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SCUOLA DI INGEGNERIA INDUSTRIALE E DELL'INFORMAZIONE

Executive Summary of the Thesis

Multiphysics analysis of accidental transients for a Molten Salt Fast Reactor

Laurea Magistrale in Nuclear Engineering - Ingegneria Nucleare

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1. Introduction

In the context of the Generation-IV International Forum [1], the Molten Salt Fast Reactors have been chosen as the representative reactor concept for the liquid fueled family. The peculiarity of the circulating fuel, which also acts as coolant, leads to a strong coupling between neutronics and thermal-hydraulics caused by the delayed neutron precursors drift, the power release and production directly in the coolant, and the strong negative feedback coefficients. These features have motivated, over the years, the interest in developing dedicated tools to numerically simulate the behaviour of such a unique reactor with the effort to ensure coupling in the same environment. The OpenFOAM toolkit proved to be suitable for the implementation of these multiphysics codes. This work follows the multiphysics approach while pursuing the objective of investigating the reactor dynamic response to accidental scenarios, in agreement with the objectives of the Horizon 2020 Euratom SAMOSAFER project [6]. Furthermore, the goal is to assess the harsh working conditions to which the reactor is subjected in terms of thermo-mechanical loads and irradiation. To do so, steady state simulations are performed on a 3D domain, representing a 16^{th} of the reactor, in order to assess the nominal operating conditions and provide a starting point for the transient scenarios modelling. The first accidental event taken into account involves a failure of the primary pumps, namely an Unprotected Loss of Fuel Flow (ULOFF). Then, the focus moves to the intermediate loop, and the second unintended event consists of a degradation of the heat transfer properties that compromises the heat removal provided by the heat exchanger, i.e., an Unprotected Loss of Heat Sink (ULOHS). Finally, in order to get an all-encompassing view of the dynamic behaviour of the MSFR, melting and solidification phenomena are included in the solver in order to provide a tool to inspect the behaviour of the innovative safety barrier of freeze valves.

2. Multiphysics Solver

In light of the multiphysics approach, the solvers employed throughout this work, developed at the Politecnico di Milano [2, 4], couple neutronics and thermal-hydraulics in the OpenFOAM environment. The thermal-hydraulic part returns temperature and density in order to update the cross sections. The other way around, the neutronic part gives the fission power density as an outcome, which is fed as a volumetric source to the energy equation. The process is iterated till convergence. Two versions of the solver are available, one for the steady state, i.e., *msfrSimpleFoam*, and the other for transient simulations, i.e. *msfrPimpleFoam*.

2.1. Thermal-hydraulics subsolver

The thermal-hydraulic part of the subsolver implements an incompressible single-phase version of the Reynolds-Averaged Navier-Stokes equations. The thermal properties are considered constant, but the buoyancy effects are taken into account thanks to the Boussinesq approximation. In order to simulate the pump and the heat exchanger, a momentum source and a heat sink are included. The steady state and transient solvers are based on SIMPLE and PIMPLE algorithmic models, respectively.

2.2. Neutronic subsolver

For the neutronic part of the solver, the multigroup diffusion approximation is adopted, and transport equations for delayed neutron and decay heat precursors are included in the solvers. Albedo boundary conditions can be imposed to represent the blanket and the reflectors. The Doppler and thermal expansion feedback effects are reproduced by linear and logarithmic temperature corrections of the group constants. A power iteration routine is available to obtain the value of the effective multiplication factor in order to achieve criticality at the user-specified power level.

2.3. Melting subsolver

Following a work previously presented at Politecnico di Milano [7], the solver is enriched by the possibility to simulate melting and solidification phase change. Numerical models to treat the latent heat and the velocity transitions are therefore incorporated in the *msfrPimpleFoamSolver*. The first phenomenon is accounted for by modifying the energy equation following the *Apparent Heat Capacity* or the *Source Term Method*; the other phenomenon is accounted for by introducing a source term in the momentum equation that suppresses the velocity in the solid phase, according to *Darcy Source Term*.

3. Steady State Analyses

The steady state analyses simulate a 3D geometry representing a 16^{th} of the reactor fueled with molten salt, whose properties are shown in Table 1. The domain includes the core, the cold and hot legs, the pump, and the heat exchanger. These last two components are represented by a momentum source and a heat sink. For the neutronic part, six energy groups for the fluxes, eight for delayed neutron precursors, and three for the decay heat precursors are solved. The target nominal power, volumetric flowrate, and minimum temperature at the core inlet are 187.5 MW, 0.28125 m^3/s and 923 K, respectively.

Parameter	Symbol	Value	Units
Density	ρ	4306.71	kg/m^3
Specific heat capacity	c_p	1593.94	J/ kg K
Laminar viscosity	ν	$5.89\ 10^{-6}$	m^2/s
Th. expansion coeff.	β	$1.1912\ 10^{-4}$	1/K
Intermediate temp.	T_{ext}	908	K
Prandtl n°	Pr	23.87	-
Turb. Prandlt n°	Pr_t	0.85	-
Schmidt n°	Sc	20	-
Turb. Schmidt n°	Sc_t	0.85	-

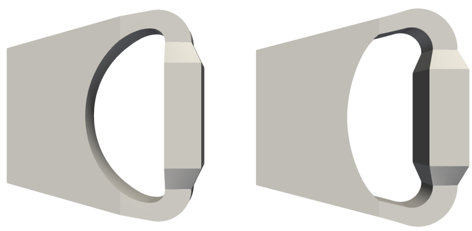
Table 1: Molten salt properties.

3.1. Sensitivity Analyses

Sensitivity analyses are performed to investigate how different modelling choices intrinsic in the numerical approach affect the outcomes of the steady state simulation.

3.1.1 Geometry

Two geometries are tested, Fig.1, with the parameters suitably tuned to meet the nominal condition requirements. The outputs show good agreement even if geometry (b) demonstrated slightly more accentuated recirculation next to the blanket wall.



(a) (b)

Figure 1: CAD parts of the geometry.

3.1.2 Mesh refinement

In order to get a proper initial reference case for the transient simulations, the outcomes of the *msfrSimpleFoam* solver are fed to the *msfrPimpleFoam* solver in order to evaluate the condition at which the domain stabilises while keeping constant the parameters of the sources. In doing so, some oscillations in the volumetric flowrate and on the power produced in the core arise. The cause of this oscillatory behaviour can be attributed both to the turbulent flow and to numerical issues. This sensitivity analysis shows that, up to a certain level, finer refinement of the mesh helps reduce the amplitude of these oscillations.

3.1.3 Pre-implemented sources

OpenFOAM provides pre-implemented sources suitable to represent the heat sink and the momentum source previously mentioned. The *SemiImplicitSource* and the *CodedSources* are compared to represent the primary pump. The *CodedSources* describes better the profile of the flow in the heat exchanger and pump zones, forcing the fluid downward, but it also leads to higher recirculation next to the blanket zone.

3.1.4 Turbulence

Two eddy viscosity turbulence models are tested, i.e., *Realizable* $k-\varepsilon$ and $k-\omega\,SST$. The outcomes are very similar, with a maximum difference, evaluated for the main operational parameters, of 1.93% for the volumetric flowrate.

3.1.5 Boundary conditions

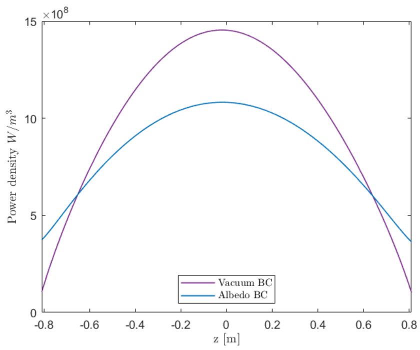


Figure 2: Axial power density profile for albedo and vacuum boundary conditions.

A simulation in which the albedo boundary conditions are imposed on the blanket and the upper and lower reflector walls is compared with vacuum boundary conditions. Fig.2 illustrates that the power density profile axially is more flat for the albedo boundary conditions and the same holds for the radial profile. The flux values for each energy group are higher for the albedo boundary conditions by a factor ranging from 1.6 to 13.5.

3.2. Reference case

For the steady state of the reactor at nominal operating conditions, the geometry (a), the *SemiImplicitSource*, the *Realizable* $k-\varepsilon$ and vacuum boundary conditions are chosen. Figs.3 and 4 depict the temperature and velocity distributions of the reference case at steady state, while Table 2 presents the values of the main operational parameters.

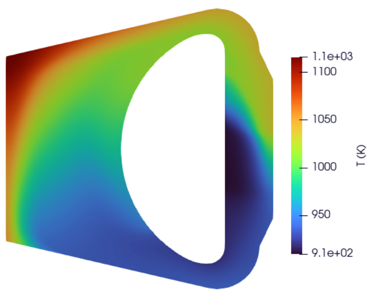


Figure 3: Temperature at steady state.

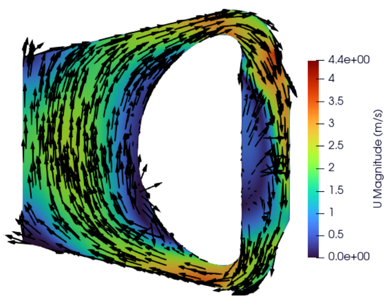


Figure 4: Velocity at steady state.

Output	Units	Value
$T_{min,inlet}$	K	922.77
$\Delta\bar{T}$	K	95.18
T_{max}	K	1114.49
$\bar{T}_{core}$	K	981.81
$\dot{V}$	m^3/s	0.2818
Q_{core}	MW	184.75
Q_{total}	MW	186.7

Table 2: Main operational parameters.

3.3. Feedback coefficient evaluation

The MSFR is characterised by strong negative feedback coefficients related to the Doppler and thermal expansion effects. In order to evaluate the feedback coefficient, two simulations are run with fixed constant temperature fields set at 900 and 1000 K. The velocity field is imposed as the one resulting from the reference steady state simulation. Only the neutronics equations are solved to evaluate the effective multiplication factor thanks to the power iteration routine. The resulting thermal feedback coefficient is $\alpha_{thermal}$ = -5.645 pcm/K, in good agreement with the reference of -5 pcm/K found in literature [1]. Another peculiarity of the MSFR is the delayed neutron precursors drift induced by the circulating liquid fuel. In order to estimate the reactivity inserted in the case of precursors hold back, two simulations are run with a temperature field fixed uniformly at 1000 K. In the former, the velocity is also set to zero, while the latter exploits the steady state velocity field. The reactivity insertion caused by the precursors hold-back is 173.6 pcm.

4. ULOFF

The first accidental scenario taken into account is the Unprotected Loss of Fuel Flow (ULOFF). The event consists of a failure of the primary pumps that in this work is assumed to be symmetric, i.e., involving all sixteen pumps and occurring unprotected, i.e., without mitigation. In order to simulate this accident, an exponential reduction of the momentum source with a time constant of 5 s is implemented [3].

4.1. Numerical results

During the transient, the volumetric flowrate declines up to a value supported by the onset of natural circulation. As the flowrate initially decreases, the corresponding increase in the power-to-flow ratio causes the mean temperature to increase, Fig5. This rise triggers the thermal feedback effects, resulting in a drop in the power produced in the primary loop. As time progresses, the power-to-flow ratio keeps increasing due to the precursors hold back contribution, but its slope gradually flattens due to the reduced power. As a result, the mean temperature also rises at a milder rate. During the transient, the maximum temperature in the top centre part of the core reaches a peak and then declines while the region with the hottest temperature expands, involving a larger part of the upper reflector and blanket walls. The minimum temperature at the core inlet decreases up to a value close to the intermediate salt temperature, so the heat removal provided by the heat exchanger reduces even with a constant global heat transfer coefficient. Starting from the thermal feedback coefficient evaluated in Section 3 and the mean temperature variation from the steady state to the end of the transient, a reactivity insertion of -150 pcm can be estimated.

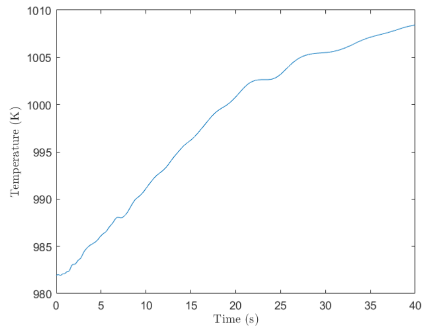


Figure 5: Mean temperature time profile (ULOFF).

5. ULOHS

The second accidental scenario presented in this thesis consists of a degradation of the heat removal provided by the heat exchangers, or Unprotected Loss of Heat Sink (ULOHS). Even in this case, the accident is considered symmetric and unprotected. To simulate this event, the parameters of the heat sink representing the heat exchanger are manipulated, i.e., the intermediate salt temperature and the global heat transfer coefficient. On the contrary, the primary pumps are assumed to be in a working state, so the volumetric flowrate is left constant. Two scenarios are simulated; the former more realistic, the latter more severe [3].

5.1. *Case A*

The first case scenario is simulated through an exponential reduction of the global heat transfer coefficient and an increase of the intermediate salt temperature with a time constant of 5 s.

5.2. Numerical results

The deterioration of the heat transfer capabilities results in an increase of the minimum temperature at the core inlet and, in turn, of the mean temperature of the core, Fig.6. This increment triggers the counteraction of the feedback effects, causing a decline in the power produced in the primary loop. Since the volumetric flowrate is constant, the power-to-flow ratio drops during the transient, contrasting with the increase in the mean temperature related to the progressive loss of cooling capabilities of the heat exchanger. This leads to an increase in the mean temperature, followed by a decreasing trend. The maximum temperature reduces during the transient due to the power reduction while the minimum temperature at the core inlet increases, and it is strongly affected by the scenario modelling since the limits imposed on the exponential trend drive the maximum value reached at the core inlet.

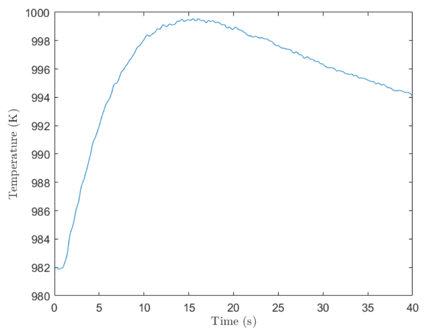


Figure 6: Mean temperature time profile (ULOHS *Case A*).

5.3. *Case B*

The second ULOHS transient scenario is simulated by imposing a step decrease of the global heat transfer coefficient, which is instantaneously fixed to zero. This severe accidental condition is thought to be as conservative as possible.

5.4. Numerical results

The instantaneous suppression of heat removal causes a steep increase in the mean temperature at the core inlet and, as a result, in the mean temperature in the core, Fig.7. These increments result in a significant drop in the total power produced in the core due to the feedback effects and hence in the power-to-flow ratio.

The maximum temperature also is subjected to a rapid decline in the first seconds of the event. As the simulation progresses, the non null power production combined with the completely adiabatic conditions leads all the temperatures evaluated to assume an increasing trend, which is expected to continue even after the 40 s simulation interval.

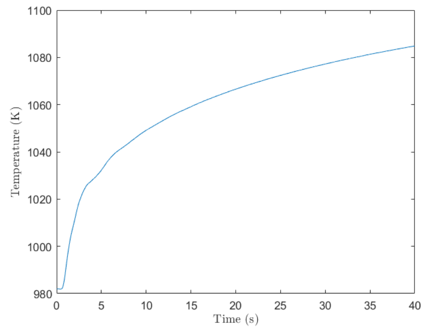


Figure 7: Mean temperature time profile (ULOHS *Case B*).

6. Melting and solidification

This final part aims at verifying the correct implementation of the *phaseChangeMsfrPimpleFoam* performed in this work. The solver couples the features of the *msfrPimpleFoam* with the melting and solidification modelling developed at the Politecnico di Milano [2, 7].

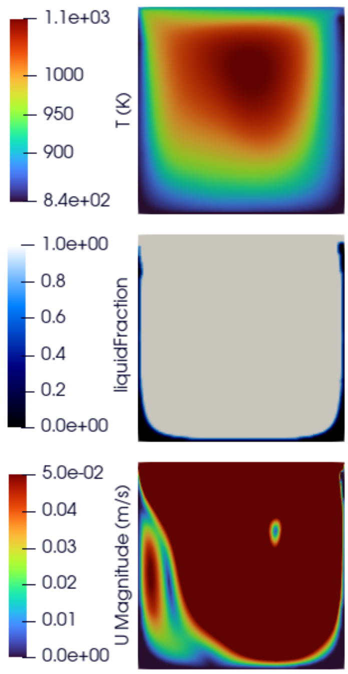


Figure 8: Temperature, liquid fraction and velocity in the coupling case study.

Two benchmarks available in the literature [5, 8] are selected to test separately the parts of the solver. In both cases, a great deal of agreement is demonstrated. Then, in order to verify the proper coupling performed by the multiphysics solver, a preliminary case study of a 2D cavity is simulated, solving the thermal-hydraulics, neutronics, and solidification. A step-by-step approach is employed together with suitable parameters to highlight the formation of a solid layer. The results prove that all the phenomena involved are treated properly, providing physically reasonable outcomes for the solidification layer as well.

7. Conclusions

The ultimate goal of this thesis was to investigate the MSFR behaviour under nominal operating conditions and during accidental scenarios also to assess the conditions on the containment of the MSFR. In order to evaluate the harsh working conditions, in terms of thermal load and irradiation, to which the reactor is subjected, numerical simulations are employed. The multiphysics solver exploited throughout the thesis,i.e., *msfrSimpleFoam* and *msfrPimpleFoam* was at first updated to OpenFOAM v8. Then, the transient solver was coupled with numerical models to deal with melting and solidification phenomena. For the steady state assessment, sensitivity analyses were performed on the 3D domain representing a 16^{th} of the reactor. These comparisons highlighted how different modelling choices intrinsic to the numerical approach affect the distributions of variables. Furthermore, the necessity for accurate design prescriptions for the pump and the heat exchanger as well as a definitive geometry for the domain is inferred. Subsequently, the purpose of the transient simulations was to evaluate the time evolution of variables in response to unintended failures of primary and/or intermediate loop components. The 3D domain and the multiphysics solver are suitable for proper capture of the dynamic behaviour of the MSFR. Both the ULOFF and ULOHS scenarios demonstrated compliance with the safety limits imposed by the performance degradation of structural material subjected to unintended loads, even if the ULOFF proved to be more concerning. The final part of this work established the groundwork for a deeper understanding of the freeze valves. The integration of the transient solver with the melting and solidification models allows for the simulation of an accidental event requiring the activation of the freeze plugs in a unique case study. This advancement may provide a chance to expand the range of possible unintentional events that can be investigated with multiphysics solvers.

References

[1] M Allibert, M Aufiero, M Brovchenko, S Delpech, V Ghetta, D Heuer, A Laureau, and E Merle-Lucotte. Molten salt fast reactors. In *Handbook of generation IV nuclear reactors*, pages 157–188. Elsevier, 2016.

[2] Manuele Aufiero. Development of advanced simulation tools for circulating fuel nuclear reactors. 2014.

[3] A. Cammi, E. Cervi, J. Krepel, D. Lathouwers, D. LeCarpentier, S. Lorenzi, M. Massone, R. de Oliveira, S. Poumerouly, A. Rineiski, M. Tiberga, and S. Wang. Analysis of accidental transients. *Deliverable D4.4 of the SAMOFAR Project, Horizon 2020*, 2017.

[4] Eric Cervi. An innovative multiphysics modelling approach for the analysis and the development of the generation iv molten salt fast reactor. 2020.

[5] N Hannoun, V Alexiades, and TZ Mai. A reference solution for phase change with convection. *International Journal for Numerical Methods in Fluids*, 48(11):1283–1308, 2005.

[6] SAMOSAFER official website. `https://samosafer.eu/`.

[7] Davide Tartaglia. Numerical modelling and simulation of melting phenomena for freeze valves analysis in molten salt reactors. 2021.

[8] M Tiberga, R de Oliveira, E Cervi, J A Blanco, S Lorenzi, M Aufiero, D Lathouwers, and P Rubiolo. Results from a multi-physics numerical benchmark for codes dedicated to molten salt fast reactors. *Annals of Nuclear Energy*, 142:107428, 2020.