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Channel Analysis of the AP-Th 1000 Reactor Concept

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1. Introduction

Thorium had its golden age between the 1960s and 1980s through intensive studies on a global scale, with the aim of establishing a promising basis for future nuclear fuel cycles. However, after demonstrating the feasibility of fuel cycle concepts using thorium, the United States decided to focus their studies on liquid metal fast regeneration reactors using uranium and plutonium. Due to this, global interests in the development of thorium fuel cycles continued, however, at a slower pace, with investments mostly by India [1].

All this global mobilization for the study of thorium as a nuclear fuel is due to its favorable characteristics not only for a specific reactor technology, but for a wide application possibility. Thorium is found in abundance in the earth's crust, reaching around three to four times greater than the amount of current uranium, being normally found in the form of oxides, phosphates and silicates, such as the isotope ^{232}Th 100%, having a half life span of 1.4×10^{10} years, becoming stable at ^{208}Pb [2].

The energy potential of thorium can be maximized, since it can be easily obtained as a product or sub-product of deposits mined from other activities, which have greater added value due to minerals such as rare earth elements and/or titanium [3]. Thorium-based fuels contain fewer radioactive elements, in addition to being smaller in volume and mass than conventional uranium-based nuclear waste. The thorium fuel cycle provides an efficient way to reduce existing plutonium stockpiles, through its use to initiate the thorium fission chain reaction, and other combinations of cycles that can be conducted.

The use of thorium as a nuclear fuel in different types of reactor technology is not only related to its neutronic properties, but also to its thermophysical properties. Thorium dioxide has a high melting point, high thermal conductivity, low coefficient of thermal expansion and excellent chemical stability when compared to fuels based on uranium and plutonium [4]. These properties give thorium an expansion in terms of application and can be used in high and low temperature reactors.

The AP-Th 1000 is an advanced concept of the American AP1000 reactor, which uses a fuel mixture

(MOX) of uranium and thorium instead of traditional uranium dioxide fuel. This new core proposal has been studied since 2015 by the group led by Dr. José Rubens Maiorino and has already provided relevant results about the neutron behavior, however, in this work an initial analysis of the thermohydraulic characteristics of this core will be presented.

2. Methodology

We start by evaluating the thermophysical characteristics of the materials (density, specific heat, thermal conductivity, etc.) that make up the flow channel (fuel, gap, cladding, and coolant). This step is relevant mainly because the MOX fuel has correlations that do not fit very well with the reactor's operating range. Both operating conditions and geometric characteristics of the AP-Th 1000 core were kept the same as the standard AP1000 core and are available in the Westinghouse manuals [5].

We use a mixture of uranium and thorium as fuel, with a content of 24% UO_2 in the mixture. We develop the geometry and mesh using the Design Modeler and MESHING tools, respectively. Both software is present in the Ansys package. Figure 1 illustrates the three-dimensional model of the channel geometry.

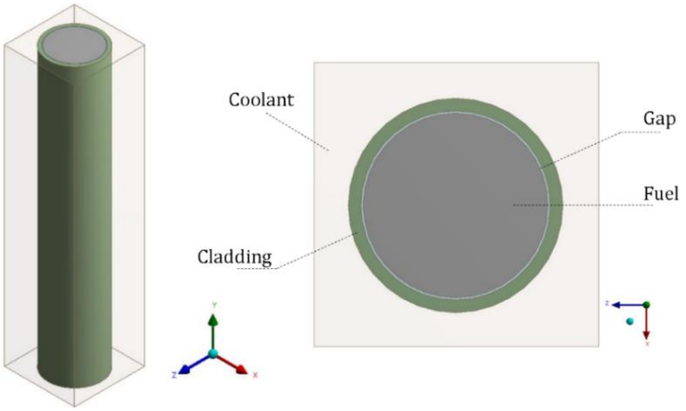


Figure 1: The computational domain of the geometry channel.

We established a simpler mesh to provide a result in a shorter time while maintaining good mesh quality criteria, to obtain an initial model for understanding the main thermohydraulic parameters of the AP-Th 1000. Figure 2 shows the discretization of the domain under analysis.

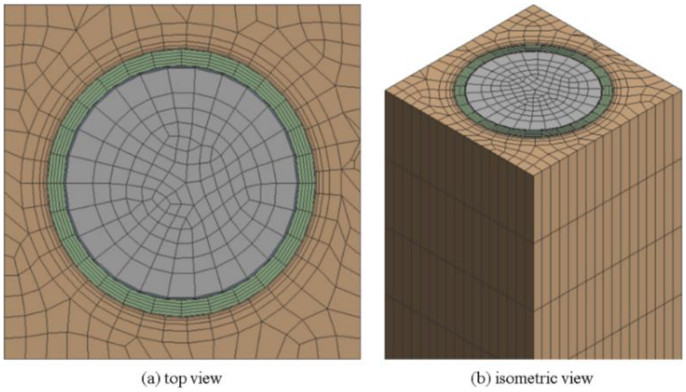

(a) top view
(b) isometric view

Figure 2 : Mesh model of computational domain

We applied inflation in the contact region between the external surface of the cladding and the coolant to more accurately capture the heat transfer in this region, even using an initial mesh, that is, without the mesh sensitivity study. The mesh used in this study has 1.7 million elements. We evaluated the mesh quality using four criteria, Orthogonal Quality, Skewness, Jacobian Ratio, and Aspect Ratio. Table I shows the mesh metrics.

Table I: Mesh metric summary.

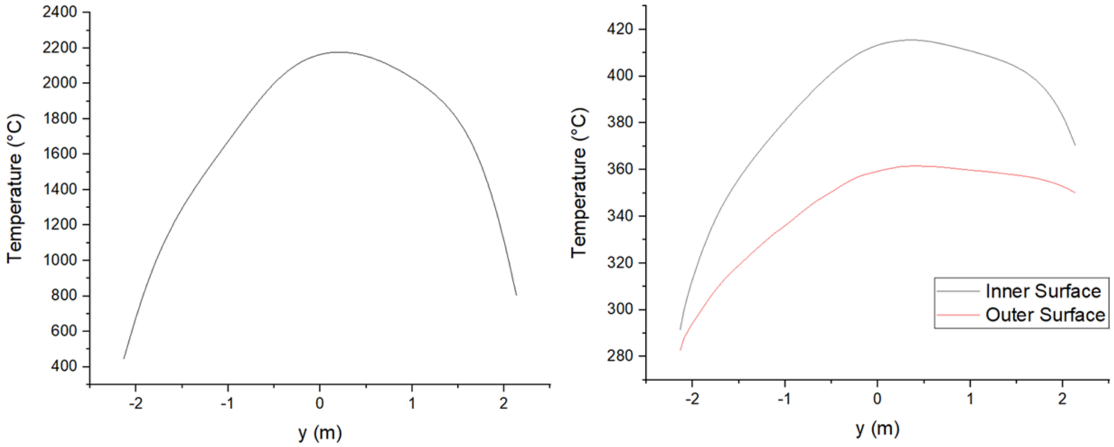
Parameter	Minimum	Maximum	Average
Orthogonal quality	0,22215	0,9998	0,97828
Jacobian Ratio	0,10035	1	0,88215
Skewness	0,010167	0,78233	0,11732
Aspect Ratio	1,2509	100,59	12,18

As previously mentioned, the operating conditions of the AP-Th 1000 concept and AP1000 reactor are the same, so the temperature at the channel entrance is 279°C, the system pressure is 15.5MPa, and the coolant flow rate is 0.296577 kg/s. We use the IAPWS-IF97 library to define coolant properties.

3. Results and Discussion

To start the thermohydraulic study of the AP-Th1000 concept, as in any other, the first parameter to be observed is the temperature, as this must not exceed the operating limits. Although the characteristics of the AP-Th 1000 and AP1000 reactors are similar, their operating limits will not be the same, and this is due to the fuel characteristics. An example of this variation can be illustrated by the melting point of UO_2 and ThO_2, once the uranium dioxide has a melting point of around 2800°C, while thorium dioxide is a little higher, reaching 3300°C.

We analyze the AP-Th 1000 concept at the beginning of the cycle (BOC) through the hot channel to determine the maximum operating values. Figure 3 shows the temperature distribution at the centerline of the fuel domain and the temperature profiles on both cladding surfaces.



(a) Fuel center line

(b) Inner and outer surface of the cladding

Figure 3: Temperature distribution on the fuel centerline and on both cladding surfaces.

A more detailed analysis of the fuel correlations (Density, Specific Heat, and Thermal conductivity) and other materials is necessary, regardless of whether the value of this temperature is within the operating limits of the reactor, as well as the mesh used for the calculations. We verify that the maximum temperature reached in the cladding is 415.45°C, which is a good result once 400°C is the value reported by Westinghouse to the AP1000 reactor case.

4. Conclusions

The initial and simplified hot channel analysis of the AP-Th 1000 concept at the beginning of the cycle (BOC) was carried out to determine the maximum temperatures in the fuel and the cladding. Temperature limit results for the BOC were obtained for a linear power of 489.9 W/cm and giving 2176.8 °C and 415.45°C as the maximum fuel and cladding temperatures, respectively. These initial values demonstrated that operational at the beginning of the cycle is possible. However, with a better treatment of the thermophysical properties and the mesh of the problem through a mesh sensitivity study, it should present results closer to those reported by Westinghouse for the AP1000 core.

The Westinghouse AP1000 reactor report provides a temperature close to 1800 to 1900°C for the fuel (UO_2) and a cladding temperature around 400°C. However, the temperature obtained in this work for the cladding is optimal and should present a short variation since the definition of Zircaloy correlations is consistent. On the other hand, the determination of correlations for the properties of MOX fuel is more difficult due to its application interval.

Future works will present a sensitivity study of the mesh, the exact definition of the correlations used in each material present in the study, and the disclosure of the other thermohydraulic parameters of the channel. These thermohydraulic parameters will present in all reactor operation steps (BOC, MOC, and EOC)

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