Uncertainty Analysis on the Pump Flow Transient Phenomena in the Molten Salt Reactor Experiment

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INTRODUCTION

Molten salt pump flow transient tests, including pump startup and pump coastdown tests, were conducted at the Oak Ridge National Laboratory's Molten Salt Reactor Experiment (MSRE) in 1965. The MSRE pump transient tests were conducted at zero power (i.e., isothermal) to determine the effect of flow transients on the core reactivity. The pump startup transient started from the stationary salt configuration. During the pump startup test, the speed of both the fuel pump and the coolant pump was increased from zero to the rated speed to induce the flow transient. The reactivity effects of the flow transient were measured by recording the control rod position as function of time which was controlled by the flux-servo controller unit in attempting to maintain the criticality condition. After the system reached the steady state, the motor of each pump was turned off to initiate the pump coastdown transient. The reactivity effects of this flow transient were measured similar to the startup test. The reactivity response can be then obtained using the control rod integral worth curve by transforming the recorded rod positions to reactivity worth. A detailed description of the MSRE pump transient tests can be found in Ref. [1].

Experimental data were collected and documented in many ORNL legacy reports [1-3]. As part of the MSRE transient benchmark development at the Virginia Commonwealth University (VCU), we visited and extracted the experimental data. Meanwhile, we developed a neutronics and thermal-hydraulics coupled computational model on the Multiphysics COMSOL platform to simulate the MSRE primary loop flow transient phenomena under the pump startup and coastdown conditions [4]. Our computational model successfully predicted the flow behavior in most segments of the MSRE. However, nonnegligible discrepancies in the reactivity response predictions to experimental data were observed in both flow transient tests. In this work, a preliminary uncertainty analysis on the key characteristic parameters involved in the computational model is performed to gain some understandings of the impact of these parameters in MSRE pump flow transient phenomena.

METHODOLOGY

This section presents a brief description of the computational model and uncertainty quantification (UQ) approach employed in the analysis.

Experimental Data

The experimental uncertainties in the reactivity response MSRE pump transients are documented. The sources of uncertainty in the reactivity response are the rod position measurement and the control rod worth calibration. The MSRE has two control rod position indicators [2]. The coarse indicator rotates 5 degrees per inch of control rod movement. The fine indicator rotates 60 degrees per inch and has a sensitivity of $0.05-in$. The period measurement method was used to obtain the differential-worth of the control rods. Following the period measurements, rod drop measurements were conducted to check the self-consistency of the rod worth measurements. All rod drop measurements were within the 5% band of self-consistency with the rod calibration results [3]. The uncertainties in the control rod calibration come from the rod position measurements, period measurements, and the uncertainties in the theoretical dynamic parameters. However, it is assumed in this work that the uncertainties in the integral worth curve are negligible compared to the uncertainty in the rod position measurement during the transient. The uncertainty in the rod position is assumed to be equal to the position sensitivity indicator. This value is used to obtain an upper and lower limit of the inserted reactivity. The reactivity is assumed to follow uniform distribution within this interval.

Computational Model

In this work, a one-dimensional neutronics and fluid flow coupled model was developed and implemented in COMSOL Multiphysics The model is described by Eq. (1).

$$
\begin{aligned}
&\frac{1}{v_1}\frac{\partial \varphi_1}{\partial t} - \frac{\partial}{\partial z} D_1 \frac{\partial \varphi_1}{\partial z} + \Sigma_{r1}\varphi_1 = (1-\beta)\sum_g \nu\Sigma_{fg}\varphi_g + \sum_{k=1}^{6}\lambda_k C_k, \\
&\frac{1}{v_2}\frac{\partial \varphi_2}{\partial t} - \frac{\partial}{\partial z} D_2 \frac{\partial \varphi_2}{\partial z} + \Sigma_{r2}\varphi_2 = \Sigma_{s,1\to 2}\varphi_1, \\
&A\frac{\partial C_k}{\partial t} + Au\nabla_t \cdot C_k = A\beta_i \sum_g \nu\Sigma_{fg}\varphi_g - A\lambda_k C_k, \quad k = 1,\cdots,6. \qquad (1) \\
&A\frac{\partial \rho}{\partial t} + \nabla_t \cdot (A\rho u) = 0, \\
&\rho\frac{\partial u}{\partial t} + \rho u \cdot \nabla_t u = -\nabla_t p - f_D \frac{\rho}{2d_h} u|u| + F.
\end{aligned}
$$

A detailed description of this model and the implementation in COMSOL can be found in Ref. [4] and [5]. Eq.(1) requires an additional model for the pump transient to provide the pump flow rate as function of time, which can be obtained by the momentum balance equations for centrifugal pumps given by:

$$\begin{gathered}\sum \frac{L_i}{A_i}\frac{dq}{dt} + K_{cl}\frac{q^2}{2\rho} = \rho g h_p, \\ I\frac{d\omega}{dt} = M_{em} - M_h - M_f\end{gathered} \quad . \tag{2}$$

Eq. (2) is used to predict the flow rate in the primary loop based on the measured pump speed. The details of solving Eq. (2) for the MSRE primary pump during the startup and coastdown transients are found in Ref. [6].

Sensitivity and Uncertainty Analysis

The sensitivity analysis (SA) step is firstly carried out to quantify the importance of various model parameters based on their relative contribution to the model output variability. Sobol's method [7] is one of the commonly used methods for global sensitivity analysis. Sobol's method uses ANOVA-representation (Analysis of Variance) to expand the variance of the computational model into summands of increasing dimension. For a model of n input parameters, the variance decomposition takes the form [8]:

$$D = \sum_{i=1}^{n} D_i + \sum_{i<j} D_{ij} + \cdots + D_{1,\cdots,n}\,, \tag{3}$$

where the total model variance D is decomposed into contributions from single parameters D_i, pairs of parameters D_{ij}, and so on. The variance decomposition can be calculated using Monte Carlo simulation [9]. The Sobol's SA indices are defined as the ratio of the partial variance corresponding to a subset of variables to the total variance:

$$S_{i_1\cdots i_s} = \frac{D_{i_1\cdots i_s}}{D}\,. \tag{4}$$

The total-order Sobol's index measures the contribution of the parameter with all possible combinations with other parameters and is defined as:

$$S_i^T = S_i + \sum_{j\neq i} S_{ij} + \cdots + S_{1,\cdots,n} = 1 - S_{-i}\,. \tag{5}$$

The first-order Sobol index will be used to identify the parameters with significant impact on the simulated reactivity.

In the UQ step, a Monte Carlo sampling approach is applied to these identified parameters individually by propagating the uncertainties in these parameters to the reactivity response uncertainty.

RESULTS

This presents the implementation details and the results from the SA and uncertainty analysis. The MATLAB based tool UQLab [10] is used to conduct SA on the computational model. Eleven input parameters are considered in this study, including the delayed neutron (DN) fractions, the salt volume in the core and in the outer loop, the fuel salt density, the flow rate, and the fluid inertia, and so on.

The delayed neutron precursor (DNP) parameters are generated using Serpent based on ENDF/B-VII.0 data. The decay constants, DN fractions, and the standard deviation (STD) of the fractions are listed in TABLE I.

TABLE I. Decay constants and the mean and STD of the DN fractions used to generate samples for SA.

Group	Decay constant $\lambda_i\left[s^{-1}\right]$	DN fraction $\beta_i\left[\times10^{-4}\right]$	STD of DN fraction $\sigma_{\beta_i}\left[\times10^{-6}\right]$
1	0.0124	2.04	0.84
2	0.0318	10.74	1.87
3	0.1093	10.41	1.88
4	0.3171	29.65	3.20
5	1.3538	8.64	1.01
6	8.6405	3.04	1.01

The DNP parameters are assumed to follow Gaussian distributions. All other parameters are assumed to follow uniform distribution. A list of the nominal values of the other parameters and their distribution intervals is provided in TABLE II.

TABLE II. The nominal values, lower limits, and upped limits of the flow parameters used in SA.

Parameter	Nominal value	Lower limit	Upper limit
Salt density [kg/m^3]	2337	2321	2353
Flow rate [m^3/s]	0.0757	0.0719	0.0795
Flow inertia $\sum L_i/A_i$ [m^{-1}]	3345	3178	3512
Core flow area [m^2]	0.399	0.379	0.419
Pump flow area [m^2]	0.055	0.050	0.061

Monte Carlo sampling approach was used to sample input distribution using 2600 points. The Quantities of Interest (QoI) in this work is the reactivity response as function of time. Therefore, the model has multi-output (i.e., an output for each time step). For simplicity, the sensitivity analysis is applied for a subset of the output vector representing the output at six different time points. The results of the sensitivity analysis are presented in terms of the first-order Sobol's index and are shown in Fig. 1.

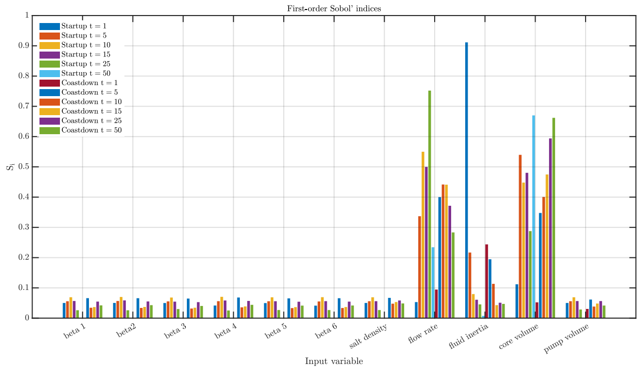

Fig. 1. First-order Sobol's indices for each of the studied input parameters. Each colored bar represents the index evaluated at a specific time point.

Fig. 1 shows the results at six different time points for each of the two tests. These results indicate the uncertainties in the DN fractions estimated by Serpent have a small contribution to the output variability compared to the uncertainties in the flow parameters. The parameters that have the largest contribution to the model variability are the flow rate and the core volume. This can be explained by the effect of the two parameters on the salt residence time in the core. The fluid inertia has a large contribution to the model output only at the start of the transient. This is under expectation as the flow inertia determines how fast the flow moves in the transient. The salt density and the pump volume tend to have a small contribution to the model variability. It's important to note that the dominant effect of the uncertainties in the flow parameters may be a result of the large uncertainty interval assumed for these parameters compared to the uncertainty intervals for DN fractions.

The SA is followed with the analysis of uncertainty propagation for each individual parameter. The parameters that have significant contribution on the model variability are addressed in priority. For each parameter a sample of 500 points is drawn from the assumed distribution and the model is evaluated for each point. The model uncertainty is evaluated by calculating the mean and standard deviation (STD) of the calculated responses.

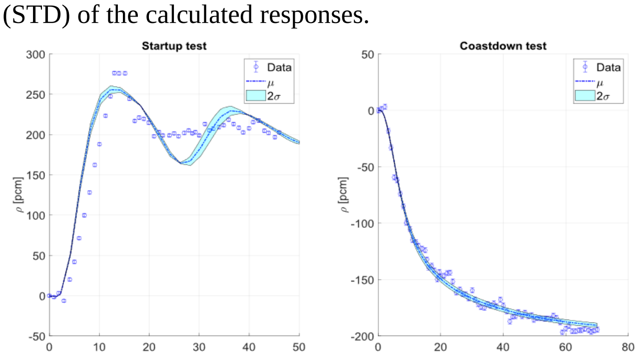

Fig. 2. Uncertainty interval of the reactivity response due to uncertainty in the flow rate.

Fig. 2 shows the model uncertainty due to the flow rate uncertainty. The mean of the calculated responses (μ) is compared to the experimental data. The shaded area has a width of two STD (2σ) and represents the uncertainty interval. The results for the startup test indicate that the uncertainty on the flow rate does not explain the discrepancy between the experimental data and the computational model. On the other hand, a good agreement between the data and the computational model is observed for the coastdown case.

Fig. 3 shows the effect of the uncertainty of the salt volume in the core, or equivalently the salt residence time. The uncertainty interval for the startup response due to the core volume is slightly larger than that due to the flow rate. Similar to the flow rate effect, the core volume uncertainty (or salt residence time) does not explain the discrepancy with the experimental data. For the coastdown case, the uncertainty interval is larger towards the end of the test.

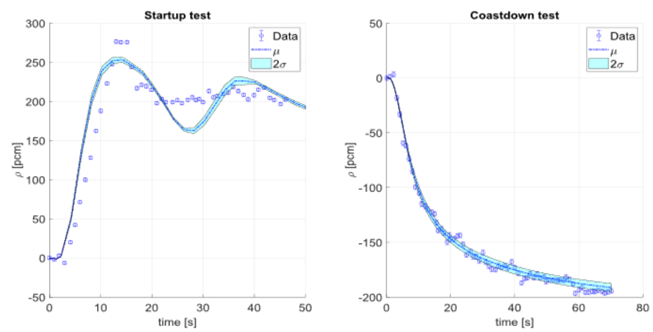

Fig. 3. Uncertainty interval of the reactivity response due to uncertainty in the salt volume inside the core.

The effect of the uncertainty in DN fractions of the six families is studied collectively. The decision for not studying them individually is based on the SA results that indicate they have small effect on the model variability. Moreover, the relative contribution among the different DNP families is expected to be proportional to the production fraction of each family. Fig. 4 shows the propagation of the uncertainty in DN fractions. As predicted by the SA step, the uncertainty in DN fractions has a relatively small contribution to the model variability.

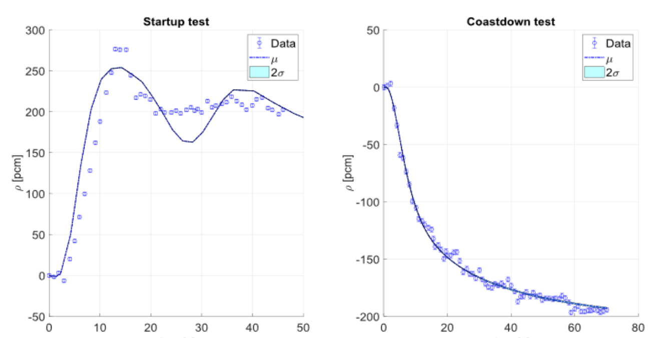

Fig. 4 Uncertainty interval of the reactivity response due to uncertainty in DNP fractions.

Finally, the model uncertainty due to the combined uncertainties in all parameters considered in this study is evaluated by running the model using the 2600 samples described in the SA step. Fig. 5 presents the mean and STD of the response. The uncertainty in the reactivity response of the startup test does not explain the discrepancy with the experimental data. This indicates that there is a large bias in the computational model for this case or there are other parameters that may have significant impact on the model predictions (i.e., cross sections). The calculated response for the coastdown case is in good agreement with the experimental data. However, a deviation from the experimental data starts at about 60 seconds.

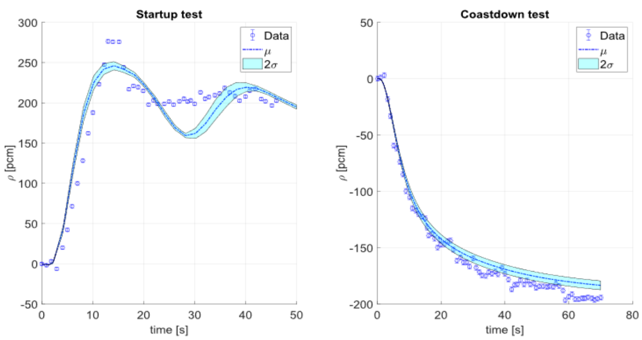

Fig. 5. Uncertainty interval of the reactivity response due to uncertainties in the eleven parameters considered.

CONCLUSIONS

This work performs the sensitivity and uncertainty analysis of various parameters on the calculated reactivity response of the MSRE pump transient tests. The two parameters that contribute most to the model variability are the flow rate and the core volume. These two parameters impact the salt residence time in the core and the external loop. The third parameter that has impact on the salt residence time is the pump volume. This parameter is shown to have a small contribution to the model variability. This may be a result of the small salt volume in the pump compared to the reactor core, thus a 10% deviation from the nominal value in this parameter would result in a small perturbation to the salt residence time. The contribution of the DN fractions is small compared to the flow parameters. This may be a result of the small uncertainty in the parameters as estimated by Serpent.

There is a generic difference between the reactivity response to the startup test and the coastdown test. Although the two tests are similar isothermal flow transients, the generic difference arises from the initial conditions. The startup test starts from stationary conditions. As a result, the DNPs are distributed in the core according to power distribution and they essentially do not exist in the outer loop. This initial condition results in an oscillatory solution when the bulk of salt initially filled the core is circulated back into the core. The DNPs in this bulk of salt, and consequently the magnitude of reactivity oscillation, will depend on the initial concentration as well as the amount of mixing with the salt in the outer loop. This makes this scenario challenging for system-level codes due to the lack of mixing capabilities. On the other hand, the coastdown test starts from a flowing condition and the DNPs are distributed across the circulation loop. The absence of the heterogenous distribution of DNPs makes this scenario suitable for a system-level code. This difference explains why the model predictions for the coastdown case are much better with experimental data compared to the startup case.

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