Thermal-Hydraulic and Reactivity Analysis of a Passive Molten Salt Fast Reactor Under Marine Rolling Motion

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1. Introduction

The decarbonization of the marine sector has accelerated the search for alternative propulsion systems with low carbon emissions [1]. According to the International Maritime Organization, greenhouse gas reduction from shipping is a critical global objective. Among advanced reactor concepts, the Molten Salt Reactor (MSR) has gained attention for marine applications due to its inherent safety characteristics, compact configuration, and high thermal power density [2].

The Passive Molten Salt Fast Reactor (PMFR) adopts a natural circulation–driven primary system and liquid fuel configuration. While the liquid-fuel design provides strong temperature feedback and high boiling margins, it also implies sensitivity to flow redistribution under external motion. In marine environments, ship motion such as rolling induces periodic variations in body forces, potentially altering internal flow fields and temperature distributions.

Because MSRs exhibit strong thermal feedback, even moderate temperature distortion may influence reactivity behavior. Therefore, it is necessary to evaluate both thermal-hydraulic and neutronic responses under externally imposed motion.

In this study, the thermal-hydraulic behavior of the PMFR core under rolling motion was analyzed using OpenFOAM, and the corresponding reactivity variation was evaluated using Serpent through a one-way coupling approach.

2. Numerical method and conditions

2.1 Target Reactor and Thermal-Hydraulic Model

The PMFR considered in this study is a natural circulation–based molten salt fast reactor with an approximately 10 m tall primary system [3, 4]. To reduce computational cost, only the active core region was modeled. The cylindrical active core has a height of 1.95 m and a diameter of 2 m. **Figure 1** shows the computational domain of the active core region and the mesh distribution used for the thermal-hydraulic analysis.

Thermal-hydraulic simulations were performed using the buoyantPimpleFoam solver. The computational domain consisted of approximately 3.56 million cells. The SST k–ω turbulence model was applied. The reactor thermal power was set to 300 MWt, and a volumetric heat source distribution was imposed based on a 39 × 20 nodal power profile obtained from neutronic analysis.

To isolate the direct influence of externally imposed body-force variation, the inlet mass flow rate was fixed as a boundary condition. System-level natural circulation degradation was not considered in this study. Detailed numerical conditions are summarized in **Table 1**.

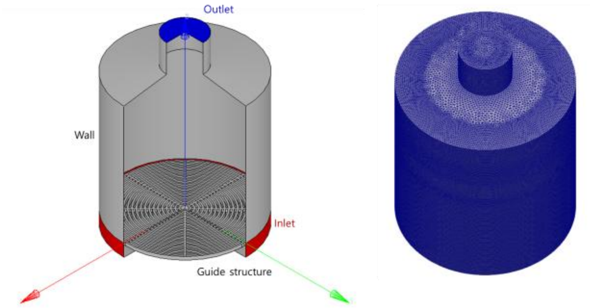

Fig. 1. Geometry and mesh of target calculation region (Active core of PMFR)

Table 1: Numerical analysis condition for OpenFOAM transient analysis

	Value	Remarks
Solver	buoyantPimpleFoam	
Turbulence model	RANS (SST k-omega)	
Time step	0.0005 s	Max courant number < 1
Time scheme	Euler	Implicit, First order
Target power	300 MWt	Internal heat source in active core
Heat source	Volumetric heat source	39X20 power distribution from Serpent
Radiation model	N/A	
Velocity	Inlet condition: 2315.75 kg/s	No-slip condition at the wall

2.2 Modeling of Rolling Motion

Rolling motion was implemented using the tabulatedAccelerationSource function available in OpenFOAM. A periodic rotational motion with a fixed period of 10 s was prescribed. Three maximum rolling angles—5°, 30°, and 40°—were analyzed to evaluate the influence of motion amplitude. The corresponding angular velocity and angular acceleration were defined consistently with the imposed period, allowing direct comparison of amplitude effects on the internal thermal-fluid field.

Figure 2 illustrates the imposed periodic rolling motion with a fixed period of 10 s. The sinusoidal variation of angular displacement results in corresponding variations in angular velocity and acceleration, which directly affect the body-force term in the momentum equation.

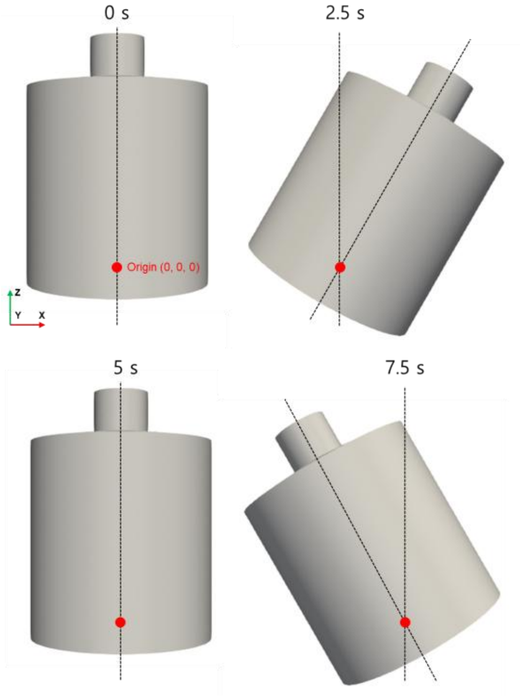

Fig. 2. Schematic of the rotational motion over time

2.3 Neutronics Evaluation

The spatial temperature fields obtained from the thermal-hydraulic analysis were mapped onto a 39 (axial) × 20 (radial) nodal for neutronics calculations.

A one-way coupling strategy was adopted, where the temperature distribution from OpenFOAM was used to update material temperatures in Serpent without feedback to the CFD model. The purpose of this approach is to evaluate neutronic sensitivity rather than to simulate a fully coupled transient reactor behavior.

The objective was to assess the neutronic sensitivity to motion-induced spatial temperature distortion rather than to predict fully coupled transient reactor behavior.

3. Results and discussions

The calculated results indicate that rolling motion significantly affects both the mean temperature and spatial temperature distribution within the core. As shown in **Figure 3**, the mean core temperature exhibits periodic oscillations synchronized with the imposed rolling motion. The amplitude of oscillation increases significantly with rolling angle, particularly in the 40° case. For the 5° case, the influence of rolling was negligible, and the mean temperature variation remained below 0.12 K from the initial state. However, when the maximum rolling angle increased to 30°, the mean temperature rose by approximately 2 K, and a periodic fluctuation corresponding to the 10 s rotation period was observed. In the 40° case, the mean temperature increased by about 3.4 K, and the maximum-to-minimum difference during one rolling cycle reached approximately 5.5 K. These results suggest that larger rolling amplitudes enhance flow non-uniformity and modify buoyancy-driven circulation patterns, thereby increasing the overall core temperature.

The effective multiplication factor exhibited periodic oscillations synchronized with the imposed rolling period, as shown in **Figure 4**. The phase of the reactivity variation clearly follows the temperature oscillation with an inverse relationship, reflecting the negative temperature feedback characteristic of the reactor. The maximum reactivity differences were approximately 82 pcm, 119 pcm, and 130 pcm for the 5°, 30°, and 40° cases, respectively. Notably, the magnitude of reactivity variation was larger than what would be predicted solely from the mean temperature change based on the estimated temperature feedback coefficient, indicating that spatial temperature distortion contributes to additional neutronic effects beyond bulk temperature feedback.

Further examination of cross-sectional temperature contours, presented in **Figure 5**, reveals that rolling motion generates distinct high- and low-temperature regions that shift periodically with the rotation phase. The temperature field becomes increasingly asymmetric as the rolling amplitude increases. In the 40° case, the maximum local temperature difference within the core reached approximately 100 K, which is substantially larger than the mean temperature variation. This pronounced spatial temperature distortion explains the amplified reactivity response, as localized temperature variations alter the neutron spectrum and reaction rates non-uniformly across the core region. The results imply that under actual transient conditions, motion-induced temperature asymmetry could significantly influence power density distribution and reactor stability.

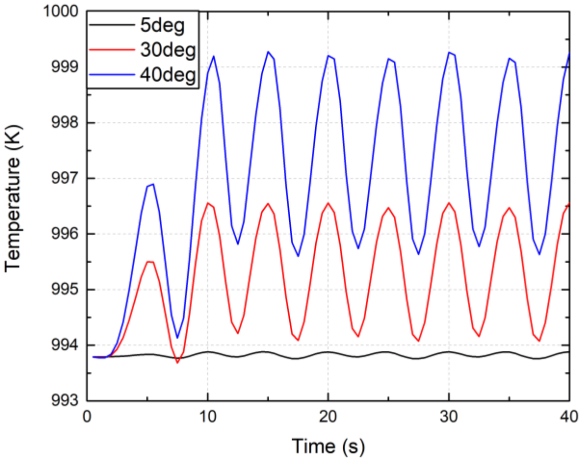

Fig. 3. Core mean temperature over time

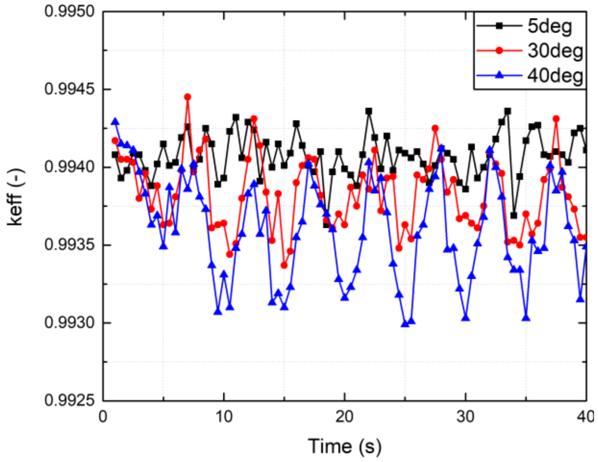

Fig. 4. Effective multiplication factor over time

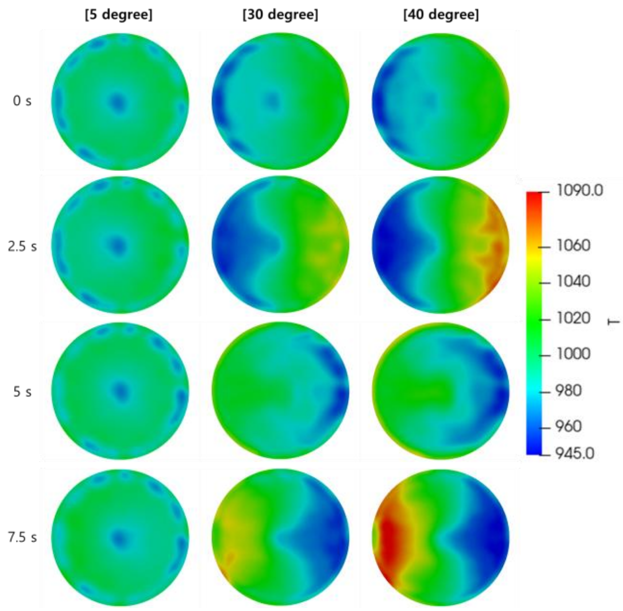

Fig. 5. Temperature variation within the central core cross-section over time

4. Conclusions

This study evaluated the thermal-hydraulic and neutronic behavior of a Passive Molten Salt Fast Reactor under marine rolling motion using a one-way coupled analysis between OpenFOAM and Serpent. The results demonstrate that increasing rolling amplitude leads to higher mean core temperature and larger periodic temperature fluctuations. The effective multiplication factor oscillates inversely with the mean temperature, following the imposed rolling motion. However, the reactivity variation exceeds the level expected from mean temperature change alone due to significant spatial temperature distortion within the core. In the 40° case, local temperature differences of up to 100 K were observed, highlighting the importance of spatial non-uniformity effects. These findings indicate that marine rolling motion can induce substantial internal temperature asymmetry in liquid-fuel reactors, and such effects should be carefully considered in safety evaluation and transient analysis of marine MSR systems.

To more comprehensively capture these effects, the present one-way coupling framework should be extended to a two-way coupled approach in future work, allowing for the incorporation of feedback mechanisms, natural circulation flow variations induced by marine motion, and reactor stability assessment through secondary system control under realistic transient conditions.

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