Effect of Turbulent Diffusion on Delayed Neutron Precursors in the Molten Salt Reactor Experiment (MSRE)

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INTRODUCTION

Molten Salt Reactors (MSR) are among the candidate designs of Gen IV nuclear reactors. The key aspects of MSR arise from the adoption of a liquid fuel in the form of a solute in a molten salt mixture such that the fuel carrier salt is circulated in the primary loop during the reactor operation. This alters the distribution of fission products inside the core, and thus the flow effects on delayed neutron precursors (DNPs) play a crucial role in neurons balance in MSR. The flow effects on the DNP distributions must be considered to accurately model the neutronics behavior of the reactor.

The distribution of DNPs can be affected by advection in the flow field, molecular and turbulent diffusion of the DNPs concentrations. The diffusion effect of the DNP distributions is normally considered of lower importance compared to the advection effect and is typically ignored in the DNPs mass balance [1-4]. Other studies [5, 6] recognized the effect of the turbulent diffusion on the DNPs distribution. It was shown in Ref. [5] that changing the turbulent Schmidt number Sc_T, which is defined as the ratio of momentum diffusivity (kinematic viscosity) and mass diffusivity, over two orders of magnitude will change the core reactivity by about 20 pcm. It was also shown in Ref. [6] that turbulent diffusion has non-negligible effect of the steady state distribution of DNPs for the molten salt fast reactors (MSFR).

There is lack in studies on the transient effect of DNPs diffusion especially for system-level codes where a low order representation is used. This work aims to study the effect of turbulent diffusion on the transient response of the Molten Salt Reactor Experiment (MSRE) during the pump transient test [**Error! Reference source not found.**].

MATHEMATICS MODELS

A one-dimensional (1D) system-level model was developed and implemented in COMSOL Multiphysics [8]. In standard notations, the multigroup (MG) neutron diffusion model coupled with the six-families of DNPs mass balance are given by

$$\begin{aligned}&\frac{1}{\nu_g}\frac{\partial \varphi_g}{\partial t}-\nabla\cdot D_g\nabla\varphi_g+\Sigma_{r,g}\varphi_g=\\&\frac{\chi_{pg}(1-\beta)}{k_{eff}}\sum_{g'=1}^{G}\nu_{g'}\Sigma_{f,g'}\varphi_{g'}+\sum_{g'\neq g}^{G}\Sigma_{s,g'\to g}\varphi_{g'}+\sum_{i=1}^{I}\chi_{dg,i}\lambda_i C_i\end{aligned}, \quad (1)$$

$$\begin{aligned}&A\frac{\partial C_i}{\partial t}+\nabla\cdot[AuC_i]=\\&\nabla\cdot(D_i\nabla AC_i)+\frac{A\beta_i}{k_{eff}}\sum_{g'=1}^{G}\nu_{g'}\Sigma_{f,g'}\varphi_{g'}-A\lambda_i C_i\end{aligned}. \quad (2)$$

The 1D flow model in channels can be given in the form [8]

$$\begin{aligned}&A\frac{\partial \rho}{\partial t}+\frac{\partial(A\rho u)}{\partial z}=0\\&\rho\frac{\partial u}{\partial t}+\rho u\frac{\partial u}{\partial z}=-\frac{\partial p}{\partial z}-f_D\frac{\rho}{2d_h}u|u|+\mathbf{F}\end{aligned}. \quad (3)$$

This system of equations is solved using a fully coupled scheme with the generalized alpha method as a time stepping algorithm.

The diffusion coefficient for the i^{th} family of DNPs, denoted as D_i in Eq.(2), accounts for molecular and turbulent diffusion effects of precursors, and thus it is given by

$$D_i = D_{c,i} + D_{T,i}\ , \quad (4)$$

where $D_{c,i}$ and $D_{T,i}$ denote the molecular and turbulent diffusion coefficients, respectively. There is lack of measurements of the molecular diffusion coefficients of DNPs in the MSRE salt. As a result, the molecular diffusion coefficient is taken as a constant 5×10^{-9} m^2/s [9] in this study. The turbulent diffusion coefficient is given as:

$$D_T = \frac{\upsilon_T}{Sc_T}\ , \quad (5)$$

where the subscript i is omitted, υ_T is the eddy viscosity component of viscosity that describes momentum transfer due to fluid turbulent mixing, and Sc_T is the turbulent Schmidt number mentioned earlier. For a system-level model, where the flow channels are represented using 1D segments, empirical correlations can be used to model the diffusion due to turbulent mixing. For turbulent flow in pipes. Taylor correlation (i.e., Taylor dispersion coefficient) can be used to model the turbulent diffusion coefficient. Taylor dispersion coefficient for turbulent flow is given by [8]:

$$D_T = 10.1\frac{d_h}{2}u\sqrt{\frac{f_D}{2}}\ , \quad (6)$$

where d_h is the hydraulic diameter and f_D is the friction coefficient. Note with the Taylor correlation, D_T has shown

with a dependency of the flow rate and hydraulic friction condition at each segment of the fluid circulation loop.

MSRE PUMP TRANSIENT TEST

The fuel salt carrier in MSRE is FLiBe molten salt. The fuel circulation loop consisted of the reactor vessel, primary pump, the shell-side of heat exchanger, and connecting pipes. The salt circulation time in the primary loop is ~25 seconds. Detailed geometrical parameters of the MSRE can be found in Ref. [10]. A schematic representation of the MSRE salt circulation loops is shown in Fig. 1.

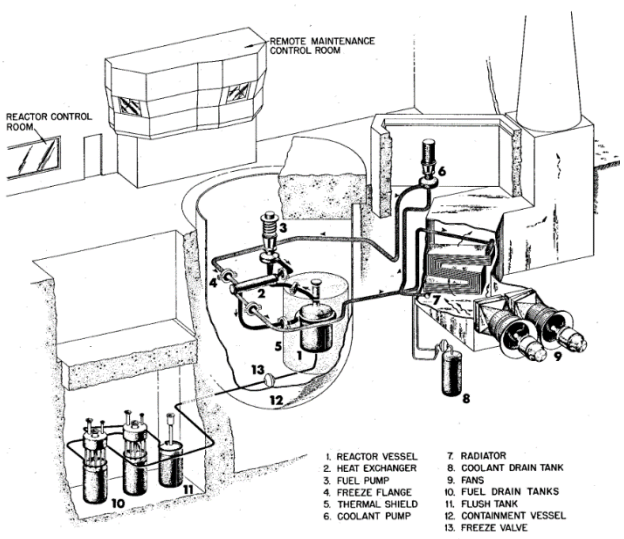

Fig. 1. Schematic view of the MSRE salt circulation loops.

During the operation of the MSRE, serval experimental tests were conducted to verify the characteristics of MSRs. The pump transient test is a set of tests conducted at zero power to determine the effect of flow transient on the reactor criticality [**Error! Reference source not found.**]. The pump startup test started from the steady state, stationary fuel configuration. From this condition, the pump speed was increased to the rated speed. The drift of the fuel with flow rate caused a fraction of DNPs to decay outside the core which altered the core criticality. An automatically driven control rod was used to compensate for the change in reactivity due to the lost delayed neutrons. The reactivity change can be then obtained from the reactivity worth of the measured control rod positions. After the system reached a steady state, the pump coastdown started by turning off the pump motor. The core criticality was kept in a similar manner as the startup test. A detailed description of the pump transient test can be found in Ref. [11].

To model the MSRE pump transient test, the MSRE fuel salt loop geometry is cast into a 1D model, conserving the residence time and salt volume in each component. The 1D geometrical parameters of the MSRE model are given in Table I. The common thermophysical parameters of the MSRE fuel salt are given in Table II.

Table I. Geometrical parameters of the 1D model for the MSRE fuel circulation loop.

Component	Length [m]	Effective flow area [m^2]	Volume [m^3]	Residence time [s]
Core	1.67	0.425	0.7086	9.4
Upper plenum	0.35	0.850	0.2973	3.9
Line 100 horizontal	1.83	0.013	0.0236	0.3
Line 100 vertical	0.81	0.045	0.0365	0.5
Pump	0.57	0.045	0.0255	0.3
Line 101	1.70	0.013	0.0220	0.3
HEX	2.44	0.071	0.1729	2.3
Line 102	4.65	0.013	0.0600	0.8
Distributor + downcomer	6.28	0.044	0.2751	3.6
Lower plenum	0.34	0.827	0.2834	3.8
Total	-	-	1.9963	25.2

Table II. Thermophysical properties of the fuel salt [12].

Property	Unit	Fuel salt
Density	kg/m^3	$2575-0.513\cdot T(^{\circ}C)$
Heat capacity	J/kg-K	2386.47
Thermal conductivity	W/m-K	1.0
Dynamic viscosity	Pa-s	$11.6\times10^{-5}e^{\frac{3755}{T(K)}}$

The standard two-group (2G) neutron energy structure with a cutoff at 0.625 eV is used for the neutron diffusion model. A 1D consistent diffusion model is established and used for the MSRE neutronics calculations [13]. Monte Carlo based 3D transport code Serpent is used to generate the radial-leakage-corrected, homogenized cross sections for the diffusion model. DNPs data, including the delay neutron fractions (DNFs) and precursor decay constants, are also obtained from Serpent based on the nuclear data library ENDF/B-VIII.0. The adjoint-weighted DNFs are used in this study to account for softer spectrum of delayed neutrons. The DNPs data used in this work are summarized in Table III.

Table III. Delayed neutron parameters.

i	Decay constant λ_i [s^{-1}]	Adjoint-weighted delay neutron fraction $\beta_{eff,i}$
1	0.01334	0.000225
2	0.03274	0.001249
3	0.12078	0.001170
4	0.30282	0.002671
5	0.84966	0.001093
6	2.85376	0.000468

Total	-	0.006877

RESULTS AND DISCUSSION

A quasi-static approach is used to solve the mathematical models [13]. The effective multiplication factor k_{eff} of the reactor is dynamically updated to keep the total power constant, mimicking the control rod movement. The reactivity inserted during the transient is calculated from the change in k_{eff} :

$$\rho_{in}(t) = \frac{k_{eff}(t) - k_{eff}^{0}}{k_{eff}(t) \times k_{eff}^{0}} \quad , \tag{7}$$

where k_{eff}^{0} is k_{eff} at the initial time, and $k_{eff}(t)$ is k_{eff} at a time t . The pump flow rate during the pump transient [11] is used as boundary condition for the fluid flow model.

For comparative study, the system is first solved without considering the turbulent diffusion. Only the small and constant molecular diffusion coefficient (5×10^{-9} m^2/s) is considered in this case. Fig. 2 illustrates the calculated reactivity response compared to the experimental data for this case. Note both the pump startup and coastdown transients are depicted in the figure, and the experimental data is presented with 1-σ uncertainties. The uncertainties are estimated based on $0.025-in$ error in the measured rod positions and 2.5% error in the integral rod worth curve [14].

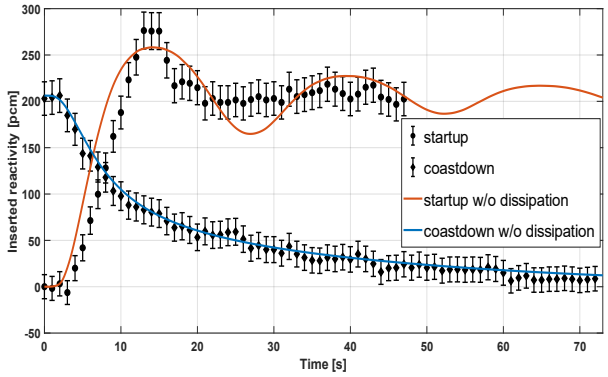

Fig. 2. The reactivity response during the pump transient test without considering the turbulent diffusion.

As shown in Fig. 2, for the coastdown transient, the model predicted reactivity response is in excellent agreement with the experimental data. However, for the startup transient, though the model predictions are in good agreement with the measured reactivity at the peak and steady state, the model predictions show larger reactivity oscillations compared to the experiment. The oscillations appear with a periodic time of ~25 s, which is speculated to be associated with the recirculation of the salt portion that initially filled the core and has higher concentration of DNPs. Neglecting the turbulent diffusion effect in the simulation would cause the higher concentration portion to dissipate at a slower rate, which in turn resulted in the reactivity oscillations.

To address the effect of turbulent diffusion on the reactivity response, a second set of calculations were performed with turbulent diffusion coefficients estimated by the Taylor correlation [i.e. Eq.(6)]. Fig. 3 shows a comparison between the calculated reactivity with and without the turbulent diffusion correlation.

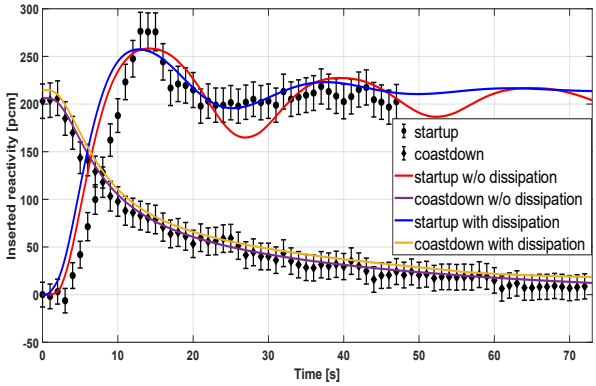

Fig. 3. The reactivity response during the pump transient test with and without considering the turbulent diffusion.

As shown in Fig. 3, the turbulent diffusion correlation has a damping effect on the reactivity oscillations for the startup test, which is expected. The steady state reactivity is higher than the case with no turbulent diffusion by about 8 pcm. This increase indicates that the turbulent mixing reduces the effective residence time of DNPs due to the additional transport mechanism. The slight overestimates in reactivity response at the initial starting stage of the startup test suggests that using Taylor correlation for turbulent flow may be not valid at the starting stage of the test when the flow is in the laminar regime. The effect of the turbulent diffusion can be more clearly explained by examining the evolution of the number of DNPs inside the core during the startup test shown in Fig. 4. The oscillations in the total number of DNPs in the core are significantly damped when adding the turbulent diffusion term.

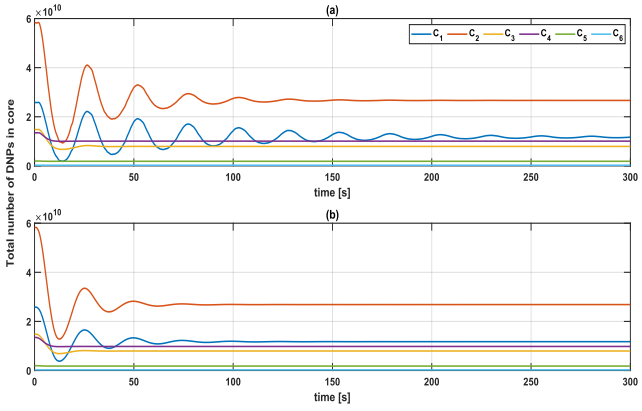

Fig. 4. The total number of DNPs during the pump startup test: (a) with no turbulent diffusion, and (b) with turbulent diffusion considered by the Taylor correlation.

The mean absolute error in the reactivity response for the whole startup transient is 19 pcm for the turbulent diffusion corrected model. This is slightly lower than the error for the uncorrected model, which is 21 pcm. Despite capturing the transient very well, the accuracy of predictions only increased slightly due to the larger error at the starting stage of the test and the 8 pcm increase in steady state reactivity. For the same reason, the error in the coastdown predictions for the corrected model is 9 pcm compared to 7 pcm for the uncorrected model.

CONCLUSIONS

In this work, the effect of turbulent diffusion on the reactivity response to the MSRE pump transient test is investigated. A Multiphysics coupled computational model is developed and implemented in COMSOL to simulate the change in reactor reactivity due to the flow transient. The neutronics model employs the 2G neutron diffusion model and six-families DNPs model. A 1D pipe flow model was used to simulate the fuel flow in the primary loop with the transient flow rate used and boundary conditions.

For comparative purposes, two sets of calculations were conducted in the work. One neglects the turbulent diffusion coefficient for DNPs, and the other uses the Taylor correlation to approximate the turbulent diffusion in pipes. The calculation results indicated that the turbulent diffusion has a non-negligible effect on the distribution of DNPs and consequently affects the reactivity response in both MSRE pump transients, while the effect is more noticeable in the startup transient test.

For the startup test, the transient 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 that 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. Neglecting turbulent dissipation of this bulk will result in overestimation of the reactivity oscillations. 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 reduces the importance of turbulent diffusion.

The studies show that the adoption of Taylor correlation for turbulent diffusion in pipes improved the accuracy of predicting the reactivity response except in the initial phase of the startup test when the flow rate is sufficiently low, and the flow is in the laminar regime. More studies are needed to address the suitable correlations for both the molecular and turbulent diffusion on the response on of MSRs. Also, higher level models (2D/3D) are needed to study the effects of the MSRE geometrical characteristics (especially in the downcomer and lower plenum) on the DNPs mixing.

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