# THERMAL STUDIES ABOUT THE HIGH TEMPERATURE ENGINEERING TEST REACTOR

**Maria Elizabeth Scari, melizabethscari@yahoo.com**
**Antonella Lombardi Costa, antonella@nuclear.ufmg.br**
**Claubia Pereira, claubia@nuclear.ufmg.br**
**Maria Auxiliadora Fortini Veloso, dora@nuclear.ufmg.br**
**Patrícia Amélia L. Reis, patricialire@yahoo.com.br**
**Mario Cerrogrande Ramos, marc5663@gmail.com**

Universidade Federal de Minas Gerais – Departamento de Engenharia Nuclear – Escola de Engenharia, Av. Antônio Carlos, n∘ 6627, Campus UFMG, PCA 1, CEP 31270-901, Belo Horizonte, MG, Brasil

Instituto Nacional de Ciências e Tecnologia de Reatores Nucleares Inovadores/CNPq, Brasil

***Abstract.*** *A thermal model for the HTTR (High Temperature Engineering Test Reactor) has been developed using the RELAP5 code. The HTTR is a high temperature gas-cooled reactor (HTGR) developed, designed, constructed, and operated by the Japan Atomic Energy Research Institute (JAERI). The construction of the HTTR began in March 1991 and was completed in May 1996. Fuel loading began in July 1998 and the first criticality was attained in November 1998.The first full power operation with average outlet temperature was completed in December 2001. It is a helium-cooled and graphite-moderated with a thermal power of 30 MW. The HTTR fuel consists of a spherical fuel kernel of enriched UO$_2$. These fuel kernels are coated and form a sphere with 0.92 mm diameter. The spheres are arranged in a fuel compact and the sintered compact fuels are arranged in a vertical array, a fuel rod. The fuel rods are inserted in graphite prismatic hexagonal blocks. There are four types of fuel rods with different uranium enrichment along the core. Approximately 95 % of the thermal power in the active core is generated by the fuel elements and the rest by the graphite moderator. In this work, a HTTR core inlet and outlet coolant temperatures, heat structures temperature and pressure drop have been reproduced using a RELAP5 model. The results have been compared with the available data. The reactor core has been simulated and the calculations were performed using the point kinetic model. It is demonstrated that the developed model is capable of reproducing the thermal reactor behavior in steady state operation.*

*Keywords: nuclear engineering, nuclear reactor, thermo-hydraulic model*

## 1. INTRODUCTION

The High Temperature Engineering Test Reactor (HTTR) was constructed and operated by the Japan Energy Agency (JAEA). It is a helium-cooled, graphite-moderated reactor, with 30 MW of thermal power. The major objectives of the HTTR are to establish and upgrade the technological basis for advanced high temperature gas–cooled reactors (HTGRs) and to conduct various irradiation tests for innovative high temperature basic researches (Bess et al., 2009). Fig. 1 shows the vertical cross section of the HTTR.

The construction of the HTTR began in March 1991 and was completed in May 1996. Fuel loading began in July 1998 and the first criticality was attained in November 1998.The first full power operation with average outlet temperature was completed in December 2001 (IAEA, 2003). In the Tab. 1 is shown the configuration of the HTTR core.

The HTTR fuel consists of a spherical fuel kernel of enriched UO$_2$. There are 12 different enrichments between 3.4 and 9.9 wt.%. These fuel kernels are 0.60 mm diameter. The kernels are coated by four isotropic materials, forming the TRISO (Tristructural-isotropic), a 0.92 mm diameter sphere. The materials are: Porous Carbon (PC), a low density pyrolitic carbon, forming the first layer, the buffer; a high density carbon, pyrolitic carbon (PyC) forming an inner layer of PyC (iPyC); a ceramic material, the Silicon Carbide (SiC); and an outer layer of PyC (oPyC). The TRISO keeps the structure until 1600 $^0$C.

The spheres are arranged in a fuel compact with 10 mm of internal diameter, 26 mm of external diameter and 39 mm height. The sintered compact fuels are arranged in a vertical array of 14 of them forming a fuel rod with 577 mm in length and 34 mm in outer diameter. The fuel rods are inserted into graphite prismatic hexagonal blocks with 580 mm height and 360 mm flat-to-flat. Vertically, 5 fuel blocks constitute a fuel column. Fig. 2 illustrates these elements.
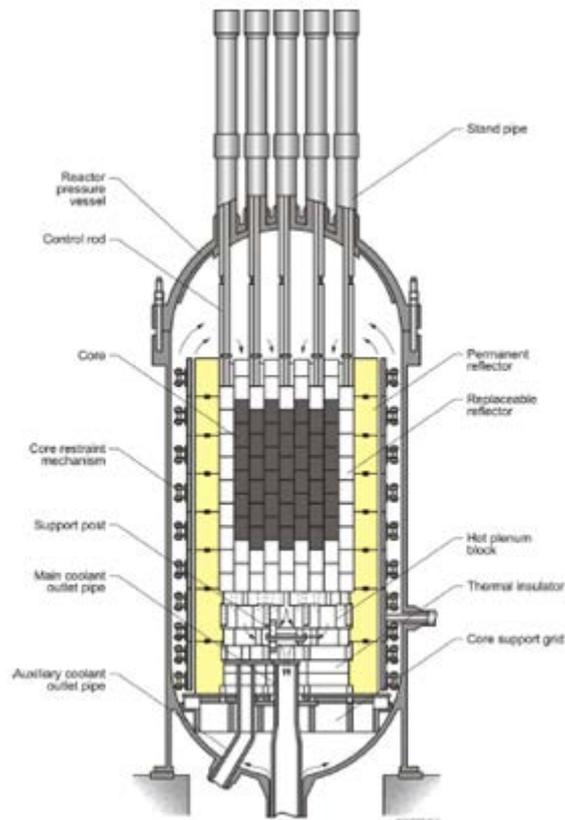
Figure 1. Vertical cross section of the HTTR (Bess et al., 2009).

Table 1. Geometrical parameters of the HTTR (Bess et al., 2009).

| Parameter | Value |
|---|---|
| Equivalent Core Diameter | 2.3 m |
| Effective Core Height | 2.9 m |
| Number of Fuel Assemblies | 150 |
| Number of Fuel Columns | 30 |
| Number of Pairs of Control Rods | |
| In Core | 7 |
| In Reflector | 9 |
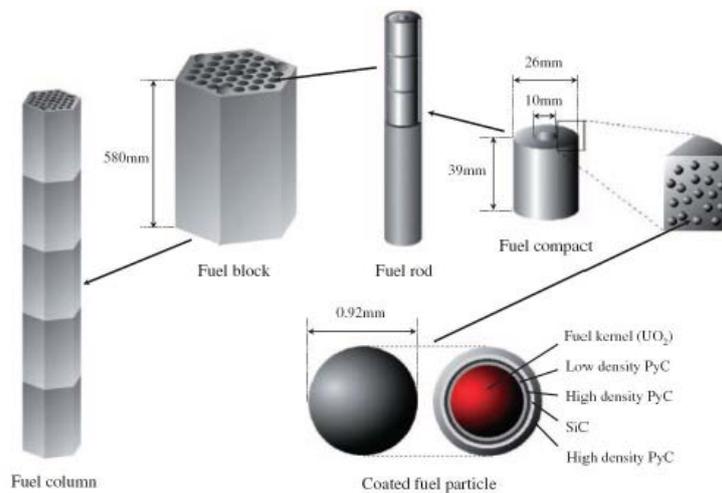


Figure 2. HTTR Fuel Column, Fuel Block, Fuel Rod, Fuel Compact and Coated Fuel Particle (IAEA, 2003).

The fuel pin has a 26.25 mm inner diameter. There is a 3.5 mm annular gap between the block hole and the fuel rod. The Helium flows downward through this gap. In the Fig. 3, is shown the cross section of the HTTR fuel rod.
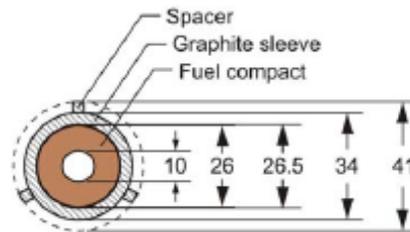


Figure 3. HTTR fuel rod cross section (Bess J. D. et al, 2009).

In the HTTR core, there are 30 fuel columns, 19 control rods columns and 12 replaceable reflector columns arranged as shown in Fig. 4. The fuel columns have 12 different uranium enrichments (between 3.4 to 9.9 wt.%) forming four separated zones. The internal zones, 1 and 2, have fuel columns with 33 pin fuel rods, and zones 3 and 4 have fuel columns with 31 pin fuel rods. Approximately 95 % of the thermal power in the active core is generated by the fuel elements and the rest by the graphite moderator. Thermal and irradiation conditions become severe for the blocks at the outer region of the core. Because of this, the outer fuel blocks contain 31 fuel rods (IAEA, 2003).
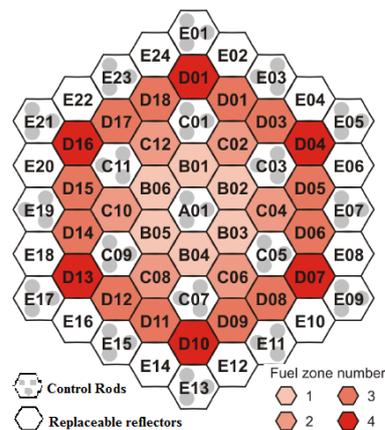


Figure 4. Columns distribution in HTTR core (Bess et al., 2009).

The total fuel column consists of 5 fuel blocks and two top graphite replaceable reflector blocks and two bottom replaceable reflector blocks. The second and third blocks contain burnable poisons pellets that are more enriched than the pellets in the other positions. The fuel columns of the four zones are presented in Fig. 5. The numbers in each block represents the uranium enrichment (wt.%) in the TRISO fuel and the natural boron content (wt.%) in the burnable pellets ($UO_2$/Boron).



Figure 5. HTTR Columns Fuel Zones ($UO_2$/Boron) concentration (Bess J. D. et al, 2009).

The power distribution in the core according to the four zones is presented in the Tab. 2.

Table 2. Relative power distribution in the core of the HTTR (IAEA, 2003).

| Axial Fuel Layer | Fuel Zone Number | | |
|---|---|---|---|
| | 1 | 2 | 3+4 |
| 1 | 0.031944 | 0.033058 | 0.096679 |
| 2 | 0.060489 | 0.062328 | 0.170170 |
| 3 | 0.060698 | 0.057048 | 0.158590 |
| 4 | 0.033081 | 0.034271 | 0.095860 |
| 5 | 0.021392 | 0.022164 | 0.062224 |

The thermal hydraulic parameters of the HTTR are shown in Tab. 3.

Table 1. Thermal Hydraulic parameters for the HTTR (Fujikawa et al., 2004).

| Parameter | Value |
|---|---|
| Thermal Power | 30 MW |
| Average Power Density | 2.5 W/cm³ |
| Inlet Coolant Temperature | 395 ºC/668 K |
| Outlet Coolant Temperature | 850 ºC -1123 K (Rated operation mode) 950 ºC -1223 K (High-temperature test operation mode) |
| Fuel Temperature Limit | 1600 ºC (IAEA,2003) |
| Primary Coolant Pressure | 4 MPa |
| Helium Mass Flow Rate | 12.4 kg/s (Rated operation mode) 10.2kg/s (High-temperature test operation mode) |

## 2. RELAP5-3D MODELING

In this work, RELAP5-3D version 3.0 has been used to perform the simulations (Fujikawa et al., 2004). The reactor point kinetics model implemented in previous versions of RELAP5 was used in the simulations. The RELAP5 code was originally designed to simulate light water reactors (LWR). The hydrodynamic model is two-fluid model for flow of a two-phase steam-water mixture that allows noncondensible component as, for example, Helium, in the steam phase and/or a soluble component in the water phase. In this way, it is possible to use RELAP5 with only Helium and no steam. The working fluid only exists in one phase and behaves like an ideal gas (Huda and Obara, 2008). Such criteria were used in the present model. The loss coefficients in the channels were adjusted to give the adequate mass flow rate. The RELAP5 card number 110 was defined as "Helium".

In the model, each fuel column is represented by three heat structures (HS) and one pipe, simulating the coolant channel. The first and third heat structures are graphite only, representing the graphite blocks in the Fig. 5. The second heat structure has fuel and represents the fuel blocks in the Fig. 5. The channel dimensions depend on the simulated column if it has 33 or 31 pins. Fig. 6 shows the shape of the HS used. The quantity of material is calculated for one fuel rod and is multiplied by the number of pins (31 or 33) according to the channel, in the RELAP5. The graphite block is divided between the fuel rods.
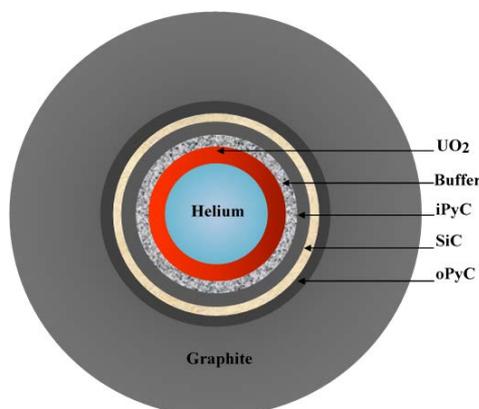


Figure 6. Heat Structure used in the HTTR.

Table 4 shows the mesh point number used according to the layers of different materials utilized. Also shows the radius of the material utilized in the Heat Structure.

Table 2. Mesh point and radius used to simulate the Heat Structures.

| | Helium | UO$_2$ | Buffer | iPyC | SiC | oPyC | Graphite |
|---|---|---|---|---|---|---|---|
| Mesh point | 2 | 4 | 6 | 8 | 10 | 12 | 20 |
| Radius (x10$^{-3}$ mm) | 5.000 | 6.810 | 6.761 | 7.164 | 7.531 | 8.258 | 28.413 (33 pin) 29.591 (31 pin) |

In the Fig. 7 is shown the RELAP5 nodalization of the HTTR core. The columns are represented by the pipes 201 to 230 with their corresponding HS from 201 to 290. Pipes from 201 up to 206 are 33 pin columns, and are correspondents to the columns in the fuel zone number 1, in Fig.4. Pipes from 207 up to 212 correspond to the fuel zone 2 (33 pins too). Pipes from 213 to 224 are 31 pins and correspond to the fuel zone 3. Pipes 225-230 correspond to the fuel zone 4 in Fig. 4 and are 31 pins too. The TMDPVOL 500 and the SJ 300 components represent the core inlet coolant. The Time Dependent Volume (TMDPVOL) 600 and the Single Junction (SJ) 400 components represent the core outlet coolant. The pipes are divided in 9 axial volumes, and the heat structures are divided in two, five and two axial volumes, corresponding to those in Fig.5. Each axial volume has 0.58 m, corresponding to the blocks in Fig.2.
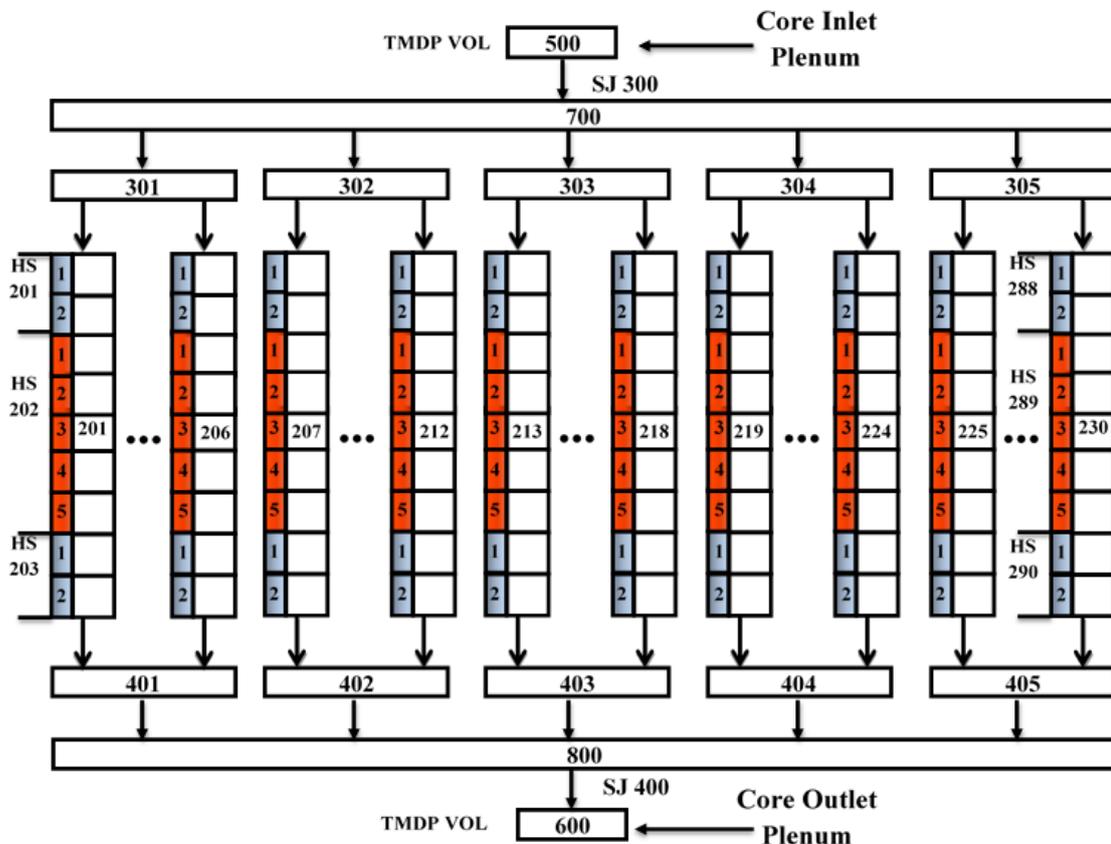


Figure 7. HTTR core RELAP5 nodalization.

Simulations are performed for the rated operation mode and for high temperature operation mode, as listed in Tab. 3.

### 3. RESULTS

Figure 8 presents the inlet and outlet coolant temperature in steady state calculation, in simulation of the rated operation mode and high-temperature test operation mode. The core inlet temperature values for both modes are 668 K. The outlet coolant temperature for the rated mode is 1126 K and for the high temperature mode is 1221 K. The values are very similar to those from the Tab. 3.
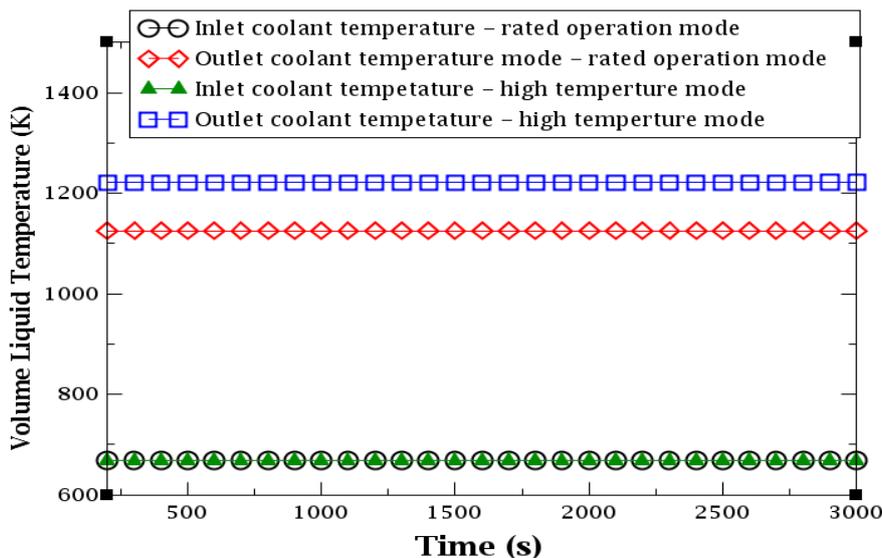
Figure 8. Inlet and outlet coolant temperature for the rated operation mode and high temperature operation mode.

Figure 9 shows the coolant mass flow rate for rated operation mode and high temperature operation mode. For the first one, the mass flow rate is 12.7 kg/s and for the second one is 10.5 kg/s. These are very close of the reference data in Tab. 3.
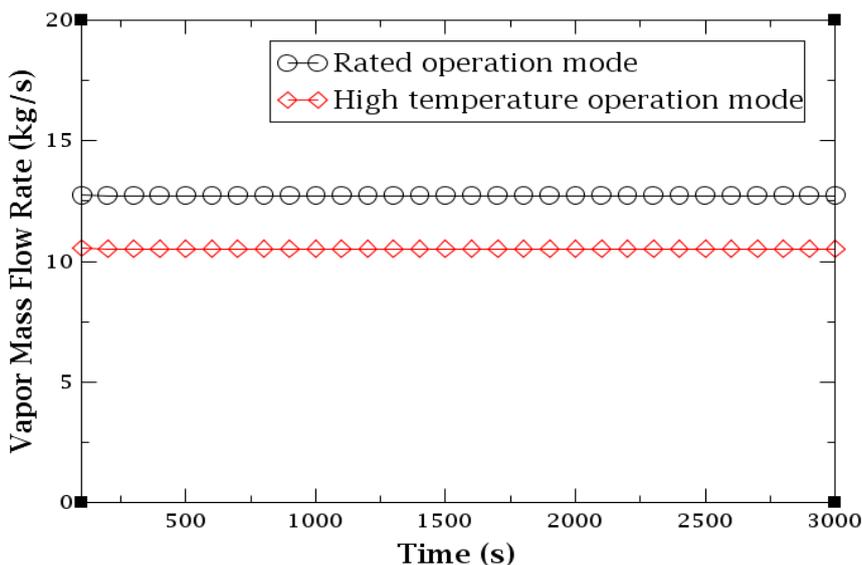


Figure 9. Coolant mass flow rate for rated operation mode and high temperature operation mode.

Figure 10 shows the coolant mass flow rate for rated operation mode in channels 201(0.44 kg/s), 207(0.44 kg/s), 213(0.41 kg/s), 219(0.41 kg/s) and 225(0.41 kg/s). The mass flow rate is the same in the channels 201 to 212 and in the channels 213 to 230 because they have the same number of pins and consequently, the same flow areas.

Figure 11 shows the coolant mass flow rate for high temperature operation mode in channels 201(0.36 kg/s), 207(0.36 kg/s), 213(0.34 kg/s), 219(0.34 kg/s) and 225(0. kg/s). The mass flow rate is the same in the channels 201 to 212 and in the channels 213 to 230 because, as in the case analyzed firstly, they have the same number of pins and consequently, the same flow areas.

Figure 12 shows the temperatures in HS 202 and HS 289 for rated operation mode and high temperature operation mode. The mesh points were defined as in Tab. 4.
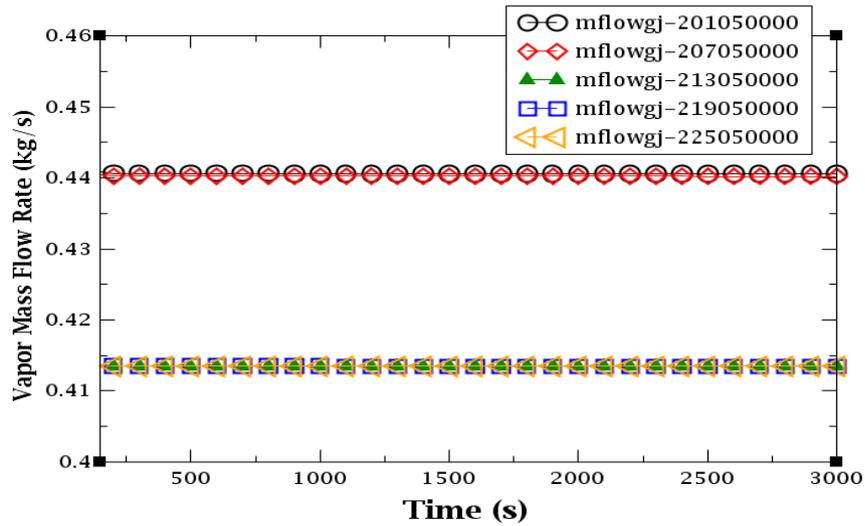
Figure 10. Mass flow rate in some channels for the rated operation mode.
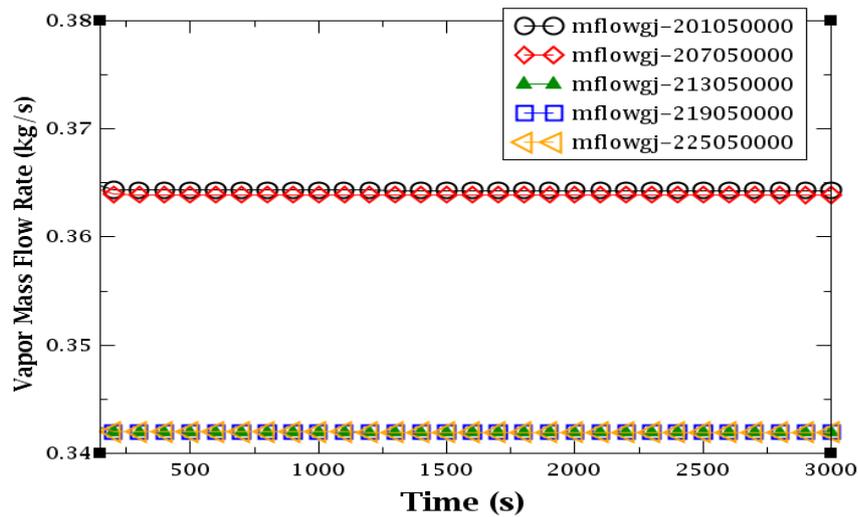


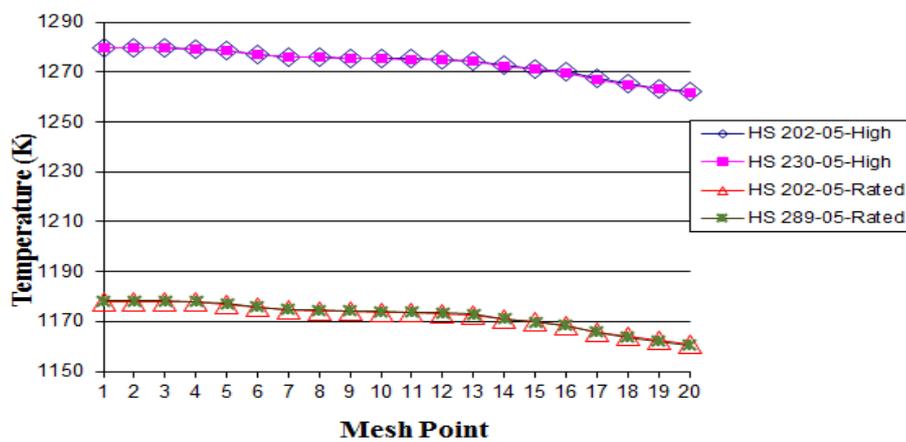Figure 11. Mass flow rate in some channels for the high temperature operation mode.



Figure 12. Temperatures in HS 202 and HS 289 for rated operation mode and high temperature operation mode.

## 4. CONCLUSIONS

An initial thermal study of the HTTR using the RELAP5 code has been performed. The results presented similar thermal hydraulic behavior in comparison with the references presented in Tab. 3. In the rated operation mode, the expected outlet coolant temperature is 1123 K and the simulated is 1126 K the error is 0.3 %. In the same mode the mass flow rate expected is 12.4 kg/s and the simulated is 12.7 kg/s the error is 2.4 %. In the high temperature operation mode the outlet coolant temperature expected is 1223 K and the simulated is 1221 K this means the error is 0.2 %. In this mode, the expected mass flow rate is 10.2 kg/s and the simulated is 10.5, the error is 2.9 %. Future work consists in to incorporate more reactor details beyond the core in the model and also to simulate transient events.

## 5. ACKNOWLEDGEMENTS

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