A procedure for coupled neutron physics and thermal hydraulic simulation of gas-cooled ADS

R. Dagan, V. Sanchez, C.H.M. Broeders,

Forschungszentrum Karlsruhe GmbH
Forschungszentrum Karlsruhe

Postfach 3640,
D-76021 Karlsruhe

dagan@irs.fzk.de

1. Introduction

The gas coolant option is, due to its passivity to chemical reactions and due to the favorable void reactivity feedbacks compared to Liquid Metal (LM) coolants, one of the promising solutions for an accelerator driven system (ADS). As earlier realized for LM cooled ADS with the procedure SAS4ADS [1], simulation tools to analyze the steady state and transient behavior of gas-cooled ADS have to be developed. In this contribution the coupling of the thermal hydraulic code ATHENA with the neutron physics capabilities of the KAPROS-E system [2] is presented.

2. The calculation tools

2.1. The thermal hydraulic code ATHENA

ATHENA [3] is a thermal hydraulic code system simulating a wide range of transients and postulated accidents of nuclear systems. It represents an extension of the best-estimate code system RELAP5/MOD3 [4]. Its unique feature to handle not only light water but also several gases as working fluid, makes ATHENA an attractive tool for the safety evaluation of innovative systems like transmutation machines (ADS). A generic approach allows the modeling of complex systems including different circuits, many components e.g. pumps, valves, turbine, pipes, control system components. A full set of equations for the fluid-dynamic system can be numerically solved assuming a non-homogeneous and non-equilibrium two phase flow model. Particular models account for chocked flow, flow at abrupt area changes, form losses etc. The code can also handle forced and natural convection for gas coolant following various types of incidents. Thereafter, reliable simulations for gas-cooled systems are covered by the ATHENA modeling. The power amplitude of ATHENA is governed by point kinetic model and an external source can be integrated in the model. The overall coupling procedure is similar to the coupled code system for liquid metal coolants -SAS4ADS [1].

2.2. The modular code system KAPROS-E

The code system KAPROS-E is described in [2] in some detail. For the investigation of gas cooled ADS the cross section calculations and the determination of neutron fluxes and power distributions are performed with KAPROS modules. The modularity of KAPROS-E allows coupling for the implementation of diffusion as well as transport solutions, e.g. the codes CITATION [5] and DIF3D [6] for hexagonal core structures. In this way a coupled system of ATHENA and KAPROS can provide a comprehensive analysis tool for gas-cooled systems with updated data transfer between the thermal hydraulic and the neutronic parts. The preliminary results shown in the section 4 are based on the diffusion code CITATION, sufficient at this stage, to demonstrate the overall behavior of the gas-cooled system.

2.3. The coupled system KAPROS-E / ATHENE

In ATHENA the dependency of the neutron physics parameters on the thermal hydraulic properties is pre-defined and fixed throughout the calculation. In the coupled system those parameters should be modified, based on a full 3D flux calculation within KAPROS-E every time step. Moreover a source “shut off” and “startup” option should be implemented in the ATHENA part in connection with the neutron physics part. In section 4 the required steps for coupling are performed manually for an actual steady state application.

3. Gas-cooled core design for ADS

In the PDS-XADS project, of the 5. European Community Framework Program, the use of existing high enriched MOX fuel is considered. Thus the manufacture costs are strongly reduced while the incineration of the plutonium isotopes and minor actinides can be analyzed. A preliminary core design based on the utilization of slightly modified existing SNR300 fuel assemblies is shown in figure 1. The inner zone is lead bismuth buffer zone in which the external source is located. The 3rd and 4th rings are loaded with 42 SNR300 fuel assemblies of type C1-MAGNOX [7]. This type of fuel is enriched by 19.45% fissile plutonium. The outer rings contain 60 sub-assemblies C2-LWR [7] where the fissile plutonium enrichment reaches 26.4%. This double enrichment strategy flattens considerably the flux distribution and reduces the peak factor to 1.46. Moreover shutting off the source causes only minor changes in the system sub-criticality, enhancing the reliability of the system during source trips. A large reflector surrounds the fuel sub-assemblies, consisting of structural material and helium gas at equal volumetric proportion. The active core height is 95 cm. The core power is 80 MW_{Th}. The multiplicity of this core is 0.957 with activated source. Other fuel loadings could also be considered if higher criticality level is being selected. In this case another six subassemblies could be added to the outer fuel ring. However, the permissible criticality level is connected to thermal hydraulic considerations and thereafter a coupled code system is inevitable for core analysis.

4. Preliminary results

At the present stage the ATHENA code is used for the steady state mode only. The ATHENA-simulations are performed using the neutron physics parameters predicted by KAPROS-E, e.g. the axial power profile is manually transferred for the thermal hydraulic computation. ATHENA predicts the local parameters of the core, e.g. fuel average temperature, coolant density, pressure etc. along the core height. In the next stage, an automatically simulation is planned, as already realized with KAPROS-RELAP5 coupling [2]. The updated properties of the fuel cladding and coolant will be inserted into KAPROS-E input for the calculation of the modified space-dependent power distribution using updated cross-section data according to parameters predicted by ATHENA.

A thermal hydraulic simplified core model for the gas-cooled ADS-system was developed for the ATHENA/KAPROS-E simulation. In the ATHENA-model, the core is represented by one coolant channel with 9 axial nodes representing the 95 cm active core height. The corresponding flow area, hydraulic diameter, heated and wetted perimeters, etc. are part of the input. The fuel pins are simulated by one representative heat structure that is connected to coolant channel by convective boundary conditions. The axial power profile predicted by the neutron physics part of KAPROS-E was part of the input for the heat structure in ATHENA. For the reactor power of 80 MW_{Th} a helium mass flow rate of about 62 kg/s was fixed in the input. The helium temperature at the core inlet was taken from the reference design [8].

The results obtained from ATHENA are mainly connected to normal operation. In figure 2 the fuel clad and gas coolant temperature along the hottest channel are shown. The maximal clad temperature is 791 K far from its melting temperature at about 1700 K. The fuel temperature is also very low and is about 1700K below the melting point. The pressure drop along the active core is 0.15 bar. This is well below the value of 1 bar indicated in [8] for the total pressure taking into account the volumes below and above the core. The value of 1 bar pressure drop is an important constraint to assure that natural circulation takes place under accidental conditions to remove the decay heat from the system. The predicted core heat up is 249 K. This is in good agreement with the ~250 degrees value reported in [8].

5. Conclusions and perspectives

The current manually coupled system of the ATHENA gas-cooling option with validated neutron physics codes of the KAPROS-E system allowed for a preliminary thermal hydraulic design of gas-cooled ADS. The results of the ATHENA code fit well with the temperature and pressure requirements of similar systems. Together with the existing neutron physics codes a basic configuration is accomplished. More modifications are under development in the ATHENA code and within the KAPROS-E system, which will enable a dynamical transient simulation for particular gas-cooled core systems.

ACKNOWLEDGEMENTS

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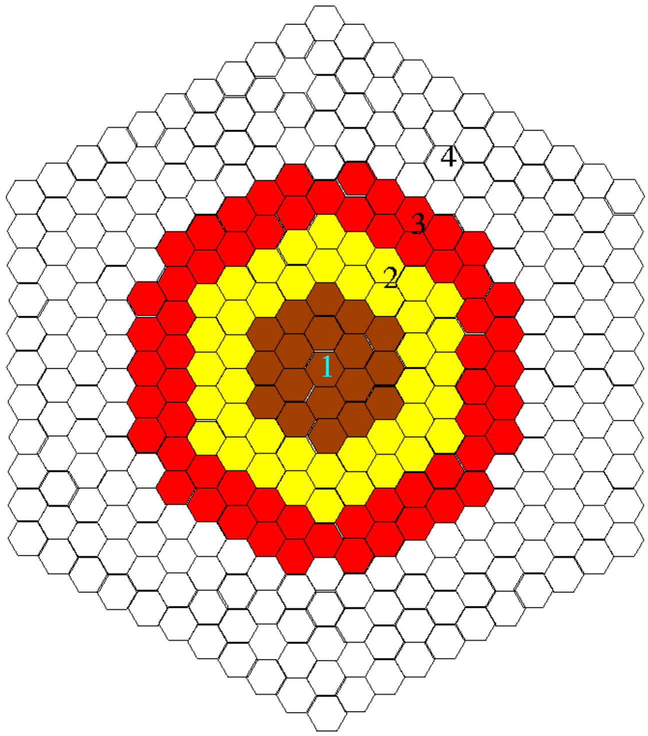

Figure 1: 80 MW_{Th} gas cooled core configuration. The inner zone (1) is lead bismuth source area. The next one (2) consists of 42 low enriched SNR300 fuel elements. The outer fuel zone (3) is highly enriched SNR300 fuel elements. The reflector (4) a helium cooled structural material mixture.

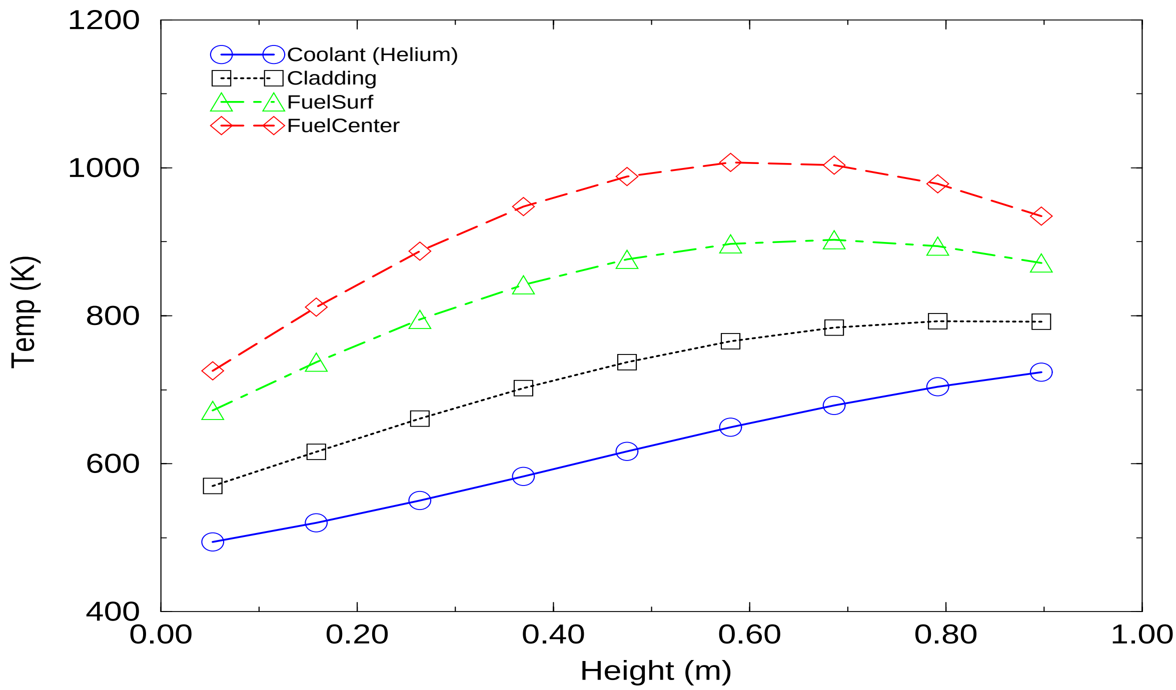

Figure 2. Predicted axial temperature of the coolant, cladding, fuel surface and fuel centerline for the steady state conditions of the gas-cooled ADS based on the code ATHENA. The system power is 80 MW_{Th}.