THERMAL HYDRAULIC MODELLING OF A HIGH TEMPERATURE NUCLEAR REACTOR

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ABSTRACT

In the last years, the interest in the innovative LS-VHTR (Liquid-Salt-Cooled Very High-Temperature Reactor) has been growing. The advantages of using liquid salt as coolant is mainly related with its high efficiency of heat transfer, operation at low pressures, high volumetric heat capacity compared with gas and sodium, possible optical inspection and low corrosion rate. The LS-VHTR is a reactor of 2400 MW_t cooled by liquid Li_2BeF_4 (Flibe) salt. The main aim was to verify the model capability comparing the calculation results with the available data. A thermal modeling of 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.

INTRODUCTION

The LS-VHTR is one of the IV generation reactors. This reactor uses coated-particle graphite-matrix fuels and a liquid-fluoride-salt coolant [1].

In the LS-VHTR there is a modification of the VHTR and a new way to combine four new technologies: (1) successful use of coated-particle graphite-matrix fuel in helium-cooled reactors; (2) reactor plant and safety systems similar to that developed to the liquid-metal cooled fast reactors; (3) low-pressure liquid-salt coolants studied and researched for liquid fuel reactors; and (4) Brayton power cycles at high-temperatures. The mix of these four technologies makes it possible to design a high-powered, high-temperature reactor that can economically produces hydrogen or electricity and has a fully passive safety mechanism [2].

The LS-VHTR uses coated-particle graphite-matrix fuels. This type of fuel can be subjected to fuel-failure temperatures in excess of 1600°C without damage.

The utilization of a liquid salt as coolant has different advantage related with high Prandtl number which becomes softer the phenomenon of thermal shock transparency similar to water and gas, allowing optical inspection, simplifying the supply of fuel and maintenance, and low corrosion rate [3]. A drawback aspect of liquid salts is the high melting temperature (between 350 ºC and 450 ºC); however, since the reactor operates at high temperatures, this is not a problem. The salt used for coolant is called Flibe (66% LiF and 34% BeF_2). The Flibe has small neutron absorption and scattering cross section, which makes it relatively transparent to neutrons [4].

The LS-VHTR has cylindrical core and reflector providing an improved neutron economy, heat transfer and coolant transport; the reactor has a total of 265 blocks in a configuration shown in the Fig.1 [2]. In this way, there is an increase of the total VHTR power compared with the gas cooled reactors. Each fuel block consists of a graphite hexagonal element with 216 fuel channels with diameter of 12.7 mm, 108 coolant channels with diameter of 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 [4]. The geometrical parameters used are listed the Table 1.

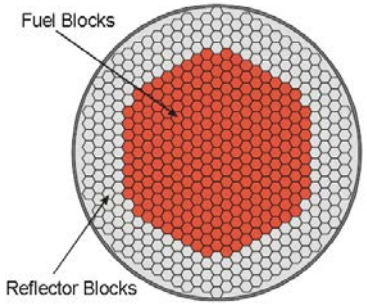

Figure 1 LS-VHTR core [2]

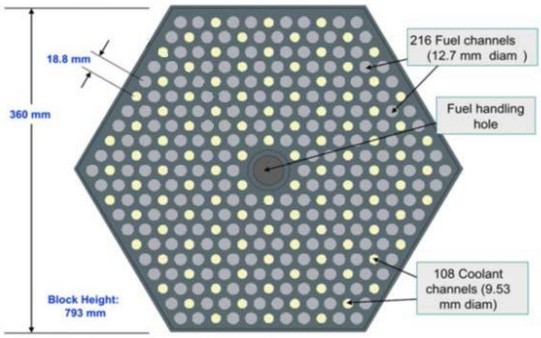

Figure 2 The LS-VHTR block [4]

Table 1 Geometrical parameters of the LS-VHTR [3]

Parameter	Value
Coolant channel diameter, mm	9.53
Fuel compact diameter, mm	12.45
Fuel channel diameter, mm	12.7
Fuel channel pitch, mm	18.8
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, mm	360
Gap between hexagonal blocks, mm	1.0
Heated length, m	7.93

An initial thermal analysis of the LS-VHTR was performed in a previous work [5] 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 modelled to represent one coolant channel, filled with Flibe, and two fuel channels, with two gaps, immersed in graphite moderator matrix [5]. The aim of the present study was to develop a nodalization of the reactor core modelling all hexagonal blocks using the thermal hydraulic RELAP5-3D code.

LS-VHTR CORE NODALIZATION

RELAP5-3D 3.0.0 code [6] 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 [7]. 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 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. Then working fluid only exists in one phase and behaves like an ideal gas [8].

In this way, the LS-VHTR has been modelled using the RELAP5-3D code. In the developed model, 53 thermal hydraulic channels (THC) were considered to represent the 265 fuel columns of the core, that is, each thermal channel represents 5 LS-VHTR columns with the corresponding heat structure (HS). It was used 53 THC to reproduce with more details the core. This will be important when also the neutronic simulation in coupled mode calculation will be used to perform the simulations.

The baseline fuel block design considered is the same as that considered in the work of Davis and Hawkes, 2006 [4]. It was calculated the average volume of fuel, graphite and helium corresponding to each modelled thermal hydraulic channel shown in the Fig.3a. It was selected the molten salt as the working fluid in the hydrodynamic system. The specific thermodynamic properties of the LiF-BeF_2 are used in the calculations.

Heat Source

Modelling heat structures in the RELAP5 code is possible to predict heat conduction across the solid boundaries of the hydrodynamic volumes. Heat transfer can be modelled through fuel pins or plates, steam generator tubes, and pipe and vessel walls. Surface multipliers are used to convert the unit surface of the one-dimensional calculation to the actual surface of the heat structure [6]. Thermal conductivities and volumetric heat capacities as functions of temperature can be input in tables. Finite differences are used to advance the heat conduction solutions. Each mesh interval may contain different mesh spacing, different material, or both. Boundary conditions can be simulated by using tables of surface temperature versus time, heat transfer rate versus time, heat transfer coefficient versus time, or heat transfer coefficient versus surface temperature.

In the present model, 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. A radial view of one of the modelled heat structures is represented in the Fig. 3b, that is a representation of 5 blocks shown in the Fig. 3a.

The point kinetics option was used in the calculations. The axial power distribution was calculated considering a cosine profile. The decay heat is calculated from the ANS-79.1, the 1979 Standard data for ^{235}U. To perform the thermal calculations, the data of volumetric heat capacity and heat transfer coefficient of the standard UO_2 fuel, the helium in the gap and the graphite were considered.

The initial conditions used to simulate the core are shown in Table 2.

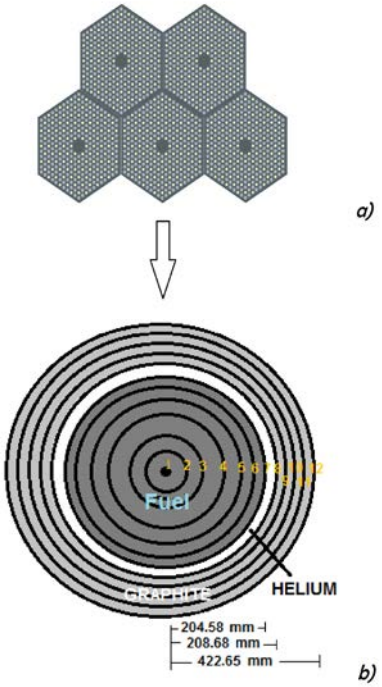

Figure 3 a) columns of the LS-VHTR; **b)** corresponding heat structure modelled in RELAP5-3D

Table 2 Initial conditions for the LS-VHTR [6]

Parameter	Value
Core total power, MW	2400
Core mass flow rate, kg/s	10,264
Core inlet temperature, °C	900
Core outlet temperature, °C	1000
Average fuel temperature, °C	1093
Maximum fuel temperature, °C	1329
Core pressure drop, MPa	0.211
Vessel pressure drop, MPa	0.276

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 meters corresponding to the active length of 7.93 m. Two time dependent volumes, 101 and 800, represent, respectively, the inlet and outlet core plena. The components 700 and 100 are single junctions and the pipes from 201 up to 253 represent the coolant channels. The idea of to model the complete core with several regions is, in the future, to perform a multi-dimensional neutron kinetics modelling using the NESTLE code [6] and then to simulate a 3D thermal-neutron kinetic coupled calculation allowing specific local core investigations during a transient. An upper view of the core regions, in the 3D reconstruction, is shown in the Figure 5. The channels 1, 2, 3 .., 53 are, respectively, the channels identified as 201, 202, 203 …, 253, in the RELAP5 nodalization.

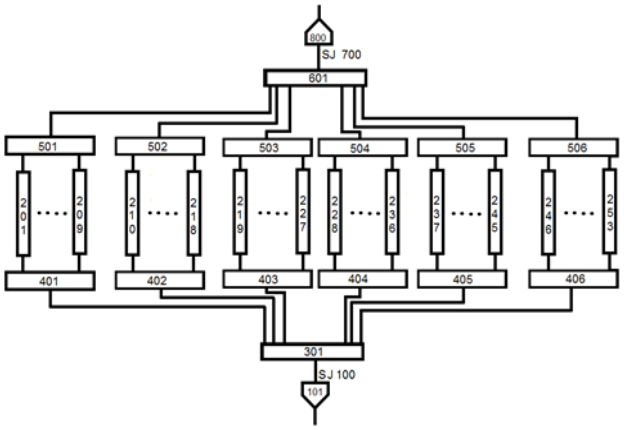

Figure 4 LS-VHTR core reactor modelled in the RELAP5-3D

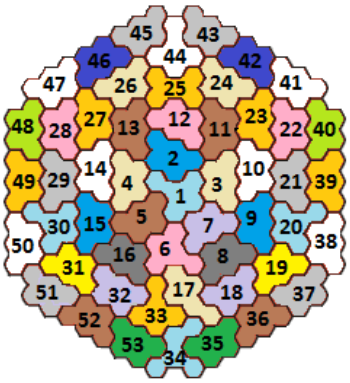

Figure 5 The 53 THC modelled in RELAP5-3D

STEADY STATE CALCULATION

The calculated temperature along the heat structure is shown in the Fig. 6. Each point represents an axial node of the structure, from 1 up to 24. The temperature of each axial point is the average of the radial meshes temperatures of the structure. The temperature increases along the channel reaching maximum value in the axial node 24, following the expected behavior.

The temperature in the fuel center line is illustrated in the Fig. 7. This distribution follows the behavior of the initial power distribution along the fuel that is an approximately cossenoidal axial distribution where the maximum power is near to the half of the heat structure.

In the Fig. 8 is shown the temperature behavior in the upper, middle and bottom positions taking into account the radial temperature distribution.

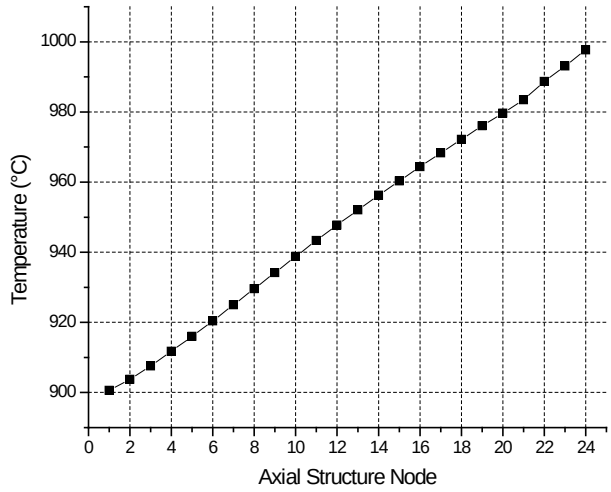

Figure 6 Average axial heat structure temperature

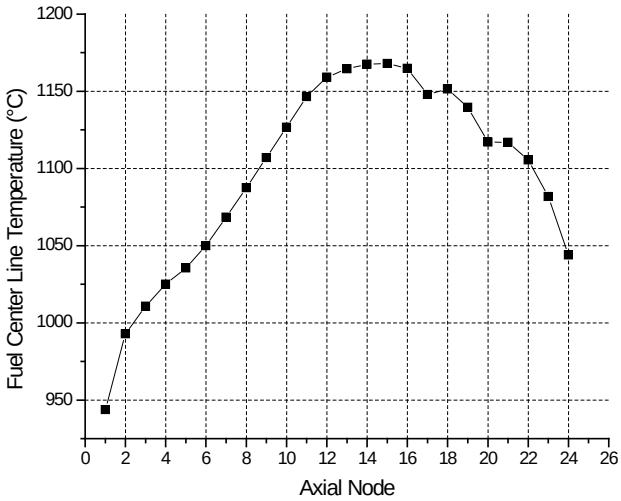

Figure 7 Fuel center line axial temperature distribution following a cossenoidal behavior

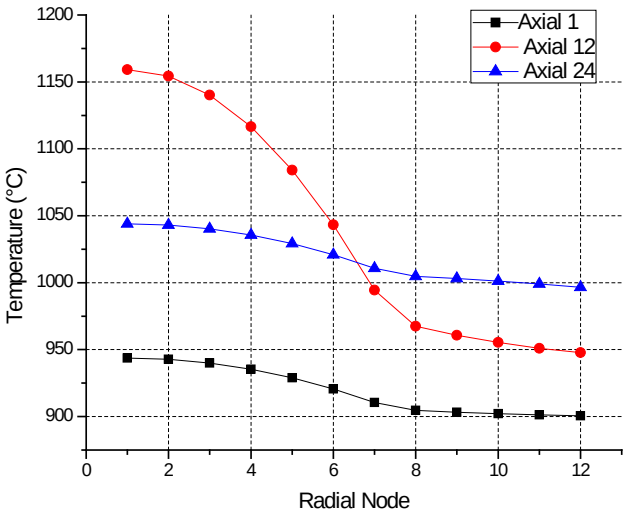

Figure 8 Average axial heat structure temperature

The calculated pressure along the thermal hydraulic channels is shown in the Fig. 9. 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 0.20 MPa, which is very close to the pressure drop from the reference data (0.21 MPa as shown in Table 2).

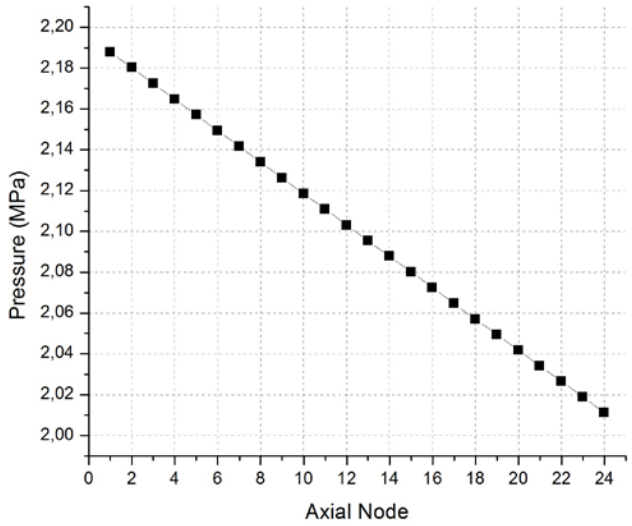

Figure 9 Pressure drop along the coolant channel

The increase of the coolant temperature along the channels is shown in the Fig. 10. The temperature increase by almost 100 °C along the channel as it was expected. The same behavior was observed to all the 53 thermal channels.

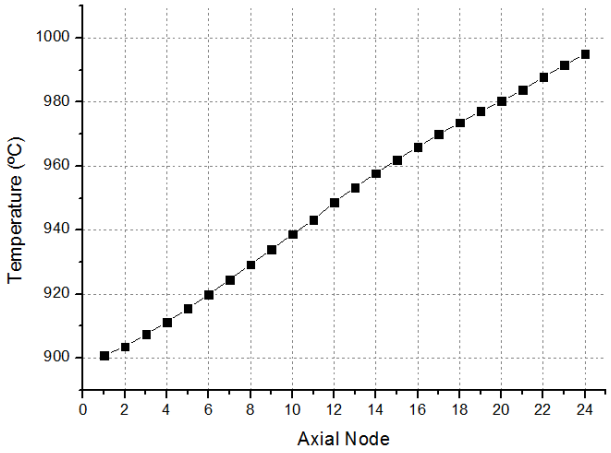

Figure 10 Coolant temperature increase along the THC

In the Table 3 is presented a comparison between the calculated results with the RELAP5-3D and the reference data for the steady state conditions with the difference calculation. As it is possible to verify, in a general way, the parameters are in good agreement each other.

Table 3 Steady state calculation in comparison with the reference data

Parameter	Reference Data [2]	Calculation Value	E*(%)
Core inlet temperature, °C	900.0	900.85	0.1
Core outlet temperature, °C	1000.0	995.04	0.5
Average fuel temperature, °C	1093.0	1066.0	2.5
Core pressure drop, MPa	0.21	0.20	4.8

*Error = 100 x (calculation – experimental)/experimental

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 Li_2BeF_4 (Flibe) salt presented similar behaviour in relation to those of the reference one.

The next step of this work is to complete the core nodalization considering more details including safety mechanisms and neutronic parameters to perform a more realistic reactor simulation using the multidimensional capabilities of the RELAP5-3D.

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