

Investigation of corner subchannel of ceramic assembly of ALLEGRO reactor

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Gas-cooled Fast Reactor (GFR) is one of the generation IV reactor concepts. The fast neutron spectrum and high outlet temperature of the core make this reactor type a contributor to the sustainability of the nuclear technology. One of the main challenges of the concept is the development of new fuel assembly types, which can withstand the high temperature [1][2]. Because of the high temperature, the thermal conditions of the core have to be known in detail.

The main issue of this paper is to investigate the corner subchannel of the ceramic core of the GFR demonstrator, ALLEGRO. First, models were built for the bare rod bundle to determine inlet boundary conditions for the further models. These models were also used to investigate the effect of the simplification of the geometry. The second step was to develop a model, which included active length ceramic rods with four spacer grids in the region. This model described the heat transfer in the active part of the rod bundle and the heat conduction in the clads. Main purpose of this model is to describe the thermal conditions in the region more accurately.

Keywords—CFD, ALLEGRO, Thermal hydraulics, GFR

I. INTRODUCTION

From the viewpoint of their technological development the fast neutron reactors in operation (fast reactors) "are a step behind the conventional reactors" [WNA, 2014]. Gas-cooled Fast Reactor (GFR) is one of the innovative generation IV reactor concepts. The fast neutron spectrum and high outlet temperature of the core make this reactor type a contributor to sustainability of the nuclear technology. The fast neutron spectrum permits a much better utilization of fissile material resources and reduction of amount of nuclear waste through transmutation. The high outlet temperature of Helium coolant (about 850 °C) allows a high energy conversion efficiency (43-48%) and new applications like hydrogen or synthetic hydrocarbon production. The high thermal cycle efficiency competes with the efficiency of the modern hydrocarbon-fired power plants.

Before construction of an electricity producer GFR (2400 MW_{th}) [1][2], a reactor must be built, which will demonstrate the feasibility of the concept. In order to achieve the above goal, construction of an experimental reactor of 75 MW_{th} (ALLEGRO) is planned after 2020 [3]. The development is currently underway within the framework of national and international projects.

Reactor ALLEGRO serves as a technology required to develop and demonstrate the viability of the concept. The reactor will initially use MOX (Mixed OXide) fuel with steel cladding and later switch to high temperature resistant carbide fuel with ceramic cladding. One of the main challenges of the concept is the development of new fuel assembly types, which can withstand the high temperature [1][2][3]. Because of the high temperature, the thermal conditions of the core have to be known in detail.

The main issue of this paper is to investigate the corner region of a ceramic fuel assembly. The first detailed CFD models of this assembly were developed with the code ANSYS CFX 15.0 in order to analyze its thermal hydraulics. The simulation results were compared to results of empiric correlations. First, the impact of the simplification of the model geometry was considered. Using this model, the inlet boundary conditions for the active length bundle models were also determined. Two cases simulated with the active length model are compared, which differ in the modelling of the fuel cladding.

II. BARE ROD BUNDLE SIMULATIONS

A. Description of models

There are 87 ceramic fuel assemblies in the ceramic core of the ALLEGRO reactor. The fuel will be (U,Pu)C in a ceramic composite cladding made of SiC. There are 90 fuel rods in a fuel assembly with an outer rod diameter of 9.1 mm (Figure 1). The rods are arranged in a triangular lattice with a rod pitch of 11 mm. Total length of the rods is 1.35 m, from which the active section is 0.86 m long.

According to the preliminary design four honeycomb spacer grids in the active length will hold the rods in their position. The distance between the spacers is 246 mm. The assemblies have hexagonal shrouds of SiC. The coolant is helium, which has a mass flow of 36.1 kg/s, pressure of 7 MPa and inlet temperature of 400 °C in the core.

In the model of the corner region of the ceramic assembly symmetry boundary conditions should be applied appropriately therefore more geometrical concepts are considered. Four different geometrical models are built with varying degrees of possibilities offered by the symmetry boundary condition. In Figure 1 the investigated concepts are shown, the green lines represent the boundaries of the models.

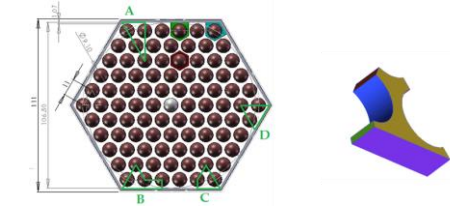


Fig. 1. Cross-section of an ALLEGRO ceramic fuel assembly and geometry of model C

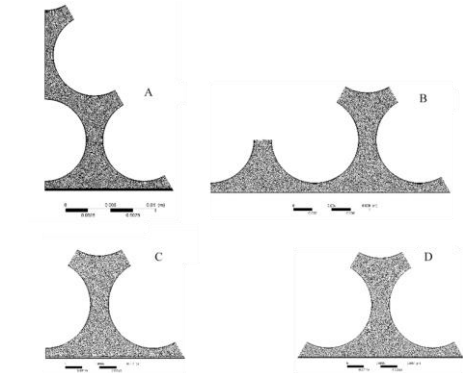


Fig. 2. Meshes of the bare rod bundle models for corner region

Meshes of different densities are created for each geometrical models in order to perform a mesh sensitivity study. The sensitivity study shows that the investigated mesh densities do not affect significantly the results, which will be used as inlet boundary conditions of the active length model. The meshes include prismatic elements in the inner regions and hexagonal elements next to the walls to ensure that the hydraulic boundary layer is described more precisely in the simulations.

The boundary conditions of the models are similar to the boundary conditions of our simulations for the inner subchannels [4]. The vertical plane surfaces with the exception of the shroud are defined as symmetry boundary conditions taking into account the geometrical symmetry. The upper and lower surfaces are connected with periodical interfaces and mass flow boundary condition is set up. With this method a fully developed turbulent flow can be described, which is independent of the axial direction. Material properties of the Helium are given at 400 °C and 7 MPa. For the isothermal simulations BSL Reynolds stress model is chosen. As convergence criteria 10^{-6} are prescribed for the RMS values of the residuals.

B. Results of bare rod bundle simulations

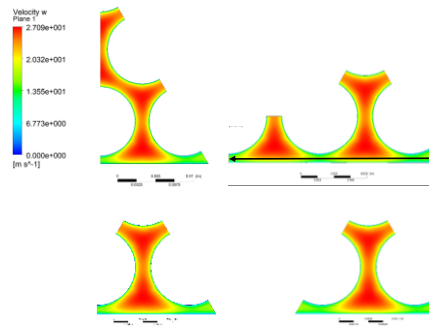


Fig. 3. Axial velocity distributions in the bare rod bundle models (A, B, C and D models)

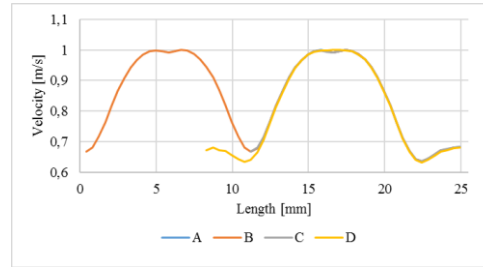


Fig. 4. Axial velocity profiles calculated with different models (line position given in Figure 3)

The axial velocity distributions are shown in Figures 3 and 4. The results of the A, B and C models are similar but the results of the model D are different from these. This is caused by the difference in the selection of the vertical boundaries of the models.

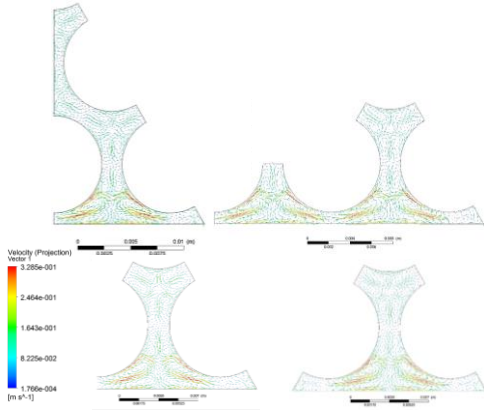


Fig. 5. Cross flows in different geometries (A,B,C and D models)

The cross flows also differ in a similar way (Figure 5). The model bounded with symmetry surfaces of 60° (model D) does not provide adequate results therefore this geometry is not suitable for the development of the active rod bundle models. Models A and B are rejected because of the larger number of elements. Model C is considered the most appropriate one to create active length rod bundle models. From the results of the model C calculated with different grids the friction factors are evaluated. These friction factors are compared to the results of the Rehme correlation [5] (Table 1) in order to verify them. The CFD results agree acceptably with the results of the Rehme correlation. It must be mentioned that the differences are the highest for the finest mesh but the inaccuracy of the measurement correlations has to be taken into account.

TABLE I. FRICTION FACTORS CALCULATED WITH CFD MODELS AND REHME CORRELATION

Mesh	λ calculated with CFD model [-]	λ calculated with Rehme correlation [-]	Difference [%]
C1	0.0291	0.0268	8.58
C2	0.0287	0.0268	7.08
C3	0.0285	0.0268	6.34

III. INVESTIGATIONS FOR CORNER REGION OF ACTIVE ROD BUNDLE

A. Description of models

The model of the corner region of the active rod bundle includes four spacers with the distance between them of 246 mm. The mesh resolution of the fluid domain agrees with the J2 mesh resolution defined in our previous work [4]. The mesh contains tetrahedral elements around the spacer and layers of prismatic elements next to the walls.

Above and under the tetrahedral regions, (in the bare rod bundle sections) the mesh consists of prismatic elements in the inner regions with hexahedral layers next to the walls (Figure 6). The model consists of four mesh domains, which are connected with interfaces.

At the lower surface of the model inlet boundary condition is given and velocity, turbulent kinetic energy and turbulent kinetic energy dissipation distributions are prescribed. The distributions are determined with the C2 bare rod bundle model. For the upper surface outlet boundary condition is defined with 0 Pa relative pressure. The reference pressure is the operating pressure of the system (7 MPa). The surface heat flux of the rods depending on the height is specified with a quadratic polynomial based on neutronics computations [6]. The temperature of the fluid at the inlet is 400°C . Temperature dependent material properties are defined for SiC and Helium. The material properties are given with polynomials based on published data [7][8].

Two different models have been created. The models take into account the structural elements such as claddings of rods. The first model (CR1 - CoRner 1) includes nor the rod claddings neither the assembly shroud (~ 26.7 million elements). In the second model (CR2) 1.08 mm thick SiC rod claddings and physical process of heat conduction in them are considered (~ 27.3 million elements). The rod claddings are meshed with hexahedral elements. In the calculations BSL Reynolds stress turbulence model is used.

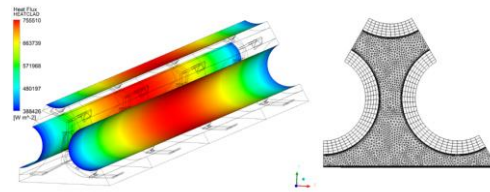


Fig. 6. Heat flux distribution on the inner surfaces of the claddings and mesh of the model

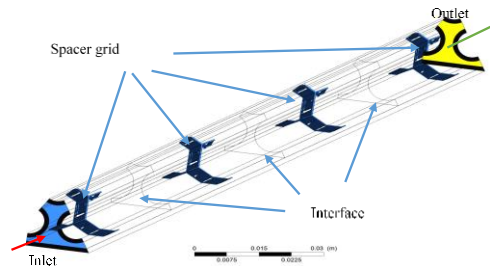


Fig. 7. Structure of the model geometry and boundary conditions

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B. Results of models

Figure 8 shows the axial velocity distributions behind the second spacer grid in the distances 1D and 5D from it. The effect of the spacers on the flow can be clearly observed at 1D behind it. Downstream from the spacers (in the distance 5D) their effect is reduced and the velocity distribution converges to a similar one in the bare rod bundle. After the spacer grids at the same distances the characteristics of the velocity distributions are identical.

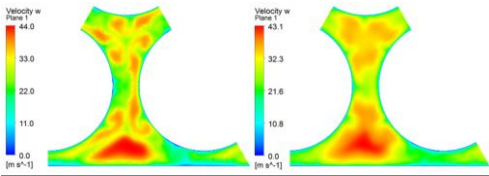


Fig. 8. Cross-sectional velocity distributions behind the second spacers at 1D and 5D.

Figure 9 shows the temperature distributions behind the fourth spacers at 1D calculated with models. The lower right corner of the model CR1, between the assembly shroud and cladding namely in the narrowest flow cross-section the coolant heats-up strongly. This phenomenon is less observable in the CR2 model. In this case the heat conduction in the claddings decreases the value of the thermal maximum. In the inner subchannels, similar temperature distributions are formed as shown in our previous work [4]. It can be observed a lower temperature region between the rods against the wall and assembly shroud. The lower temperature values are caused by the higher mass flow of this region and bounding unheated surface (assembly shroud). The thermal gradient in the claddings is well observable, which is an effect of the low thermal conductivity of SiC. The section of the corner rod which is surrounded by higher temperature corner subchannel has a higher temperature.

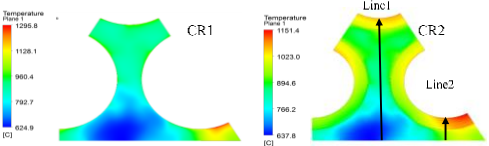


Fig. 9. Cross-sectional temperature distributions behind the fourth spacers at 1D

At altitude of 784 mm the maximum of the cladding temperature (T_{max}) is located. At this altitude the temperature distributions along some lines (Figure 9) are evaluated. The results can be seen in Figure 10.

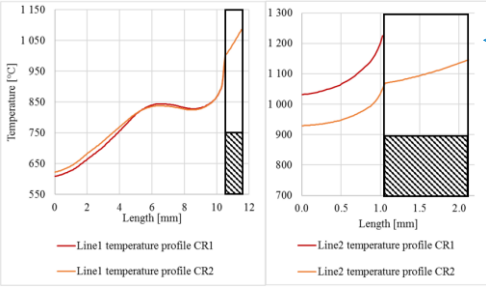


Fig. 10. Temperature distributions along Line1 and Line2 at altitude T_{max}

The temperature distributions along Line1 are very similar near the cladding but different next to the assembly shroud. The temperature maximum in the inner rod cladding is about 1100 °C. Line2 is in the narrowest flow cross-section. The temperature profiles along it differ and temperature is higher calculated with the model CR1 due to neglecting the rod claddings.

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Figure 11 shows the cross-sectional average coolant and cladding temperatures distributions along the length. The Average temperatures of the coolant cladding and the cladding coolant are continuously increasing apart from the surroundings of the spacers. The temperature of the cladding is locally lower at the spacers due to the enhanced mixing caused by them.

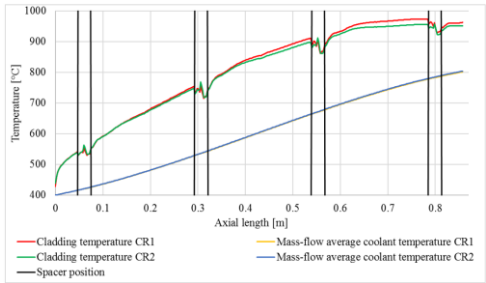


Fig. 10-Fig. 11. Temperatures of the cladding and the coolant along the length of the bundle

Model	Maximal temperature in fluid [°C]	Maximal temperature in cladding [°C]
CR1	1339.71	-
CR2	1136.85	1237.41

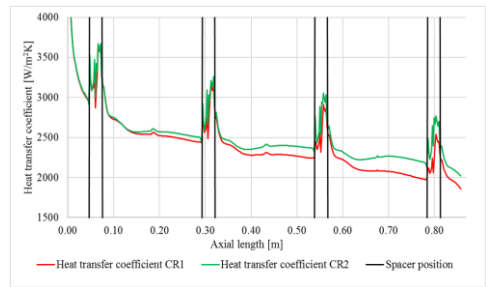


Fig. 11-Fig. 12. Heat transfer coefficients along the length

Axial change of the heat transfer coefficient is calculated from the cross-sectional average coolant temperatures and the heat flux values (Figure 12). At all spacers and immediately behind them peaks can be observed in the value of the local heat transfer coefficient similarly to the case of the inner subchannels [4]. The heat transfer coefficient calculated from the CFD results is compared to the value calculated with Rehme heat transfer correlation [6]. The CFD heat transfer coefficient is in a good agreement with the results of Rehme correlation. For model CR2 the values are higher, which is

caused by the smallest difference between the wall and the average coolant temperature.

IV. SUMMARY

The objective of this study is to investigate the flow and thermal conditions in the corner regions of ALLEGRO ceramic fuel assemblies. As a first step simplified bare rod bundle geometry is selected and simulations are performed with it. The results of these simulations is-are used as inlet boundary conditions for the active rod bundle models. The mesh resolution for building the active bundle model is selected based on our previous work.

The active rod bundle model is elaborated by considering the effects of the rod claddings. The model with claddings gives less conservative results with smaller temperature maximums. Considering the computational resources and the model accuracy, modelling the rod claddings is necessary.

We will continue this research with modelling the heat transfer in the assembly shroud as well. Moreover, will we examine the effect of the turbulence models on the simulation results. Based on the presented results the most critical regions of the ceramic fuel assemblies are the corner sregions. To solve this problem thermal power of the corner fuel rods can should be reduced or the convective heat transfer can should be intensified.

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REFERENCES

[1] L. Bělovský, Project ALLEGRO, He-Cooled Fast Reactor Demonstrator, Nordic-Gen4 Seminar, Lappeenranta, Finland, September 4-5, 2014

[2] C. Poette, F. Morin, V. Brun-Magaud, JF. Pignatell, ALLEGRO 75 MW Cores Definition at Start of GOFATR, CEA/DEN/CAD/DER/SESI/LC4G/NT, August 26, 2010

[3] P. Liška, G. Cognet, The ALLEGRO Project – European Project of Fast Breeder Reactor, 1st International Nuclear Energy Congress, Warsaw, May 23-24, 2011

[4] G. Orosz, S. Tóth, CFD Vizsgálatok az ALLEGRO Kerámia Kazetta Belső Szubcsatormájára, Nukleon, 2016. május

[5] N. E. Todreas, M. S. Kazimi, Nuclear Systems I, Thermal Hydraulic Fundamentals, Massachusetts Institute of Technology, 1990

[6] S. Tóth, B. Kiss, E. Gyuricza and A. Aszódi, CFD Investigation of ALLEGRO Fuel Assemblies, The 15th International Topical Meeting on Nuclear Reactor Thermal - Hydraulics, NURETH-15, Pisa, Italy, May 12-17, 2013

[7] H. Petersen, The Properties of Helium: Density, Specific Heats, Viscosity, and Thermal Conductivity at Pressures from 1 to 100 bar and from Room Temperature to about 1800 K, Copenhagen, Denmark September, 1970

[8] M. Zabiego, V. Brun-Magaud, E. Castelier and M.L. Flem, A set of Data Considered for the GFR Pin Design Provided by CEA as an Input to JRC-ITU's Computations within the Frame of the GoFastR Project, CEA, Cadarache, France, 2011.

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