Development of a Simulation Tool for a Preliminary Analysis of the MSR Core Dynamics

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ABSTRACT

The MSR (Molten Salt Reactor) is one of the six innovative concepts of nuclear reactors envisaged by the GIF-IV (Generation IV International Forum) initiative for the long term evolution of the nuclear technology, in the direction of a more sustainable, safe, proliferation resistant, and economic power generation. The MSR is characterised by a complex and highly non-linear behaviour, which requires a careful investigation, as a consequence of some unusual features like the presence of a fluid fuel and the drift of delayed neutron precursors (DNP) along the primary loop. In this paper, the MSR core dynamics is analysed with reference to the MSRE (Molten Salt Reactor Experiment). Numerical models featured by increasing complexity are presented. In particular, a zero-dimensional model has been developed, and two other models introducing a one-dimensional discretization for the DNP drift and/or the heat convection have been also elaborated. The variety of developed models represents a starting point in the set-up of a complete simulation tool for MSR dynamics, suitable for calculations with different degrees of accuracy and numerical complexity.

1 INTRODUCTION

In the recent years there has been a growing interest in the Molten Salt Reactor (MSR) [1,2]. Actually, the MSR meets many of the future goals of nuclear technology, in particular for what concerns an improved sustainability and unique characteristics in terms of actinide burning and waste reduction [2,3]. Thanks to its favourable features, this reactor has been considered in the framework of the Generation IV International Forum [4,5].

In MSRs, the molten salt plays the role of both coolant and fuel, thus creating a complex and highly coupled physical environment. The transient analysis of such systems requires dedicated simulation tools (see for example [6,7]), able to take into account peculiar features like the delayed neutron precursor (DNP) drift and the subsequent decay out of the core. The present work describes and discusses different numerical approaches to the problem and focuses the attention on the modelling of the entire primary loop, with reference to the MSRE [8]. A classical lumped model is considered as well as one-dimensional models taking into account the heat and DNP transport. It is shown that one-dimensional models are necessary in order to properly describe the peculiar behaviour of the system.

The paper is organized as follows. Section 2 introduces geometry and parameters of the MSRE. Sections 3, 4 and 5, deals with neutronics, thermo-hydraulics and primary loop
modelling, respectively. Finally, in sections 6 and 7 the numerical implementation and the obtained results are discussed.

2 ANALYSED GEOMETRY

The MSR technology embraces a large number of different core configurations [1]. In particular MSRs can operate with a fast or thermal neutron spectrum, as incinerator or breeder or converter, in critical or subcritical conditions. In this scenario, an important role is played by the graphite-moderated breeder reactor using thorium or uranium fuel cycle. Actually, this kind of reactor has been the first MSR extensively studied and a little prototype (the Molten Salt Reactor Experiment - MSRE) was already built during the sixties at Oak Ridge National Laboratory (ORNL). The notable availability of experimental data and the existence of a well defined design make the MSRE a suitable reference for the present study.

As already mentioned, the MSRE is a graphite-moderated reactor. In particular, the core is composed by graphite blocks arranged in order to form rectangular channels. In these channels, a laminar (or nearly laminar) flow is established. The fluid is a fluoride salt containing both the fissile and the fertile material. The MSRE worked using both $^{232}$Th-$^{233}$U and $^{238}$U-$^{235}$U as fertile-fissile materials. The heat generated inside the core is transported through a heat exchanger to a secondary loop (still working with a mixture of fluoride salts) and is then dissipated in the environment by means of a radiator. The present paper focuses on the primary loop, considering the inlet temperature in the secondary side of the heat exchanger as fixed.

A schematic representation of core and plant layout is reported in Figure 1, while the main design parameters of the MSRE are listed in Table 1. As concerns the data of Table 1, it is worth noting that the original 10 MW$_{th}$ design has been considered, while the reactor actually worked at only 8 MW$_{th}$. Some of the data reported below cannot directly be found in the original ORNL reports [8], but have been obtained through a preliminary thermal characterization of the MSRE plant [9]. As concerns the neutronics data, reference is made to the use of $^{235}$U as fissile material.

![Figure 1: Schematic representation of the MSRE core and plant layout [10](image)](image)
Table 1: Reactor data adopted for the numerical simulations [10-12]

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power</td>
<td>10 MW&lt;sub&gt;th&lt;/sub&gt;</td>
</tr>
<tr>
<td>Power fraction generated in the salt</td>
<td>0.93</td>
</tr>
<tr>
<td>Core active height</td>
<td>1.72 m</td>
</tr>
<tr>
<td>Flow rate in the primary loop</td>
<td>171.2 kg·s&lt;sup&gt;-1&lt;/sup&gt;</td>
</tr>
<tr>
<td>Mass of salt in the core</td>
<td>1448 kg</td>
</tr>
<tr>
<td>Specific heat of primary salt</td>
<td>1983 J·kg&lt;sup&gt;-1&lt;/sup&gt;·K&lt;sup&gt;-1&lt;/sup&gt;</td>
</tr>
<tr>
<td>Mass of graphite in the core</td>
<td>3627 kg</td>
</tr>
<tr>
<td>Specific heat of graphite</td>
<td>1757 J·kg&lt;sup&gt;-1&lt;/sup&gt;·K&lt;sup&gt;-1&lt;/sup&gt;</td>
</tr>
<tr>
<td>Heat transfer coefficient between primary salt and graphite</td>
<td>36000 W/K</td>
</tr>
<tr>
<td>Flow rate of secondary salt</td>
<td>105.7 kg·s&lt;sup&gt;-1&lt;/sup&gt;</td>
</tr>
<tr>
<td>Mass of salt in the heat exchanger (fuel side)</td>
<td>342 kg</td>
</tr>
<tr>
<td>Mass of salt in the heat exchanger (coolant side)</td>
<td>117 kg</td>
</tr>
<tr>
<td>Specific heat of secondary salt</td>
<td>2416 J·kg&lt;sup&gt;-1&lt;/sup&gt;·K&lt;sup&gt;-1&lt;/sup&gt;</td>
</tr>
<tr>
<td>Heat transfer coefficient between primary and secondary salt</td>
<td>82800 W·K&lt;sup&gt;-1&lt;/sup&gt;</td>
</tr>
<tr>
<td>Inlet temperature of the secondary salt in the heat exchanger</td>
<td>807.5 K</td>
</tr>
<tr>
<td>Cold leg transit time</td>
<td>8.67 s</td>
</tr>
</tbody>
</table>

3 MODELLING OF NEUTRON AND PRECURSOR POPULATIONS

All the models presented in the paper share a common description for the neutron population. In particular, the classical lumped approach considering one energy-group and six DNP-groups has been adopted. According for example to [13], it can be written:

\[
\frac{dN(t)}{dt} = \frac{\rho - \beta}{\Lambda} N(t) + \sum_{i=1}^{6} C_i(t) \lambda_i
\]  

As concerns the reactivity \( \rho \), it is obtained as

\[
\rho = \rho_0 + \alpha_g \Delta T_g + \alpha_s \Delta T_s + \rho_h
\]  

The term \( \rho_0 \) is the reactivity compensation needed to counterbalance the reactivity loss due to DNP decay out of the core, in order to guarantee steady-state conditions. It should be noted that \( \rho_0 \) results from the DNP modelling, considering a stationary condition, while the term \( \rho_h \) represents an additional reactivity insertion through control rods and is an input for the model. The terms \( \Delta T_g \) and \( \Delta T_s \) are the link between thermo-hydraulic and neutronic models and represent the variation in the (possibly weighted) averages of the salt and graphite temperatures.

As to DNP modelling, it requires some caution because of the drift along the core and the out-of-core decay. For solving the problem, two different approaches have been followed.

3.1 Zero-dimensional model

A first way to consider the DNP decay outside the core is the adoption of the classical lumped model (see for example [13]), but with two additional terms describing the DNP's leaving the core and re-entering it. It results [14]:

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\[
\frac{dC_i(t)}{dt} = \frac{\beta_i}{\Lambda} N(t) - \lambda_i C_i(t) - \frac{\Gamma C_i(t)}{M_s} + \frac{\Gamma C_i(t - \tau_p)}{M_s} e^{-\lambda_i t} \tag{3}
\]

This model is simple and straightforward, but it has the drawback of not considering the effect of DNP drift (with consequent axial build-up) inside the core. Actually, this effect is peculiar of MSRs and is worth being analysed.

### 3.2 One-dimensional model

In order to fully comprehend the effect of the DNP motion in a MSR, it is preferable to include in the model at least one dimension. To do this, it is necessary to switch from an Ordinary Differential Equation (ODE) to a Partial Differential Equation (PDE). In particular, diffusion is neglected and an equation is adopted in the form:

\[
\frac{\partial c_i(x, t)}{\partial t} + \frac{\Gamma H}{M_s} \frac{\partial c_i(x, t)}{\partial x} = \frac{\beta_i}{\Lambda} n(x, t) - \lambda_i c_i(x, t) \tag{4}
\]

where \(n(t)\) is derived from the value of \(N(t)\) imposing a sinusoidal shape (which is thought to well approximate the actual power shape) and the requirement

\[
N(t) = \int n(x, t) dx \tag{5}
\]

The DNP density derived from Eq. (4) is used as input for Eq. (3) by imposing

\[
C_i(t) = \int c_i(x, t) dx \tag{6}
\]

### 4 THERMO-HYDRAULIC MODELLING

Similarly to the case of DNPs, also for the thermo-hydraulic model a zero-dimensional and a one-dimensional approaches have been considered.

#### 4.1 Zero-dimensional model

The first model is based on simple energy balances for the molten salt and the graphite. Assuming constant the fuel and graphite properties, and considering an incompressible flow, it results:

\[
M_s c_{p,s} \frac{dT_s(t)}{dt} = \Gamma c_{p,s} \left[ T_{in}^{sw}(t) - T_s^{sw}(t) \right] + \gamma P(t) + U \left[ T_g(t) - T_s(t) \right] \tag{7}
\]

\[
M_s c_{p,g} \frac{dT_g(t)}{dt} = (1 - \gamma) P(t) - U \left[ T_g(t) - T_s(t) \right] \tag{8}
\]

where the kinetic terms have been neglected as well as the terms describing the effect of pressure drop. It can be observed that the power flowing from the graphite to the salt has been described by means of an overall heat transfer coefficient \(U\) (see Table 1). An additional
equation is required for the system and can be obtained by assuming the temperature \( T_s \) of the salt as equal to the average between inlet and outlet temperatures, i.e.:

\[
T_s(t) = \frac{T_{s \text{ in}}(t) + T_{s \text{ out}}(t)}{2}
\]  

(9)

Such model is simple and physically meaningful, but it has a fundamental drawback. In fact, according to Eq. (9) and considering that \( T_s \) is governed by a differential equation and cannot experience sudden variations, a step-variation in the inlet temperature forces the outlet temperature to a step in the opposite direction, which is clearly unphysical.

4.2 One-dimensional model

Similarly to the neutronic model, the accuracy of the thermo-hydraulic model can be improved by considering the problem as one-dimensional. Also in this case the diffusivity is neglected and the temperature distribution is computed according to the following equation

\[
\frac{\partial T_s(x,t)}{\partial t} + \frac{\Gamma H}{M_s} \frac{\partial T_s(x,t)}{\partial x} = \frac{H}{M_s c_{p,s}} \left[ \gamma q'(x,t) + \frac{U}{H} [T_g(x,t) - T_s(x,t)] \right]
\]  

(10)

while the graphite temperature has been modelled as

\[
\frac{\partial T_g(x,t)}{\partial t} = \frac{H}{M_g c_{p,g}} \left[ (1-\gamma) q'(x,t) - \frac{U}{H} [T_g(x,t) - T_s(x,t)] \right]
\]  

(11)

It can be noticed that the axial heat diffusion inside the graphite has been neglected. Actually, this is a reasonable assumption deriving from the high ratio between height and diameter of the graphite elements in graphite-moderated MSRs [15].

5 OUT-OF-CORE MODELLING

The out-of-core part of the primary loop has been modelled considering two pure time delays for the hot and cold legs and a simple energy balance for the heat exchanger. The latter has been modelled according to zero- or one-dimensional approaches analogous to those described in paragraph (4.1) and (4.2). In particular, zero- or one-dimensional approaches are chosen coherently with the core modelling. A difference with respect to the models described above is the presence of two fluids, which requires the implementation of two equations (instead of one) like Eqs. (7) or (10). The heat exchange between the two fluids has still been computed by means of the Newton law, adopting a suitable heat transfer coefficient (see Table 1).

6 NUMERICAL IMPLEMENTATION

The analytic models presented in the previous sections have been implemented in SIMULINK [16], which is able to deal with ODEs only. For this reason, it has been necessary to introduce a discrete form for Eqs. (4), (10), (11) as well as for the equations describing the heat exchanger. Such form has been obtained by applying an upwind scheme of discretization to the spatial derivatives [17].
For what concerns the thermo-hydraulic of the core, the discretization has been carried out in order to limit the lowest number of nodes to three, i.e., one for the graphite and two for the molten salt. Having at least two equations for the salt allows to avoid the imposition of an additional equation like Eq. (9), thus preventing from the related unphysical behaviour of the outlet temperatures. As regards the heat exchanger, it has been chosen to consider a simple four-node discretization whenever the one-dimensional model is adopted.

7 RESULTS AND DISCUSSION

The neutronic and thermo-hydraulic models discussed above have been combined in three overall models. A first model is a fully lumped model combining zero-dimensional approaches for both the involved phenomena. A second model combines a zero-dimensional model for the DNP drift and a one-dimensional model for the thermo-hydraulic behaviour. A third model is finally obtained by coupling the two one-dimensional models. In the following, the three models will be referred to as (0D-0D), (0D-1D) and (1D-1D), respectively.

In this section, the results obtained by means of the three models are compared each others as well as with a dedicated model developed at ORNL during the sixties [14]. The ORNL model, with respect to the models described in the present paper, has the peculiarity of considering also the radial dimension of the core. In addition, the effect of the temperature feedbacks on reactivity is weighted in the different parts of the core according to dedicated neutronic computations.

The power response of the system to a reactivity step of 10 pcm is reported in Figure 2. Generally speaking and with reference to the ORNL model, the overall behaviour can be explained as follows. The initial power increase due to the reactivity step is balanced in few seconds by the temperature feedbacks. These feedbacks cause a slight decrease, after which the power undergoes a plateau until the hot salt generated by the power peak re-enters the core. When this happens (at about 16 seconds), the negative temperature feedback leads to a sudden decrease in the power, which then smoothly reaches an asymptotic value featured by average salt and graphite temperatures high enough to counterbalance the initial reactivity increase.

![Figure 2: Reactor power after a 10 pcm reactivity step](image)
7.1 Comparison between the developed models

With reference to Figure 2, it is interesting to compare the response of (0D-0D) with that of (0D-1D). Two main differences can be observed. The first is the reduction of the power peak when a discretization of the thermo-hydraulics equations is introduced. This means that a fully lumped model tends to underestimate the effect of temperature feedbacks. A second difference is the slightly more oscillatory behaviour of (0D-0D). Actually, adopting such model, the power tends to oscillate around an "average value", which is represented by the power computed using (0D-1D). This fact is due to the effect discussed in paragraph 4.1, concerning the unphysical behaviour of the outlet temperatures of each component of the plant. The hypothesis of the temperature-related nature of the power oscillations is confirmed by Figure 3, where a highly oscillatory behaviour of the primary loop temperatures can be observed for (0D-0D).

Comparing (0D-1D) and (1D-1D) in Figure 2, it is possible to notice that the height of the power peak is higher (about 5%) and is reached earlier in (1D-1D). This implies that a zero-dimensional approach for the DNP drift can be non-conservative. A second observation is the slightly more oscillatory behaviour in (1D-1D) with respect to (0D-1D). This is due to the smoothing action of the zero-dimensional approach on the DNPs leaving the core. Another interesting observation is that the power decrease begins earlier in (1D-1D). This is an important consequence of considering the DNPs as distributed non-uniformly along the core. In fact, the concentration of the DNPs with lower decay constant tends to increase until the top of the core and the outflow results higher with respect to the outflow computed using the mean value of the concentration (as in (0D-0D) – see Eq. (3)). This phenomenon also affects the values of $\rho_0$, which result equal to 246 pcm and 273 pcm for (0D-1D) and (1D-1D), respectively.

To summarize, the (1D-1D) model better describes the shape of the power peak. Actually, a first peak, a plateau and the subsequent rapid decrease due to hot salt re-entering the core can clearly be observed.

7.2 Comparison with the ORNL model

The main difference between the developed models and the ORNL one is in the height of the peak. The cause of this discrepancy can partly be found in the zero-dimensionality of
the neutronic modelling, which allows neither for the "neutron importance" nor for the exact power distribution of different core regions. Actually, this problem was circumvented in the ORNL model by weighting the temperature feedback and the power in the different core regions according to dedicated neutronic computations [14]. A computation of such kind is out of the scope of the present work, but, in order to confirm its importance, the (1D-1D) model has been modified introducing a linear weighting of the feedback coefficients (higher at the top of the core). The result is shown in Figure 2 (see 1D-1D mod), where it can be noted that the power response actually gets closer to the ORNL model.

In this sense, a correct modelling of this aspect would also require to introduce the radial dimension (by considering for example more than one channel) in order to be able to fully consider both the importance (in terms of reactivity feedbacks) of different core regions and the actual power distribution. The presence of a radial dimension in the ORNL model could also explain the smoother response of the system after the power peak. Actually, the presence of parallel channels featured by different powers and flow rates suggests a smoother response of the core outlet temperatures and, consequently, of the temperature feedback when the salt re-enters the core. These aspects require further investigation.

As a final comment, it can be noted that the asymptotic value predicted by the ORNL model is different from that of the other models. This characteristic is due to both the spatial weighting of the feedback coefficients and, probably, to a different thermal resistance of the heat exchanger.

8 CONCLUSIONS

In the present paper, different models for the transient simulation of the MSRE primary loop have been presented and discussed, with reference to the system behaviour after a reactivity step. The results have pointed out the improvement of simulations by increasing the complexity of the models. In particular, the discretization of the thermo-hydraulics equations appears of importance in order to avoid unphysical oscillations of the temperatures and, consequently, of the power. The introduction of a discretization also in the DNP modelling is important to correctly simulate the shape of the power peak and the trend to the asymptotic value. In addition, the modelling of the DNP axial distribution notably affects the steady-state reactivity.

The main source of inaccuracy in the developed models has been individuated in the zero-dimensional equation for the neutron population. Actually, such equation does not properly take into account the "neutron importance" and the power density of different core regions. Such drawback could be overcome in future developments of the present work, by introducing a radial dimension and by assigning to each core position weighting factors for the temperature feedbacks and for the power distribution, according to dedicated neutronic computations. The presence of a radial dimension appears fundamental also in order to damp the excessively oscillatory behaviour resulting from a single-channel modelling.

REFERENCES


**NOMENCLATURE**

$c_i$  
DNP density – $i^{th}$ group [m$^{-1}$]

$C_i$  
DNP population – $i^{th}$ group [-]

$c_p$  
Specific heat [J·kg$^{-1}$·K$^{-1}$]

$H$  
Core active height [m]

$M$  
Mass [kg]

$n$  
Neutron density [m$^{-1}$]

$N$  
Neutron population [-]

$P$  
Core power [W]

$q'$  
Core linear power (P/H) [W·m$^{-1}$]

$t$  
Time [s]

$T$  
Temperature [K]

$T_{in}$  
Core inlet temperature [K]

$T_{out}$  
Core outlet temperature [K]

$U$  
Overall heat transfer coefficient between salt and graphite [W·K$^{-1}$]

$x$  
Axial coordinate [m]

Subscripts $s$ and $g$ are used to denote salt and graphite. The symbol $\Delta$ indicates variations.