MSRE Transient Benchmarks using SAM

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ABSTRACT

In recent years, there has been renewed interest in Molten Salter Reactors (MSRs) for their potential advantages compared to reactors that rely on solid fuel. In response to such interest, the System Analysis Module (SAM) was enhanced to include MSR-specific modeling features including a delayed neutron precursor drift model and a modified point kinetics model. This paper discusses the validation of these features using the experiments conducted in the Molten Salt Reactor Experiment (MSRE). These experiments include the pump start-up and coast-down tests at zero power and a thermal convection test. For the zero power tests, the change in pump speeds induces flow rate changes in the core that impact the precursor concentrations. This introduces a neutron imbalance and requires the adjustment of the control rods to counter-balance this effect. SAM was used to evaluate the precursor concentration in the core as a function of time, and the resulting changes in reactivity were evaluated through the modified point kinetics equation. The results show good agreement with the experimental data. It should be noted that the pump performance curve used in this analysis was re-constructed based on the initial water test data of the fuel pump. The steady-state pump curve is assumed to be applicable to transient flow operations. The thermal convection test was conducted by shutting off the pumps, reducing the inlet core temperature for 360 minutes, and allowing the power to be adjusted by the inherent feedbacks of the system. The power level during this transient was evaluated by SAM as a function of time.

KEYWORDS: SAM, MSRE, Benchmark

1. INTRODUCTION

One of the objectives of the Nuclear Energy Advanced Modeling and Simulation program within the U.S. DOE Office of Nuclear Energy (DOE-NE) is to develop modeling and simulation capabilities to predict the performance and safety behavior of a range of different nuclear reactor types. Given the recent interest in MSRs by the reactor developer/vendor industry, there has been a focus on assessing whether these advanced tools developed in the program are applicable for modeling steady-state and time-dependent conditions for MSRs with flowing fuel. The focus of this paper is on the application of one of these tools, the System Analysis Module (SAM) [1], to reproduce measured data from a set of time-dependent experiments conducted on the Molten Salt Reactor Experiment (MSRE).

SAM is a system analysis tool for advanced reactor safety analysis and can be employed for advanced reactor concepts including but not limited to Sodium-cooled Fast Reactors (SFRs), Lead-cooled Fast Reactors (LFRs), and MSRs. The tool was developed to solve the tightly coupled mass, moment, and energy transport equations. It relies on the MOOSE [2] framework for implementing governing equations and application development, on libMesh [3] for preparing finite-element mesh, and on PETSc [4] for solving linear and non-linear governing equations. In April of 2019, the US NRC has formally stated its intent to use the SAM code for advanced non-LWR design basis event analysis [5]

For MSR applications, two new features were recently implemented in SAM [6], including the precursor drift model and Point Kinetic Equation (PKE) for flowing fuel. Given the goal of having reactor developers and regulators use this code to predict safety performance for design and licensing purposes, it is important to demonstrate that these two new features implemented in SAM are able to predict transients of MSR systems correctly. For this purpose, experiments conducted in the MSRE program [7-8] were reviewed, and three experiments were selected to validate these MSR modeling capabilities in SAM. The pure thermal hydraulic validation using the MSRE water mockup test data and preliminary thermal hydraulic analysis of MSRE during normal operating condition and a postulated loss-of-flow transient were performed in an earlier study [9] using the SAM code.

2. MSRE DESCRIPTION

The MSRE is a graphite-moderated flowing fuel reactor with a designed full power of 10 MWth. The fuel salt is a mixture of lithium, beryllium, and zirconium fluoride containing uranium or thorium and uranium fluoride. It consisted of a primary loop and a secondary loop. The heat generated in the core is transferred to the secondary loop through a heat exchanger, and ultimately rejected to the atmosphere through a radiator. A schematic of the MSRE primary loop is presented in Fig. 1. The major components of the primary loop are the reactor core, the pump, the heat exchanger, and the pipes connecting each component. More detailed information about the MSRE design and components can be found in Ref.[10].

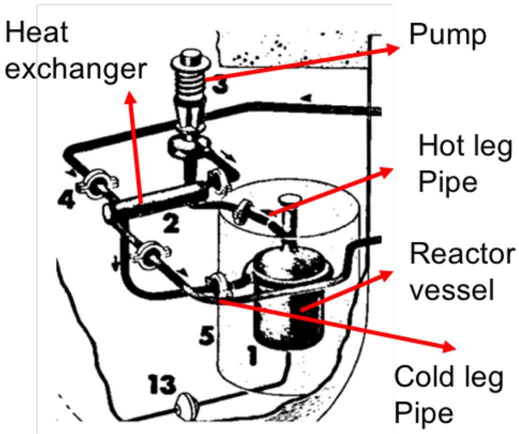

Figure 1. Schematic of the MSRE primary loop [10].

There were three experiments selected for validating the SAM code. All were chosen to benchmark the precursor drift model and the PKE for flowing fuel that were implemented in SAM. The three experiments selected include the pump startup test under zero power, the pump coastdown test under zero power, and the thermal-convection heat removal test (also commonly referred to as the “natural convection test”). Each test is discussed in the following sections with more details.

2.1. Pump Curve

To simulate the pump startup and coastdown tests in SAM, the pump head as a function of time is a required input. Neither the flow rate or velocity is a direct input into SAM, rather, the pump head is used in SAM to calculate the flow rate. However, the only pump-related parameter that is provided from the experiment is the pump speed. Therefore, in order to carry out simulation of precursor flow in the primary loop and calculate resulting reactivity changes, it is necessary to derive the transient pump head function from the pump speed function. The MSRE fuel pump homologous curve was utilized to achieve this task. In the MSRE, the initial phase of development and testing of the fuel pump was conducted with water [10]. The data obtained from this test was utilized to construct the homologous curve, which relates the pump head (H) to a variable x depending on both the fuel flow rate (Q) and the pump speed (N).

The equation of motion for the pump rotor is

$$\frac{2\pi}{60} I_p \frac{dN}{dt} = \tau_m - \tau_h - \tau_f, \tag{1}$$

where I_p is the pump moment of inertia [kg.m^2], τ_m is the electromagnetic motor torque [N.m], τ_h is the hydraulic torque [N.m], and τ_f is the total frictional torque [N.m]. The motor torque is omitted from eq. (1) when there is a loss of pump power. In this study, an analytical method was used to model the pump coastdown speed without requiring information on pump moment of inertia and hydraulic and frictional torques. This analytical method only requires two data points: the rotor lock time and the pump speed at an intermediate time. In general, the hydraulic torque is proportional to the square of speed and it dominates the right-hand side of eq. (1) at high speed. At low speed, the frictional torque becomes the dominant term and the right-hand side of eq. (1) can be approximated by a constant. The analytical solution of eq. (1) then can be approximated as

$$N(t) = \frac{\tan\left(\beta(t_e - t)\right)}{\tan\left(\beta t_e\right)}. \tag{2}$$

In eq. (2), t_e is the known rotor lock time. The parameter β can be determined using a second data point such as the pump half-time. The analytical method was compared to the MSRE fuel and coolant pump coastdown speed, and excellent agreement was observed.

Utilizing the pump speed given by the analytical model and the homologous head curve obtained from MSRE pump data, the transient coastdown flow rate in the primary loop can be predicted using SAM. An initial guess of the flow profile and pump speed from the analytical model are used to produce a pump head function which is an input in SAM. Then SAM calculates the flow taking into account the characteristics and resistances in the loop. The flow profile is fed back to the homologous curve to produce an updated head function, and the process is repeated until the flow profile calculated by SAM no longer changes in a new iteration. After only three iterations, the predicted coastdown flow behavior is obtained and shown in Fig. 2.

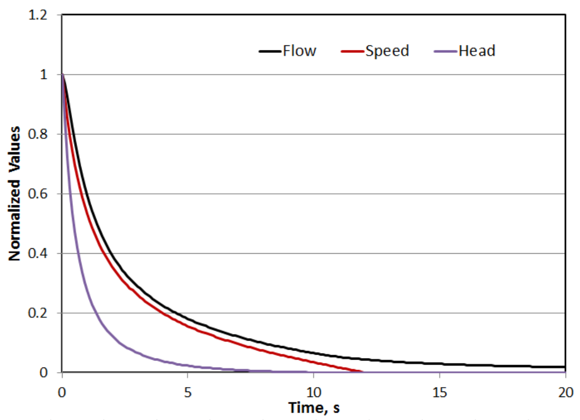

Figure 2. Normalized pump head, speed, and flow in MSRE primary loop

3. PUMP STARTUP TEST

Both the pump startup and coastdown tests [7] were part of a series of experiments conducted in 1965 under the condition of negligible power (10 Wth) while maintaining the reactor critical. In the pump startup test, the pump speed increased from 0 to 100% full speed within a couple of seconds as shown in Fig. 3. As the pump speed increased, the mass flow rate of the fuel also increased. This resulted in increased flow of delayed neutron precursors out of the core. Thus, this is equivalent to inserting negative reactivity into the core. The control rods were adjusted to keep the core critical. The control rod movement was translated into reactivity insertion using the control rod worth curve given in Ref. [7]. Then, the external reactivity insertion as a function of time becomes the main experimental measurement for SAM to benchmark.

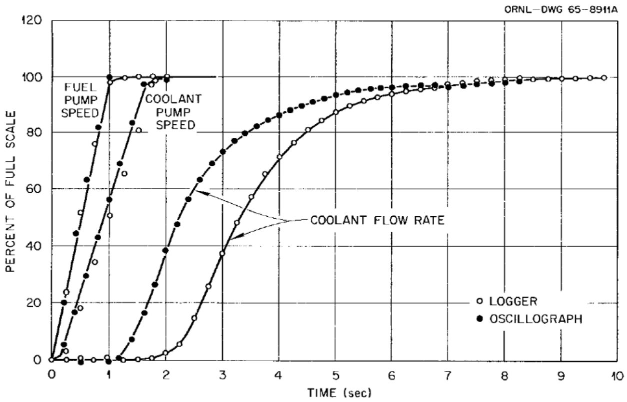

Figure 3. Pump speed variation in the pump startup test [7].

The simulation of the pump startup test in SAM took several steps:

1. The modeled system was initialized to the equilibrium state in the first SAM calculation with pump speed set to zero. Under this pump speed, the fuel salt flow rate is negligible and is mainly due to natural circulation. Thus, this situation is essentially equivalent to that of stationary fuel with precursors staying in the fuel region.
2. The pump head was calculated as a function of time based on the pump speed information and the pump curve, which is discussed is section 2.1. This was given to SAM as an input.
3. The precursor concentration as a function of time was solved by SAM for the given pump head function using the particle transport model in SAM.
4. The external reactivity required to maintain the core critical was calculated by reversing the point kinetic equation given in eq. (3), assuming constant power over time (*dn/dt* = 0).

$$\frac{\mathrm{dn}}{\mathrm{dt}} = \frac{\rho - \beta - \sum_i \left(\dot{c}_{in,i}(0) - \dot{c}_{out,i}(0)\right)\Lambda}{\Lambda} n + \sum_i \lambda_i C_i. \quad (3)$$

$\dot{c}_{in,i}(0)$ and $\dot{c}_{out,i}(0)$ are the rates of precursor Family i flowing into and out of the core at time 0. Λ is the prompt neutron generation time. $\mathrm{n(t)}$ is the normalized fission power. C_i is the number of precursors of Family i. There were six delayed neutron precursor families modeled. The decay constant λ_i, the delayed neutron fraction β_i, and neutron generation time Λ (2.6×10^{-4} seconds) are obtained from Ref. [7]. The schematic of the SAM model used for the analysis is presented in Fig. 4.

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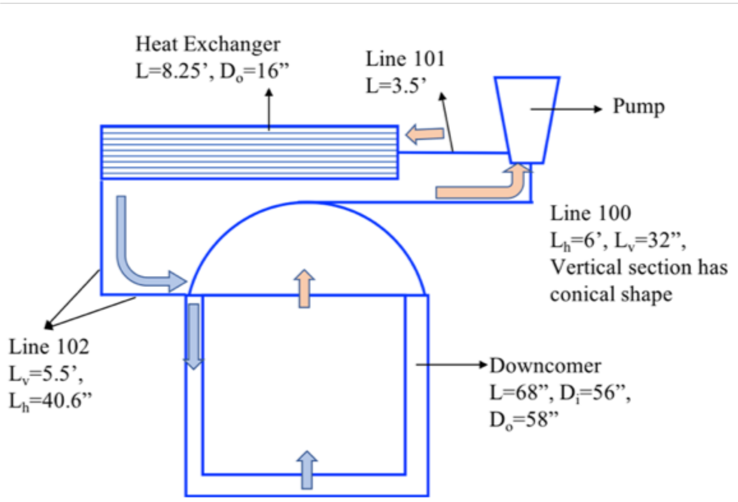

Figure 4. The schematics of the SAM model developed for the pump startup and coastdown tests.

Using the calculation procedures described above, the external reactivity required to maintain criticality was obtained. The comparison between the calculated results and the experimental measurement is presented in Fig. 5. The general trend for the calculated values agrees well with that of the experimental measurement. As soon as the pump speed increases, delayed neutron precursors start to flow out of the core. The reactivity decreases due to the loss of delayed neutrons. Thus, positive external reactivity (control rod withdrawal) is required to maintain criticality. A fraction of precursors that do not decay outside the core, *i.e.,* long-lived precursors, would eventually come back to the core. This is also observed in Fig. 5 as the external reactivity reaches a peak at around 15 seconds and starts to decrease shortly after, *i.e.*, the control rods need to be inserted due to the precursor re-entering the core. It is also observed that the calculated result using the derived pump head (see Section 2.1 for more detail) is slightly closer to the experimental measurements. The "assumed pump head" if Fig. 5 was obtained by assuming the pump head is proportional to the square of the pump speed.

The differences observed between the simulated and experimental results may be due to the PKE approximation in SAM, which assumes a constant flux distribution over time. However, due to control rod movement, the flux distribution did change during the transient. Another source for the observed difference is due to the absence of a core neutronics model. Thus, the actual power distribution may be different from the uniform and cosine distributions that were assumed.

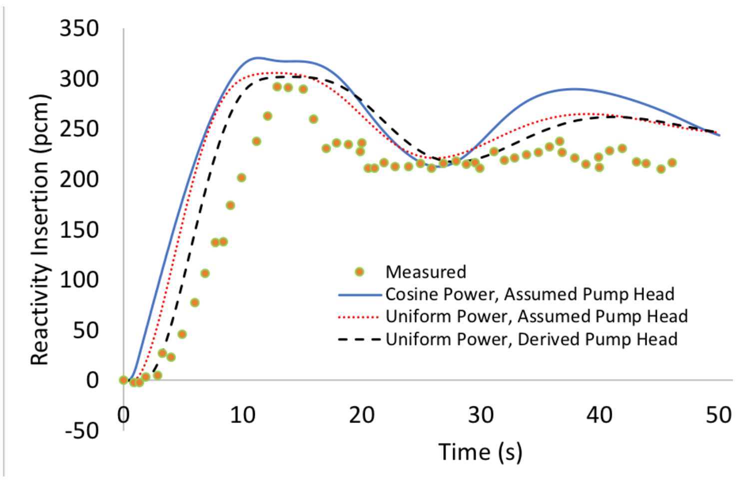

Figure 5. SAM results vs experimental measurements for the pump startup test.

4. PUMP COASTDOWN TEST

In the pump coastdown test, the pump was initially running at full speed and decreased to zero as shown in Fig. 6. The same calculation procedure developed for simulation of the pump startup test was employed. Again, the external reactivity required to maintain criticality was evaluated and compared with the experimental measurements. The comparison is presented in Fig. 7. As soon as the pump speed decreases, more precursors would stay in the core and contribute to a positive reactivity effect. The control rods need to be inserted more to counter-balance this effect. Thus, the negative external reactivity required to maintain the core critical. Again, the trend between the calculated results and the experimental measurements agrees well. The difference may be due to the use of the PKE model and the lack of a neutronics analysis.

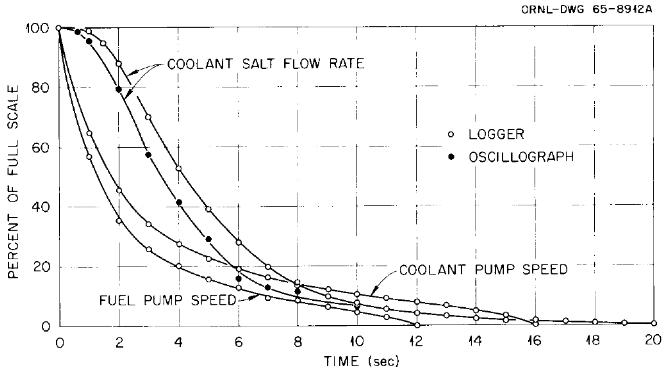

Figure 6. The pump speed as a function of time during pump coastdown test [7].

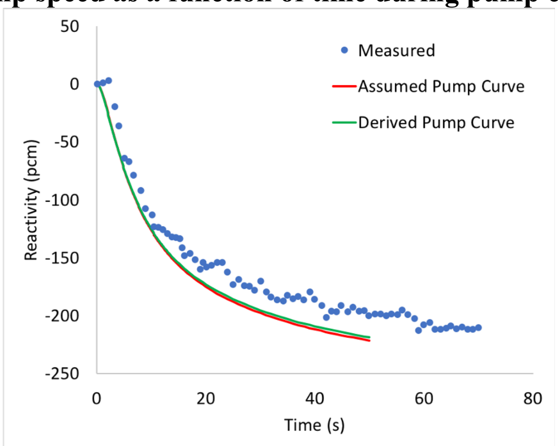

Figure 7. SAM results vs experimental measurements for the pump coastdown test.

5. THERMAL-CONVECTION HEAT REMOVAL TEST

In the thermal-convection heat removal test, the coolant flow was maintained in the secondary loop, while the radiator heat removal rate was increased in steps. During the transient, the primary pump speed remained zero, and the control rods remained in its position. Thus, the flow in the primary side was mainly driven by natural convection. The coolant temperature in the heat exchanger inlet and outlet on the primary and secondary sides were measured during the transient. The reactor power was also measured during the transient and are presented with the temperatures in Fig. 8. To simulate the transient, one needs to know the heat removal rate in the radiatior and the coolant flow rate in the secondary side, both of which were not provided in Ref. [8]. Thus, some approximation is needed to simulate this transient.

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The mass flow rate of the natural circulation is expected to be small, so all precursors that flow out of the core will decay away before re-entering the core, assuming the time for flowing through the whole loop is much greater than 50 seconds (the longest half-life of all precursor families). This means that we only need to model the core with the flow rate predicted by the temperature and power data from Fig. 8. The power is calculated from the PKE and would change due to temperature changes in the fuel salt. Based on this simplification, the SAM model consists of only the reactor core with inlet and outlet boundary conditions. The temperature and the flow rate boundary conditions were imposed at the inlet, while the pressure boundary condition was imposed at the outlet.

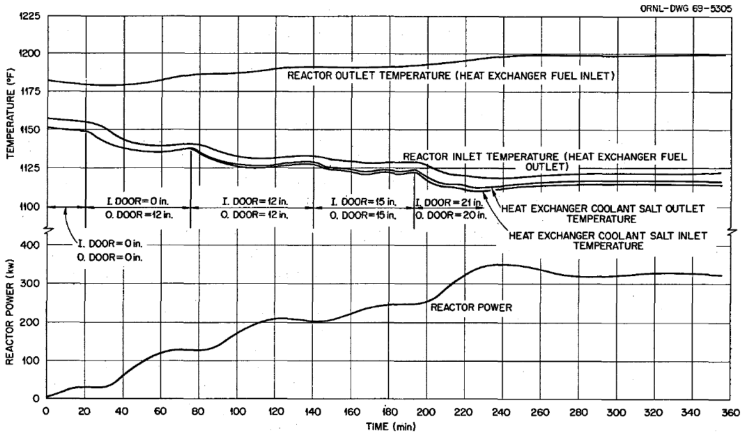

Figure 8. Salt temperature and power for the thermal-convection heat removal test [8].

Based on this simplification, the simulation was performed in three steps:

1. The mass flow rate was calculated based on the power, the outlet and inlet temperature measurements.
2. SAM was employed to find the equilibrium state of the reactor (precursor concentration at equilibrium) with the PKE model turned off.
3. A restart SAM calculation based on the previous step was performed with PKE model turned on.

The results calculated from this procedure are compared with the experimental measurements in Fig. 9. The large difference in the first 100 minutes is likely due to the experiment not starting from an equilibrium condition. This can also be observed in Fig. 8. At time zero, the heat exchanger primary side inlet temperature was observed to decrease. This means the system is not at equilibrium, since it will take some time for the information to travel to the heat exchanger inlet. A sudden increase in the heat removal rate in the heat exchanger can only affect the heat exchanger primary side outlet temperature immediately. Also, no neutronics calculation was performed, so the axial reactivity feedback variation is unknown. For this study, a cosine shape was assumed. Given these assumptions and approximations, the SAM results are still in relatively good agreement with the measurements for the thermal-convection heat removal test.

6. CONCLUSIONS

The SAM system analysis code was employed in benchmarking simulations based on three MSRE tests to demonstrate the application of the newly added precursor drift model and the modified point kinetic equations for flowing fuel. The results predicted by SAM show good agreement with the experimental measurements for all three tests but there are ways to achieve potentially better agreement such as implementing a neutronics tool to provide more accurate spatial parameters that can be incorporated in the solutions. This will be pursued among other enhancements in future work.

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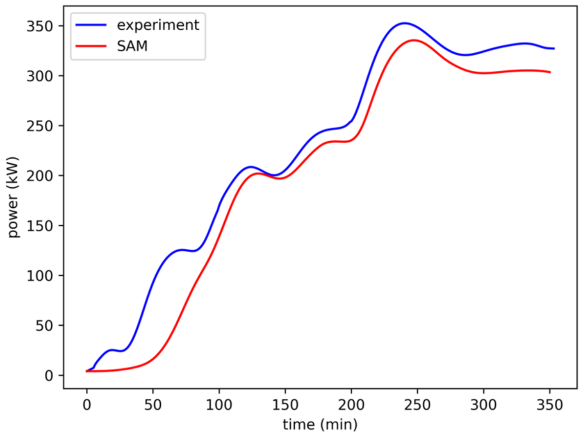

Figure 9. SAM result vs experimental measurement for the thermal-convection heat removal test.

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