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Fuel element and full core thermal–hydraulic analysis of the AHTR for the evaluation of the LOFC transient

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ABSTRACT

The Advanced High Temperature Reactor (AHTR) is a fluoride-cooled and graphite-moderated reactor concept designed by Oak Ridge National Laboratory (Holcomb et al., 2011). The modeling and optimization of the heat removal system and the core structure is required, in order to obtain an adequate heavy metal loading and to provide effective cooling capability. The single channel MATLAB model provides a simple tool to evaluate the steady state conditions for the coolant and the fuel plate and the effects of the power distribution; sensitivity studies on the main design parameters of the fuel element are performed. A RELAP5-3D single channel model is developed for the validation and comparison with the MATLAB model; this model is the starting point for the development of a full core model, enabling the study of transients. A one-third fuel assembly model is then analyzed, consisting of six fuel plates and modeling the heat conduction of graphite through RELAP5-3D conduction enclosures. Since the assembly model is not suitable for the implementation in a full core model with the same level of detail, several simplifications have been evaluated, involving the modeling of the plate through a single heat structure and the modeling of different plates through a single plate. A SCALE model of the fuel assembly was developed for the evaluation of the reactivity feedback and the power distribution in the core. The results from the neutronic evaluations and the assembly model were implemented in a full core model, involving the core, the main reactor structures, the cooling system and the safety system (DRACS). The RELAP5-3D core model was used for the evaluation of the steady state conditions and the effects of a loss of forced cooling accident (LOFC).

1. Introduction

The Advanced High Temperature Reactor (AHTR) is a fluoride-cooled and graphite-moderated reactor concept designed by Oak Ridge National Laboratory (Holcomb et al., 2011). Several innovative features are introduced with this concept: high temperature molten salt coolant, nearly non-pressurized system, high-temperature resistant TRISO fuel, supercritical steam power cycle. Integration of several different technologies, coming from established or well-known reactor types, (Ingersoll et al., 2004) makes the design of the AHTR credible but challenging. Due to the use of TRISO fuel and graphite as moderator, the core volume limits the allowed heavy metal loading; in order to obtain an adequate heavy metal loading, the heat removal system is required to provide effective cooling capability while occupying the minimum possible core volume fraction. The work presented in this paper intends to assess this aspect through the study and the modeling of the AHTR cooling systems and structures on different levels: single channel, single fuel element and complete reactor system. Moreover, steady-state conditions are considered for the characterization of the system and the development of parametric studies, but the basis for the study of the transient behavior will be presented in the final part of the work. The MATLAB and RELAP5-3D codes will be used for the modeling of the thermal–hydraulic systems and the SCALE 6.1 code will provide information about the neutronic features.

2. Single-channel analysis

In order to prepare a complete core model for the AHTR reactor, the single channel and fuel plate modeling were studied as a first step. Two approaches have been used for the single-channel model assessment:

- A steady-state approach, based on a simple MATLAB model; this model is a preliminary tool for steady-state thermal–hydraulic evaluations and parametric studies;
- A RELAP5-3D model for the validation of the MATLAB model and the evaluation of both the steady state conditions and transients; this model is the basis on which the core model will be developed.

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2.1. Single channel MATLAB model

The single-channel MATLAB model is a steady-state thermal–hydraulic model of the average (or hot) coolant channel and fuel plate; it provides an approximate temperature distribution of the plate and the main coolant thermal–hydraulic features. The primary application of this model is the study of the dependence of the average core thermal–hydraulic performance on design parameters, properties of materials and power density distribution.

The baseline design of the fuel assembly and the coolant channel used in this study are provided by ORNL in reference Holcomb et al., 2011, along with dimensions and physical properties. The elevation and the radial coordinate (orthogonal to the plate) are discretized, in order to create a suitable mesh for the calculation. The coolant temperature profile was calculated starting from the bottom of the channel and incrementally adding the temperature increase due to the power delivered by the plate to each single axial interval. Temperature-dependent coolant properties are implemented in the model, but the results show small difference with respect to the case in which properties are considered constant. The calculation of the coolant features, such as flow velocity, heat transfer coefficient and pressure drop is performed assuming the applicability of the Dittus–Boelter correlation for the Nusselt number and the Blasius formula for the friction factor (Holcomb et al., 2011).

Regarding the fuel plate temperature distribution, a one-dimensional radial approximation of the heat conduction equation is considered and it is solved for each radial interval. The thermal conductivity is considered constant within every single interval, but it can change from one interval to another, accounting for the temperature dependence; the same consideration applies to the power density, whose profile might depend on the radial coordinate.

2.1.1. Power density distribution

The axial power density distribution is approximated through a chopped-cosine profile, whose shape depends on the peaking factor or, equivalently, on the extrapolated length. A reference peaking factor of 1.3 was assumed (Varma et al., 2012); this value correspond to an extrapolated length 1.5 m longer than the core active height (5.5 m). Further evaluations were performed through SCALE, showing that the chopped-cosine profile is a good approximation, but, due to the reflection provided by the upper and lower reflectors, support plates and salt volumes, the peaking factor can be lower than 1.3. Moreover, the profile is not symmetric with respect to the core midplane: compared to the perfect chopped-cosine shape, it is higher for low elevation and lower for high elevation, due to slight coolant density reduction with increasing core elevation. The model requires further optimization, but initial results show that this reactor design can provide a relatively flat axial power profile, with a peaking factor below 1.3.

In relation to the radial power density distribution, a uniform profile was initially used for the fuel stripe only; a further development included power generation in the graphite meat and non-uniform power density profile in the fuel stripe. Different radial profiles were tested, looking at the effects produced on the maximum fuel temperature; the main aspect affecting the value of the maximum fuel temperature is the average distance of the fuel from the plate surface. Variations of ~1 °C of the maximum fuel temperature were obtained for a 2% variation of the transversal peaking factor. A SCALE simulation was run in order to evaluate the transversal peaking factor, which was found to be about 1.005%, 0.5% different from the uniform case, leading to a practically negligible (0.3 °C) increase in the maximum fuel temperature.

The previous considerations show that the maximum fuel temperature is not strongly affected by the transversal power density profile, for the following reasons:

- The fuel stripe is thin (few mm), resulting in low flux depression and low transversal peaking factor;
- The effect of the flux depression changes the shape of the power profile, but it does not affect its average distance from the surface of the plate.

2.1.2. Sensitivity studies

The MATLAB single-channel model was used to perform sensitivity studies on some parameters of the AHTR fuel assembly, including graphite conductivity, cladding thickness, fuel stripe thickness, fuel packing fraction, and coolant gap thickness.

Fig. 1 shows the maximum fuel temperature for the average fuel assembly as a function of the neutron fluence; the model accounts for conductivity dependence on both irradiation and temperature. The decrease of conductivity due to irradiation has a strong impact on the maximum fuel temperature (increase by ~80 °C, from 764 °C to 842 °C), but the value that is asymptotically reached for high neutron fluence remains acceptable (Gougar et al., 2010).

Fig. 2 shows the maximum fuel temperature as a function of the sleeve thickness. For the hot channel, maximum fuel temperature increases ~26 °C per added mm of sleeve thickness. Since the average distance of the power density distribution from the plate surface is directly affected by this quantity, the optimization of the sleeve thickness is important in order to obtain low fuel temperatures.

Fig. 3 shows the maximum fuel temperature as a function of the fuel stripe thickness; the derivative of the maximum temperature with respect to the thickness is similar to the case of the sleeve thickness variation, but slightly lower (increasing ~25 °C per mm).

Fig. 4 shows the fuel temperature dependence on the fuel packing fraction. Two opposing aspects contribute to the shape of the curve: the fuel stripe thickness reduction prevails for low packing fractions, while the fuel conductivity reduction is more important for higher packing fractions.

Further sensitivity studies were performed, in order to test the dependence of the maximum fuel temperature on the coolant channel width; a variation of both the coolant channel width and fuel stripe thickness was considered and the results are presented in Figs. 5 and 6.

The results presented in Fig. 5 are obtained assuming a constant core mass flow rate; the lowest temperature is obtained for thin fuel stripe and coolant channel, but a small coolant channel causes high core pressure drop. In order to keep the core pressure drop below 1 atm, the coolant channel must be at least 5 mm thick.

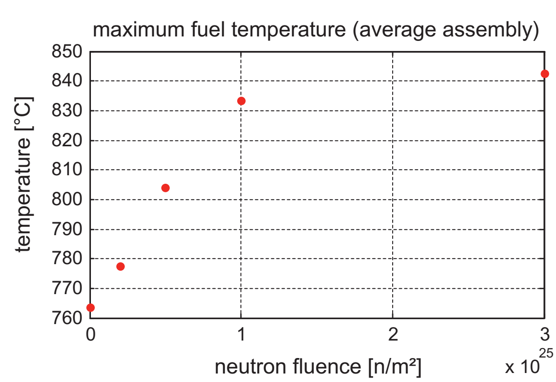

Fig. 1. Maximum fuel temperature in the average assembly for different irradiations.