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Analysis of Coupled Dynamics of Molten Salt Reactors

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SUMMARY

This work presents a preliminary analysis of the coupled thermo-hydrodynamics and neutronics of circulating nuclear fuel systems like the thermal Molten Salt Reactor (MSR), one of the "Generation IV International Forum" concepts [1]. This kind of nuclear reactor adopts a molten salt mixture, which flows up through channels in a graphite moderated core and plays the role of both heat generator and coolant [2]. In the core fission occurs within the flowing fuel salt, which then circulates in a primary heat exchanger, where the heat is transferred to a secondary liquid salt coolant; the fuel salt then flows back to the reactor core (see Figure 1).

MSRs are featured by a strong coupling between neutronics and thermo-hydrodynamics, which can be properly treated by means of a multi-physics approach. In this paper a simple 2-D geometry, representing a typical channel of a sub-critical MSR that comprises both the flowing molten salt fuel and the graphite matrix, has been considered. Physics of such system can be modelled by means of eight coupled partial differential equations, describing the fluid motion and the balances of energy, neutrons and precursors (see Table 1). With reference to this complex and highly non linear environment, COMSOL® confirmed as an adequate tool to catch some relevant features of both the steady state and the dynamic behaviour of the considered MSR channel. Analyses have been carried out for both laminar and turbulent flow regimes, focusing on the influence that graphite has on such system, in the light of a thermo-hydrodynamic validation discussed in a parallel work on the basis of both an analytical framework and a code-to-code (COMSOL® vs. FLUENT®) comparison [3]. In particular, the time constants of some physical quantities have been discussed: namely, the neutron flux, the precursors concentration, the fluid temperature and the graphite temperature, whose time evolution is of extreme interest for the investigation of the dynamic behaviour as well as of the most appropriate control strategy to be adopted in the current development of Molten Salt Reactors for Generation IV.

In short, this study has provided important information about the channel behaviour of a sub-critical MSR and paves the way for further progress concerning more complex and design-oriented simulations, which should consider more representative geometries of the power channels (if not of the whole reactor core) and more details in the neutronic modelling of both the molten salt and the graphite, as well as of their "nuclear" interaction.

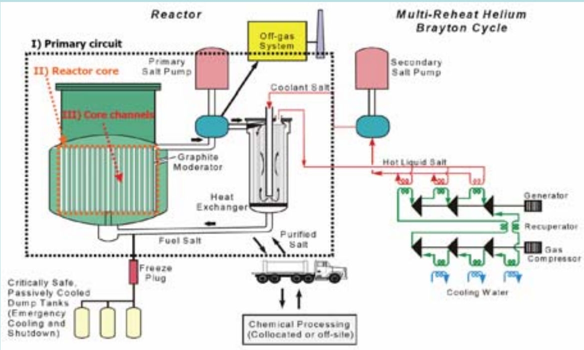
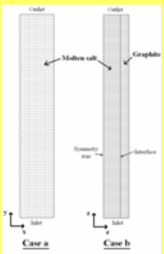


Figure 1. Typical layout of a nuclear power plant based on thermal (graphite moderated) MSR technology (from Ref. [2]): I) primary circuit; II) reactor core; III) core channels.

MULTI-PHYSICS MODEL

The multi-physics modelling adopted in this work consists of eight coupled partial differential equations describing the fluid motion (RANS – Reynolds Averaged Navier-Stokes equations with the standard k-ε turbulence model), the energy balance, the neutron and the precursors balances (see Table 1).

Figure 2. Geometry and mesh structure of the analyzed systems.



Geometry

Two different 2-D geometries have been considered for the analyses, i.e.: a Cartesian (x,y) geometry (0.58 m x 3.46 m rectangular box) representing a finite region of a sub-critical reactor (case a, as in Ref. [4]); an axial symmetric cylindrical geometry (r,z) representing a MSR (sub-critical) core channel (case b, shown in Figure 2). The channel considered in the present work is featured by an inner and outer graphite radius of 0.29 m and 0.43 m, respectively, and a height of 3.46 m.

It is worth noting that the size of the channel, in which the molten salt circulates, is a key design issue for MSRs, influencing relevant parameters like the moderation ratio, the total reactivity feedback coefficient, the breeding ratio, the graphite lifetime and the initial fissile inventory; a critical discussion of such effects, which are out of the scope of this work, can be found in [2].

Fluid motion:

$$\rho\frac{\partial \mathbf{u}}{\partial t}+\rho\mathbf{u}\cdot\nabla\mathbf{u}=\mathbf{F}+\nabla\cdot\left[-p\mathbf{I}-\frac{2}{3}\rho k\mathbf{I}\right]+\nabla\cdot\left[(\eta+\eta_t)\left(\nabla\mathbf{u}+(\nabla\mathbf{u})^T-\frac{2}{3}(\nabla\cdot\mathbf{u})\mathbf{I}\right)\right]$$

$$\partial\rho/\partial t+\nabla\cdot(\rho\mathbf{u})=0$$

$$\rho\frac{\partial k}{\partial t}+\rho\mathbf{u}\cdot\nabla k=\nabla\cdot\left[\left(\eta+\frac{\eta_t}{\sigma_k}\right)\nabla k\right]-\rho\varepsilon+\eta_t\left[\frac{1}{2}\left(\nabla\mathbf{u}+(\nabla\mathbf{u})^T\right)^2-\frac{2}{3}(\nabla\cdot\mathbf{u})^2\right]-\frac{2}{3}\rho k\nabla\cdot\mathbf{u}$$

$$\rho\frac{\partial \varepsilon}{\partial t}+\rho\mathbf{u}\cdot\nabla\varepsilon=\nabla\cdot\left[\left(\eta+\frac{\eta_t}{\sigma_\varepsilon}\right)\nabla\varepsilon\right]-\rho C_{\varepsilon 2}\frac{\varepsilon^2}{k}+C_{\varepsilon 1}\frac{\varepsilon}{k}\left\{\eta_t\left[\frac{1}{2}\left(\nabla\mathbf{u}+(\nabla\mathbf{u})^T\right)^2-\frac{2}{3}(\nabla\cdot\mathbf{u})^2\right]-\frac{2}{3}\rho k\nabla\cdot\mathbf{u}\right\}$$

Energy balance:

$$\rho C_{P,f}\frac{\partial T_f}{\partial t}-\nabla\cdot\left[(k_f+k_T)\nabla T_f\right]=S_f-\rho C_{P,f}\mathbf{u}\cdot\nabla T_f$$

$$\rho_g C_{P,g}\frac{\partial T_g}{\partial t}+\nabla\cdot(-k_g\nabla T_g)=S_g$$

Neutrons and precursors balance:

$$\frac{1}{v_n}\frac{\partial\phi}{\partial t}=D_n\nabla^2\phi-\Sigma_a\phi+(1-\beta)\nu\Sigma_f\phi+\lambda c+S_n$$

$$\frac{\partial c}{\partial t}-D_c\nabla^2 c=\beta\nu\Sigma_f\phi-\lambda c-\mathbf{u}\cdot\nabla c$$

Further expressions:

$F_\perp=0$ $\eta_T=\rho C_\mu k^2/\varepsilon$

$F_{//}=-g\alpha\rho_0(T_f-T_0)$ $k_T=C_{P,f}\eta_T/Pr_T$

$\rho=\rho_0\left(1-\alpha(T_f-T_0)\right)$ $S_f=\nu\Sigma_f\,\varepsilon_f\,\phi$

$\tau_g=C_{P,g}m_g/(hA)$

Nomenclature

A	interface heat transfer surface		[m²]
c	precursors concentration		[m⁻³]
$C_{P,f}$	specific heat capacity of fluid	1983	[J·kg⁻¹·K⁻¹]
$C_{P,g}$	specific heat capacity of graphite	1760	[J·kg⁻¹·K⁻¹]
$C_{\varepsilon 1}$	k-ε model constant	1.44	[-]
$C_{\varepsilon 2}$	k-ε model constant	1.92	[-]
C_μ	k-ε model constant	0.09	[-]
D_c	precursors diffusion coefficient		[m²·s⁻¹]
D_n	neutron diffusion coefficient	0.05	[m]
$F_\perp$	horizontal component of volume force		[N·m⁻³]
$F_{//}$	vertical component of volume force		[N·m⁻³]
g	gravity acceleration	9.80	[m·s⁻²]
h	heat transfer coefficient		[W·m⁻²·K⁻¹]
I	identity matrix (2x2)		[-]
k	turbulent kinetic energy		[m²·s⁻²]
k_f	thermal conductivity of fluid	0.45	[W·m⁻¹·K⁻¹]
k_g	thermal conductivity of graphite	31.2	[W·m⁻¹·K⁻¹]
k_T	turbulent thermal conductivity		[W·m⁻¹·K⁻¹]
m_g	mass of graphite		[kg]
n	neutrons		[-]
p	pressure of fluid		[Pa]
Pr_T	turbulent Prandtl number	0.85	[-]
S	amplitude of external neutron source	$1.4\cdot 10^{13}$	[n·m⁻³·s⁻¹]
S_g	energy source term within graphite	$4.7\cdot 10^{5}$	[W·m⁻³]
S_n	external neutron source		[n·m⁻³·s⁻¹]
t	time		[s]
T_0	reference temperature	830	[K]
T_f	temperature of fluid		[K]
T_g	temperature of graphite		[K]
$\mathbf{u}$	velocity vector		[m·s⁻¹]
v_n	average velocity of neutrons	2200	[m·s⁻¹]
α	coefficient of volume thermal expansion	$3.5\cdot 10^{-4}$	[K⁻¹]
β	fraction of neutrons emitted by precursors	$6.0\cdot 10^{-3}$	[-]
ε	turbulent dissipation rate		[m²·s⁻³]
ε_f	heat produced per fission reaction	$3.2\cdot 10^{-11}$	[J]
η	dynamic viscosity of fluid	$2.0\cdot 10^{-3}$	[Pa·s]
η_T	eddy viscosity		[Pa·s]
λ	decay constant of precursors	0.3	[s⁻¹]
$\nu\Sigma_f$	average number of neutrons per fission × fission macroscopic cross section	1.96	[m⁻¹]
ρ	density of fluid		[kg·m⁻³]
ρ_0	reference density of fluid	2000	[kg·m⁻³]
ρ_g	density of graphite	1843	[kg·m⁻³]
σ_k	k-ε model constant	1.0	[-]
σ_ε	k-ε model constant	1.3	[-]
Σ_a	absorption macroscopic cross section	1	[m⁻¹]
τ_g	time constant of graphite		[s]
ϕ	neutron flux		[n·m⁻²·s⁻¹].

Table 1. System of equations and material properties (for the molten salt from Ref. [5], for the graphite from Ref. [6]).

RESULTS

The initial state assumes the reactor to be at zero power, with an established hydrodynamic pattern. A start-up transient has been simulated, adopting for the external neutron source a cosine spatial shape [4]. The physics of the system brings to the attainment of a steady state by relaxing the initial conditions. Simulations have been carried out for both cases a and b in turbulent flow with a Reynolds number (Re) equal to $8\cdot 10^4$. Moreover, for the case a, further analyses have been performed with Re = $8\cdot 10^5$ and compared to the simulations with laminar flow of Ref. [4].

Case a

In laminar flow the buoyancy effect (according to the Boussinesq approximation) is more important than in the turbulent one because the fluid temperature is higher, and the fluid recirculation is more evident; as a consequence, the precursors are more concentrated in the upper part of the domain for the turbulent case (see Figure 3). The different flow regimes significantly influence the dynamic behaviour of the system, as shown in Figure 4: the time constant of the fluid temperature in the two considered turbulent regimes is lower than in laminar flow, showing a relevant dependence on the imposed inlet velocity, which also affects the precursors time evolution.

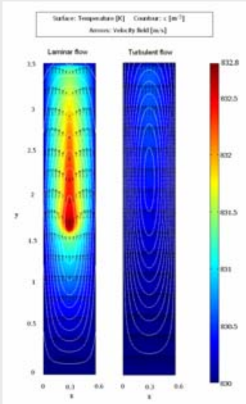


Figure 3. Case a: temperature (surface), precursors concentration (contour) and velocity field (arrows) for steady state conditions in both laminar (from Ref. [4]) and turbulent (present work, with Re = $8\cdot 10^4$) flows.

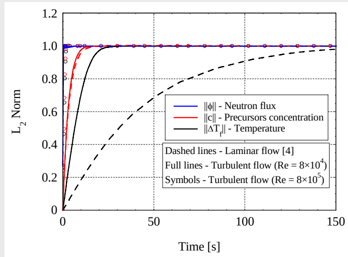


Figure 4. Case a: system time evolution.

Case b

A specific feature of the graphite + molten salt (fuel/coolant) system, unlike the externally cooled solid fuel rods adopted in the conventional nuclear reactors, is shown in Figure 5: initially, the heat is transferred from the fuel/coolant to the graphite matrix, but a situation is eventually reached where the radial heat flux is inverted between them. This behaviour is clear in Figure 6: in the simulated transient, and in any case in steady state operation, the graphite temperature results higher than the molten salt temperature, due to the assumed heat transfer boundary conditions. The radial temperature profile of the graphite is affected by the heat transfer coefficient (h) with the molten salt: the value of the Nusselt number (Nu = 461) obtained in this case results in a very good agreement with that achievable by means of the well-known Dittus-Boelter correlation, as thoroughly discussed in [3]. As shown in Figure 7, the neutron flux, the precursors concentration, the fluid and graphite temperatures exhibit very different time scales, which are relevant for the operation and the control of the reactor and, more in general, of the overall nuclear power conversion system, as discussed in [4]. It must be noticed that the time constant of graphite is much greater than the other ones; moreover, its order of magnitude can be caught by using the simple formula for τ_g given in Table 1.

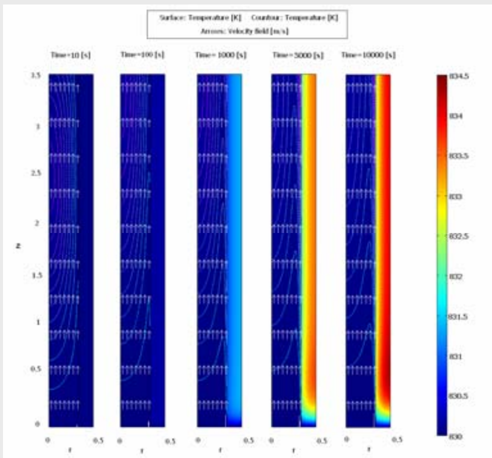


Figure 5. Temperature (surface and contour) and velocity field (arrows) at different times.

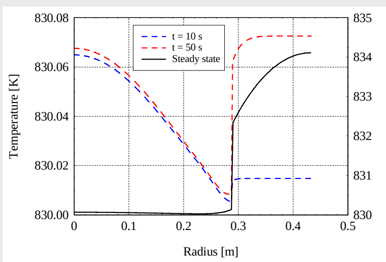


Figure 6. Case b: temperature radial profiles on the channel mid-plane at different times (dashed lines – left axis) compared to the steady state solution (full line – right axis).

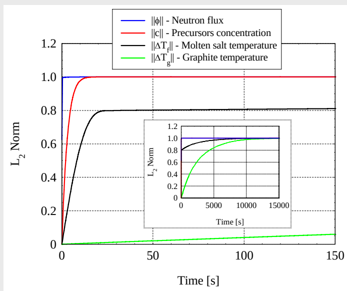


Figure 7. Case b: system time evolution.

Main References

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