THERMAL HYDRAULIC REACTOR CORE CALCULATIONS BASED ON COUPLING THE CFD CODE ANSYS CFX WITH THE 3D NEUTRON KINETIC CORE MODEL DYN3D

A. Grahn, S. Kliem, U. Rohde
Forschungszentrum Dresden-Rossendorf, Institute of Safety Research

J. Schütze, Th. Frank
ANSYS Germany GmbH

1. Introduction

In order to get the correct feedback on the core reactivity, analyses of postulated reactivity initiated accidents in nuclear reactors require the coupled solution of the neutron transport equation, the equations of heat conduction in the fuel and the heat and momentum transport in the coolant. The code DYN3D developed at Forschungszentrum Dresden-Rossendorf is a neutron kinetic core model, which solves in its basic version the three-dimensional neutron diffusion equation in two energy groups for fuel assemblies with rectangular and hexagonal cross sections [1]. Recently the code was extended to an arbitrary number of energy groups and a simplified transport approximation for neutron flux calculations in fuel assemblies with quadratic cross section was implemented [2]. DYN3D's thermal hydraulic part is based on a one-dimensional representation of the coolant flow in the fuel assemblies. It has therefore only limited capabilities of modeling the cross flow between fuel assemblies.

The CFD code ANSYS CFX [3] is the reference CFD code of the German CFD Network in Nuclear Reactor Safety. One of the goals of the co-operation inside this network is the development of CFD software for the simulation of multi-dimensional flows in reactor cooling systems. This includes the coupling of the CFD code ANSYS CFX with the 3D neutron kinetic core model of DYN3D, in order to extend the description of the coolant flow and of the convective heat transport to three dimensions. This may finally lead to more plausible temperature and power distributions in the core.

The present paper gives an overview on the implementation of the coupling and two examples of full reactor core calculations.

2. Coupling of ANSYS CFX and DYN3D

The coupling approach is based on the selection of best-in-class software tools for the simulation of each of the phenomena to be described by the coupled codes. For this, the module predicting the coolant flow within DYN3D is replaced by a fully three-dimensional CFD simulation using ANSYS CFX. A detailed and spatially resolved modeling of the whole reactor core down to the fuel pin level in the CFD code is not feasible for practical applications at present and in the foreseeable future. It is possible to achieve acceptable computation times only by modeling the reactor core as a porous region. This reduced resolution of the structures in the core affects the thought location of the interface between the CFD code and the neutron kinetics core model. An incorporation of the bare neutron kinetics model of DYN3D only, as it was done in the internal coupling of ATHLET and DYN3D [4], is not possible because the heat transfer from the fuel pins to the coolant cannot be calculated by ANSYS CFX due to the above mentioned restrictions. Therefore, it was decided to define the physical data interface at the level of the volumetric heat release rate into the fluid. The CFD code ANSYS CFX calculates the fluid dynamics in the reactor coolant inside the core. It provides the velocity, temperature, density and boron concentration fields to DYN3D. Based on these parameters DYN3D determines the nuclear power, calculates the fuel temperature distribution and the heat transfer to the coolant. The volumetric heat source is given back to ANSYS CFX. It should be noted that in the current prototype, the coupling is restricted to single-phase flow conditions [5].

In the coupled calculation, ANSYS CFX acts as the master program; DYN3D is implemented as a set of subroutines. A 3D volume mesh-to-mesh transfer of field quantities between ANSYS CFX and DYN3D had to be implemented taking into account the largely different mesh resolutions used in the two codes. A 3D-volume mesh-to-mesh transfer for arbitrary data fields was implemented in CFX. The conservation of the data during transfer is properly ensured. The DYN3D coarse nodalisation is represented by a separate, coarsely meshed zone in CFX. This coarsely meshed zone is also available for post-processing DYN3D data in CFX-Post. Both zones co-exist side-by-side in CFX.

For steady-state calculations an iteration scheme between ANSYS CFX and DYN3D was implemented. In the DYN3D stand-alone case the thermal hydraulics is brought to convergence at each iteration step before going to the solution of the neutron-kinetic equations. In the coupled code calculation the approach is different: DYN3D is called at the end of each iteration step of ANSYS CFX. In this way, the number of iterations between the codes increases, but this implementation requires less total computation time as the dominant part of the computation time is spent on ANSYS CFX.

At the current stage of the implementation no iteration between ANSYS CFX and DYN3D is carried out during transient calculation. An explicit coupling approach is applied. DYN3D is called at the end of each time-step.

3. Steady-state problem simulations

3.1. KONVOI-type reactor at hot full power

The first case calculated is a PWR core with 193 fuel elements operating at full power. The coolant enters the core at a temperature of 280 °C and has a pressure of 15.8 MPa. The boron concentration is 1364 ppm and the total mass flow of the coolant is 18600 kg/s. Figure 1 shows the computational grid used for the simulation. It consisted of 1,602,392 hexahedral mesh nodes. The temperature distribution in the central plane is shown in Fig. 2, while Fig. 3 compares the horizontal temperature profiles that were found with the coupled code and with the stand alone DYN3D code in the central plane at the core outlet. The temperature distribution results from the heat source distribution shown in Fig. 4. In Fig. 5, the distribution of the horizontal x-component of the velocity is shown. A lateral coolant flow at a velocity in the order of 1.5 cm/s from the circumference of the core centre can be seen. It is driven by the acceleration of the liquid in the centre due to the stronger heating. This flow increases the exchange of heat in the lateral direction by advection and leads to a 'smearing' of the step-like temperature profile that has been found in a pure DYN3D calculation with its 1D thermal hydraulic model (cf. Fig. 3).

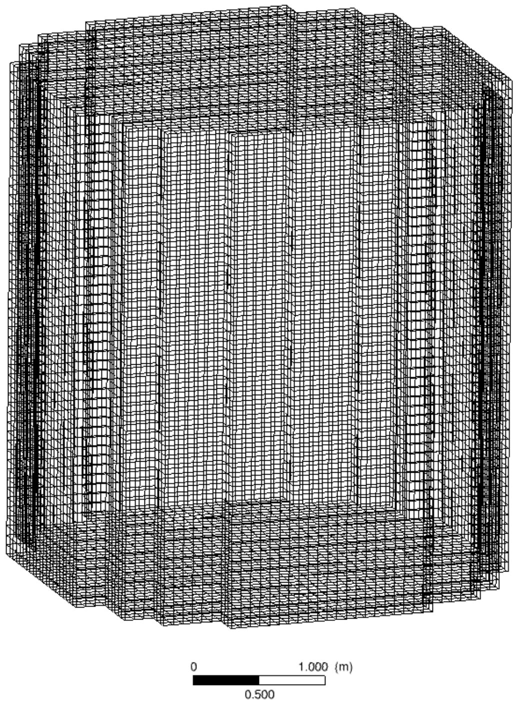


Fig. 1: Computational grid of a 193 element PWR core

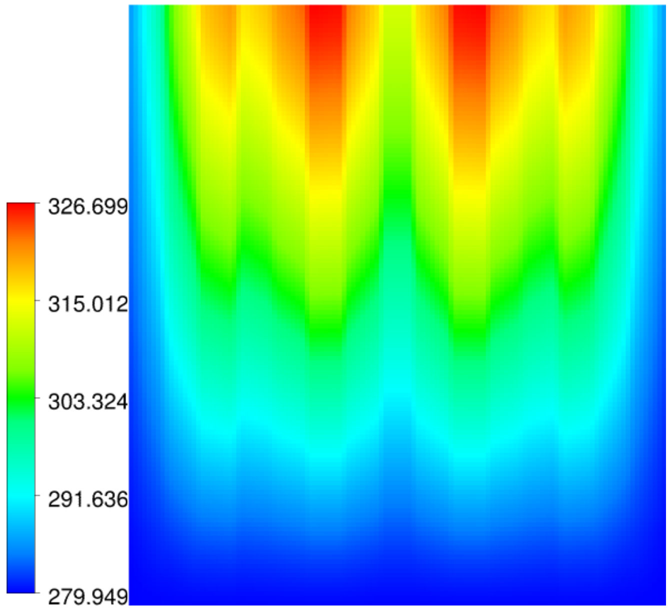


Fig. 2: Temperature (°C) distribution in the z-x plane

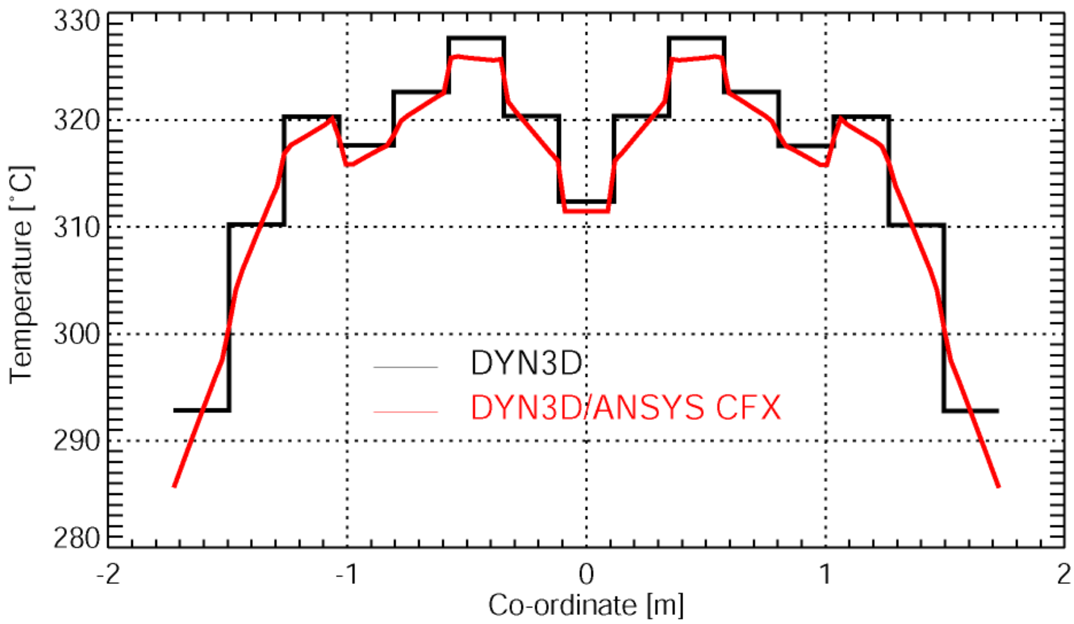
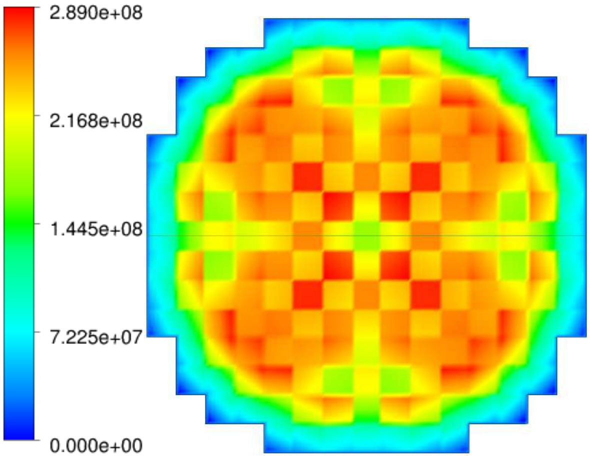


Fig. 3: Horizontal temperature profiles in the core's central plane at the core outlet as computed by the coupled code (red) and by DYN3D alone



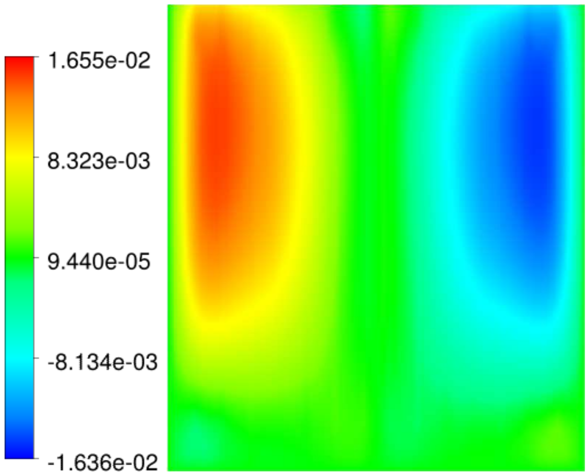
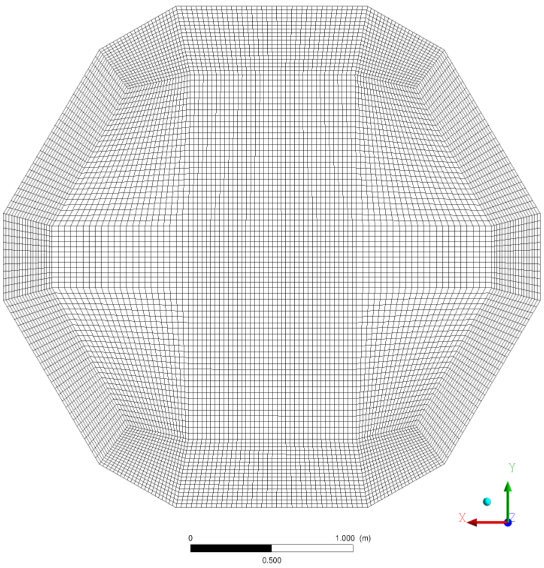


Fig. 4: Heat source (W/m^3) distribution at z=0.5 m above bottom

Fig 5: Distribution of the x-component of coolant velocity (m/s) in the z-x plane

3.2. VVER-1000 reactor core

The second case is a VVER-1000 core with 163 hexagonal fuel elements with a total power of 3000 MW. It is fed with a coolant mass flow of 18000 kg/s. Temperature and pressure of the coolant at the entry are 285 °C and 15.72 MPa, respectively. The boron concentration amounts to 952 ppm. An unstructured, tetrahedral mesh was used for the flow simulation, which consisted of 1,256,818 nodes (Fig. 6). The temperature and heat source distributions are shown in Figs. 7 and 8. It should be noted that the steep temperature changes between neighbouring fuel assemblies found in the simulation are due to the fact that a core configuration at the begin of a fuel cycle is used with relatively big differences in the power of the single fuel assemblies.



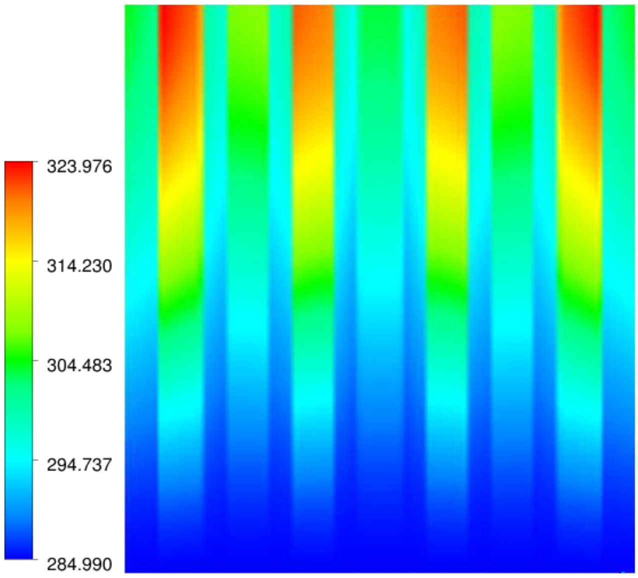


Fig. 6: Computational grid (top view) of a VVER-1000 core

Fig. 7: Temperature (°C) distribution in the z-y plane

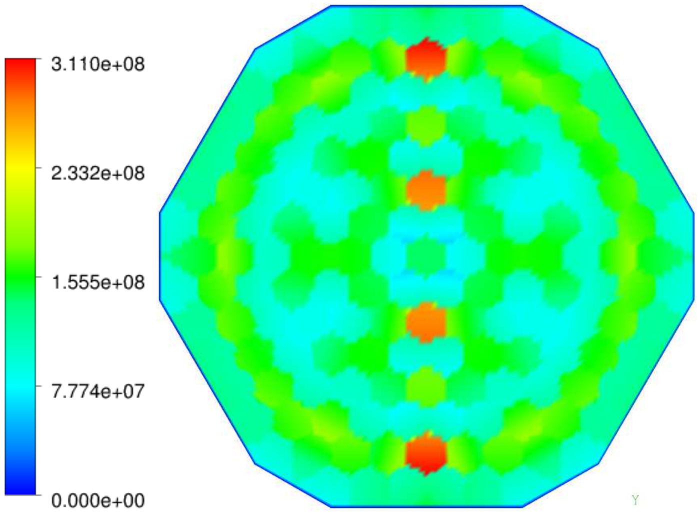


Fig. 8: Heat source (W/m^3) distribution at z=1.38 m above bottom

The same effects as in the PWR case can be observed but the cross flow is less pronounced in the VVER case. This is connected with the fact that the fuel assemblies with higher power production are not concentrated in the inner part of the reactor core.

4. Conclusions and future work

The coupling of the CFD code ANSYS CFX with the neutron-kinetic core model DYN3D was demonstrated by steady state simulations of two different reactor cores. It could be shown that the coupled code system ANSYS CFX/DYN3D allows for analyses with more plausible results of coupled thermal hydraulics – neutron kinetics problems because three-dimensional coolant flow and heat transport can now be simulated.

Further verification and validation is needed before its application to accident scenarios. The extension of the coupling to two-phase flow conditions is a further precondition to carry out realistic accident analyses. However, at the current stage, a range of scenarios can already be treated, which involve three-dimensional flows, such as the local blockage of spacer grid areas by insulation material debris in the aftermath of a loss of coolant accident. For this purpose, a fibre deposition model, which has been implemented in ANSYS-CFX, was successfully applied in a PWR situation with hot-leg injection of particle laden emergency cooling water [6].

Acknowledgment

The projects this paper is based on were funded by German Federal Ministry of Economics and Technology (Contract numbers 150 1328 and 150 1358).

References

[1] U. Grundmann, U. Rohde, S. Mittag, "DYN3D – Three Dimensional Core Model for Steady-State and Transient Analysis of Thermal Reactors", Proc. PHYSOR2000, CDROM (2000)

[2] C. Beckert, U. Grundmann, “Development and verification of a nodal approach for solving the multigroup SP3 equations”, Annals of Nuclear Energy, 35/1, pp. 75-86 (2008)

[3] ANSYS Inc., ANSYS 12.0 User’s Guide, Canonsburg, PA, USA (2009)

[4] Y. Kozmenkov, S. Kliem, U. Grundmann, U. Rohde, F.-P. Weiss, “Calculation of the VVER-1000 coolant transient benchmark using the coupled code systems DYN3D/RELAP5 and DYN3D/ATHLET”, Nucl. Eng. Design, 237, pp. 1938-1951 (2007)

[5] S. Kliem, U. Rohde, J. Schütze, Th. Frank, “Prototype coupling of the CFD code ANSYS CFX with the 3D neutron kinetic core model DYN3D”, Proc. Annual Meeting on Nuclear Technology 2010, paper 104, INFORUM GmbH, Berlin (2010)

[6] T. Höhne, A. Grahn, S. Kliem, and F.-P. Weiss, “CFD simulation of fibre material transport in a PWR core under loss of coolant conditions”, submitted to KERNTECHNIK