay autonomous. With internal coupling on the other hand, the two codes are merged into one code, which is usually faster and therefore possibly more accurate, but this requires more adjustments and the merged code must be validated separately. The external coupling is becoming a standard calculation technique for the analysis of transients in a light water reactor (Peltonen and Kozlowski, 2011), but it is also done for less common reactor types such as the high temperature reactor (Boer et al., 2010) or the molten salt reactor (Kópházi et al., 2009).

A downside of coupling a deterministic neutronics solver with a thermal-hydraulics solver, is the limited accuracy of the deterministic method. When a deterministic neutronics calculation is done, there is always a number of approximations applied, such as discretisation in time, space, energy and angle. Also, more fundamental approximations might be needed, such as homogenisation or application of diffusion theory, which makes it difficult to estimate the error in such calculations. It is possible to verify the final result with a stand-alone Monte Carlo calculation (Broeders et al.,

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2003), but this is only possible if the temperatures and densities are known.

1.2. Coupled Monte Carlo thermal-hydraulics calculations

A recent development in the field of coupled calculations is the coupling between a Monte Carlo neutronic calculation and thermal-hydraulic analysis. Presently this can be achieved only for steady-state calculations, with a fixed power level. Therefore, only the thermal-hydraulic effects that influence the power profile in a reactor are taken into account in the Monte Carlo calculation and the feedback mechanisms that influence the total power are neglected; only the static effect on the reactivity can be analysed, neglecting the dynamic nature of the feedback.

The first occurrence in the literature of the coupling of a Monte Carlo neutronics code with a thermal-hydraulics code was in 2003, when MCNP4C was coupled with SIMMER-III by Mori et al. (2003), but in this case there is no iterative process. The thermal-hydraulics code SIMMER is run once to calculate the temperature profile for MCNP.

Next, in 2004 Bakanov et al. (2004) coupled TDMCC with STAR-CD, but there is little description of the method. A demonstration has been given of a coupled calculation of a fuel assembly, but there is no discussion on the accuracy of the calculation. Joo et al. (2004) used MCCARD to verify the DeCART transport code, both coupled with a simplified feedback script. Here the results of a coupled analysis of a mini core seem to match relatively well between MCCARD and DeCART.

Next, coupling methods have become part of research tools, with the coupling of stand-alone codes, such as MCNP and STAFAS. Waata et al. (2005a) implemented this method to analyse the HPLWR (Waata et al., 2005b).

Meanwhile, the developments continued, focusing on an increased efficiency of the neutronics calculation, with Tippayakul et al. (2008) who used a nodal code to improve fission source convergence, Sanchez and Al-Hamry (2009) worked on the improvement of the convergence of the coupled solution and the mapping between the two codes is further optimised by Seker et al. (2007a). A different direction of research is to develop partly internal coupling (Leppänen et al., 2012) or complete internal coupling investigated by Griesheimer et al. (2008). In these works (some) thermal-hydraulics models are integrated in the Monte Carlo code.

The most recent developments focus on increasing the flexibility of the coupling scheme, making it generally applicable (Hoogenboom et al., 2011; Ivanov et al., 2011) and extension of the coupled calculations to whole-core applications (Kotlyar et al., 2011; Vazquez et al., 2012). The hybrid deterministic/stochastic method which increases the efficiency of the Monte Carlo calculation is further developed by Espel et al. (2013).

1.3. Coupled Dynamic Monte Carlo

This work combines the coupled calculations with the transient calculations in order to perform transient calculations including feedback, using only a Monte Carlo approach for the neutronics part of the calculation.

The Monte Carlo code is coupled to a sub-channel code, which is a fast thermal-hydraulics code, but not a high-fidelity code. Although it might seem more logical to couple a computational-expensive high-fidelity neutronics code to a high-fidelity thermal-hydraulics code, the efficiency of the sub-channel code is more useful during the development of a new method. The theory can be extended easily to any kind of external code, including a high-fidelity computational fluid dynamics (CFD) code (Seker et al., 2007b).

First the theory of the coupling is discussed, next there are three test cases: a proof of principle in simplified geometry, a pin cell on a long time scale and a mini core in a short time scale with a strong transient.

2. Theory

To couple Monte Carlo to thermal-hydraulics in a transient calculation first the initial conditions must be calculated and from this starting point the coupled transient part is started. The possible schemes to do this are discussed in Section 2.1.

The other challenges are specific for Monte Carlo: variance estimation and temperature dependent cross sections. When performing a coupled calculation it should be acknowledged that part of the calculation is not stochastic and this can influence the variance estimation. The implications are discussed in Section 2.3. As the coupling will also create a large number of temperatures, different methods to handle this broad range are discussed in Section 2.4.

2.1. Coupling scheme

In nuclear reactor modelling, it is common to use an operator-splitting technique to solve a multi-physics problem. Although this approach does not take into account the non-linearities which are present in a typical coupled reactor physics problem (Ragusa and Mahadevan, 2009), it is a logical place to start the development of a new coupling technique. When the possibility of coupling Monte Carlo with thermal-hydraulic feedback is demonstrated, more advanced coupling schemes can be investigated.

There are three ways of coupling the thermal-hydraulics calculation and the neutronics calculation: implicit, semi-implicit and explicit. The implicit scheme iterates the coupled codes per time interval until the combined codes have converged. When converged the scheme will continue to the next time interval, as depicted in Fig. 1. The advantage of this scheme is that it can be unconditionally stable, which allows for larger time intervals. However, the downside of this scheme is that it requires major alterations to the existing solvers to allow for the iteration steps. Also, there is a lot of data exchange between the coupled codes and therefore this scheme is usually implemented using internal coupling, making the implementation even more complex. A first attempt was made by Mahadevan et al. (2011) to use a Jacobian-free Newton–Krylov method to perform implicitly coupled calculations with the code system KARMA. On the other hand Watson and Ivanov (2012) incorporated implicit coupling in the TRACE/PARCS code system by explicitly forming the full Jacobian matrix and solving for a global residual.

For the semi-implicit method, the calculation of the current time interval is partly based on data of the previous time interval and partly on the data of the current time interval. For example, when the TRAC-PF1/NEM code calculates the fluxes and the power production, it uses coolant temperatures and densities of the current time interval, but fuel rod temperatures of the previous time interval (Ivanov and Avramova, 2007).

In most cases the explicit coupling scheme is used, since this is the easiest to implement and codes do not have to be altered, so validated codes can be used. Also, it is a fast method since there is no iteration involved, allowing the use smaller time intervals. When using this method one should beware that the time interval is small enough to ensure stability.

The temperature and density profiles are calculated with the thermal-hydraulics code and with these profiles the power distribution is calculated. This power distribution is then used in the thermal-hydraulics code. This scheme is depicted is Fig. 2 and this is also the scheme used in this work, because of its calculation speed and the possibility to couple externally.