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CFD Analysis of a Small Modular Reactor using Porous Medium Model

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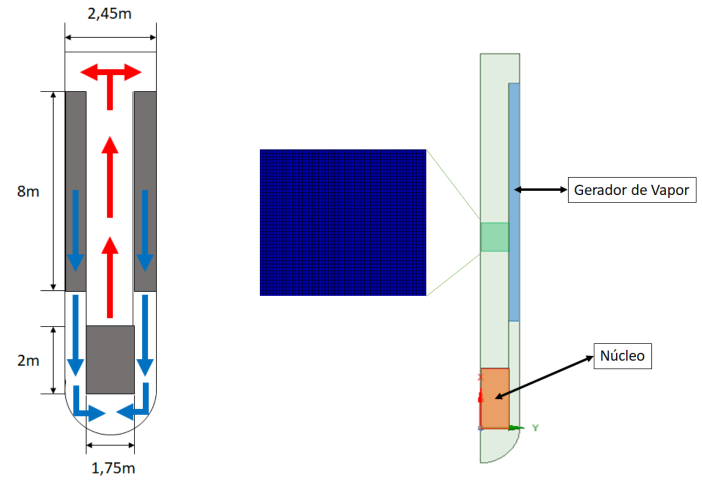
1. Introduction

There is a global interest in the development of small modular reactors (SMRs). One type of SMR currently under development in several countries is the integral pressurized water reactor (iPWR). In this design the main components of the primary circuit are placed within the reactor pressure vessel eliminating the need for primary circuit pipework, with the intention of enhancing safety and reliability. This study aims to analyze an iPWR-type SMR without the presence of reactor coolant pumps (RCP), operating only under natural circulation. For natural circulation to occur, the height of the reactor core (heat source) must be lower than the height of the steam generator (heat sink). When the primary coolant passes through the core, the increase of temperature induces a density gradient, therefore increasing the buoyancy effect, causing the coolant to flow upward in the riser. Although, as the tube bundles geometry is quite complex, only a small part of the tubes can be accurately modelled using a detailed geometry. Therefore, it is necessary to seek alternatives that simplify the geometry. In this work, the tube bundles were simplified by using a porous media model.

2. Methodology

In this study, a SMR with pressurized water is analyzed focusing on the natural circulation phenomenon. The core used in the current analysis consists of 37 fuel assemblies with 17×17 fuel rod array. The diameter of the core is 1.75m with an active height of 2.0m. The steam generator was assumed as a vertical cylinder with around 6000 tubes in a triangular array. Fig. 1(a) represents a simplified scheme of a SMR operating under natural circulation. The simulations were performed using the ANSYS Fluent v.19.2 Software. In this study, the primary circuit of an integral type SMR was modelled, which can be seen in Fig. 1(b). Due to the symmetry of the problem, the simulations were carried out with a 2D axisymmetric model with respect to the reactor centerline and with a mesh containing 161211 elements.

In order to describe the fluid flow, the mass, momentum and energy conservation equations were used.



(a) SMR scheme (b) Geometry and Mesh

Figure 1: Simplified scheme of the SMR (a) and the geometric model (b).

Continuity Equation:

$$\frac{\partial \rho}{\partial t} + \bigtriangledown \cdot (\rho \vec{u}) = 0 \tag{1}$$

Momentum Equation:

$$\frac{\partial (\rho \vec{u})}{\partial t} + \bigtriangledown \cdot (\rho \vec{u} \vec{u}) = - \bigtriangledown \cdot \left(\vec{\vec{\tau}} \right) + \rho \vec{g} \tag{2}$$

Energy Equation:

$$\frac{\partial}{\partial t} (\rho E) + \bigtriangledown \cdot (\vec{u} (\rho E + p)) = \bigtriangledown \cdot \left(k_{eff} \nabla T - \sum_j h_j \vec{J}_i + \left(\vec{\vec{\tau_{eff}}} \vec{u} \right) \right) + S_h \tag{3}$$

where ρ is the density of the fluid , $\vec{u}$ the velocity, E is the internal energy, k_{eff} is the effective conductivity, T is the temperature, h_j is the j-ith component of enthalpy, and S_h is the volumetric heat generation source term.
For the core and the steam generator, the porous media model was utilised to describe the tube bundles, thus simplifying the geometry model. The porous media model incorporates an empirically determined flow resistance in a region of the model defined as "porous". In essence, this model adds a momentum sink in the governing momentum equation, represented by:

$$S_i = - \left(\frac{\mu}{\alpha} u_i + C_2 \frac{1}{2} \rho |u| u_i \right) \tag{4}$$

The coefficients α (permeability) and C_2 (inertial resistance factor) are calculated using the Darcy - Forchheimer equation. Finally, the transport equations for single-phase flow are multiplied by the porosity γ, defined by the volume fraction of the fluid within the porous region, and then the correspondent source term is added in the energy equation the distribution of heat generation in a cylindrical and homogeneous core is expressed by the following source term [2]:

$$S_{core} = q_0''' J_0 \left(\frac{2.405y}{R} \right) \sin \left(\frac{\pi x}{L} \right) \tag{5}$$

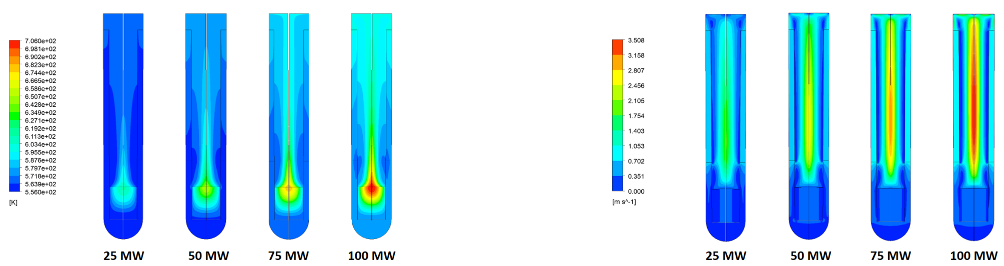
where q_0''' is the volumetric heat generation at the core's center, L the active core height J_0 indicates the Bessel function of the first kind of order zero and and R, the core radius.
In the steam generator, the source term is expressed by the condition of convective heat transfer between the primary and secondary circuit tube bundles:

$$S_{SG} = h_{SG} \left(T_W - T \right) \frac{A_S}{V_{SG}} \tag{6}$$

where h_{SG} is the heat transfer coefficient in the steam generator, T_W is the secondary loop temperature, A_S is the tube's superficial area and V_{SG} is the steam generator volume.
In this study, the primary coolant of the SMR was subcooled pressurized water at 15.5 MPa. As the objective is to observe the steady-state natural circulation phenomenon, the phase change effects were not taken into account, in addition all walls were treated as adiabatic.

3. Results and Discussion

In the following results, the steady state analysis is presented for the core power ranging from 25 MW up to 100 MW. Fig. 2(a) presents the temperature contours in the SMR. By the temperature contours, it is possible to observe that, for the studied power range, the temperature profile remain similar, however, with increasing temperatures according to the power level. Fig. 2(b) presents the velocity contours in the investigated SMR. As expected, the velocities in the core and in the steam generator, which were modelled as porous media, are uniform.

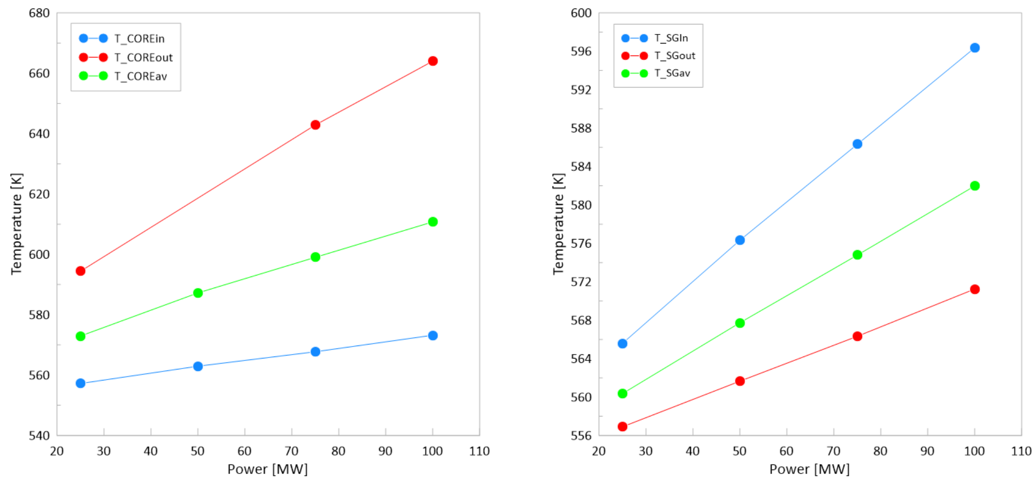


(a) Temperature

(b) Velocity

Figure 2: (a) Temperature and (b) Velocity contours in SMR at 25MWt, 50MWt, 75MWt and 100MWt.

In general, the highest values of speed are observed at the center of the riser and at the core outlet, due to the buoyancy forces caused by the heating in the core. Fig. 3(a) and 3(b) show the values obtained through simulations for the average, inlet and outlet temperatures of the core and the steam generator, respectively, as functions of the reactor power.



(a) Core (b) steam generator

Figure 3: Inlet, outlet and average temperatures of (a) Core and (b) Steam generator as a function of the reactor power.

4. Conclusions

This work shows the feasibility of modeling an iPWR type SMR using porous media model, with spatially varying volumetric heat generation rate in the reactor core. Two-dimensional steady state natural circulation of single-phase primary coolant in a SMR is analyzed by using the commercial CFD code ANSYS Fluent Software v19.2. In order to model the tube bundles in the core and in the steam generator, the porous media model was utilized. The analysis of the results was carried out with power levels of 25MWt, 50MWt, 75MWt and 100MWt. For a qualitative analysis, the temperature (Fig. 2(a)) and velocity (Fig. 2(b)) profiles were compared between all power ranges. In order to perform a quantitative analysis, the temperatures at the inlet and outlet of the core (Fig. 3(a)) and steam generator(Fig. 3(b)) as well as the average temperature in each were compared.

Acknowledgments

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