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Preliminary numerical analysis of the flow distribution in the core of a research reactor

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ABSTRACT

The thermal-hydraulic safety analysis of research reactors establishes the safety criteria to ensure the integrity of the fuel elements in the reactor core. It assures that all core components are being adequately cooled during operation. It is necessary to know if the average mass flow rate (and their standard deviation) among the fuel assemblies are enough to cool the power generated during operation. Once satisfied such condition, it allows the calculation of the maximum heat flux transferred from fuel assemblies to the coolant, and if the maximum cladding temperatures are below the limits set by the safety criteria. Among the objectives, this study presents a methodology for a preliminary three-dimensional numerical analysis of the flow distribution in the core of the IEA-R1 research reactor, under steady state condition. For this, the ANSYS-CFX® commercial code was used to analyze the flow dynamics in the core, and to visualize the velocity field. It was possible to conclude that a homogeneous flow distribution for all standard fuel assemblies were found, with 2.7% deviation from the average mass flow. What turned out to be negligible and can be assumed that there is a homogeneous distribution in the core. Complex structures were find in the computational domain. Once known the core flow dynamics, it allows future studies to determine whether the heat flux and temperature conditions abbeys thermal-hydraulic safety criteria.

1. Introduction

The thermo-hydraulic safety criteria establishes design limits that assures the safety of a nuclear facility. Among them, there is the minimum mass flow that each fuel assembly must receive to remove all heat generated by nuclear fission.

Among the 227 nuclear research reactors around the world, 51 are pool-type (Ames et al., 2012), among them is the IEA-R1 reactor (Umbehaun et al., 2015). This reactor is designed to couple the components of the core to a matrix plate, which in turn, is connected to a trunk of pyramid, which is responsible for the change of cross section, from rectangular to circular, which allows the coupling between the core components and the primary circuit. In this way, the water flows through the upper to lower region (downward direction).

Its 5x5 configuration consists of 20 standard fuel assemblies (SFA), 4 control fuel assemblies (CFA) and 1 central beryllium irradiator. Around this arrangement are installed all other components that aid in the safe operation of the reactor, such as reflectors, irradiation devices, fission chambers, and others. Figure 1 illustrates in a simplified way the IEA-R1 reactor core.

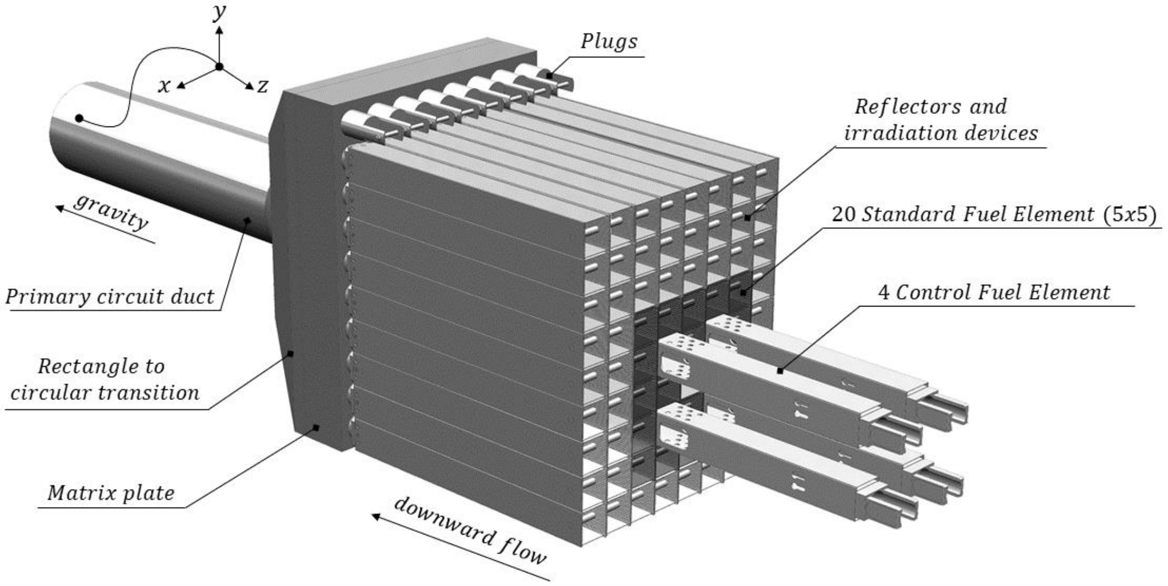

Figure 1 – IEA-R1 reactor core

The core shown in Figure 1 has some thermo-hydraulics particularities. Among them, are two factors, the first one is the lack of alignment between the 5x5 arrangement and the duct of the primary circuit, as shown in Figure 2. And second, the presence of a major part of components that do require to be cooled, therefore, they act as closed holes (Plugs).

Such combination induces the formation of a complex flow dynamics, which can result in the heterogeneous flow distribution between all fuel assemblies.

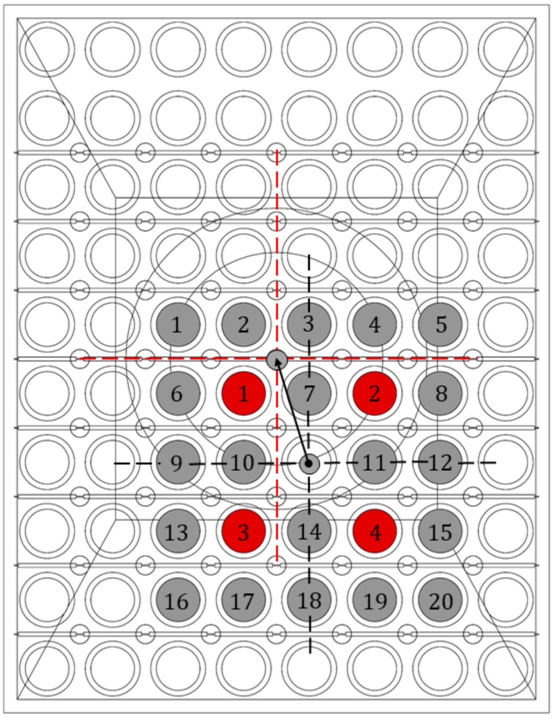

Figure 2 –Lack of alignment between the arrangement and primary circuit.

Among the studies, (Tian et al., 2005) showed that the flow distribution in nuclear reactors is a determining factor in the distribution of the inlet temperature, which contributes to the elevation of the internal temperature gradient, altering the power distribution.

In this way, numerical analyzes are important tools to visualize such behavior, since the instrumentation of a real model is often infeasible. The study of (Bae et al., 2013) showed the amplitude of mass flow deviation is around 2%, which could indicate a homogeneous behavior and minor consequences. However, such conclusion does not agree with the studies of (Chen et al., 2014), which states that these small deviations can generate large temperature gradients in the reactor core. This allows to conclude from the studies (Xia et al., 2016), that the flow distribution must be investigated individually to analyze the thermal-hydraulic consequences.

2. Objectives

A three-dimensional numerical analysis of the IEA-R1 reactor core is presented, modeled using the commercial code (ANSYS-CFX®, 2013) which allows to present a preliminary estimate of the flow distribution between the standard fuel assemblies, as well as details of the flow dynamics inside the reactor core.

3. Computational domain, simplifying hypotheses and boundary conditions

For the construction of the mathematical model some simplifications from the real geometry were necessary. Among them:

(i) All components that do not require refrigeration have been suppressed.

(ii) The standard fuel assemblies (SFA) and control fuel assemblies (CFA) control elements were suppressed, however, a coefficient of pressure drop that allows to consider their hydraulic resistance in the system was considered (K). This coefficient is calculated from Equation (1), from the studies of (José Alvim de Castro et al., 1990; Umbehaun, 2000) and (Umbehaun, 2000).

$$K = \frac{2\,\Delta P_{FA}\,\rho}{{v_{nozzle}}^{2}} \tag{1}$$

Being, ΔP_{FA} de pressure drop in the fuel assembly [Pa], ρ the fluid density [kg/m^3], v_{nozzle} the average velocity at the nozzle (outlet) [m/s].

The absence of the SFA and CFA domains does not cause any losses in the analysis, since the internal flow dynamics is already known by the studies of (Taesung and Garland, 2006), (Maximo Torres et al., 2006) and (Henrique and Giovanni, 2018).

(i) The contacts between components were considered as perfect contacts, i.e. there is no possibility to consider such small gaps for a numerical analysis, although it is known they exist (Maximo Torres et al., 2002).

(ii) The presence of the lateral flow channels (space between core components) were considered without simplifications, in order to consider the pressure drop caused by them.

(iii) The existence of a region open to pool (between the core components and the matrix plate) was considered and simplified to evaluate the by-pass promoted from this region.

In this way, the geometry is represented by Figure 3 with the illustration of some boundary conditions. The fluid considered is pure subcooled water, with an average temperature of 32.7 ° C (Hainoun et al., 2014), and average hydrostatic pressure of 0.169MPa. The water properties were obtained using the IAPWS-97 table (Wagner, W.; Kretzschmar, 2008). Thus, the boundary conditions are shown below:

(i) The wall surfaces are adiabatic and admitted with $20\mu m$ of roughness.

(ii) The primary mass flow is set at 211 kg/s, according with (Umbehaun et al., 2015).

(iii) The regions open to the pool have null static pressure.

(iv) The coefficient of pressure drop (K) for SFA and CFA is considered according to (José Alvim de Castro et al., 1990) and (Umbehaun, 2000).

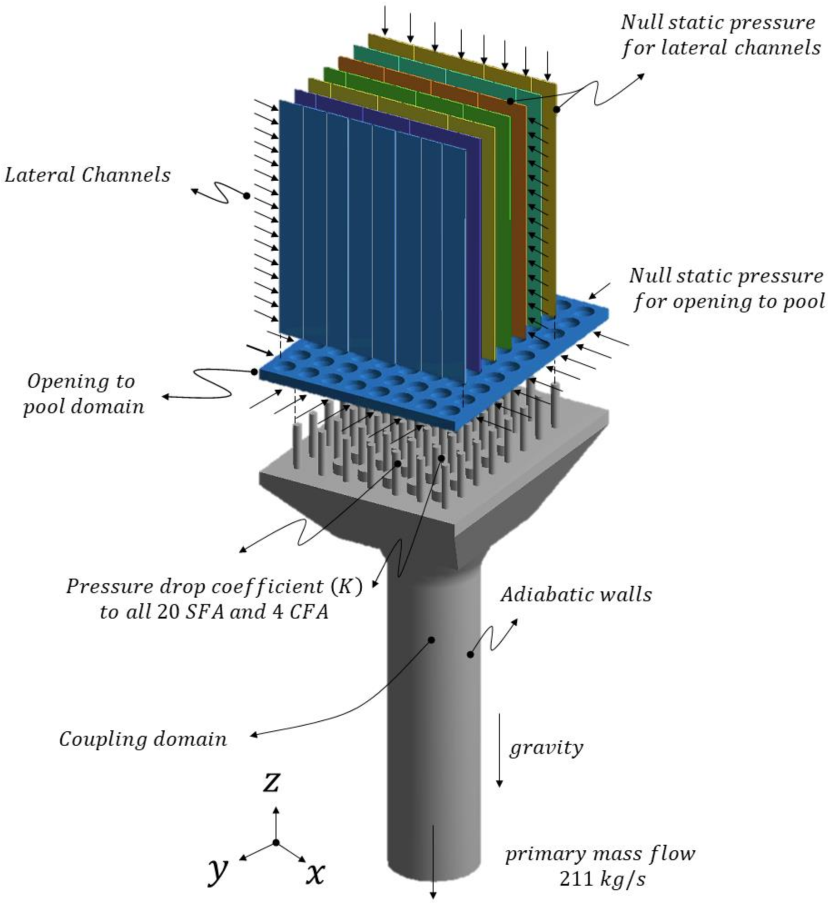

Figure 3 – Illustration of the boundary conditions.

4. Mathematical Model

The mathematical model assumes steady state condition, as well as the flow of water in liquid condition. The hypotheses of (i) Newtonian fluid, (ii) incompressible and isothermal flow, as well as (iii) the validity of the Stokes hypothesis (F. White, 1991) and (iv) negligible influence of viscous dissipation terms in all computational domain. Thus, the conservation equations of mass and moment are presented by Equation (2) and (3).

$$\frac{\delta U_i}{\delta x_i} = 0 \tag{2}$$

$$-\frac{1}{\rho}\frac{\partial p}{\partial x_i} + 2\frac{\partial}{\partial x_j}\left(\upsilon S_{ij}\right) = 0 \tag{3}$$

Being, p the pressure, υ is the dynamic viscosity, U the velocity, ρ the fluid density and S_{ij} the symmetric tensor named strain rate tensor, presented by Equation (4).

$$S_{ij} = \frac{1}{2}\left(\frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_i}\right) \tag{4}$$

The turbulence model considered is the same proposed by (Launder and Spalding, 1974), named $k - \varepsilon$ standard two equation, which offers great advantages by the use of two transport equations, one for turbulent kinetic energy and the other for the rate of energy dissipation. A full description of the mathematical model can be found in the (Angelo, 2013).

It is noteworthy that, (Bae et al., 2013) demonstrated that both $k - \omega$ and $k - \varepsilon$ turbulence models present extremely close behaviors for the flow distribution and flow dynamics, with differences of less than 1% between them.

5. Volumetric Mesh

For correct capture of the fluid dynamics effects in the presented model, an investigation of the type of mesh and quantity of elements in each region was performed. As part of the process proposed by (Stern et al., 2008) and (Wilson et al., 2001), a successive and iterative process was carried out from an initial volumetric mesh. With this, the regions of greater interest were better discretized for boundary layer capture, pressure drop and recirculation zones. This process was repeated continuously until the desired responses had no variation greater than 0.2% in relation to the previous mesh. In this way, the geometry has a volumetric mesh of 35 million elements.

6. Convergence criteria

The numerical analysis presented was calculated until the root mean square (RMS) for the conservation of mass, momentum and turbulence were less than 10^{-4}.

7. Results

7.1 Velocity Field and Flow Distribution

To illustrate the flow distribution between the fuel elements, a color map for average velocity was constructed in the representative region of the outlet region (nozzle) of each SFA by Figure 4. Thus, it is possible to observe a behavior where the highest values of average velocity are found to be close to the primary duct region, while the most distant SFA (near the pyramid trunk walls) have the lowest values.

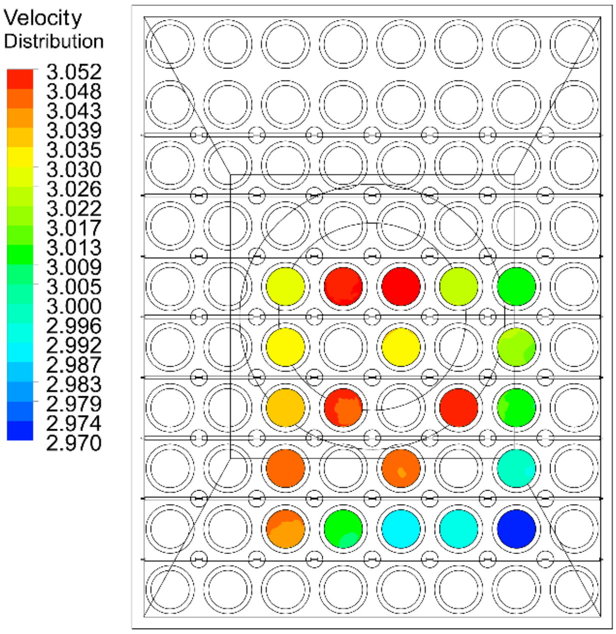

Figure 4 – Velocity distribution for SFA

In order to measure the flow distribution, Figure 5 shows a graph indicating the deviation of each fuel element in relation to the general average flow, which is 6.08 kg/s. The numbering of the axis represents the position of each SFA (shown in Figure 2).

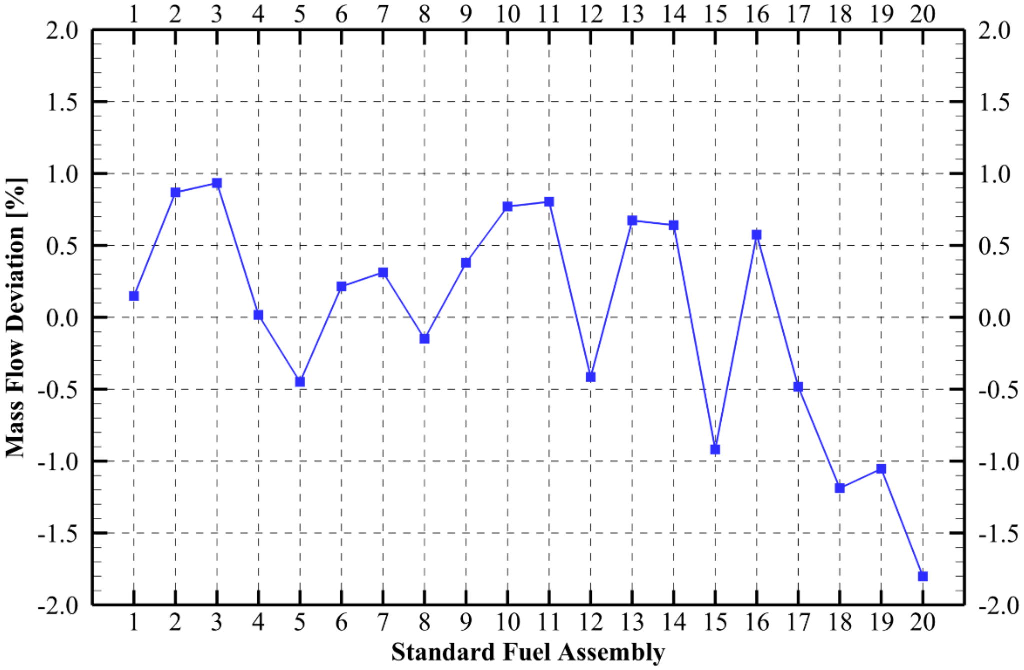

Figure 5 – Flow distribution for SFA

An oscillatory behavior can be observed for each line of fuel elements in the matrix plate, that is, the SFAs (N°1 to N°5), (N°6 to N°8), (N°9 to N°12) and so on respectively. The elements closer to the center of the domain always have higher values than the peripheral elements, with a continuous decrease in their value along the farthest line (N°16 to N°20), where the last three SFAs have the lowest values.

However, even with a seemingly heterogeneous structure of flow distribution, it can be observed the amplitude between the largest and the smallest deviation result in 2.7%, which indicate a very homogeneous distribution.

7.2 Flow Dynamics

Streamlines for velocity to all openings entering in the pyramid trunk are presented in Figure 6. The most evident effect is located in the trunk of pyramid, where due to the numerous components that do not require to be cooled, they increase the appearance of vortices, increasing the lack of homogeneity in the flow distribution.

In addition, it has been found that one third of the primary mass flow is deflected by the side channels and the opening region between the core components and matrix plate. The mass flow of these regions enters the pyramid trunk with rotational vectors (Figure 6), further favoring the appearance of turbulence in the region. Finally, only two-thirds of the mass flow of the primary circuit is actually intended to cool the SFA. This issue could be improved by closing the regions that do not require flow, making better flow distribution in the core.

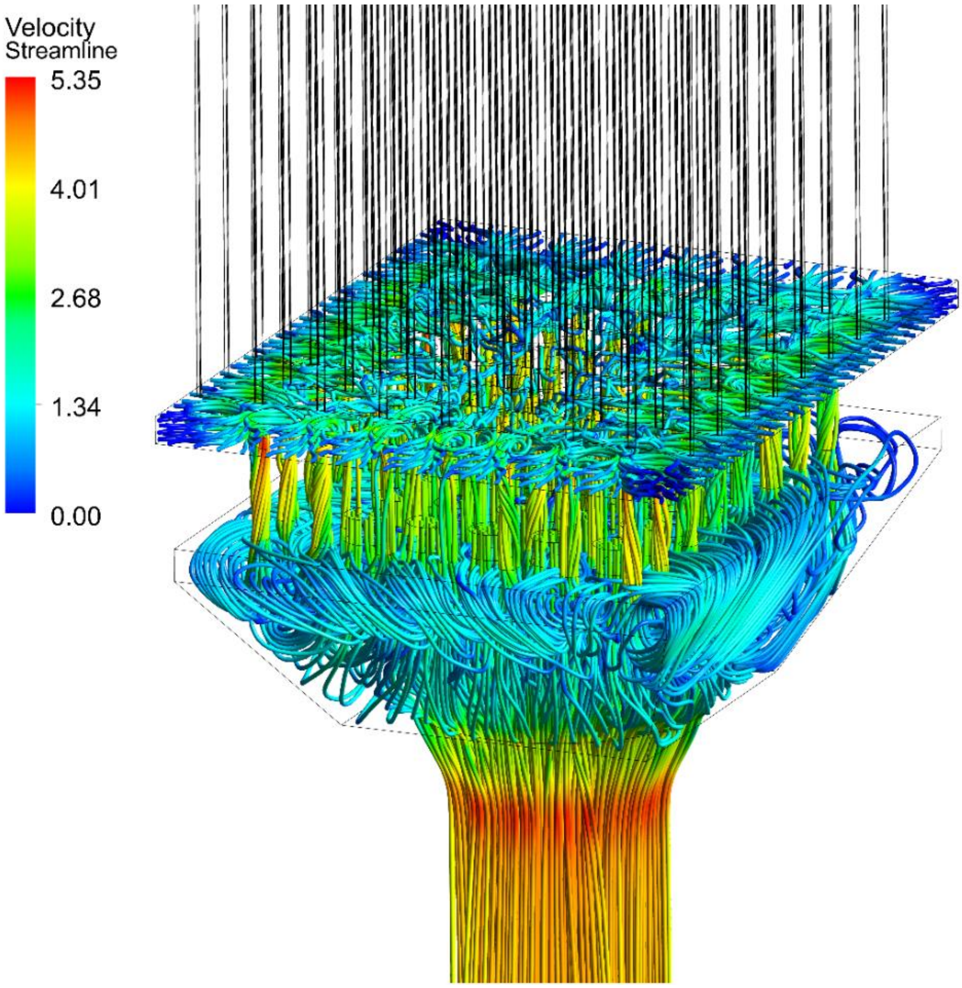

Figure 6 – Streamlines for velocity inside the reactor core

8. Conclusion

This study presented a preliminary three-dimensional numerical analysis, in steady state condition of the IEA-R1 reactor core.

A success flow analysis was made to estimate the velocity and mass flow rate distribution for all SFA. The results showed an amplitude of variation of 2.7% in relation to the average mass flow. This indicates a very homogeneous behavior despite complex structures inside the computational domain. For a better flow distribution in the core, it is suggested that the pool openings should be closed, which may decrease the flow diverted to these regions.

Therefore, it was possible to analyze the flow distribution in the SFA and core of the reactor, as well as the behavior of its flow dynamics, allowing to indicate necessary improvements for better refrigeration of the fuel assemblies, and thus ensure the safety of the installation.

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