THREE-DIMENSIONAL NUMERICAL INVESTIGATION OF A MOLTEN SALT REACTOR CONCEPT WITH THE CODE CFX-5.5

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ABSTRACT

Partitioning and transmutation of actinides and long-lived fission products is a promising option to extend the possibilities and enhance the environmentally acceptable capabilities of nuclear energy. Also the possible implementation of the thorium cycle is considered as a way to reduce the problem of energy resources in the future. For both objectives different molten salt reactor concepts were proposed mainly based on the Molten Salt Reactor Experiment of the Oak Ridge National Laboratory. Not only critical reactors but also accelerator-driven subcritical systems (ADSs) have advantages worth considering for those aims, especially those ones with liquid fuel, such as molten salts. By using liquid fuel which is the coolant medium, too, a basically different thermalhydraulic behavior is expected than in the case of solid fuel and water coolant. In this work our purpose is to present the possible use of Computational Fluid Dynamics (CFD) technology in molten salt thermal hydraulics. The simulations were performed with the three-dimensional code CFX-5.5.

1 INTRODUCTION

CFX-5.5 is a three-dimensional computational fluid dynamics code which is capable to simulate forced and natural convection, heat transfer (radiation, conduction and convection), single and multiphase flows in different geometries. By using a non-structured tetrahedral volumetric mesh for the finite volume solving method almost any kind of flow and heat transfer problems can be simulated. Both steady state and transient simulations can be carried out by the numerical solution of the mass, momentum and energy equations [1].

We considered basically a homogenous reactor concept. In this case the critical core (which is also the flow region itself) is one homogenous volume filled with the fluid molten salt fuel. The original geometry is based on previous publications. Different geometries were designed in order to take into consideration the better flow and heat generation properties of such a reactor. The calculations were carried out with approximated power distributions. These investigations could make up a basis for calculations for a possible multiregion molten salt reactor concept recently proposed by Hungarian researchers [2]. For more reliable results real reactorphysical calculations will have to be carried out. For this the analysis of the transmutational capabilities of such a molten salt reactor recently carried out by Hungarian physicists will be a very important background [3].
The fluid was fluoride based molten salt. The nominal thermal power was defined as in earlier proposed reactor concepts. We investigated different inlet and outlet geometry options, different core layouts. The simulations have shown the importance of three-dimensional modelling especially when the multiregion concept will be the subject of simulations.

2 BACKGROUND

Since the first molten salt reactor program in the United States in the ‘50s and ‘60s [4] the interest for molten salt concepts has risen as partitioning and transmutation research programs are under way all around the world. In the nominally 10 MW unit of the Molten Salt Reactor Experiment (MSRE) of Oak Ridge National Laboratory the fluoride fuel was axially pumped through a grid of graphite blocks. The flow channels were relatively thin compared to the volume of the whole reactor [5]. Later proposals featured homogenous reactor layouts where the liquid fuel is in a large, continuous volume defined by the reactor vessel (Figure 1.) [6]. In case of the first design, for the different flow channels one-dimensional calculations can be carried out but in the homogenous case we can expect three-dimensional behavior both for the flow and the temperature field.

The referring publications propose chloride and fluoride based molten salt, but most of these say the fluorides could have better physical and chemical properties – such as the effect on the neutron spectrum or the compatibility with structure materials [7].

![Figure 1: Homogenous molten salt reactor layout [6]](image)

1 - molten salt, 2 - outlet, 3 - primary loop, 4 – heat exchanger, 5 – cold leg
3 CFX MODEL OF A MOLTEN SALT REACTOR

The nominal parameters for the reactor models can be found in Table 1. These parameters were taken from the design concept of Russian scientists mentioned above [6]. It was one of the best-detailed designs with homogenous molten salt reactor published recently.

Table 1: Nominal parameters of the model

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal power [MW]</td>
<td>2500</td>
</tr>
<tr>
<td>Mass flow rate [kg/s]</td>
<td>10683</td>
</tr>
<tr>
<td>Inlet temperature [°C] ([K])</td>
<td>620 (893)</td>
</tr>
<tr>
<td>Outlet temperature [°C] ([K])</td>
<td>720 (993)</td>
</tr>
</tbody>
</table>

Applying these parameters we first designed a core geometry with different inlets geometries such as a downcomer and inlet nozzles. We examined the thermalhydraulical behavior of the different geometries and the impact of the inlets on the thermalhydraulical phenomena inside the reactor.

The fuel molten salt flows through the total lower plane of the core. The outlet is at the top of the core. The geometry is cylindrical, the core contains no structure elements or control rods. Following heated up in the core the molten salt goes through an outer heat exchanger, and then it is circulated back to the reactor vessel. In the models only the core and inlet geometries were modelled. For medium we chose the 66 LiF-34 BeF₂ (mol%) composition, in which less than one mol percent fissile material is dissolved. The physical properties of this medium are in Table 2.

Table 2: Physical properties of the fuel/heat carrier salt [7]

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Composition (mol%)</td>
<td>66 LiF-34 BeF₂</td>
</tr>
<tr>
<td>Melting point [°C]</td>
<td>458</td>
</tr>
<tr>
<td>Specific heat capacity [kJ/kg°C]</td>
<td>2,34</td>
</tr>
<tr>
<td>Density [kg/m³]</td>
<td>2050</td>
</tr>
<tr>
<td>Heat transfer coefficient [W/m²°C]</td>
<td>1</td>
</tr>
<tr>
<td>Dynamic viscosity [g/ms]</td>
<td>5,6</td>
</tr>
</tbody>
</table>

The geometry of the reactor core is in Figure 2. The inlet plane is the total lower cross section, a circle with a radius of 2 meters. The outlet is also a circle with a radius of 0.6 meters. The total volume of the core is 51.365 m³. In the further calculations this core geometry was extended with an annular downcomer and four inlet nozzles (see section 4.2 and 4.3).

In CFX-5.5 the domain of power generation shall be exactly defined. This means the power generation distribution has clearly defined boundary. This is also an important approximation of these calculations. The power distribution was another important input data which was approximated with the following expression (Eq. (1)):
where \( H \) is the total height of the core \((z=0)\) is at the lower plane), \( R \) is the maximum radius of the core, \( z \) is height and \( r \) is radius. The \( q_{\text{max}}'' \) factor was calculated in every case that the integral power in the core is 2500 MW. In the paper we present the results of our calculations carried out by nominal conditions and by using the \( k-\varepsilon \) turbulence model.

4  CALCULATIONS AND RESULTS

4.1  Calculations for simple core geometry

In this section simulation results for the simple core geometry will be presented. For the first case the core geometry was extended with a one-meter longer inlet, but not the region of the reactor core. The outlet was extended also by three meters (see Figure 3.). These extensions were adapted in order to avoid any impact in the volume of the core from the boundary conditions. The inlet boundary condition is constant nominal mass flow rate, the outlet boundary condition is constant average pressure, 1 bar. The thermal power is nominal as described above.

Figure 3: Geometry of the core (marked with light gray) and the extended inlet and outlet

Figure 4. shows the calculated temperature field. As expected, in the central region of the core a high temperature region is formed with lot higher values – the maximum is 1005.9 K – than the average outlet temperature which is 991.3 K. Since here the liquid fuel is the coolant medium also, with the presumed power distribution (Eq. (1)) this high temperature region is slightly shifted toward the outlet.

Figure 4: Temperature field in the reactor
4.2 Calculations for reactor with lower plenum

A lower plenum geometry was designed to define a more realistic inlet. The geometry and parameters of the lower plenum are shown in Figure 5. The lower plenum was placed right under the lower plane of the core. The inlet condition is 10683 kg/s nominal mass flow rate, normal to the annular plane of the bottom. The outlet condition is constant average pressure of 1 bar.

![Figure 5: Geometry of the lower plenum](image)

With the addition of the lower plenum a radially more uniform temperature field can be obtained especially in the upper half of the core (Figure 6). As the mainstream flows through the centerline of the core (Figure 7) – where the power is higher – it spends less time so the maximum temperature values are lower, such as 997.6 K. As a result of the re-circulation near the wall the fluid spends more time in the core – where the power is lower –, the temperature is closer to the temperature of the molten salt in the center. It can be stated that with an inlet layout like this it is possible to make a more uniform temperature field. This also means the possibility to lower the maximum temperature in the reactor.

![Figure 6: Temperature field in the reactor](image)

![Figure 7: Velocity field in the lower plenum and the core](image)
4.3 Calculations for reactor with downcomer and inlet nozzles

The basic downcomer and inlet geometry was given as in Figure 8. Two other inlet layouts were examined, when there is a 45° and a 22° angle between the centerline of the inlet nozzles and the horizontal. These two versions were examined because the experienced flow behavior (large backflow and recirculation) when the inlets are horizontal.

At the inlet nozzles the boundary conditions are constant 2670.75 kg/s mass flow rates, one quarter of the nominal value, on each of the four inlets.

In the horizontal layout the mainstream from the inlet is separated into two major streams which go down between a pair of inlets. Larger backflow can be experienced under the inlets (See Figure 9.). As a result of the two major streams in those segments re-circulations are formed. These are strongly affecting the temperature field in the core. This means both asimutally and radially large differences in the temperature distribution (Figure 10.).

By modelling inlet nozzles non-perpendicular to the downcomer the obtained radial temperature and velocity distributions are shown in Figure 11. and 12.
In case of the 45-degree-inlet geometry the mainstreams go down right under the inlet nozzles. The backflow in the downcomer can be experienced again but now between the nozzles. This means the characteristics of the temperature field are quite the same like in the case of horizontal inlets but it is rotated by 45 degrees. These characteristics can be compared with the results of the 22-degree-inlet geometry layout (Figure 11 and 12). Applying the 22-degree-inlet geometry the velocity field is lot more uniform than in the previous two geometries. It also means the better uniformity in the core for the velocity field. Comparing the radial distribution of the axial velocity component one meter above the lower boundary of the core the 22-degree-inlet geometry results in higher minimum values. These minimums are negatives which mean re-circulation. But the maximums are lower than in the 45-degree-inlet geometry and a wider region has almost the same velocity value (Figure 12). So the obtained temperature field is more uniform both in the lower and the upper regions of the core. It is also visible on the radial temperature distributions on Figure 11.
5 CONCLUSIONS AND PERSPECTIVES

In this paper we presented results of detailed three-dimensional thermalhydraulics calculations of a homogenous molten salt reactor concept. A concept with liquid fuel, which is the coolant medium also behaves fundamentally differently from a reactor with solid fuel and water coolant. The results have shown that CFD techniques, especially the application of the CFX-5.5 three-dimensional code, are capable to investigate such problems. The calculations have also shown the importance of three-dimensional modelling, especially when concentrated inlet geometries are applied. The work presented in this paper will be a good basis for further simulations especially when we want to investigate the multiregion molten salt reactor concept. But for obtaining more reliable results detailed reactorphysical calculations will have to be carried out, with the help of SCALE and TORT codes.

This paper is based on the diploma work of author Bogdán Yamaji [8].

REFERENCES


[8] Yamaji Bogdán: A sóolvádékos reaktor és a hozzá kapcsolódó hűtőkőr termohidraulikája; Diplomamunka, Témavezető: Dr. Csom Gyula, Dr. Aszódi Attila; BME NTI, 2002 június (In Hungarian)