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Thermal study of the modular high-temperature gas-cooled reactor

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ABSTRACT

The Modular High-Temperature Gas-Cooled Reactor (MHTGR) is an advanced power plant being a coupling between a modular helium cooled reactor and a gas turbine. The gas-cooled reactor types are of great interest due to their potential to provide heat for high-temperature process in addition to high thermal-to-electric power conversion efficiency and inherent safety features. The MHTGR is helium-cooled, graphite-moderated and uses Triso-coated fuel particles immersed in a cylindrical-shaped graphite matrix. The annular core and fuel blocks are based on the FSV (Fort Saint Vrain) reactor design. In this work, a MHTGR model developed in the RELAP5-3D code is presented, as well as its verification for steady state calculations. The core simulation was performed considering three power values: 350, 450 and 600 MWth. The heat transfer along the blocks was investigated taking into account the diversion flow. The radial power distribution within the compact fuel was assumed to be uniform for the analysis. Radial and axial normalized power factors were specified for each axial segment in the heat structures coupled to the thermal hydraulic channels that shape the reactor core. In the analyses, coolant and fuel temperatures, pressure drop and mass flow rate were verified at steady state conditions. The results were very close to the reference ones demonstrating that the developed model is capable to reproduce the MHTGR core in steady state operation.

Keywords: **MHTGR, RELAP5-3D, Thermal Analysis.**

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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 it has 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 nuclear power plants (generation IV) [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 [2]. 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 a part 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 [3].

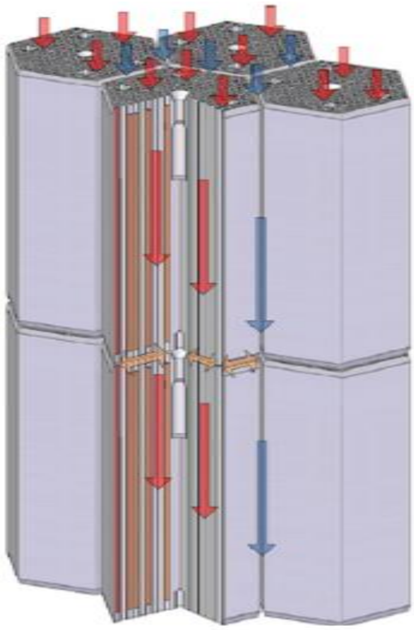


Figure 1: *Mass flow along the fuel blocks (red arrows: in the coolant channels; blue arrows: bypass; beige arrows: crossflow.*
Adapted from [3].

The thermal hydraulic code RELAP5-3D has been successfully used to simulate fourth generation reactors. For example, simulation of the LS-VHTR (liquid-salt-cooled very high temperature reactor) was performed whit a RELAP5 model developed to represent the complete core with all hexagonal blocks and the salt recirculation system to predict the core inlet and outlet coolant temperatures, heat structures temperature, and pressure drop [4]. The HTTR (High Temperature Engineering Test Reactor) was also modeled; it is a helium-cooled, graphite-moderated reactor, with 30 MW of thermal power and spherical fuels kernels with enriched UO_2. Data of fuel and coolant temperature were compared with those from literature; the RELAP5 reproduced relatively well the temperature behaviour in spite of the the calculated values were sligthly underestimated [5]. In addition, the core of the High Temperature gas cooled Reactor (HTR-10) was modeled in RELAP5. It is a small reactor, with thermal power of 10 MW, developed in China, cooled by helium gas and moderated by graphite. The reactor has particular characterist because it uses spherical fuel elements being balls of 6 cm of diameter. In the initial core, fuel elements and graphite dummy balls (graphite balls without nuclear fuel) constitute the pebble bed. The fuel temperature calculated in such work [6] rises along the core with expected average values and presents a behavior similar to that presented in the benchmark used for the model verification.

2. MATERIALS AND METHODS

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 flow; then only the diversion flow was considered, since its effect on the flow distribution along the fuel blocks needs further studies on the heat distribution along the reactor core. The amount of coolant passing 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 [7, 8]. The axial power profile used in modeling with RELAP5-3D is illustrated in Figure 2 for MHTGR and it was based in the United States Government document [9]. It is the same to 350, 450 and 600 MWth.

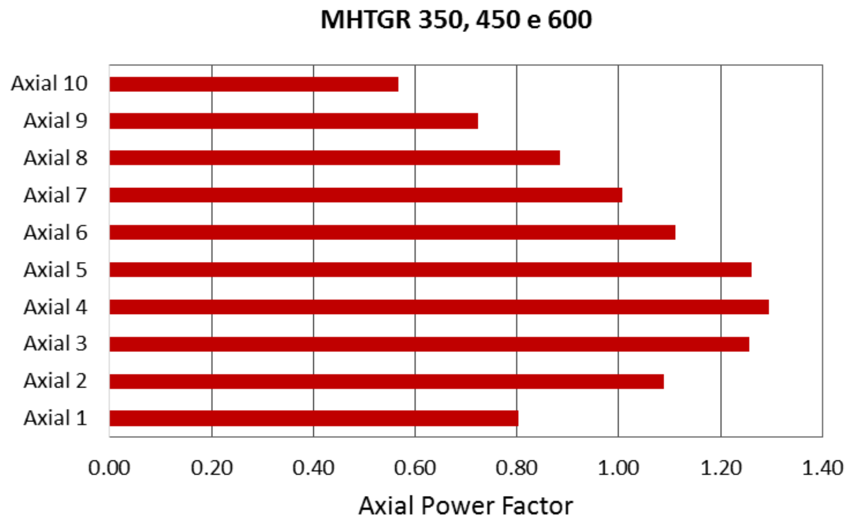


Figure 2: *Axial power distribution along the MHTGR reactor core.*
Source: adapted from [9].

For the radial power distributions for the MHTGR (300, 450 and 600MW), the radial power factors are represented for each ring considering the number of blocks in each one [9]. The radial power profile used in the RELAP5-3D modeling is illustrated in Figure 3.

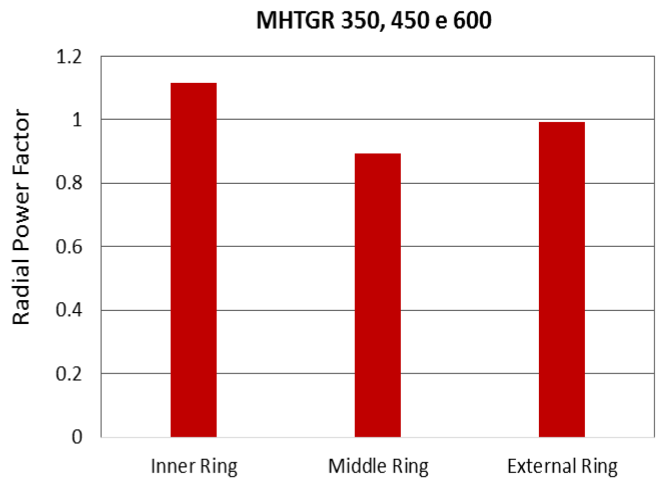


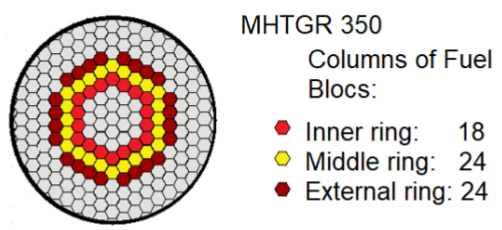
Figure 3: *Radial power distribution along the MHTGR reactor core.*
Source: adapted from [9].

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 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 one THC as it can be seen in Figure 4, 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.



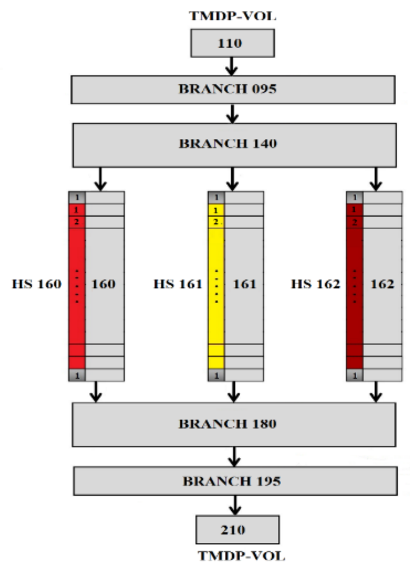


Figure 4: *Left: representation of the division of the three regions in the core of helium-cooled reactors; Right: core nodalization in RELAP5 with three thermal hydraulic channels.*

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 5. 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 in a future work as a starting point for the transient executions in the case of the 350 MW MHTGR. Morever, in the Figure 6 is shown the pressure behavior along any thermal hydraulic channel simulated to the MHTGR 350 MWth.

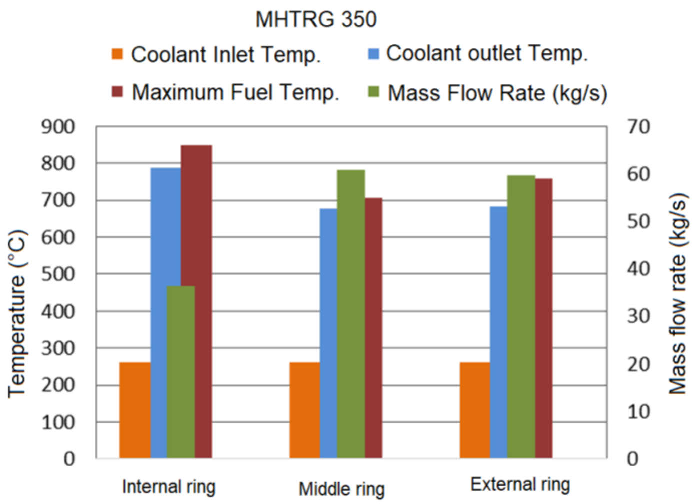


Figure 5: *Coolant inlet and outlet temperatures (in orange and blue), maximum fuel temperature (wine) and mass flow rate (green)-Relap5 Model for MHTGR 350 MWth.*

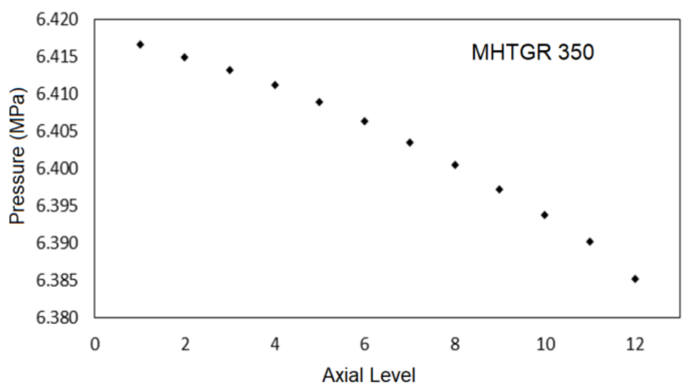


Figure 6: *Pressure behavior along any THC of the MHTGR 350 MWth.*

In Table 1 it is possible to see the steady state calculation results for MHTGR at 350, 450 and 600 MWth in comparison with reference data. 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 1: Main results for the MHTGR.

	MHTGR Ref. [10]			**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. CONCLUSION

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 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.

This is a work in progress. Future studies will be performed using computational fluid dynamics (CFD) to obtain more accurate flow and temperature distributions in steady state and also in transient conditions as, for example, in the case of pressurized loss of forced cooling (P-LOFC), which is caused by an abnormal trip of the main helium circulator or turbine in the power conversion system and it is a postulated accident in HTGRs.

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