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Safety Enhancement in the Molten Salt Fast Reactor (MSFR)

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Abstract: This study presents a new modification for the cooling circuit design of the Molten Salt Fast Reactor MSFR to solve the problem of high temperatures in the hot spots regions that affect the reactor safety. These high temperature regions appear as a result of the salt recirculation of the liquid fuel. This problem causes a decrease in the delayed neutron fraction value $\beta_{eff.}$. This decrease in $\beta_{eff.}$ reduces the safety of the reactor because it shifts it more close to the prompt critical state. The new modification depends on distributing the flow between the side and the centre by adding a coolant circuit passes through the core centre from the bottom to the top. At the end of this study we see that this new design moderated the hot spots and reduced the maximum temperature to about 1120 k. This value is greater than the core outlet temperature by about 77 k and smaller than the maximum temperature of the benchmark design by about 160 k. The design also reduced the salt velocity from the benchmark value 3.9 m/s to the value 2.38 m/s.

Keywords: MSFR TRITON COMSOL.

1. INTRODUCTION

The Molten Salt Fast Reactor (MSFR) was chosen by the Generation IV International Forum (GIF) in 2008 as a representative molten salt reactor fitting the Gen IV criteria because of its fast spectrum, sustainability, and waste minimization, and the use of thorium as fertile element owing to its proliferation resistance [1]. MSRs are unique reactors and make use of a salt mixture that acts simultaneously as fuel and coolant, transferring the heat by convection from the core to external heat exchangers. The rationale behind the MSR technology can be identified in the high power density, design flexibility, intrinsic safety, and simplified fuel handling allowed by the adoption of liquid fuel. The reference MSFR in this study is a 3000 MWth. It has a spectrum of fast neutron with Thorium fuel cycle. The active region of the core is defined as the salt volume in which the nuclear fissions happen. It contains the flowing salt in the injection zone (in the bottom of the core). The fuel initial composition is LiF-ThF4-233UF4 with 77.5 % LiF. The central cavity, and the extraction zone (in the top of the core). There is no solid moderator or any internal support structure in the MSFR except for the materials of the wall. The salt temperature increase $\Delta T = 100$ K. The operating temperatures are 650°C for the inlet temperature and 750°C for the outlet temperature. The lower limit is due to the melting point of the salt (565°C) and the upper limit is imposed by the performance of the structural materials (limit around 800°C). The core working parameters were defined after performing various parametric studies seeking for low neutron losses, low reflector irradiation and minimal fissile inventory, while maintaining a fuel salt volume in the heat exchangers large enough to ensure that salt cooling by $\Delta T = -100$ K is feasible. The resulting core shape is roughly a cylinder with half of the entire salt volume inside the core and the rest is located in the external loops. The lower and upper walls of the core are neutronic reflectors. A NiCrW hastelloy has been selected as a structural material candidate for the reflectors walls (and for all other internal walls in contact with the fuel salt). The upper reflector is submitted to mechanical, thermal (the fuel salt's mean temperature in the extraction area is around 750°C with possible spatial and time dependent fluctuations) and radiation constraints. The combination of high temperature and high radiation levels seems to be the biggest challenge for the proposed alloy so that the surface of the upper reflector may require a thermal protection. Due to the significant lower inlet temperature, the lower reflector is under reduced thermal stress. Its specificity is to be coupled to the draining system. This component serves as a radial reflector and a neutron shield for the protection of the fuel loops external components (pipes and heat exchangers). In addition to the protection function, the blanket is used to improve the reactor breeding capabilities. The blanket containment walls are made of a Ni-based alloy to resist corrosion. They have an external layer of Boron Carbide on the outer wall to further reinforce the shielding. The salt in the blanket is of the same type as in the core but with 22.5 mol% of Th and without initial fissile material. Since the thorium present in the fertile is exposed to the neutron flux, it will generate ^{233}U. A small fraction of ^{233}U produced in the blanket will fission. So, the fission products are produced in the blanket and they need to be extracted. In addition, the power arising from the ^{233}U fissions (13MW) and from the captures on thorium (24MW) will heat-up the fertile salt in the blanket. It has been found that this heat cannot be evacuated through the blanket walls by a natural convection mechanism of the fertile salt. Therefore a fertile blanket external cooling system will be necessary. If the breeding is not necessary, the MSFR design could be simplified by replacing the blanket by an inert reflector, identical to the axial reflectors. Optimized shapes of the blanket may be suggested to improve the thermal flow inside the core [2].

Several studies were done to minimize the temperature in the hot spot regions of MSFR. These regions of high temperature are formed due to the salt recirculation near the piping penetration of the core by the cooling loops [3]. In the project EVOL, they tried to solve this problem by design new shape for the core that has a curved geometry instead of the benchmark cylindrical design [2] that is shown in Fig. 1. This modification succeeded in preventing the occurrence of hot spots but it caused an increase in the maximum velocity to approximately 7 m/s. This velocity increase is undesirable because it may causes erosion. Aufiero presented a fast-running computational tool model in the phase of design optimization of the components of the fuel loop. He reported the maximum core temperature as 1300 K [4]. Fiorina discussed the importance of the design enhancement needed for the fuel velocity and temperature of the MSFR core [5]. Hu developed a code to simulate the Molten Salt Reactors and reported 1200 K maximum temperature [6]. Li showed that The range of the temperature of the MSFR design is between the salt freezing point (838 K) and the melting point of the nickel alloy used in the core structure (approximately 1600 K) and these points must be considered as the margin points in the steady state and the transients analysis [5, 7]. Daher et al. succeeded in reducing the hot spots by a new flow design with. a maximum velocity equal to 4.36 m/s [8, 9].

This study shows a new modification in the flow design aims to reduce the maximum temperature and velocity.

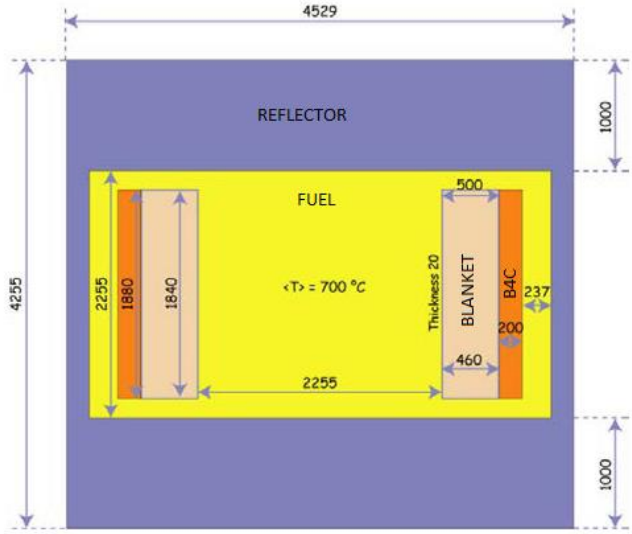

Fig. 1. Benchmark Model used in neutronic simulation (dimensions in mm) [2].

1.1. The new design description

The new modification design is shown in Fig.2 and Fig. 3. It depends mainly on dividing the total mass flow rate between the cooling branches described in the benchmark [2] and a new cooling branch with ratio 2:1. This branch drives the salt in the upward direction from the inlet in the lower centre of the core to the outlet in the upper centre of the core. Beside this new flow branch, the ends of the blanket and the penetration regions of the new flow circulation were curved. The radii of the curves of the blanket ends and the centre flow circulation were changed to select the optimum values. The ends of the blanket and their surrounding reflector layers are curved by fillets with 0.18 m and 0.2 m radius respectively. And the penetration regions of the new flow circulation are curved by fillets with 0.5 m radius. The length and the diameter of the centre cooling branch pipes are 2.1238 m and 0.9483 m respectively. The mass flow rates of the side and the centre cooling branches are 12374.7 Kg/S and 6187.35 Kg/S respectively.

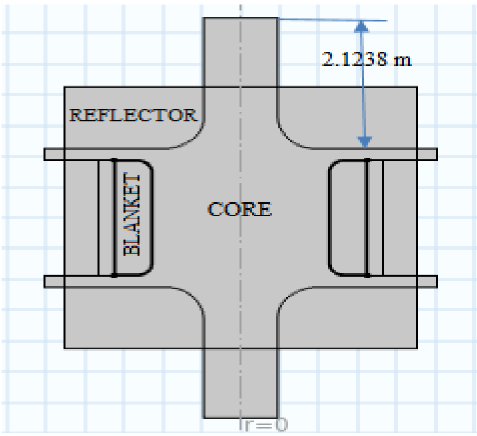

Fig.2. The new modification design as described by COMSOL.

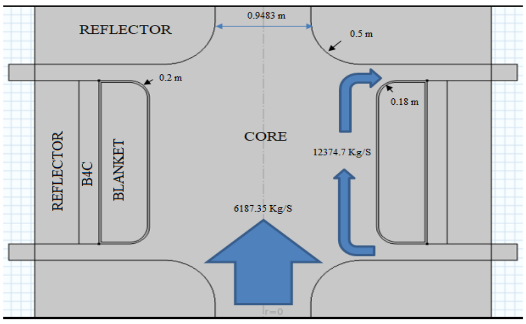

Fig. 3. Zooming view of the new design shows dimensions and flow directions

2. Calculation tools

The calculations were performed in several steps. In the beginning, the code TRITON (one of the SCALE package) was used to find the nuclear constants of the neutron diffusion equation with the nine neutron energy groups that were used in EVOL project [2] and the library ENDF- B7 at temperature 900 K. The second step was done by repeating the previous step with different temperatures using the following equation to find the fuel and blanket densities for each temperature [2].

Density ρ (g/cm3) = 4.094 – 8.82*10^{-4} (T-1008) (1)

After that, Excel was used to find the equations describe the nuclear constants as a function of the temperature. These functions were introduced in COMSOL to solve the neutron diffusion equation for the benchmark design [2]. The last step was repeated to use the new modification design for the flow circulation with different values for the centre pipes and curves radii. The delayed neutrons calculations were calculated by COMSOL using the transport of diluted species module.

The nine-group diffusion equation and the six-group delayed neutron equation (Equations. 1, 2) [13] can be presented as follows:

$$\frac{1}{v^g}\frac{\partial \phi^g}{\partial t} + \frac{u}{v^g}\cdot \nabla\phi^g - \nabla\cdot D^g\nabla\phi^g + \Big[\Sigma_a^g + \sum_{g'=1,\neq g}^{9}\Sigma_s^{g\to g'}\Big]\phi^g = \sum_{g'=1,\neq g}^{9}\Sigma_s^{g\to g'}\,\phi^{g'} + \frac{1}{k}\left(1-\beta_{eff}\right)x_\rho^g\sum_{g'=1}^{9}\nu\,\Sigma_f^{g'}\,\phi^{g'} + \sum_{i=1}^{6}x_i^g\,\lambda_i c_i \quad (2)$$

$$\frac{\partial ci}{\partial t} + u\cdot\nabla C_i + \lambda_i c_i = \frac{1}{k}\beta_i\sum_{g=1}^{9}\nu\,\Sigma_f^g\,\phi^g \quad (3)$$

The left and the right hand sides in the two equations define the loss and the production mechanisms, respectively. The subscripts a, s, and f refer to absorption, scattering, and fission, respectively. The superscript g is the number of the energy groups of the neutrons and i is the precursor. v^g is the neutron speed of group g (cm/s), ϕ is the neutron flux (n/cm^2/s). D is the diffusion constant (cm), Σ is the macroscopic removal cross section (cm^{-1}), x is the fraction of the delayed neutrons, ν is the average number of neutrons produced by fission induced by a neutron, λ is the decay constant (s^{-1}), β is the fraction of the produced delayed neutrons, C_i is the precursor concentration (cm^{-3}), and u is the fuel's velocity vector (cm/s).

3. Results and discussion

By using the physics controlled mesh with extremely fine size it was found that the multiplication factor k_{eff} of the benchmark design is 1.0065, The maximum temperature is about 1280 K, and the maximum velocity is about 3.9 m/s as shown with Fig.4 and Fig.5.

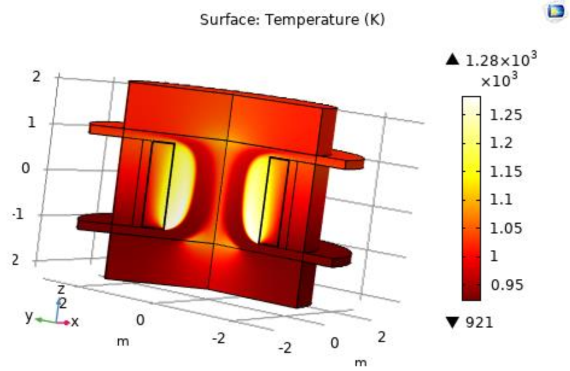

Fig.4. The temperature distribution of the MSFR benchmark design using COMSOL

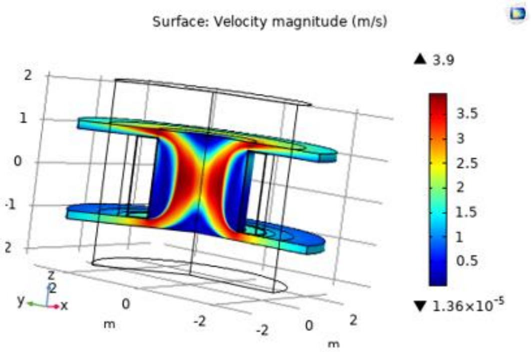

Fig. 5. The velocity distribution of the MSFR benchmark design using COMSOL

By using the physics controlled mesh with the extremely fine mesh (maximum size is 1.69 cm) for the modified design as used in the benchmark, it was found that the multiplication factor k_{eff} is 1.0199, The maximum temperature is 1120 K, and the maximum velocity is 2.38 m/s. The maximum temperature of the new design, the temperature profile of the old and new designs, the maximum velocity of the new design, and the velocity profile of the old and the new designs are shown from Fig. 6 to Fig. 11 respectively. From These figures we can notice a large decrease in the maximum temperature by comparison with the maximum temperature of the benchmark design (1280 K as shown in Fig. 4 and Fig. 7). This decrease is about 160 K. There is also a decrease in the fuel velocity about 1.52 m/s (from 3.9 m/s to 2.38 m/s as noticed by comparison between the values of the old design in Fig. 5 and Fig. 10 and the values of the new design in Fig. 9 and Fig. 11). The maximum temperature value of the new design is far from the melting point of the reflector material (1600) K and the critical velocity is low enough to avoid corrosion problems. By using the user controlled mesh with sizes 4 cm, 5 cm, 6 cm, 7 cm the maximum temperature of the modified design was the same value that is 1080 K.

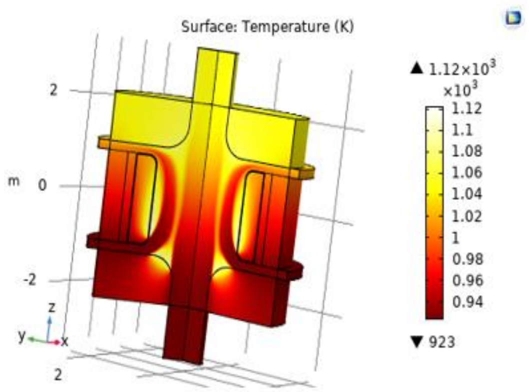

Fig. 6. The temperature distribution of the MSFR first modified design using COMSOL

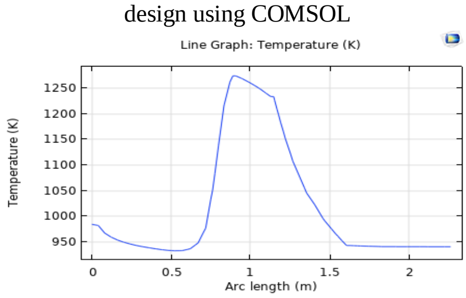

Fig. 7. The benchmark temperature distribution as modeled by COMSOL with cutline in the maximum temperature zone

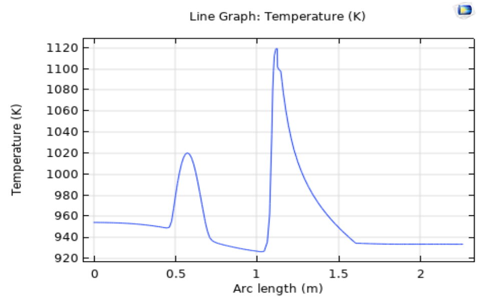

Fig. 8. The temperature profile of the MSFR modified design with cut line through the highest temperature zone using COMSOL.

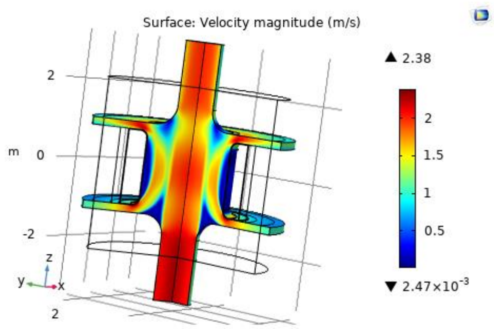

Fig. 9. The velocity distribution of the MSFR modified design using COMSOL.

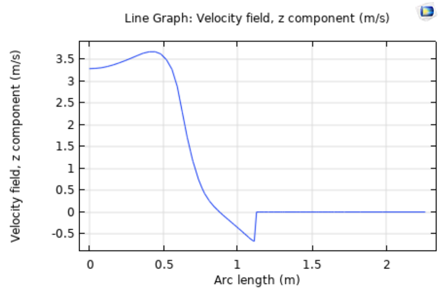

Fig. 10. The benchmark velocity profile as modeled by COMSOL with Centre cutline

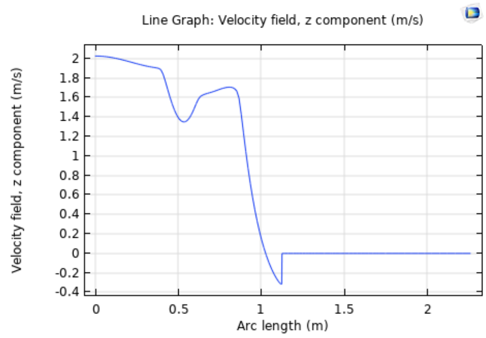

Fig. 11. The velocity profile of the MSFR modified design with cut line through the core centre using COMSOL.

Table 1 shows the delayed neutrons data as extracted from TRITON. This data was used in COMSOL to calculate the delayed neutrons contribution in the multiplication factor considering the motion of the fuel. From results the delayed neutrons fraction values were calculated for the benchmark and the modified designs. The results showed an increase in the delayed neutron fraction by about 67 pcm, from 119 pcm to 186 pcm. This increase is desired for the reactor safety because it makes the reactor more controllable far from the prompt critical state [10].

Table 1. The delayed neutrons precursors data for the six groups using TRITON for the benchmark.

Delayed neutron fraction β	0.0002 91483	0.0006 66053	0.0007 65932	0.001 14085	0.0003 27382	0.0001 37248
Decay constant λ	0.0124 981	0.0359 455	0.1376 58	0.318 067	1.2197 2	3.1522 7

4.Conclusion

The results proved that the modified design of the MSFR succeeded in reducing the maximum temperatures in the hot spots regions. The maximum temperature was reduced from 1280 K to 1120 K (160 K decrease) and the maximum velocity was reduced from 3.9 m/s to 2.38 m/s (1.52 m/s decrease). This decrease in the temperature and the velocity is enough to avoid the problems of corrosion or melting of the reflector materials. The new design not only kept the fuel velocity low but it also reduced its value enough to avoid erosion. The code COMSOL proved to be a very good tool in simulating the MSFR by coupling of the neutronic and thermal hydraulic models. This coupling succeeded in solving the problem of the difficulties resulting from the decay of the delayed neutrons out of the core.

Acronyms and abbreviations

MSR Molten Salt Reactor
MSFR Molten Salt Fast Reactor
EVOL Evaluation and Viability Of Liquid fuel fast reactor system

Nomenclature

K_{eff} effective multiplication factor
β delayed neutron fraction
λ decay constant

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