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A Preliminary Performance Analysis of Load-Following Capability in Molten Salt Reactor with Reactor Regulating System using GAMMA+

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1. Introduction

Molten Salt Reactors (MSRs) have been studied by various research groups over many years because of its inherent safety characteristics, high temperature operation, and the potential for compact reactor designs.

Unlike Pressurized Water Reactors (PWRs), the MSRs are normally designed to be operated at near-atmospheric operating pressure with the high heat transfer capacity. The lower operating pressure reduces the likelihood of release of radioactive materials caused by discharging phenomena during accidents, and the higher heat transfer capability allows the efficient heat removal performance and lightweight designs.

Owing to these characteristics, the MSRs have been attracting the many attentions as potential mobile reactors, and they are additionally expected to meet the conservative requirements for load-following capability even in the remote areas.

The many research groups in various fields have focused on the individual components such as reactor physics, heat exchanger design, thermal properties of molten salts, and power conversion systems; however, the studies related to the interactions among the components and transient responses using the non-safety control systems such as Reactor Regulation System (RRS) are still limited.

In this paper, the transient analyses were performed for an MSR system under the load following operation. The reactor, control element, fuel salt loop, intermediate loop, and control systems for power maneuvering are developed by using GAMMA+ program. For the conservative analysis, the power maneuvering rate was set to be 5%/min ramp change, and the power range specified as 100-20-100%.

2. Thermal-Hydraulic Modeling

A system level simulation was conducted by using GAMMA+ program. The system configuration and its nodalization used in this study are shown in the Fig. 1. The system is consisted of:

- Reactor core and control element,
- Fuel salt loop (primary system),
- Coolant salt loop (Intermediate system),
- Power conversion loop (boundary condition), and
- Reactor regulating system

The nodalization was constructed to enable efficient rapid calculations and to accurately predict thermal-hydraulic phenomena in the system. The configuration of reactor core was sphere shape, and the upward molten salt flow was provided from bottom.

The helical once-through heat exchanger and the finned-tube heat exchanger were selected to accommodate the required thermal power. The helical type heat exchanger installed in horizontal direction transfers the heat from the primary loop to intermediate loop, while the finned-tube heat exchanger installed in vertical direction delivers the heat from the intermediate loop to power conversion loop.

To predict variations of reactor thermal power, the Nuclide-groups Transport Kinetics (NTK) was used, which enables the prediction of thermal power in both the active core region and inactive fuel salt loop [1].

3. Control Strategy and Modeling

The control strategy was developed based on the RRS of a commercial PWR [2]. The reactor power control was achieved by adjusting control element position.

The position signal of control element was generated by two control signals: Temperature error signal (T_{err}) and Power error signal (P_{err}). The T_{err} is deviation between the reference and measured temperatures corresponding to the power demand, P_{err} is difference between the demand and measured reactor power.

The flow rate of power conversion loop is controlled by the deviation between the reference air flow rate corresponding power demand and measured air flow rate. The power demand was provided by general tables of time-power demand program.

The RRS signal process was implemented by iterative trial-and-error, involving gain tuning, ensuring controller effects, and verifying the stable operations.

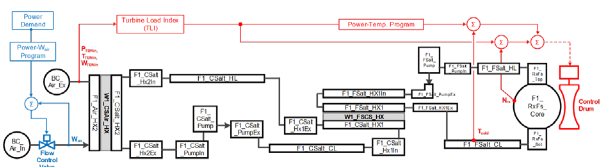


Fig. 1. System nodalization of GAMMA+ program to simulate the load-following operation

4. Initial and Boundary Conditions

The initial conditions for the transient analysis were established at the steady-state operation with 100% rated thermal power. The loop temperatures of fuel salt loop, coolant salt loop, and power conversion loop were set to the design nominal values, respectively.

A control strategy was adopted to maintain a constant reactor inlet temperature during the entire transient analysis. The salt flow rates in the primary system and intermediate system were determined to provide the heat balance under nominal operation condition.

The boundary conditions were imposed by changing the turbine inlet flow rate only. Although, the turbine inlet and outlet pressure and temperature are expected to change during transients, they were assumed constant in the preliminary analysis because the detailed design of power conversion loop may be subjected to change.

The power maneuvering operation was initiated by imposing a power demand signal that changed from 100 % to 20 % for 960 sec (16 min) with a conservative ramp change rate of 5%/min. The part load operation of 20% was maintained until 2,000 sec. The power increased from 20 % to 100 % for another 960 sec, and the full power operation was maintained until simulation reaches the termination time. The normalized initial conditions, boundary conditions, and other input data are summarized in Table 1.

5. Calculation Results

Fig. 2 shows the simulation results during transient. The results confirmed the operability of MSR system during the part load operation with the RRS control strategy. The normalized reactor power and the normalized air flow rate of power conversion system showed that those follow the power demand with good agreement (see Fig.2 (a) and (b)).

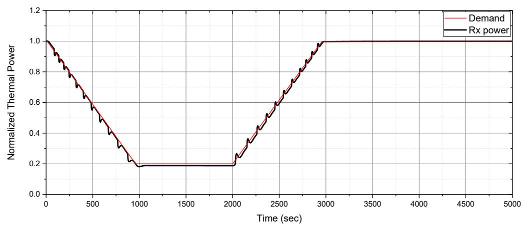
Table I: Normalized Initial and Boundary Condition

Parameter	Normalized values
Thermal power	1.0
Temperature	
- Primary loop (hot/cold)	1.000 / 0.954
- Secondary loop (hot/cold)	0.978 / 0.846
- Power conversion loop (hot/cold)	0.969 / 0.662
Flow rate	
- Primary loop	1.000
- Secondary loop	1.000
- Power conversion loop	1.000
Thermal power and Turbine flow rate	
- 0 – 960 sec	1.0 – 0.2
- 960 – 2,000 sec	0.2 – 0.2
- 2,000 – 2,960 sec	0.2 – 1.0
- 2,960 – 5,000 sec	1.0 – 1.0
Control element worth	
- 0.00 °	-
- 10.00 °	9.915E-03
- 20.00 °	2.080E-02
- 30.00 °	7.233E-02

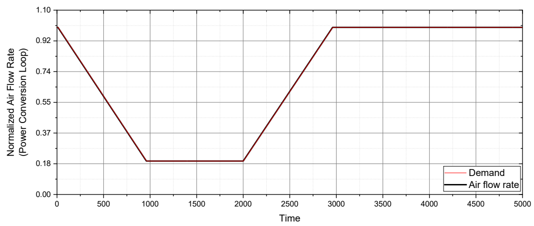
The reactor inlet temperature was controlled to remain constant, and the outlet temperature followed the specified design point as described in the power-temperature control program during the transient. Some of fluctuation is caused by the band hysteresis control logics during the power maneuvering (see Fig.2 (c))..

The control element position was inserted for the negative reactivity during power decrease, and it was withdrew for decreasing the negative reactivity during power increase. The most negative reactivity is induced by control element operation and the most positive reactivity is results from density changes of fuel salt. The total reactivity is appropriately changed by control element position and other feedback effects (see Fig.2 (d) and (e)).

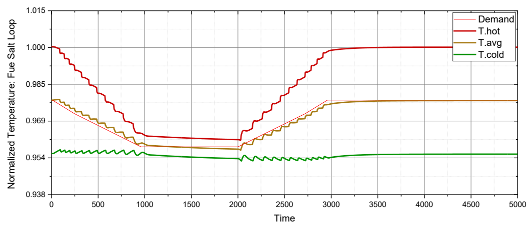
The control element signal is designed to be mainly governed by the T_{err} signal than the P_{err} signal. This dependency is optimized by adjusting the gain values (K_p) for the P_{err} signal in the RRS. In addition, the various control logics such as filtered derivative compensator (f_{dev}), proportional-integral (PI) controller, and rate limit (rlim) controller were designed for the load following performance analysis (see Fig.2 (f)).



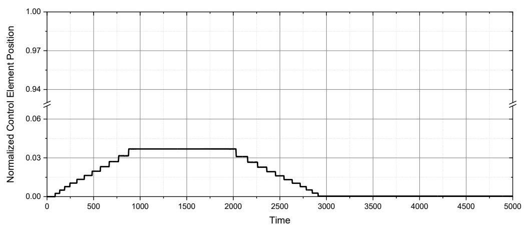
(a) Normalized reactor power and power demand



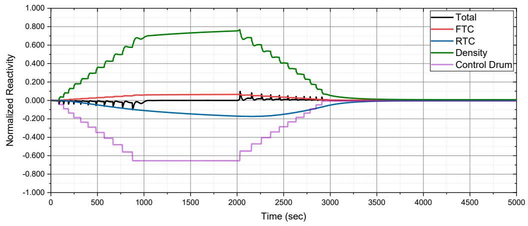
(b) Normalized air flow rate of power conversion loop



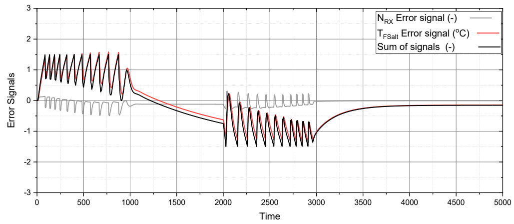
(c) Normalized temperature of fuel salt loop



(d) Normalized control element position



(e) Normalized reactivity changes



(f) Control signals: P_{err} and T_{err}

Fig 2. Transient analysis results using GAMMA+ program

6. Conclusion

This study simulated the MSR system with a PWR based the RRS which adapted for the preliminary performance analysis of MSR load following operation. The molten salt reactor, control element, fuel salt loop, intermediate loop, and control signal process system (RRS) are successfully implemented by using GAMMA+ program. The results confirm the robust transient performance with control element operation during conservative load-following transient. In this study, the power conversion system was considered as boundary condition; therefore, in future work, the transient analyses that incorporate the power conversion system and reflect its dynamic characteristics will be conducted.

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