Id.: EN-03

THERMAL-HYDRAULIC MODELLING AND STADE STATY ANALYSIS OF A LS-VHTR REACTOR

M. C. Ramos, A. L. Costa, M. A. F. Veloso, C. Pereira

Universidade Federal de Minas Gerais
Departamento de Engenharia Nuclear, Escola de Engenharia
Av. Antônio Carlos CEP 131270-901 Belo Horizonte, MG, Brasil

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

marc5663@gmail.com

Palavras-Chave: LS-VHTR, RELAP5-3D

ABSTRACT

The Liquid-Salt-Cooled Very High-Temperature Reactor (LS-VHTR) is a liquid salt cooled and TRISO fueled reactor, which presents very good features in terms of power production and safety aspects. The advantage of using liquid salt as coolant is mainly related with its high efficiency of heat transfer and operation at low pressures. This work evaluates the thermal hydraulic performance of the heat removal system and the reactor core, in steady state conditions as well as during accidental transients, starting from the single channel level and concluding with the full core model. The LS-VHTR is a new reactor concept that introduces some different features in relation to other nuclear reactors. In this way, a thermal modeling of this reactor has been developed using the RELAP5-3D code using a point kinetic model. A modeling with three channels has been presented. The core coolant temperature increase, the core coolant mass flow and the pressure along the core were simulated and presented in good agreement with the expected behavior

1. INTRODUCTION

The Liquid-Salt-Cooled Very-High-Temperature Reactor (LS-VHTR) is a variant of the gas-cooled very high-temperature reactor (VHTR) concept and combines several new technology assets such as successful use of coated-particle graphite-matrix fuel in helium-cooled reactors; reactor plant and safety systems similar to that developed to the liquid-metal cooled fast reactors; low-pressure liquid-salt coolants studied and researched for liquid fuel reactors; and Brayton power cycles at high-temperatures. The LS-VHTR project goal is to provide an advanced design which offers the potential for higher power output, improved efficiency of electricity production, and higher operating temperatures leading to significant reduction in plant capital costs, as well as its use in high-temperature process heat applications that can economically produces hydrogen [1].

The LS-VHTR core uses coated-particle graphite-matrix fuel have uranium oxycarbide fuel kernels which is coated with multiple layers of pyrolytic carbon and silicon carbide to form a microsphere of 0.8 mm diameter that prevents release of radionuclides at very high temperatures. These microspheres fuel are frequently referred to as “TRISO” fuel and are incorporated into a graphite-matrix fuel compact, which, in turn is loaded into a hexagonal fuel block, which provides more control of the fuel and coolant volume fractions and geometry. Fig. 1 shows the TRISO fuel and a typical fuel compact and prismatic graphite block, which is the fuel assembly shape utilized in the LS-VHTR.

A total of 265 columns of fuel blocks are assembled into a cylindrical geometry with nonfueled graphite reflector blocks filling in the region between the outer diameter of the core and the reactor vessel. Fig. 1 provides a plan view of the core and reflector geometry. This cylindrical shape improved neutron economy, heat transfer, transport of liquid coolant and increase the total power output compared with the VHTR gas-cooled. LS-VHTR uses a closed primary cooled loop immersed in a tank containing a separate buffer salt. This design allows the use of a better salt in the primary coolant loop, that is, a salt that have better coolant properties but is not so good financially [2].

The advantages of using liquid salt as coolant is mainly related with its high efficiency for heat transfer, operation at low pressures, high volumetric heat capacity compared to gas and sodium, possible optical inspection and low corrosion rate. A drawback aspect of liquid salts is the high melting temperature (between 350^0C and 450^0C), however, since the reactor operates at high temperature, this is not a problem. The salt used for coolant is called Flibe (66% LiF and 34% BeF_2). The Flibe has a small neutron cross section, which makes it relatively transparent to neutrons [3].

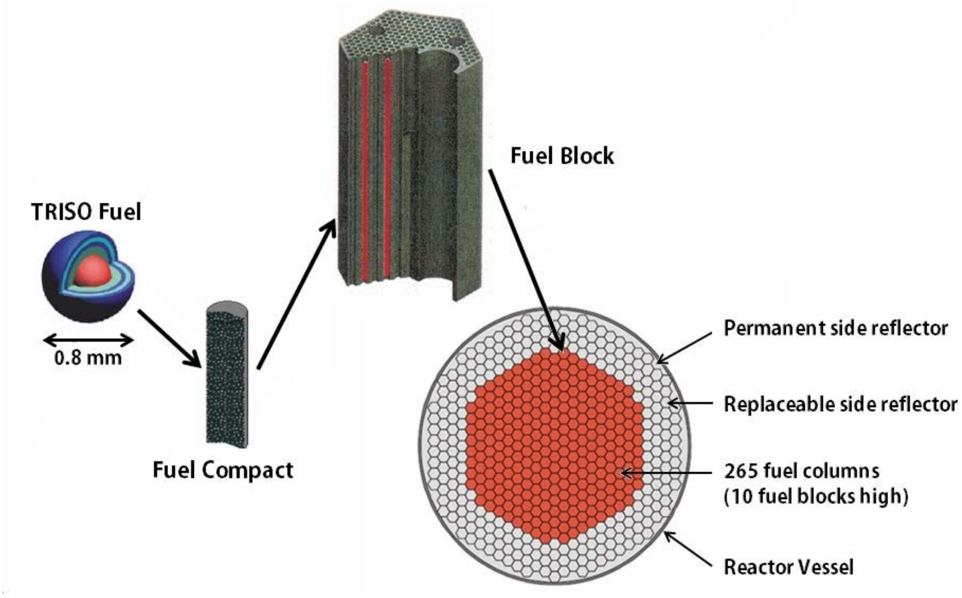

Fig.1. Design of the LS-VHTR core.

2. METHODOLOGY

In this study the baseline fuel block design considered is the same as that considered in the work of Davis and Hawkes, 2006. Each fuel block consists of a hexagonal element of 216 fuel channels, with diameter of 12.7 mm, 108 coolant channels with diameter 9.53 mm and a fuel handling hole. The flat-to-flat distance of the block is 360.0 mm and the channel pitch is 18.8 mm. The baseline block is shown in Fig. 2. The geometrical parameters used in this study are presented in Tab. 1 [2].

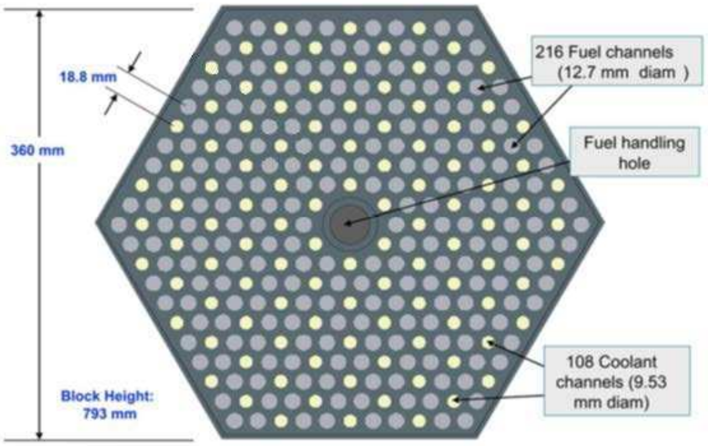

Fig. 2. The LS-VHTR block.

Tab. 1. Geometrical parameters of the LS-VHTR [2]

Parameter	Value
Coolant channel diameter	9.53 mm
Fuel compact diameter	12.45 mm
Fuel channel diameter	12.7 mm
Fuel channel pitch	18.8 mm
Number of coolant channels per block	108
Number of fuel channels per block	216
Number of fuel columns	265
Flat-to-flat distance of hexagonal blocks	360 mm
Gap between hexagonal blocks	1.0 mm
Heated length	7.93 m

An initial thermal analysis of the LS-VHTR was performed in a previous work [4] where the simulation of only one unit cell was considered in the RELAP5-3D code. Each unit cell, represented as a part of the hexagonal fuel block, was modeled to represent one coolant channel, filled with Flibe, and two fuel channels, with two gaps, immersed in graphite moderator matrix [4]. In the present work, a thermal modeling by this reactor has been developed using the RELAP5-3D code using a point kinetic model. The core inlet and outlet coolant temperatures, the coolant mass flow, pressure drop and the temperatures along the core were simulated. The results have been compared with the available data. The developed model demonstrated that the RELAP5-3D is capable of reproduce the thermal behavior of the LS-VHTR in steady state operation.

RELAP5-3D code can employ a variety of coolants in addition to water, the original coolant employed in early versions of the code. Liquid metals (sodium, potassium, NaK, lithium, Flibe) and cryogenic fluids (hydrogen, helium, nitrogen) are some of the available coolants [5]. In this way, the RELAP5-3D can appropriately simulate high temperature reactors. The RELAP5 code versions were originally designed to simulate light water reactors (LWR). The hydrodynamic model is a two-fluid model for flow of a two-phase steam-water mixture that allows non condensable components 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, as in the case of a HTR simulation.

In this way, the LS-VHTR core has been modeled using the RELAP5-3D code. In the developed model, 3 thermal hydraulic channels represent three regions across the core as shown in Fig. 3. The inner region groups the rings 1, 2, 3 and 4. The rings 5, 6, 7 and 8 constitute the middle region. The outer region is composed of the two outer rows of fuel assemblies; rings 9 and 10. A summary of the characteristics of the groups is given in Tab. 2.

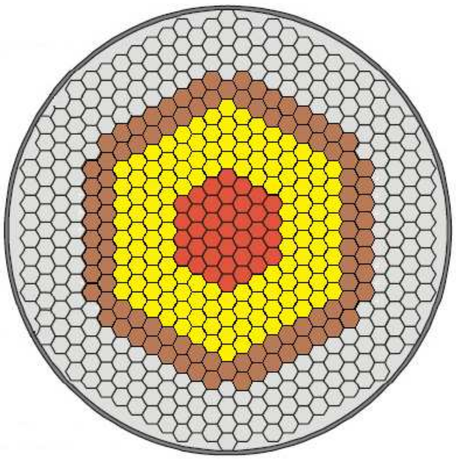

Fig. 3. Inner, middle, and outer region of the LS-VHTR core.

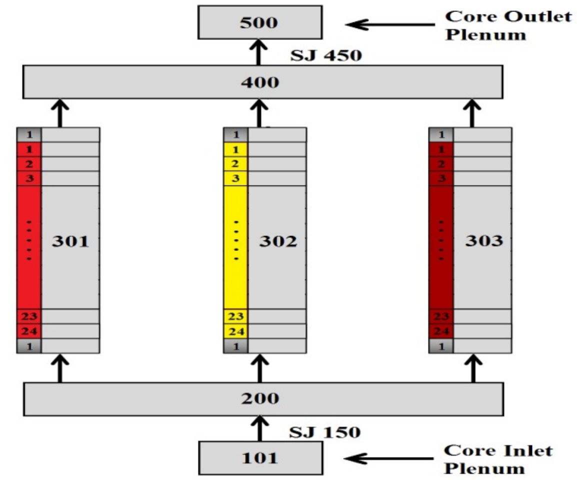

Fig. 4. LS-VHTR core reactor modeled in the RELAP5-3D.

Tab. 2. Description of the model core regions.

	Group 1	Group 2	Group 3
Number of assemblies in the region	37	132	96
Fraction of total number of assemblies	14 %	50 %	36 %
Power generated by the region	447.2 MW	1277.8 MW	674.1 MW
Fraction of total power	18.6 %	53.2 %	28.1 %
Peak to average radial factor	1.33	1.07	0.78

The complete core model is illustrated in Fig. 4. The coolant channels were represented by the component of the type pipe and were divided in 24 axial volumes of 0.3304 m corresponding to the active length of 7.93 m. Two time dependent volumes, 101 and 500, represent, respectively, the inlet and outlet core plenum. The components 450 and 150 are single junctions and the pipes from 301 up to 303 represent the coolant channels.

The Heat Structure (HS) simulate the power source of each channel and they were divided axially according to the same quantity of the thermal channel volumes. All HS have 12 radial meshes, being 6 intervals to the fuel region, 1 interval for the helium gap and 4 intervals representing the graphite region. The thermodynamics properties of the LiF-BeF$_2$ were selected to perform the calculations. The point kinetics option was used in the calculations, the data of volumetric heat capacity and heat transfer coefficient of the standard fuel compact, the helium in the gap and the graphite were considered. The initial conditions used to simulate the core are shown in Tab. 3.

Tab. 3. Initial conditions for the LS-VHTR [2].

Parameter	**Value**
Core total power	2400 MW
Core mass flow rate	10,264 kg/s
Core inlet temperature	900 °C
Core outlet temperature	1000 °C
Core pressure drop	0.211 MPa

The radial power distribution profile used in this work was calculated by ORNL [1] and is shown in Fig. 5. This distribution was generated using Monte Carlo code MCNP4C or a 10-ring core model. The axial power profile chosen is based on a profile used by ORNL to model the LS-VHTR [2].This axial power distribution profile is used to calculate the heat transferred to the coolant channels in each axial segment of the pipes modeling the core reactor, an internal source multiplier value was specified for each axial segment of the three heat structures modeling the fuel channels of the three rings of the core. These values are multiplied by the total power to obtain the power generated in the heat structure [6]. These values are shown in Fig. 6.

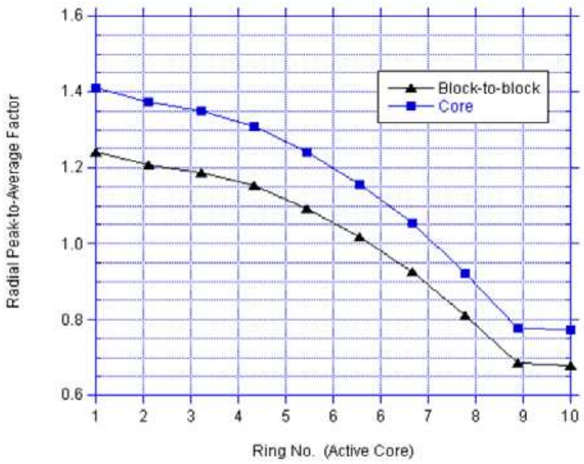

Fig. 5. Radial power profile for the 10-ring ORNL LS-VHTR.

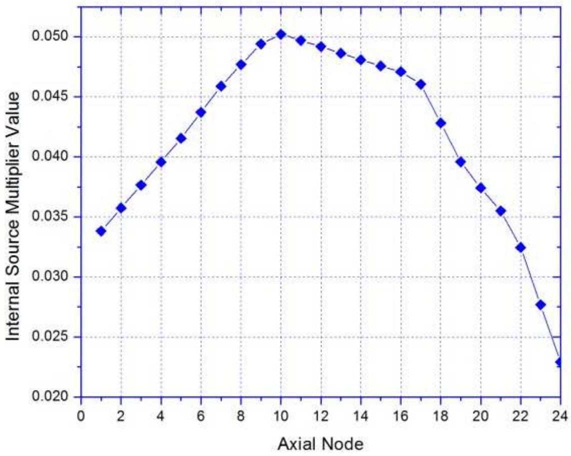

Fig. 6. Internal source multiplier value.

3. RESULTS

The calculated average temperature along the heat structure 302 is shown in the Fig. 7. Each point represents an axial node of the structure, from 1 up to 24 (1 is the bottom and 24 is the top). The temperature of each point is the average radial temperature of the corresponding axial node in the structure. In Fig. 8, the temperature distribution for each axial and radial node of the heat structure 302 is plotted, the inner region is fuel (1 to 6 radial node), middle region is helium (only 7 radial node) and outer region is graphite (8 to 12 radial node).

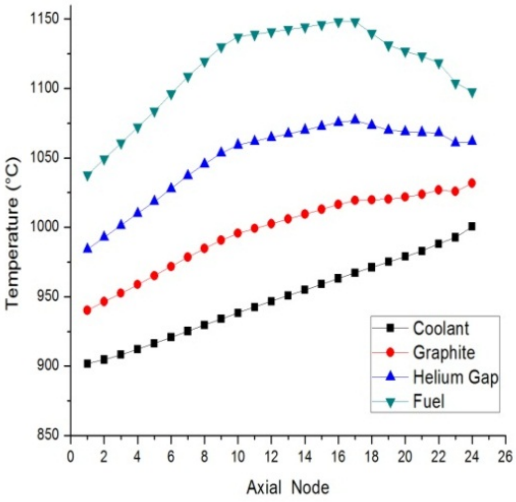

Fig. 7. Mean axial heat structure temperature along the high.

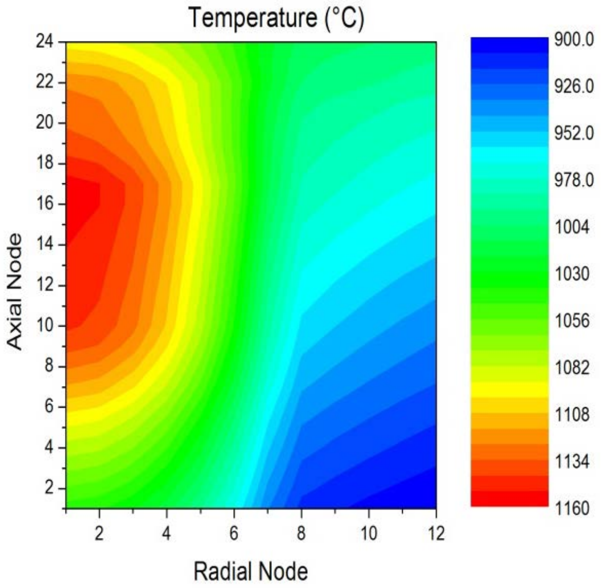

Fig. 8. Temperature distribution of the heat structure 302.

Fig. 9 shows the inlet and outlet core pressure. The calculated pressure along the thermal hydraulic channels is shown in the Fig. 10. Each point represents an axial node of the structure, from 1 up to 24. The pressure decreases along the channel reaching minimum value in the axial node 24, as the expected behavior. The pressure drop obtained by the calculation in this work is 0.18 MPa, which is very close to the pressure drop from the reference data (0.21 MPa as shown in Tab. 3). This difference may be due to the configuration the heat structure.

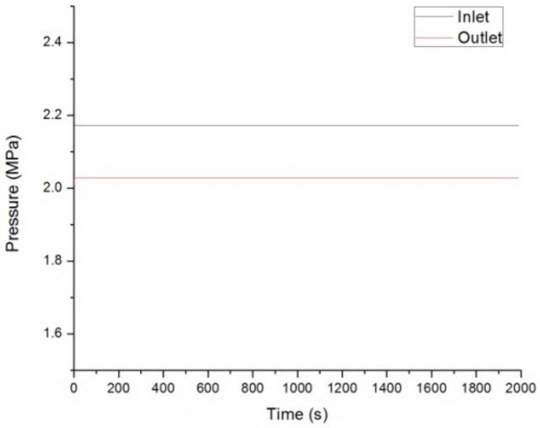

Fig. 9. Pressure drop along the core reactor.

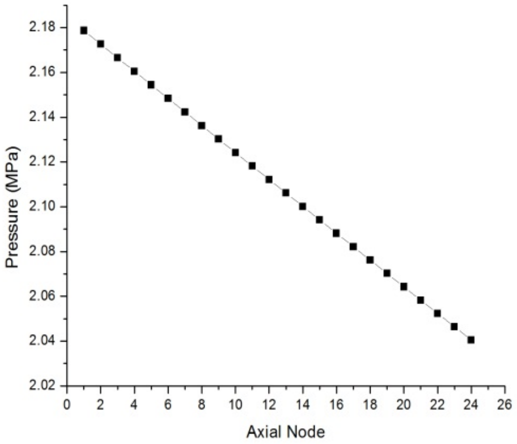

Fig. 10. Pressure distribution of the heat structure.

4. CONCLUSIONS

Core thermal analysis of the LS-VHTR reactor has been performed in this study using the RELAP5-3D code. Then, simulations of thermal parameters of the reactor cooled by liquid Li2BeF4 (Flibe) salt presented similar behaviour in relation to those of the reference presented in Tab. 3.

ACKNOWLEDGMENTS

The authors are grateful to the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (CAPES), the Fundação de Amparo à Pesquisa do Estado de Minas Gerais (FAPEMIG), and the Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq) for the support. Thanks also to Idaho National Laboratory (INL) for the license to use the RELAP5-3D computer software.

REFERENCES

[1] D. T. Ingersoll et al., Status of Physics and Safety Analyses for the Liquid Salt-Cooled Very High-Temperature Reactor (LS-VHTR), ORNL/TM-2005/218, Tennessee, USA (2005).

[2] D. T. Ingersoll et al., Trade Studies for the Liquid-Salt-Cooled Very High-Temperature Reactor: Fiscal Year 2006 Progress Report, ORNL/TM-2006/140, Oak Ridge National Laboratory, Tennessee, USA (2007).

[3] C.B. Davis and G. L. Hawkes, "Thermal-Hydraulic Analyses of the LS-VHTR", Proceedings of ICAPP 2006, Reno, Nevada, USA (2006).

[4] M. E. Scari et al., "Thermal hydraulic modeling of the LS-VHTR", Proceedings of the 2013 International Nuclear Atlantic Conference INAC 2013, Recife, Brazil (2013).

[5] A. L. Qualls and T. L. Wilson, "Dynamic System Model of LS-VHTR to Estimate Design Parameter Impacts on Safety Margin and Reactor Economics", Proceedings of ICAPP 2006, Reno, Nevada, USA (2006).

[6] The RELAP5-3D© Code Development Team, RELAP5-3D© Code Manuals, INEEL-EXT-98-00834, Idaho National Laboratory (2009).

[7] P. E. MacDonald, NGNP Preliminary Point Design Results of the Initial Neutronics and Thermal-Hydraulic Assessments, INEEL/EXT-03-00870, Idaho, USA (2005).