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Molten Salt Reactor thermal-fluid dynamics evaluation using a CFD code for a theoretical power density distribution

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1. Introduction

The Molten Salt Reactors (MSR) are reactors in which the fuel is mixed with the coolant, thus flowing through the reactor core and system components. This coolant-fuel mix is a salt, having interesting physical properties that allows the reactor to operate with low pressure and high temperatures without compromise its safety since the reactor remains operating only while the salt is flowing, which requires the salt to be above a minimum temperature to become liquid. In addition, since the salt have an elevated vapour pressure, it does not boil even with the operational pressure being low [1].
The MSR have being proposed initially by the Oak Ridge National Laboratory (ORNL) to aircraft propulsion during the Cold War but, despite of the good results and the prototype constructed, the program was closed. Recently, the EVOL project have being proposed based on the initial concept of the ORNL. The EVOL reactor is a fast reactor in which the core is a cylinder surrounded by a Thorium blanket, where the fuel, ^{233}U, is produced [1].
Despite of the simple concept, the thermal hydraulics of the MSR such as the EVOL is still an object of research since a change in the molten salt flow (the coolant) properties could affect other physical properties of the salt and the reactor and its operation. A better understand of the salt flow properties could be accessed by using a CFD (Computational Fluid Dynamics) code, in which the flow domain is discretized in small volumes and the governing equations are solved (mass, momentum and energy conservation equations). In this manner, the CFD codes are an important tool to investigate how and the extension in which a change in the coolant flow properties could affect other reactor properties or be affected by the changes in the reactor neutronics [1].
In this work, the ANSYS-CFX® code was used to perform an initial evaluation of the EVOL molten salt coolant properties using a theoretical power density distribution. The simulations had considered two turbulence models, the κ-ε and SST, this last being a hybrid model between the κ-ε and κ-ω models and had the results compared with Linden (2012), which simulates the EVOL reactor and that the work is being used as a benchmark since there is no experimental data available for comparison [1].
The initial results consist in flow properties distributions, which were compared with the benchmark work. The pressure and temperature distributions agree well with the benchmark work (Linden, 2012) for both turbulence models while the turbulence viscosity and other flow properties have a better agreement for the SST turbulence model indicating that a wall function have being used in the benchmark

work to simulate the flow next to the walls since the κ-ε was the model used in the benchmark and the SST model includes a wall function that is automatically adjusted by the CFX® code [1].
Additional investigation is under course to evaluate the dependency of the results within the turbulence models, mesh refinement and the coolant flow properties for other power density distributions.

2. Methodology

The present work has performed the numerical simulations using a commercial CFD code – ANSYS- CFX® academic license – which have models suitable for the simulations performed in the present work.
The simulations were performed for a 3D flow domain, for 1/16 of the EVOL cylindrical core due to the core symmetry, which aid to reduce the mesh volumes required to discretize the flow domain and the computational effort.
Two simplified branches were added to simulate the inlet and outlet tubes through the molten salt flows in and out of the reactor core. These tubes are only of secondary importance for this stage of the research since there is no fission and power being produced inside them and the main objective is to understand if there is any influence of the flow properties change to the power distribution and neutronics.
In this work, two turbulence models were used to perform the simulations: the κ-ε and SST. The former is the same used in the benchmark work while the last was choose due to it be a hybrid model (between the κ-ε and κ-ω models) and the ability to simulate better the flow next to the walls. In this manner, a comparison of the results using the ANSYS- CFX® with the benchmark could be done as well as an evaluation of the influence of the turbulence models on the results.
It was setup that the turbulence level as medium (5%), the intermediate value in the CFD code. The turbulence level is a measure of the change of local velocity of the flow change with respect to the flow average velocity.
The residuals were used as convergence criteria. The simulations converge for residuals below $1x10^{-5}$. The residuals represent the difference between the values obtained in an iteration and the previous iteration. This value was setup since it does not impose a severe computational effort and is low enough to reduce the errors in the property values. Besides the residuals, also the imbalances were monitored to ensure the quality of the results. The imbalances are in percentage form and represents the extent to which the conservation of mass, momentum and energy is achieved.
The properties of the molten salt were inserted in the CFD code considering the equations and values available in the benchmark work. After selecting the turbulence model, it was performed 4 different runs. For the first run, it was assumed that the molten salt such as thermal conductivity and physical density are constant. In the second run, the thermal conductivity was let to vary according the relation given by Linden (2012), as given by equation (1). In the third run only the salt physical density varies according the relation given by Linden (2012), as given by equation (2). In the fourth, both properties – thermal conductivity and physical density – were let to vary according equations (1) and (2).

$$k = 0{,}928 + 8{,}397 \times 10^{-5} T \quad (1)$$

$$\rho = \left(4{,}094 - 8{,}82 \times 10^{-4}(T - 1008)\right) \times 10^{3} \quad (2)$$

In which T [K] is the salt temperature in an arbitrary point in which the calculus of the thermal conductivity or salt physical density are performed. Equations (1) and (2) are valid in the interval of 891-1020K (618-747°C) and 893-1126K (620-850°C), respectively according EU (2019)
The initial power density distribution assumes a theoretical case of a bare cylinder and is the form as given by equation (3) according to the neutron diffusion theory. In this manner, it means that the blanket of Thorium surrounding the core does not have any influence in the power density distribution and core neutronics. In addition, it was considered that the blanket region does not produce significant power, as does in the reference work. In this manner, every wall of the 1/16 cylinder was assumed to be adiabatic. Due to the symmetry of the volume domain, the two faces of the domain simulated was assumed to be periodic.

$$q'''(r,z) = \frac{3{,}63PJ_0(2{,}405\frac{r}{R})\cos(\pi\frac{z}{H})}{V} \quad (3)$$

In which r and z are the radius and height in which the calculus is performed, respectively, R is the core radius, H is core height, V is the core volume and J_0 is the Bessel function of order zero. The r and z in equation (1) consider the coordinated system centered in the core ((r=0 and z=0 in the middle of the height of the core).

3. Results and Discussion

The results obtained in this first part of the research demonstrated that for the theoretical power density distribution there is a good agreement of the temperature and pressure profiles with the benchmark, with the SST model producing values closer to the reference value, indicating that in the benchmark work a wall function have been used during the simulation. Notwithstanding, it was verified only a minor change in the thermal conductivity and salt physical density, indicating that other properties such as the concentration gradient should be only marginally affected. The Figures 1 and 2 presents the temperature and pressure profiles for the run 1 with the κ-ε model. In this manner, these results would support the efforts in the evaluation of the influence of these minor changes in the flow and molten salt properties over other reactor properties and neutronics.

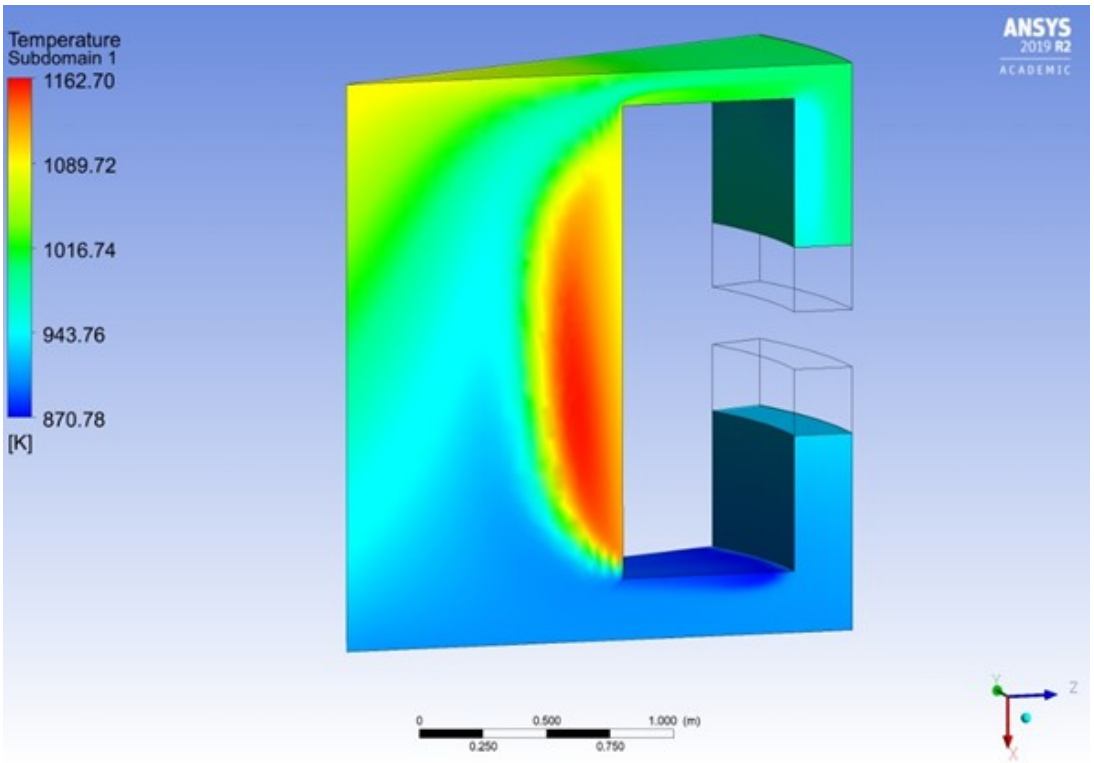

Figure 1: Temperature profile for constant salt properties for κ-ε model.

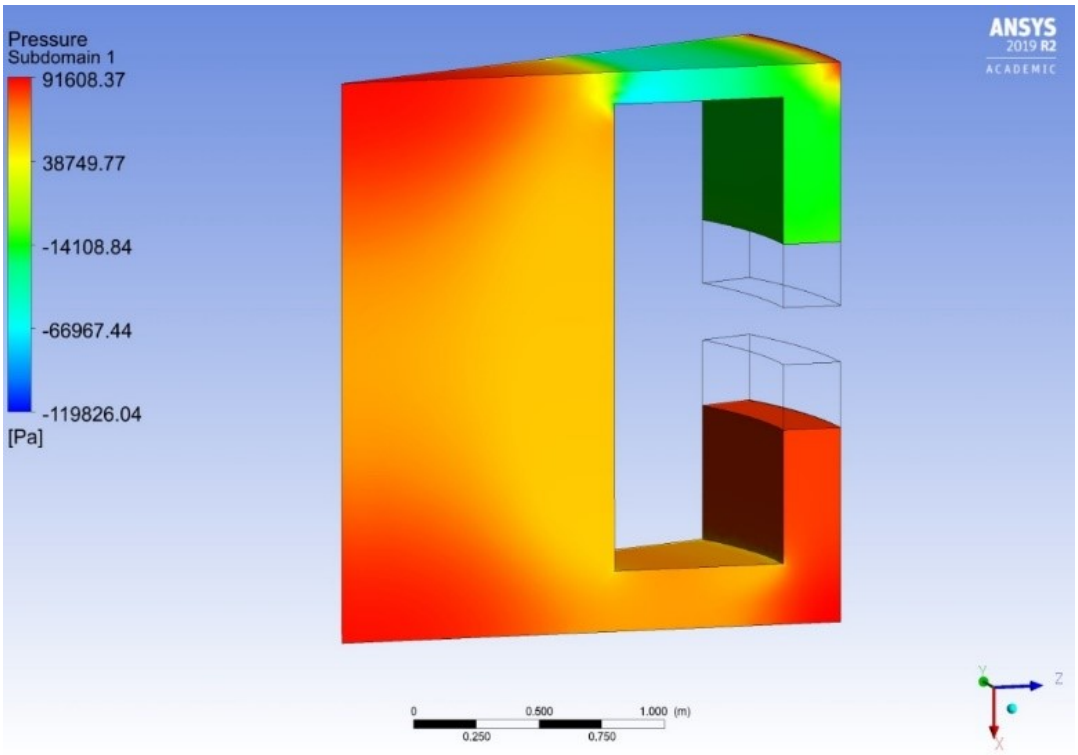

Figure 2: Pressure profile for constant salt properties for κ-ε model.

4. Conclusions

The ANSYS-CFX® code was able to reproduce the molten salt flow properties with the better results being obtained with the SST turbulence model. As part of the research, these results would be used to evaluate if the minor variation in the salt flow properties affects other reactor properties and the power density.

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References

[1] LINDEN, E. van der; *Coupled neutronics and computational fluid dynamics for the molten salt fast reactor: featuring a physical description of the precursor transport in liquid turbulent nuclear fuels*. Master Thesis, Delft University of Technology, Netherlands, 2012.

[2] EVOL (Project n° 249696) Final Report. EU. Report. https://cordis.europa.eu/docs/results/249/249696/final1-final-report-f.pdf. 2019.