Demonstrating m-SMR Multi-Physics System Design with Integrated Monitoring

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***Abstract*—This study presents a conceptual miniaturized Small Modular Reactor (m-SMR) multi-physics system emphasizing coupled thermal-neutronic behavior and real-time monitoring. Oscillatory temperature and neutron flux profiles indicate non-uniform heat transfer and localized hotspots, posing thermal management challenges. A thermal stress spike at $1.5s$ suggests structural instability due to rapid thermal or mechanical effects. The results highlight the need for real-time monitoring with predictive analytics and call for adaptive control and high-fidelity simulations to enhance anomaly detection and ensure robust operation under extreme conditions.**

***Index Terms*—Monitoring, Neutron, Physics, Small Modular Reactor**

I. Introduction

Integrating nuclear reactors into critical infrastructure increases security risks due to radiological hazards and potential misuse of atomic materials [1]. Incidents like Chernobyl and Fukushima highlight the need for robust safety systems [2]. A unified safety, security, and safeguards (3S) framework is crucial to mitigate risks from accidents, sabotage, and proliferation [3]. Advances in remote monitoring and AI enable real-time surveillance and predictive maintenance, improving efficiency and resilience [4].

A robust yet reliable nuclear reactor monitoring system is essential to address these challenges [5]. This system should continuously monitor reactor parameters such as temperature, pressure, and radiation levels, facilitating early anomaly detection and immediate notifications to on-site personnel and remote centers [5]. This study demonstrates the design concept of a miniaturized Small Modular Reactor (m-SMR). A simplified interface enables operators to identify and respond to issues efficiently.

II. System Methodology

This section outlines the multi-physics design and control framework for an m-SMR as in Figure 1, integrating neutronics, thermal-hydraulics, structural mechanics, and instrumentation-driven monitoring.

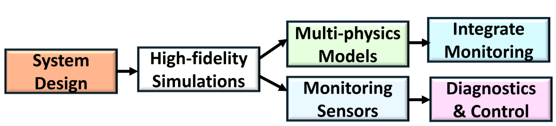

Fig. 1. Basic flow chart of the m-SMR design concept

The neutron transport is approximated using the multigroup diffusion Equation 1.

$$-\nabla \cdot D_g(\mathbf{r})\nabla\phi_g(\mathbf{r}) + \Sigma_{a,g}(\mathbf{r})\phi_g(\mathbf{r}) = \sum_{g'\neq g}\Sigma_{s,g'\to g}(\mathbf{r})\phi_{g'}(\mathbf{r}) + \frac{\chi_g}{k_{\text{eff}}}\sum_{g'=1}^{G}\nu\Sigma_{f,g'}(\mathbf{r})\phi_{g'}(\mathbf{r}). \quad (1)$$

The left side of the equation represents neutron diffusion and absorption, with $\phi_g(\mathbf{r})$ as the flux in energy group g at position $\mathbf{r}$, $D_g(\mathbf{r})$ as the diffusion coefficient, and $\Sigma_{a,g}(\mathbf{r})$ as the absorption cross-section. The right-hand includes scattering terms from other energy groups, involving cross-sections $\Sigma_{s,g'\to g}(\mathbf{r})$ and flux $\phi_{g'}(\mathbf{r})$, and fission contributions, with $\Sigma_{f,g'}(\mathbf{r})$ as the fission cross-section and k_{eff} as the multiplication factor. The neutron flux induces local volumetric heat generation in Equation 2.

$$q'''(\mathbf{r}) = \sum_{g=1}^{G}\Sigma_{f,g}(\mathbf{r})\phi_g(\mathbf{r})E_f. \quad (2)$$

Thermal behavior in solids is governed by transient heat conduction in Equation 3.

$$\rho c_p\frac{\partial T}{\partial t} = \nabla\cdot(k\nabla T) + q'''. \quad (3)$$

The incompressible Navier-Stokes and energy equations describe fluid flow and energy transport in the coolant. The coupled momentum and energy are expressed in Equations 4 for an incompressible Newtonian fluid with constant properties.

$$\rho\frac{D\boldsymbol{v}}{Dt} = -\nabla p + \mu\nabla^2\boldsymbol{v} + \rho\boldsymbol{g}, \quad \rho c_p\frac{DT}{Dt} = k\nabla^2 T + q''', \quad (4)$$

where ρ is the fluid density, $\boldsymbol{v}$ is the velocity vector, p is pressure, μ is dynamic viscosity, c_p is the specific heat at constant pressure, T is temperature, k is thermal conductivity, and q''' represents the volumetric heat generation. These equations describe the transport of momentum and heat within the fluid. Equation 5 computes the structural mechanics of thermally induced stresses.

$$\sigma_{ij} = C_{ijkl}\left(\varepsilon_{kl} - \alpha_{kl}(T - T_0)\right), \quad (5)$$

where C_{ijkl} is the elasticity tensor and α_{kl} the thermal expansion coefficient. Optimal sensor placement ensures system observability, formulated as Equation 6, enabling sensor network optimization.

$$\mathcal{O} = \text{trace}\left(\left(\sum_{i=1}^{N_s} H_i^T R_i^{-1} H_i\right)^{-1}\right) \quad \text{subject to} \quad \sum_{i=1}^{N_s} c_i \leq C_{\max}, \quad \mathbf{s}_i \in \mathcal{D}. \tag{6}$$

To ensure adaptive and safe operation, the model predictive control in Equation 7 minimizes deviations from reference trajectories.

$$\min_{\mathbf{u}(t)} \int_{t_0}^{t_0+T} \|\mathbf{x}(t) - \mathbf{x}_{\text{ref}}(t)\|^2 + \|\mathbf{u}(t)\|^2 \, dt \quad \text{subject to} \quad \dot{\mathbf{x}} = f(\mathbf{x}, \mathbf{u}), \quad \mathbf{y} = h(\mathbf{x}), \quad \mathbf{u} \in \mathcal{U}. \tag{7}$$

A system of coupled partial differential equations represents the m-SMR's coupled system integration. Neutronic behavior influences thermal profiles, which induce mechanical stresses. These are continuously monitored and adjusted in real time using integrated sensor feedback and control logic.

III. Performance Evaluation

A Python prototype was developed to replicate the core numerical structures of each component and demonstrate the coupled simulation logic. The design successfully modeled temperature, thermal stress, neutron flux, and monitoring system observability over time. Figure 2 illustrates the temperature and scaled neutron flux distributions along the reactor's position (in meters), highlighting thermal and nuclear flux behavior. The oscillatory pattern suggests potential issues with uniform heat transfer, which could lead to localized hot spots, influencing reactor design and cooling system requirements.

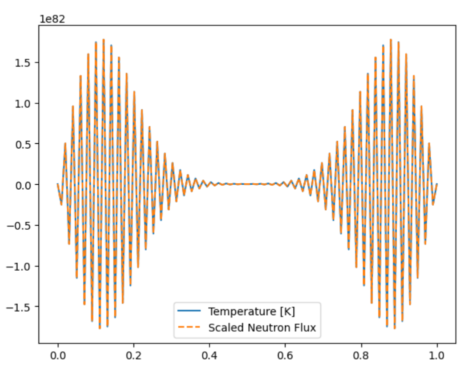

Fig. 2. Distribution of temperature (in Kelvin) and scaled neutron flux along the position (in meters) within the reactor

Figure 3 shows a significant spike in thermal stress and observability metrics around $1.5s$, suggesting a potential failure point or abnormal behavior, which can be due to thermal expansion or mechanical strain. This highlights the need for a real-time monitoring system to detect rapid stress increases and prevent catastrophic failure. It emphasizes the necessity for robust monitoring and adaptive control systems capable of withstanding extreme conditions in miniaturized reactor designs.

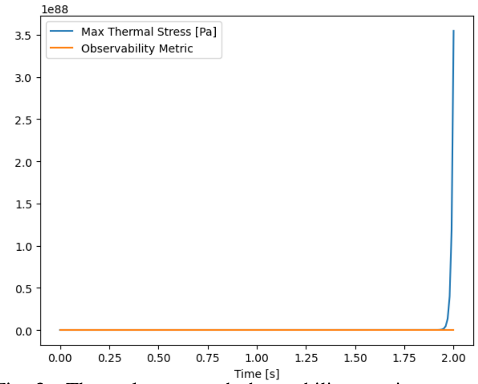

Fig. 3. Thermal stress and observability metrics over time

IV. Conclusion

The proposed concept integrates reactor physics, thermal-fluid dynamics, structural analysis, and sensor networks for real-time monitoring of m-SMR. It aims to optimize operation, enhance safety, and enable diagnostics and control, focusing on efficient thermal management and uniform temperature distribution in compact systems. Real-time monitoring of thermal stress, neutron flux, and observability, along with predictive algorithms, is key for detecting anomalies and initiating corrective actions. Advanced simulations and control systems are essential to optimize performance and prevent failures from temperature and flux oscillations.

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