ALFRED FUEL ASSEMBLY MODEL DEVELOPMENT AND VALIDATION WITH RELAP/SCDAPSIM/MOD4.1

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The purpose of this work is the model development and validation of the LFR fuel assembly during steady-state operation with RELAP/SCDAPSIM/MOD4.1 through analytical calculations. The RELAP/SCDAPSIM/MOD4.1 tool benefits of advanced materials properties for Generation IV reactors, namely properties of molten metal coolants The analyses carried out within the work are aimed at the thermal-hydraulic study of the maximum power assembly during normal operation.

Keywords: ALFRED, RELAP/SCDAPSIM, fuel assembly, thermal-hydraulic

1. Introduction

ALFRED (Advanced Lead-cooled Fast Reactor European Demonstrator) is a research infrastructure aimed at demonstrating the safety, susteinability and technical and economic viability of lead-cooled fast reactor technology in the new generation of nuclear systems, including Small Modular Reactor (SMR) designs.

The Primary Heat System of the ALFRED demonstrator [1] is pool-type with all the primary coolant contained within the Inner Vessel, as shown in the left part of Fig. 1

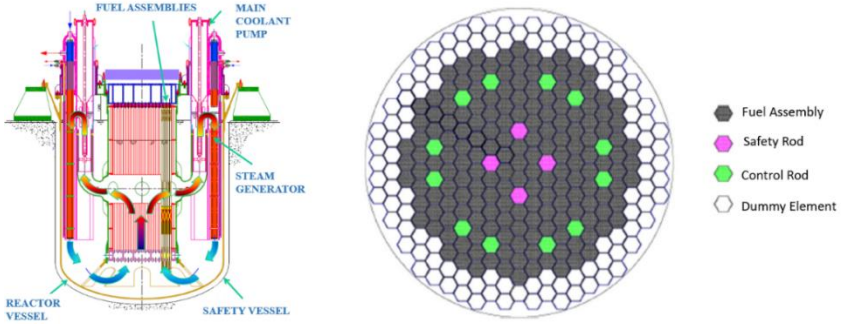

Fig. 1 A schematic figure of the ALFRED Primary Heat System (left) and cross-section through ALFRED core (right) [1], [2]

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The fuel assemblies are immersed in the molten lead coolant, except the bottom and upper parts which are located in a gas cover, for an easy handling and inspection.The reactor core consists of 171 wrapped hexagonal fuel assemblies surrounded by 108 Dummy Elements and 16 control and safety rods [2], as represented in the right side of Fig. 1. Each fuel assembly (FA) contains 127 fuel rods filled with hollowed MOX pellets, distributed in a 60 cm active region [2] with a large pitch, as depicted in Fig. 2. The pure lead coolant circulates through the coolant pumps, enters the steam generators through the lead inlets and exits the steam generators to the bottom of the Reactor Vessel where it passes back through the fuel assemblies by natural circulation.

During normal opeating conditions the coolant circulates at atmospheric pressure (~0.1 MPa) with an average inlet temperature of 400°C and an average outlet temperature of 480°C [2].

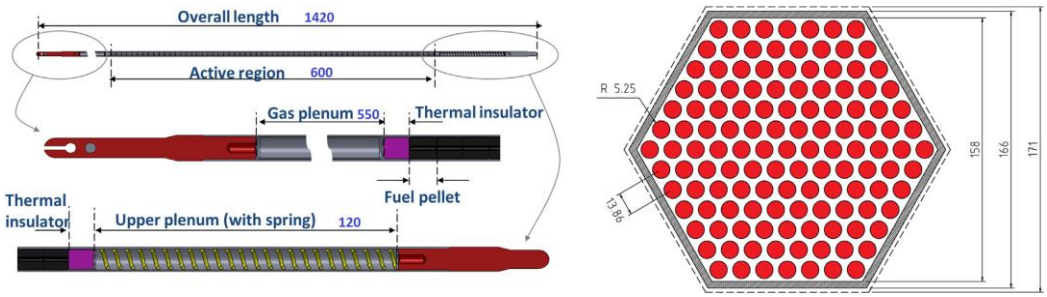

Fig. 2 ALFRED fuel pin and the active region (left) and fuel assembly cross-section (right) [2]

Within this paper, the aim is to demonstrate the capability of RELAP/SCDAPSIM/MOD4.1 code to conduct a thermohydraulic analysis of an ALFRED fuel assembly and provide accurate results regarding the temperature distribution of the pure lead coolant and the temperature distribution of the cladding. Therefore, the results obtained through running the analysis in RELAP/SCDAPSIM/MOD4.1 were compared to the results of the analytical calculation, using the same correlations implemented in the code.

2. RELAP/SCDAPSIM/MOD4.1 short description

RELAP5/SCDAPSIM code was selected to perform the present analysis, which is a code designed to predict the behavior of reactor systems during normal and accident conditions [3], developed as part of the international SCDAP Development and Training Program (SDTP). Three main versions of RELAP/SCDAPSIM are currently used by program members and licensed users to support a variety of activities. The most advanced version of the code, RELAP/SCDAPSIM/MOD4.0, is the first version of RELAP or SCDAP/RELAP5 completely rewritten to FORTRAN 90/95/2000 standards. MOD4.0 can also run a much wider variety of transients including low pressure transients with the presence

of non-condensable gases such as those occurring during midloop operations in LWRs, in pool type reactors such as ALFRED, or in spent fuel storage facilities.

RELAP/SCDAPSIM/MOD4.1 has implemented the specific thermophysical properties according to NEA Handbook on material properties [4] and Sobolev's work [5] and wall-to-fluid heat transfer correlations for single phase liquid, derived from C.B. Davis, A.S. Shieh [6] and K. Mikityuk's work [7].

3. ALFRED fuel assembly model development and validation

3.1 Fuel assembly RELAP/SCDAPSIM/MOD4.1 model development

The coolant flow through the fuel assembly is modelled with a pipe component divided into 10 identical axial volumes as described in , with a length of 0.06 m each. Two time-dependent volumes (V1 and V2) attached to the both ends of the pipe component set the boundary conditions at the inlet and outlet of the fuel assembly for coolant pressure and temperature, where pressure is maintained at atmospheric conditions of 0.1 MPa, and inlet and outlet temperatures of 400°C and 480°C respectively, as stated in [2].

Junctions J1 and J2, represented as arrows in , set the coolant flow rate at the inlet and outlet of the fuel assembly. For the steady-state analysis a constant value of 172.3 kg/s has been maintained through the inlet and outlet junctions, according to [2], which corresponds to the high-power fuel assembly. A heat structure component was used to model the heat transfer in the fuel pins, for the maximum power fuel assembly [2] of 2.25 MWth. The heat structure in divided into six radial nodes, corresponding to 5 radial intervals where the first three intervals (equally spaced) describe the MOX fuel, the fourth interval describes the gap filled with helium and the last interval represents the 15-15 Ti cladding. Fig. 4 shows the radial mesh of the fuel pin.

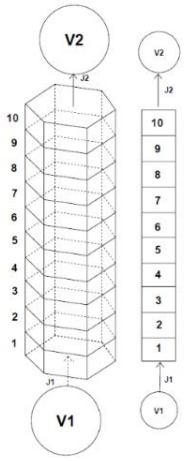

Fig. 3 Flow model of the fuel assembly

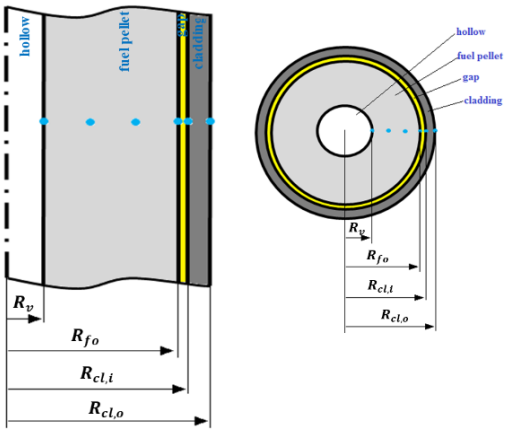

Fig. 4 Representation of the heat structure

To be noted that the heat structure left boundary was considered at 1 mm from the center of the fuel pin, in order to simulate the hollowed fuel pellet. The thermal properties of the fuel pin layers are were introduced in the input deck as tables based on the temperature variation. Specific correlations used are summarized in Table 1:

Table 1

Thermal conductivity and heat capacity of the fuel and cladding materials

MOX fuel		
Thermal conductivity [8]	$\lambda_{MOX} = (0{,}042 + 2{,}71 \times 10^{-4}T)^{-1} + 6{,}9 \times 10^{-11}T^3$	W/(m·K)
15-15 Ti cladding		
Thermal conductivity [9]	$\lambda_{15-15\,Ti} = 8.826 + 1.707 \times 10^{-2}T - 2.315 \times 10^{-6}T^2$	W/(m·K)
He gap		
Thermal conductivity [9]	$\lambda_{He} = 2.639 \times 10^{-3}T^{0.7085}$	W/(m·K)

The values of the power produced by each axial volume and subsequently the power fractions and the heat flux were determined considering the cosine linear power distribution.

Uniform radial power distribution was assumed in the analysis ($\beta = 1$), which in turn led to a fuel pellet void factor [14]:

$$F_v(\alpha, \beta) = 1 - \frac{ln\,(\alpha^2)}{\beta^2(\alpha^2 - 1)}$$

where,

$$\alpha = \frac{R_{fo}}{R_v}$$

3.2 Fuel assembly steady-state analytical model

The fuel assembly model for the analytical thermal-hydraulic calculation follows the same axial division as used in RELAP/SCDAPSIM/MOD4.1, respectively 10 axial control volumes, considering one inlet and one outlet for each volume. The outlet properties of the n^{th} volume are identical with the inlet properties of the $n^{th}+1$ control volume (where $n = \overline{1,10}$).

First step of the analytical study consists in the determination of the fuel assembly inlet enthalpy, $h_{1i} = f\left(T_{M,0}, T_{1i} = 673K\right)$, following the correlation from reference [4], with:

$$h_{Pb}\left(T_{M,0}, T_{Pb}\right) = 176.2 \cdot \left(T_{Pb} - T_{M,0}\right) - 2.4615 \times 10^{-2} \cdot \left(T_{Pb}^2 - T_{M,0}^2\right) + 5.147 \times 10^{-6} \cdot \left(T_{Pb}^3 - T_{M,0}^3\right) + 1.524 \times 10^6 \cdot \left(T_{Pb}^{-1} - T_{M,0}^{-1}\right) [J/kg]$$

where, $T_{M,0}$ – lead melting point at atmospheric pressure ($T_{M,0} = 600.6K$), and T_{Pb} – coolant (lead) temperature, in K.

The average temperatures of the coolant in a control volume are determined as:

$$\bar{T}_{Pb,n} = \frac{T_{n,i} + T_{n,e}}{2}$$

Based on the average temperature of the coolant, the thermodynamic properties can be calculated with specific correlations summarized in Table 2.

Table 2

Pure lead thermodynamic and transport properties at atmospheric pressure [4]

Parameter	Correlation	Range of applicability
Density	$\rho = 11441 - 1.2795 \cdot T\ [kg/m^3]$	$T_{M,0} < T < 1900K$
Specific volume	$v = \frac{1}{\rho}[m^3/kg]$	$T_{M,0} < T < 1900K$
Isobaric specific heat	$c_p = 176.2 - 4.923 \times 10^{-2} \cdot T + 1.544 \times 10^{-5} \cdot T^2 - 1.524 \times 10^6 \cdot T^{-2}\ [J/kg \cdot K]$	$T_{M,0} < T < 1300K$
Sonic velocity	$u = 1953 - 0.2463 \cdot T\ [m/s]$	$T_{M,0} < T < 2000K$
Thermal conductivity	$\lambda = 9.2 + 0.011 \cdot T\ [W/mK]$	$T_{M,0} < T < 1300K$

Parameter	Correlation	Range of applicability
Dynamic viscosity	$\eta = 4.55 \times 10^{-4} \cdot exp\left(\frac{1069}{T}\right)\ [Pa \cdot s]$	$T_{M,0} < T < 1470K$

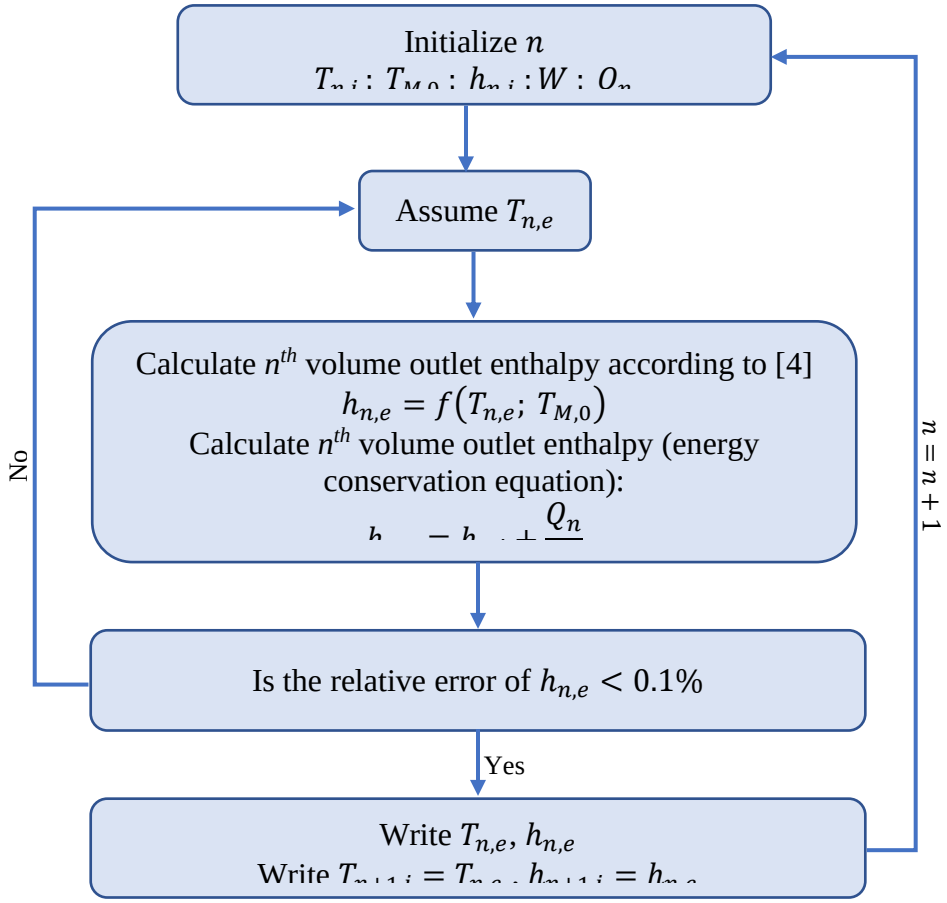

Fig. 5 Flow diagram of the coolant temperature calculation scheme

For the analytical solution of the cladding outer surface temperature, it is necessary to calculate the coolant heat transfer coefficient (HTC).

$$HTC = \frac{\lambda \cdot Nu}{d_{hy}}\ [W/(m^2 \cdot K)]$$

The available wall-to-fluid heat transfer correlations for Pb in RELAP/SCDAPSIM/MOD4.1 of the Nusselt number is determined with Mikitiuk's [7] correlation considering the pitch to diameter (p/d) ratio and the

Peclet (Pe) number. For the analytical solution of the Nusselt number the existing correlation from RELAP/SCDAPSIM/MOD4.1 will be used, as follows:

$$Nu_n = 0.047 \cdot \left\{1 - \exp\left[-3.8 \cdot \left(\frac{p}{d} - 1\right)\right]\right\} \cdot (Pe_n^{0.77} + 250)$$

with the applicability range of $1.1 < p/d < 1.95$ and $30 < Pe < 5000$ (both for triangular and square lattice), where,

$$Pe = Re \cdot Pr\ [-]$$

Reynolds and Prandtl were calculated as:

$$Re = \frac{G \cdot d_{hy}}{\eta}\ [-]$$

$$Pr = \frac{\eta \cdot c_p}{\lambda}\ [-]$$

with, G – mass flux, in $kg/(m^2 \cdot s)$; d_{hy} – flow hydraulic diameter, in m; η – dynamic viscosity, in $kg/(m \cdot s)$ or $Pa \cdot s$; c_p – isobaric specific heat, in $J/(kg \cdot K)$; λ – thermal conductivity, in $W/(m \cdot K)$

The cladding outer surface temperature of each control volume, $T_{cl,o\,n}$, was calculated based on the heat convection solution:

$$T_{cl,o\,n} = \bar{T}_{Pb,n} + \frac{q'_n}{2\pi R_{cl,o} HTC_{Pb,\,n}}$$

where, q'_n – linear power of the n^{th} control volume, in W/m and $R_{cl,o}$ – fuel pin outer radius, in m ($R_{cl,o} = 5.25\ mm$)

The cladding inner surface temperature of each control volume, $T_{cl,i\,n}$, was calculated based on the heat conduction solution:

$$T_{cl,i\,n} = T_{cl,o\,n} + \frac{q'_n}{2\pi\lambda_{cl,\,n}} \cdot ln\left(\frac{R_{cl,o}}{R_{cl,i}}\right)$$

where, $\lambda_{cl,\,n}$ – thermal conductivity of the cladding material, in $W/(m \cdot K)$, computed from
Table **1** and $R_{cl,i}$ – cladding inner radius, in m ($R_{cl,i} = 4.65\ mm$)

The fuel pellet outer surface temperature of each control volume, $T_{fo,n}$, was calculated based on the heat conduction solution in the gap:

$$T_{fo,\,n} = T_{cl,i\,n} + \frac{q'_n}{2\pi\lambda_{gap,n}} \cdot ln\left(\frac{R_{cl,i}}{R_{fo}}\right)$$

where, $\lambda_{gap,\,n}$ – thermal conductivity of the gap filled with helium, in $W/(m \cdot K)$, computed from Table 1.

The fuel pellet inner surface temperature of each control volume, $T_{fi,n}$, was calculated based on the heat conduction solution in the gap:

$$T_{fi,n} = T_{fo,n} + \frac{q'_n}{2\pi\lambda_{MOX,n}} \cdot F_v(\alpha, \beta)$$

where, $\lambda_{MOX,n}$ – thermal conductivity of MOX fuel, in $W/(m \cdot K)$, computed from Table 1.
. The cladding inner surface temperature, fuel pellet temperatures (both outer and inner surface) are calculated using an iterative process with the specific correlation for the thermal conductivities of the material layers.

4. Steady-state results and validation through analytical calculations

The power produced by each section of the fuel assembly from a control volume and heat flux at fuel pin surface calculated with RELAP/SCDAPSIM/MOD4.1 and determined through analytical calculation are represented in Fig. 6 and Fig. 7, which show similar values regarding the axial distribution.

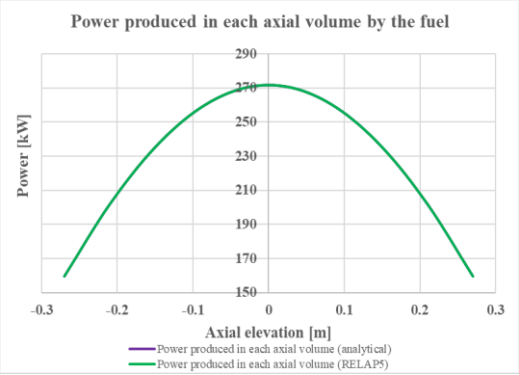

Fig. 6 Axial power distribution in the FA

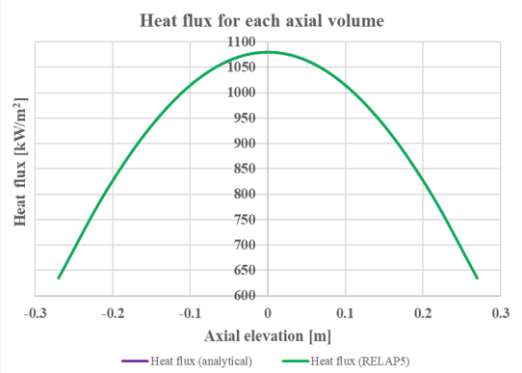

Fig. 7 Axial heat flux distribution

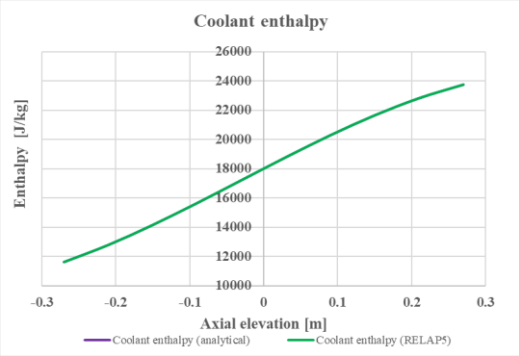

Fig. 8 Coolant enthalpy axial distribution

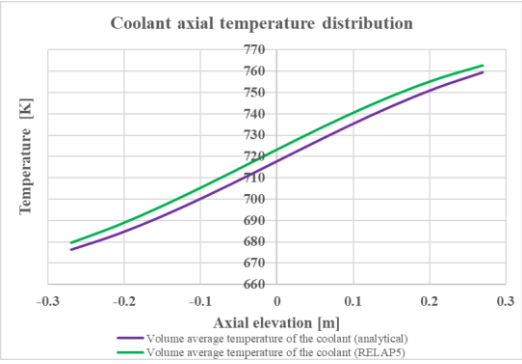

Fig. 9 Coolant axial temperature distribution

Fig. 8 represents the results comparison regarding the enthalpy obtained with RELAP/SCDAPSIM/MOD4.1 and analytical calculations. The coolant enthalpy axial distribution show no major differences due to the similar correlation used by the code and hand calculations. Fig. ***9*** shows the lead axial temperature distribution, where can be noted the similar trends for the code analysis results and analytical model, with higher values obtained through RELAP/SCDAPSIM/MOD4.1 results compared to the analytical results. These differences do not exceed 5K and may occur due to the iterative process used for analytical calculations.

Due to coolant temperature differences the dynamic viscosity resulted from the analytical model are slightly greater than the values calculated by RELAP/SCDAPSIM/MOD4.1, which will led to lower values of the Reynolds number from analytical calculations compared to code results, as depicted in Fig. 10. Peclet number shows no major differences, as shown in (axial ***distribution)*** ***Fig. 11*** since Prandtl number analytical determined is slightly greater than the predicted values of RELAP5 due to coolant temperature differences which impacts the thermodynamic and transport properties of the lead (isobaric specific heat and thermal conductivity).

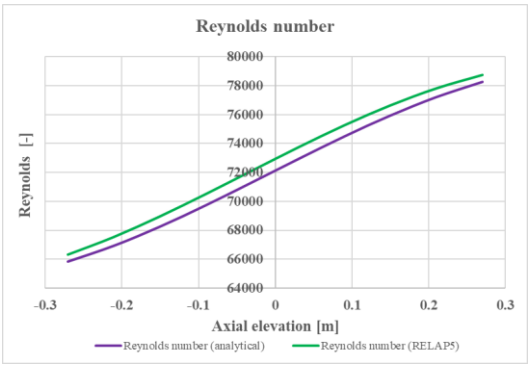

Fig. 10 Reynolds number (axial distribution)

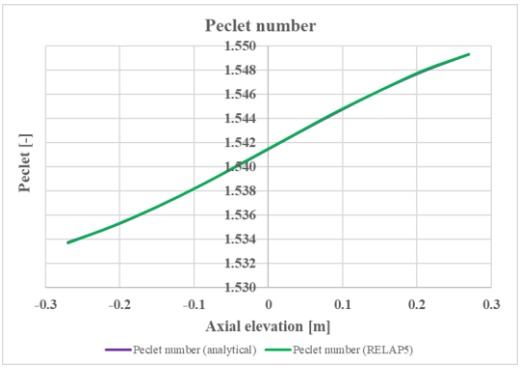

Fig. 11 Peclet number(axial distribution)

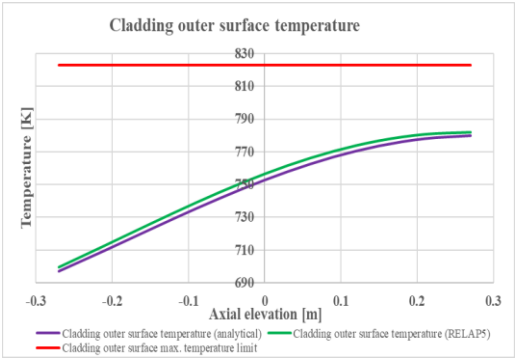

Fig. 12 Coolant dynamic viscosity

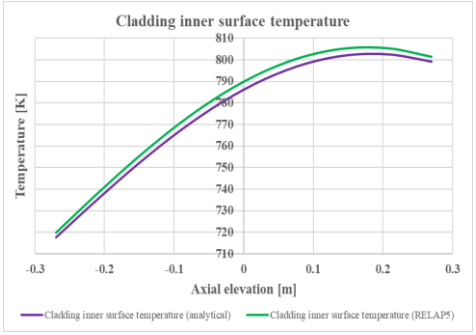

Fig. 13 Coolant thermal conductivity and HTC

Coolant dynamic viscosity ***Fig***. ***12***) predicted by RELAP/SCDAPSIM/MOD4.1 compared to analytical solution shows lower values due to predicted slightly higher values of temperatures calculated by the code and the specific correlation from Table 2.

The lead thermal conductivity variation represented in Fig. ***13*** show significant differences of the analytically calculated values and the predicted code values due to the proportionality of this parameter with coolant temperature (variation of the thermal conductivity with temperature as observed from Table 2 which can be described through a linear variation with negative slope). The heat transfer coefficient predicted by RELAP5 is also higher than the analytical solution, as can be noted in Fig. ***13*** values due to the direct correlation with the thermal conductivity values.

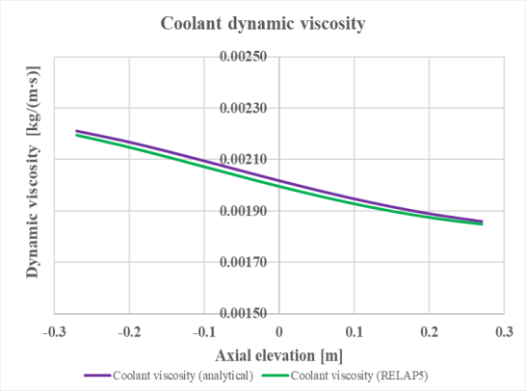

Fig. 14 Cladding outer surface temperature

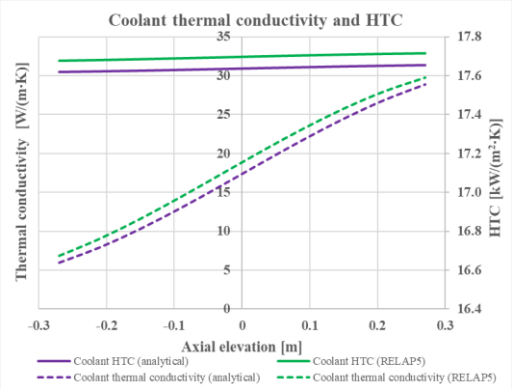

Fig. 15 Cladding inner surface temperature

Fig. ***14*** and Fig. ***15*** show the axial cladding temperature distribution. The small differences of the cladding outer surface temperatures come from the coolant temperature distribution (analytical solution values are slightly lower than RELAP5 predicted values). Temperature difference is maintained also for the inner surface of the cladding being strongly impacted by the outer surface temperatures.

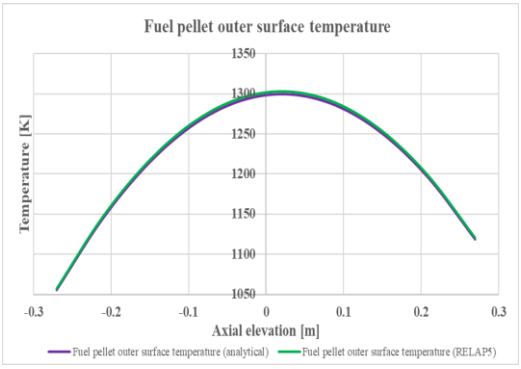

Fig. 16 MOX outer surface temperature

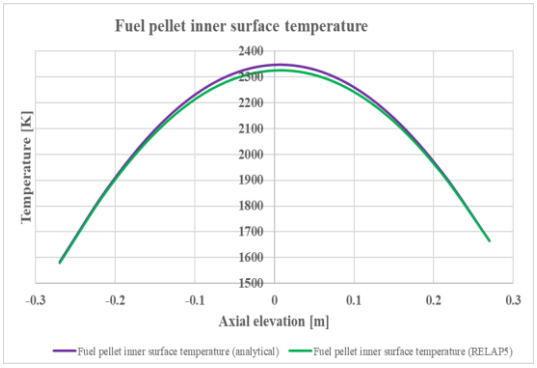

Fig. 17 MOX inner surface temperature

The MOX fuel outer surface temperatures represented above show no major differences on the analytically determined values and RELAP5 analysis results. In terms of inner surface temperatures of the MOX fuel pellet (Fig. 17), the RELAP5 results deviation from the analytical values can occur due to thermal conductivity computed by the code. RELAP5 calculates the average thermal conductivity in the fuel through interpolation from the thermal conductivity table in the input deck, while the analytical model uses the direct correlation from Table 1.

Even though the thermal conductivity as function of temperature described in the input deck is computed from the analytical correlation, the temperature abscissa is divided into 100K units (each two adjacent points describe a linear variation, compared to the correlation trendline that follows a polynomial distribution).

4. Conclusions and remarks

Within this paper it has been analyzed the ability of RELAP5/SCDAPSIM/MOD4.1 to provide accurate result regarding a thermal hydraulic analysis of an ALFRED fuel assembly. The results obtained by the simulation in the code were validated through analytical calculations that used the same correlations implemented into the code. The simulation was performed for a high-power channel (2.25 MWth) for 600s under steady-state conditions. Temperatures obtained from the simulation match with the analytical model results within slight differences of 4K in the coolant temperature, about 6K maximum temperature difference in the cladding temperatures, and maximum 20K for the inner surface temperature of the fuel pellet.

To be noted that all the compared parameters through analytical calculation were in good agreement with those resulted from RELAP5 calculation.

Another important safety aspect during normal operation (corrosion related issues of the cladding material by the lead coolant) is to limit the cladding maximum temperature at 550°C (823K) according to [1].

Fig. ***14*** shows that the cladding outer surface temperature ensures a sufficient safety margin of a minimum of 41K to the corrosion temperature limit.

R E F E R E N C E S

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