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Thermal Study of the Modular High-Temperature Gas-Cooled Reactor

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1. Introduction

The Modular Helium Reactor using a Gas Turbine (GT-MHR) is a coupling between a modular helium cooled reactor and a gas turbine; this is for the purpose of replacing the Rankine steam power cycle energy conversion system with a high efficiency Brayton power cycle conversion system which will increase the thermal conversion efficiency by ~48%. The GT-MHR will be an HTGR (High Temperature Gas - Cooled Reactor) developed in a joint program between the United States (General Atomics) and the Russian Federation. The GT-MHR was primarily developed to burn plutonium, but General Atomics is planning short-term commercial deployment with uranium fuel.

The reactor is helium-cooled, graphite-moderated and uses Triso-coated fuel particles immersed in a cylindrical-shaped graphite matrix called compact fuel, similar to other HTGR designs. The annular core and fuel blocks are based on the FSV (Fort Saint Vrain) reactor design. Furthermore, the GT-MHR is the starting point for the prismatic VHTR conceptual design. As such, much of the current VHTR project description is drawn directly from the GT-MHR; the GT-MHR design will be modified to provide higher exit temperatures (850 °C for GT-MHR and 1000 °C for VHTR) and to interface with a hydrogen production system, while meeting the goals of future fourth nuclear power plants generation [1].

In this line of advanced reactors, the Modular High-Temperature Gas-Cooled Reactor (MHTGR) is an advanced power plant concept which has been under design definition since 1984 [7]. A MHTGR model in the RELAP5-3D code is presented in this work, as well as its verification for steady state calculations. The simulations have been performed to three power values: 350, 450 and 600 MWth. The transfer of heat along the fuel blocks involves complex phenomena: the heat generated by the fissions in the Triso particle core is transferred by conduction through the different layers, to the graphite of the fuel block and finally to the coolant. Also, as the fuel blocks and reflectors are stacked in the active part of the reactor core, there are small gaps between all these blocks. These openings are defined as bypass openings.

In Figure 1, it is possible to see the coolant flow in the fuel blocks; most of the coolant flows through the coolant channels inside the fuel block, but some flows through the openings between the fuel blocks. This flow is defined as the bypass flow, which crosses the bypass opening (Bypass-gap). In addition, coolant flows through the interfacial openings between two stacked blocks. This flow is defined as a cross flow (Crossflow) and the interfacial opening is defined as a cross-gap; this opening plays a role as a flow bypass between the cooling channel and the bypass opening, which leads to complex flow distributions in the reactor core.

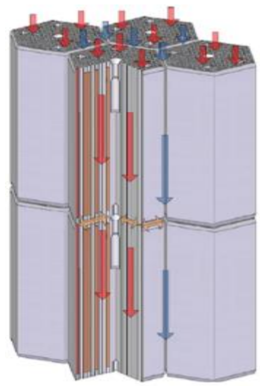

Figure 1: Mass flow along the fuel blocks (red arrows: in the coolant channels; blue arrows: bypass; beige arrows: crossflow. Adapted from [2].

2. Methodology

In this first part of the work, the heat transfer along the blocks was studied using the RELAP5-3D code without taking into account the cross flows; then only the diversion flow will be considered, since their effect on the flow distribution along the fuel blocks needs further studies on the heat distribution along the reactor core. The amount of coolant going through the bypass openings represents less than 20% of the total amount of coolant going through the entire core. These effects are more representative in gas-cooled high temperature reactors, in which this represents approximately 20% of the total coolant flow; in liquid salt-cooled reactors the cross-flow effect represents approximately 10% of the total flow [3, 4]. The axial power profile used in modeling with RELAP5-3D is illustrated in Figure 2 for MHTGR. It is the same to 350, 450 and 600 MWth.

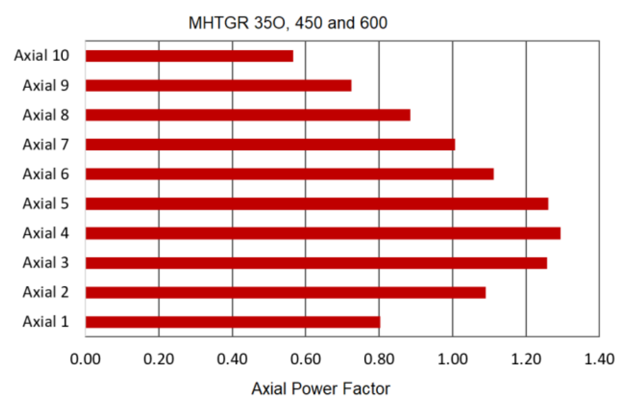

Figure 2: Axial power distribution along the MHTGR reactor core. Adapted from [5].

The radial power distribution within the compact fuel was assumed to be uniform for the analysis. Once the axial and radial power distributions are obtained or simulated, these values are used in RELAP5-3D to calculate (1) the heat transferred in each segment or axial node of the heat structure to the thermal hydraulic channels (THC) that model the core, and (2) to perform an indirect calculation of the heat transferred radially in the reactor core. Both radial and axial normalized power factors (called multiplication factors) are specified for each axial segment in the heat structures that are coupled to the thermal hydraulic channels that shape the reactor core. The normalization is performed according to the number of THC simulated in the case of radial power factors, and normalized according to the number of axial meshes, and in the case of axial power factors. These factors are characterized by subscripts representing the radial region number "g" in the reactor core and subscripts representing the axial position "i". The partial power P_{gi} supplied in the axial segment "gi" in the heat structure is given by Eq. 1:

$$P_{gi} = f_g f_{gi} P_{total} \tag{1}$$

where f_g is the normalized radial power factor, f_{gi} is the normalized axial power factor, and P_{total} is the total reactor core power. The sum of the multiplication of these normalized factors must equal unity.

The nodalization consisted of modeling each active ring of each reactor with THC as can be seen in Figure 3, considering that the active core has different types of fuel blocks. The coolant flow in each region was modeled by THC coupled with their respective heat structures.

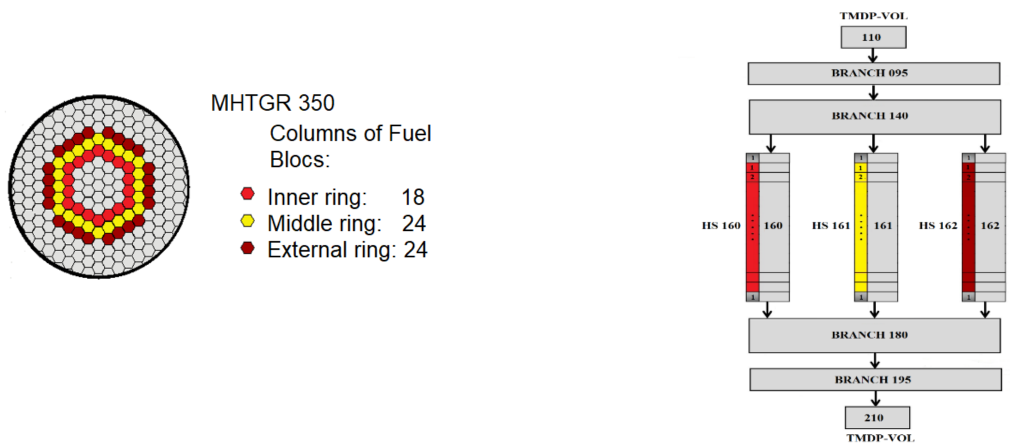

Figure 3: Left: representation of the division of the three regions in the core of helium-cooled reactors; Right: core nodalization in RELAP5.

3. Results and Discussion

Steady state results for coolant temperatures and mass flow rates at different locations in the MHTGR core are shown in Figure 4. The parameters start from their initial values and oscillate until reaching the constant value. The speed at which the parameters reach steady state depends on the initial values and options chosen for the steady state initialization mode. The values obtained will be used as a starting point for the transient executions in the case of the 350 MW MHTGR.

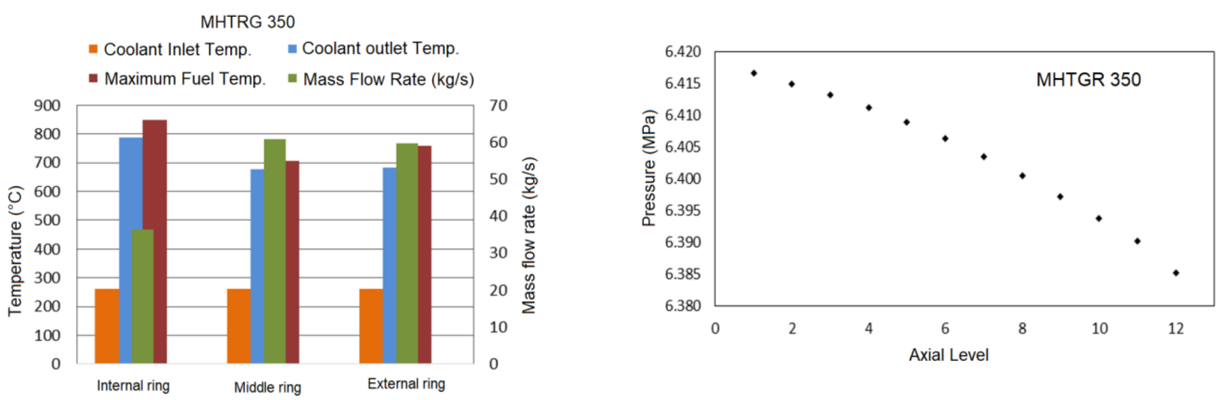

Figure 4: Left: behavior of the parameters: coolant inlet and outlet temperatures (in orange and blue), maximum fuel temperature (wine) and mass flow rate (green); Right: pressure behavior along any THC of the MHTGR350 MW.

In Table I it is possible see the steady state calculation results in comparison with reference data. In the Table are presented also results for simulated MHTGR 450 MWth and 600 MWth. At steady state, the thermal hydraulic parameters obtained for the MHTGR reactors were very close to the reference ones. For RELAP5, the ideal is that the error in the coolant temperature is less than 0.5%; in the flow, less than 2%; and in the pressure drop, less than 10%.

Table I: Main results for the MHTGR.

Parameters	MHTGR Reference [6]			MHTGR Calculation			*ΔE(%)		
	350	450	600	350	450	600	350	450	600
Outlet Temperature (°C)	687	704	750	689.2	699.7	751.5	0.3	0.6	0.2
Pressure Drop (kPa)	31,4	-	-	35.1	37.0	50.9	11	-	-
Total core mass flow rate (kg/s)	157	211	289	156.9	210.5	288.9	0.06	0.2	0.03
Maximum fuel temp. (°C)	988	-	-	948.4	878.6	899.1	4	--	--

*ΔE(%) = (reference – calculation)*100/reference

4. Conclusions

The MHTGR model and simulation in the RELAP5-3D code was presented in this work, as well as its verification for steady state calculations. The found results are in good agreement in relation to reference data. The next step is to modify the model considering transient simulations to verify if it is capable to reproduce the core behavior in conditions out of the normal operation.

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