

Multiphysics Simulations of MSFR in Marine Conditions

Hyunkyu Lee, Guillaume Gesmier, Jee Hyun Seong*

Department of Nuclear and Quantum Engineering, KAIST, 291 Daehak-ro, Yuseong-gu, Daejeon, 34141, Republic of Korea

*Corresponding author: sjhyunmit@kaist.ac.kr

***Keywords :** molten salt reactor, marine reactor, neutronics-CFD coupling, freeze-valve drain, ship motion

1. Introduction

Decarbonizing international shipping calls for a propulsion source of very high energy density, and the molten salt reactor (MSR) is an attractive candidate: it operates near atmospheric pressure, has a strongly negative temperature feedback, and can be shut down passively by draining its liquid fuel into a subcritical tank through a freeze valve. A shipborne reactor is, however, permanently subject to rolling and heaving, which modifies the body-force field acting on the fuel and therefore act on natural circulation and heat removal [1].

Because the fuel is also the coolant, its temperature and its inventory feedback on reactivity on the same time scale as the flow itself. Coupled neutronics–thermal-hydraulic analyses of MSR transients exist for land-based designs [2], but they assume a fixed inertial frame and a single-phase, filled core. Describing a marine MSR therefore requires three physics normally handled by separate codes — Monte Carlo transport, two-phase computational fluid dynamics (CFD) and reactor kinetics — to advance together through one accident.

The main contribution of this work is the construction of such a coupled framework, linking OpenMC, Ansys Fluent and a point kinetics equation (PKE) solver through a single driver, and its first application to a small marine MSR concept (K-MSR). The steady-state, unprotected loss-of-flow (ULOF) and freeze-valve drain cases below exercise the framework and do not validate a prediction of the design.

2. Reactor Model and Multiphysics Framework

2.1 K-MSR reference model

The K-MSR is a small MSR concept whose active region is a right circular cylinder of liquid fuel salt, fed from a lower plenum through 10 cm flow channels and discharging into an upper plenum, surrounded by a BeO reflector that returns a large fraction of the leaking neutrons. A freeze valve of 4 cm diameter at the bottom of the inlet pipe is kept solid by an external cooling circuit, and the plug melts passively and drains the core whenever that cooling is lost [3]. The fuel is the KCl–UCl₃ eutectic (46.0–54.0 mol %), whose solidus and liquidus coincide at 831 K [4], and the structure is Hastelloy N [5]. Table I lists the main parameters.

Table I: Main parameters of the K-MSR multiphysics model

Parameter	Value
Thermal power	6.0 MW
Salt mass flow rate	140 kg/s
Fuel salt	KCl–UCl ₃ eutectic
Melting / latent heat	831 K / 175 kJ/kg
Channel / valve dia.	10 cm / 4 cm
Cells: core/valve/OpenMC	990k / 135k / 38k
Coupling / Courant	1.25 s / 100

2.2 Coupling framework

A Python driver owns the transient clock and calls three dedicated interfaces, one per solver, and the division of labor follows what each solver can actually provide. OpenMC, being a k-eigenvalue calculation, fixes only the shape of the power distribution: it carries no absolute magnitude and no time dependence. The PKE solver supplies exactly that missing amplitude, at negligible cost compared with a time-dependent transport solution. Fluent owns the temperature, velocity and phase fields, and is the only solver that sees the core geometry change as the salt drains. Each therefore exchanges only the minimum the others need.

The steady state is obtained by Picard iteration between OpenMC and Fluent and is declared converged when $\Delta k_{\text{eff}} < 1 \times 10^{-4}$ — comparable to the Monte Carlo uncertainty of 7.8×10^{-5} — and $\Delta T_{\text{avg}} < 0.5$ K between successive iterations.

The transient sequence is shown in Fig. 1. Fluent advances with an adaptive time step limited by a global Courant number of 100, and the other two solvers are called at different rates. OpenMC is re-run once per 1.25 s coupling interval, taking the local salt temperature $T_f(r,t)$ and the helium volume fraction $x_{\text{He}}(r,t)$ from Fluent and returning the normalized power shape $q(r,t)$. The PKE solver is far cheaper and is advanced at every Fluent time step, taking the core-average temperature $T_{f,\text{avg}}(t)$ and the core-average salt volume $V_{f,\text{avg}}(t)$ and returning the normalized total power P_t/P_0 (fission plus decay heat, Sec. 2.5). The heat source on the CFD mesh is the product of the two, so that a fast power change is followed at the CFD time-step resolution while the expensive transport solution is refreshed only once per interval.

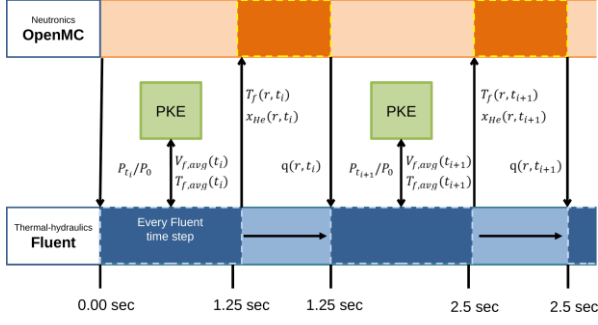


Fig. 1. Transient coupling sequence: OpenMC is called once per 1.25 s interval, while the PKE solver is advanced at every Fluent time step.

2.3 Thermal-hydraulic model and ship motions

Fluent solves the core with the implicit volume-of-fluid formulation, salt and helium being the two phases, capturing the gravity-driven drain and the ingress of helium from the top inlet. Least-squares cell-based gradients, the PRESTO! pressure interpolation, the Compressive volume-fraction scheme, a coupled pressure-velocity solver and second-order upwind discretization (first-order implicit in time) are used.

Ship motion is applied to the same mesh with a period $T = 5$ s. Rolling is imposed as a non-inertial frame rotation with an angular velocity

$$\omega(t) = \theta_{\max}(2\pi/T)\cos(2\pi t/T) \quad (1)$$

and heaving as a time-dependent gravity

$$g(t) = g_0[1 - 0.5 \sin(2\pi t/T + \varphi)] \quad (2)$$

where $\theta_{\max} = 45^\circ$ is the roll amplitude, g_0 the standard gravity and $\varphi = \pi/4$ a phase shift. The rotating frame retains the Euler, centrifugal and Coriolis accelerations, and at $\omega \approx 1$ rad/s and 2.5 m/s the Coriolis term reaches about 0.5 g and is not negligible. The two motions were imposed separately, and a combined multi-degree-of-freedom motion was not considered. Both amplitudes are bound rather than typical.

2.4 Freeze-valve subscale model

The freeze valve cannot be resolved together with the core, so a separate 135,483-cell model using the Fluent solidification/melting model was built. It is initialized with the axial gradient the cooled valve sees (831 K at the top of the plug, about 900 K at the core end) and its outer wall is then raised to 900 K to represent the loss of cooling. Melting starts at the plug periphery after about 15 s and the passage opens within a few seconds. The computed outlet flow follows a logistic law,

$$\dot{m}(t) = C + A/[1 + \text{EXP}(-B(t-t_0))] \quad (3)$$

where $\dot{m}$ is the mass flow rate at the valve outlet, C the residual flow before the plug melts, A the additional flow once the passage is fully open, $B = 2.10 \text{ s}^{-1}$ the opening rate and $t_0 = 17.26 \text{ s}$ the time at which the passage is half open ($R^2 = 0.9951$). It is this opening characteristic — a delay of about 15 s followed by an

opening in about 2 s — that is transferred to the full-core drain model.

Because the plug is initialized at its melting point whereas a real plug would sit roughly 200 K below it, the valve opens earlier than in practice: the drain results are best-estimated, and the ULOF case of Sec. 3.2, where the valve never opens, bounds a delayed opening.

2.5 Neutronics and point kinetics

OpenMC solves the transport on a 38,005-cell tally mesh refined at the core boundary, and the power distribution is returned to Fluent as an interpolated point cloud. The time-dependent power comes from a PKE solver with six delayed neutron precursor groups and three decay heat groups,

$$dN/dt = [\rho(t) - \beta_{\text{eff}}]N/\Lambda + \sum_i \lambda_i C_i(t) \quad (4)$$

$$dC_i/dt = \beta_i N/\Lambda - \lambda_i C_i(t) \quad (5)$$

where N is the neutron population, to which the fission power P_f is proportional, ρ the reactivity, β_{eff} the effective delayed neutron fraction, Λ the prompt neutron generation time, and β_i , λ_i and C_i the delayed neutron fraction, the decay constant and the concentration of the i -th precursor group. Λ was computed with OpenMC by the iterative fission probability (IFP) method, and the delayed neutron and decay heat group constants were taken from ENDF/B-VIII.0, with β_{eff} obtained as the sum of the β_i . The decay heat is computed from three decay-heat groups fed by the fission power,

$$dD_j/dt = \gamma_j P_f(t) - \lambda_{d,j} D_j(t) \quad (6)$$

$$P_t(t) = (1 - \sum_j \gamma_j) P_f(t) + \sum_j \lambda_{d,j} D_j(t) \quad (7)$$

where D_j is the decay-heat inventory of the j -th group, γ_j its share of the fission power and $\lambda_{d,j}$ its decay constant. With D_j initialized at its equilibrium value $\gamma_j P_0/\lambda_{d,j}$, $P_t = P_f = P_0$ at steady state, while after the fission power drops the D_j keep releasing heat. The PKE solver returns this total power as P_t/P_0 , and its product with the OpenMC shape $q(r,t)$ is the heat source imposed in Fluent (Sec. 2.2), so the decay heat is deposited with the same spatial distribution as the fission power. Because the fuel is drained rather than recirculated, the precursor recirculation terms are removed. Because C_i and D_j are not depleted by the drain, the whole decay heat remains in the salt left in the core, which is conservative.

The neutronics model represents a fresh, unpoisoned core and consequently gives $k_{\text{eff}} > 1$. Criticality control is outside the present scope and is assumed to provide a reactivity-flat hold-down over the transient time scale, so that every transient is driven by the change of reactivity referenced to the converged steady state,

$$\Delta\rho(t) = \Delta\rho_{\text{Th}}(t) + \Delta\rho_{\text{drain}}(t) \quad (8)$$

where $\Delta\rho_{\text{Th}}$ is the thermal feedback and $\Delta\rho_{\text{drain}}$ the reactivity lost with the drained fuel, with $\rho(0) = 0$ by construction. Both contributions are read from a second-order response surface fitted by Ridge regression to OpenMC calculations over 800–1300 K

and fill levels of 20–100 % ($R^2 = 0.9834$, residual 894 pcm), which gives an average temperature coefficient $\alpha_{Th} = -3.5$ pcm/K between 994 K and 1125 K.

3. Results

3.1 Steady state

The converged steady state gives $k_{eff} = 1.12372 \pm 0.00008$ and a core-average temperature of 994 K. Relative to the uniform 900 K reference used for the kinetic parameters ($k_{eff} = 1.12734$), the converged fields remove 286 pcm — a measure of what the coupling itself carries. The local volumetric source reaches 101 MW/m³ at the reflector interface, because the BeO block returns neutrons and most fissions occur near the core surface. The salt velocity reaches 2.5 m/s, the inlet-to-outlet temperature rise is about 100 K and the maximum local temperature is 1104 K.

3.2 ULOF transient — the no-drain bound

An unprotected loss-of-flow was simulated with the pump coast down of [2], $\dot{m}(t) = 140 \exp(-t/5)$ kg/s, without scram and with the valve closed, so this case bounds a delayed opening. The temperature rise inserts up to -455 pcm (-0.64 Δ) of thermal feedback, driving the fission power below the decay-heat level within about 50 s, fission becomes predominant again only after 176 s, once natural circulation is established. T_{avg} peaks at 1125 K at 96 s and the maximum local temperature is 1159 K at the top edge of the core, where recirculation hot spots are predicted.

3.3 Freeze-valve drain under marine conditions

Opening the valve makes the inventory term dominant: $\Delta\rho_{drain}$ reaches about -2.9×10^4 pcm (-41 Δ) after 110 s, two orders of magnitude more than the thermal contribution, and the fission power falls below the decay heat after about 31 s. Without ship motion T_{avg} peaks at 1045 K at 21 s and then decreases monotonically, with the maximum local temperature is 1095 K, 64 K below the ULOF value.

The same drain was then repeated with rolling only and with heaving only, as two further independent simulations (Fig. 2, Table II). The inventory histories (core salt volume $V_{f,avg}$ normalized by its initial value) are almost indistinguishable and nearly linear. As the runs end before the core is empty, the drain duration is evaluated from the fraction drained at 100 s, $1 - V_{f,avg}(100 \text{ s})/V_{f,avg}(0)$, which is proportional to the mean drain rate and thus inversely proportional to the time needed to drain a given fraction. At 100 s the residual inventory is 0.16, 0.15 and 0.18 (84, 85 and 82 % drained), so relative to the base case rolling shortens the drain by 1.2 % and heaving lengthens it by 2.4 %, i.e. ship motion changes the drain duration by less than 3 %. The thermal response, however, is not

symmetric. Heaving reproduces the base-case peak but superimposes ± 1.5 K oscillations at the forcing period and, by enhancing mixing, cools the core slightly faster. Rolling raises the peak by 4 K, delays it from 21 s to 31 s and leaves the core 25 K hotter at 100 s (1030 K against 1005 K). The transverse acceleration most plausibly reorganizes the internal circulation so that hot salt is retained, and a dedicated flow-field analysis should confirm this.

These results have not been compared with an independent code or with experimental data, and no sensitivity study has been carried out, they demonstrate that the framework runs the three physics consistently through a full accident sequence rather than predicting it quantitatively. Three assumptions further bound them: excess reactivity is held down by an assumed reactivity-flat control mechanism, and the valve opens earlier than a subcooled plug would, and the quoted peaks are salt rather than wall temperatures.

Table II: Drain transient for each ship motion (T in K)

Quantity	Base	Rolling	Heaving
Peak T_{avg}	1045	1049	1045
Time of peak [s]	21	31	21
T_{avg} at 100 s	1005	1030	1003
Inventory at 100 s	0.16	0.15	0.18
Drain duration change [%]	—	-1.2	+2.4
T_{avg} oscillation	—	< 1	± 1.5

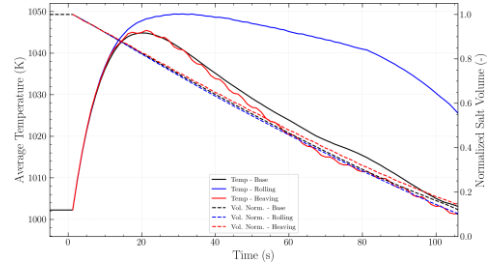


Fig. 2. Drain transient without imposed motion (base) and with rolling or heaving imposed separately.

4. Conclusions

A multiphysics framework coupling OpenMC, Ansys Fluent and a point kinetics solver has been developed for a small marine molten salt reactor. A single driver keeps the three solvers on one transient clock, refreshing the power shape every 1.25 s and the total power at every Fluent time step, so that the power distribution, the kinetics and the two-phase drain — including the freeze-valve melting — advance together through the same accident, with modular interfaces that allow any solver to be replaced.

It was exercised on a steady state, a ULOF and a freeze-valve drain, the latter repeated separately under rolling and heaving. In these first calculations the coupling shifts the steady state by 286 pcm, the no-

drain ULOF case reaches 1159 K locally against 1095 K for the drain, and ship motion changes the drain duration by less than 3 % while rolling leaves the core about 25 K hotter after 100 s. Verification and validation is the immediate next step, together with the remaining accident scenarios, a precursor transport model, and a subcooled-plug calculation.

ACKNOWLEDGEMENTS

This work was supported by the Korea Institute of Energy Technology Evaluation and Planning (KETEP) and the Ministry of Climate, Energy & Environment (MCEE) of the Republic of Korea (No. RS-2026-25537883).

This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (Ministry of Science and ICT) (No. RS-2026-25620686)

REFERENCES

- [1] J-S. Yoo, C. W. Lee, H. Hong, H. Ko, J. H. Ku, G. W. Kim, G-C. Park & H. K. Cho (2024). Experimental study on flow boiling CHF in annulus channel under heaving conditions using simulant fluid R134a targeting nuclear reactor applications. *Applied Thermal Engineering*, 236, 121906.
- [2] C. Fiorina, D. Lathouwers, M. Aufiero, A. Cammi, C. Guerrieri, J. Kloosterman, L. Luzzi, & M. E. Ricotti (2014). Modelling and analysis of the MSFR transient behaviour. *Annals of Nuclear Energy*, 64, 485-498.
- [3] Oak Ridge National Lab. (1961). MOLTEN-SALT REACTOR PROGRAM PROGRESS REPORT FOR PERIOD FROM AUGUST 1, 1960, TO FEBRUARY 28, 1961.
- [4] S. Ghosh, B. P. Reddy, K. Nagarajan, & K. H. Kumar (2014). Experimental investigations and thermodynamic modelling of KCl–LiCl–UCl₃ system. *Calphad*, 45, 11-26.
- [5] A. de Lara, A. Schubert, E. Shwageraus, & P. Van Uffelen (2023). Towards preliminary design calculations with TRANSURANUS for application of Hastelloy cladding material. *Annals of Nuclear Energy*, 192, 109973.