Thermal-hydraulic simulation of loss forced circulation in the TRIGA Mark I - IPR-R1

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Objective

Reactor refrigeration

Study the thermal-hydraulic behavior inside the pool reactor by computational fluid dynamics considering two situations:

- Forced circulation. That is, when the external coolant circuit is available.
- Natural circulation. That is, when the external coolant circuit shut down.
TRIGA Research Reactor (*Training Research Isotopes General Atomic*)

TRIGA reactors were designed and built by General Atomic. They are open-pool type reactors used for academic, research, material testing and isotope production purposes.
TRIGA IPR-R1 nuclear research reactor

- The core of the reactor can house 91 rods, with 63 fuel elements, 23 false graphite elements, a neutron source, a central irradiation tube and 3 control rods.
- It is an upward flow reactor. That is, in normal operation the coolant flows from the bottom to the top of the core.
TRIGA IPR-R1 nuclear research reactor

- Core support structure
- Rotary specimen rack
- Reflector
- Core support structure
- Control rod
- Upper plate
- Fuel elements
- Lower plate
- Plate of detail
Methodology

Reactor features

<table>
<thead>
<tr>
<th>Thermophysical properties</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heat capacity $C_p a$</td>
<td>4183 (J/kg.K)</td>
</tr>
<tr>
<td>Pressure $P_a$</td>
<td>1 (atm)</td>
</tr>
<tr>
<td>Dynamic viscosity $\mu$</td>
<td>$797.7 \times 10^{-10}$ (N.s/m²)</td>
</tr>
<tr>
<td>Prandtl number $Pr$</td>
<td>5.42</td>
</tr>
<tr>
<td>Density of ref. $\rho_{ref}$</td>
<td>995 (kg/m³)</td>
</tr>
<tr>
<td>Temperature of ref. $T_{ref}$</td>
<td>302 (K)</td>
</tr>
<tr>
<td>Thermal expansion $\beta$</td>
<td>$0.305 \times 10^{-3}$ (1/K)</td>
</tr>
</tbody>
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<table>
<thead>
<tr>
<th>Geometric and operation parameters</th>
<th>Value</th>
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<tbody>
<tr>
<td>Thermal Power $P_t$</td>
<td>100 (kW)</td>
</tr>
<tr>
<td>Number of fuels $N_c$</td>
<td>63</td>
</tr>
<tr>
<td>Number graphite elements/others $N_g$</td>
<td>28</td>
</tr>
<tr>
<td>Diameter of the pool $D_t$</td>
<td>1900 (mm)</td>
</tr>
<tr>
<td>Total pool height $L_t$</td>
<td>6400 (mm)</td>
</tr>
<tr>
<td>Core diameter $D_n$</td>
<td>441 (mm)</td>
</tr>
<tr>
<td>Reflector diameter $D_r$</td>
<td>1090 (mm)</td>
</tr>
</tbody>
</table>
A total power of 100 kW was imposed, with a sinusoidal profile for axial distribution and with a radial distribution obtained from literature simulation and experimental data (Dalle, 2002).
Governing Equations

Simulations were performed using the compressible Boussinesq solver (buoyantPimpleFoam) to estimate the density variations.

1. Continuity equation:

$$\frac{\partial \rho}{\partial t} + \frac{\partial (\rho u_j)}{\partial x_j} = 0 \quad (2.1)$$

2. Momentum equation:

$$\frac{\partial (\rho u_j)}{\partial t} + \frac{\partial (\rho u_j u_i)}{\partial x_j} = -\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j} (\tau_{ij} + \tau_{t,ij}) + \rho g_i \quad (2.2)$$

3. Energy equation (written in terms of enthalpy):

$$\frac{\partial (\rho h)}{\partial t} + \frac{\partial (\rho h u_j)}{\partial x_j} - \frac{\partial p}{\partial t} = \frac{\partial}{\partial x_k} \left( \kappa_{\text{eff}} \frac{\partial T}{\partial x_k} \right) \quad (2.3)$$

$$\kappa_{\text{eff}} = \alpha_{\text{eff}} \rho C_p$$ is the effective conductivity, $\alpha_{\text{eff}}$ is the effective thermal diffusivity and $C_p$ the specific heat.

4. To model the turbulence the standard $\kappa - \epsilon$ model was used
Numerical Model

- **Computational domain:** extruded meshes combined with non-structured meshes were used. Total mesh size: 6,978,842 cells.

- **Perforated support plates:** They were represented through porous media regions using the Darcy-Weisbach approach.

- **Heat transfer:** The floor and lateral walls were assumed as Adiabatic while a constant convective coefficient was used for modeling the heat loss through the free surface.

- **Parallel computing:** 20 nodes (80 processors) in CIMEC cluster (16 hr of calculus for each 1 hr of simulation).
Results - Forced circulation

- **Temperature:** The variations at the cross sectional planes are less than 2K and they become lower at the top side.

- **Velocity:** Blue zones correspond to downward flow and red zones to upward flow. The minimum and maximum values are between -50 mm/s to 50 mm/s. At the upper half side the flow ascends close the wall and descends through the center.
**Forced circulation**

- **Core:** Along the axial direction the temperature increases almost linearly from 310K to 330K.

- **Radial temperature distribution:** It is clearly a consequence of the pin power distribution and the location of the control and stainless steel rods.
Forced circulation

- **Core inlet:** The highest velocities are close to the periphery because of the opening windows.
- **Core outlet:** There is not a smooth velocity profile. Maximums are in the center with many peaks at the high pin power locations.

- **Core inlet:** The coolant flows mostly by the opening windows with an average velocity of 40 mm/s rising to 80 mm/s close to the rods. On the other hand, the velocity at central perforated plate remains less than 10 mm/s, but this is due to the porous media representation.
Natural circulation

Evolution of pool heating

- In normal operation \((t=28000s)\) the hot plume is mixed with the cold inlet.
- Once forced flow shut down the plume ascends up to the free surface, where only a fraction of the heat is transferred to the environment.
- The temperature increases progressively with heat rate of 5.2K per hour. After 960s (16 min) the temperature increases around 2K in the upper part of the pool.
Forced vs Natural circulation

Evolution of velocity pattern

- In contrast to the quite-steady and ordered plume, the downward flow is unstable. The flow ascend in the central zone with high velocity and slowly descend close to the laterals.

- Flow transition from forced to natural circulation takes place quickly. In 500s the hot plume due to the outlet core coolant reach a fluid flow stationary condition.
Forced vs Natural circulation

Streamlines videos

Video streamlines Velocity

Video streamlines Temperature
**Forced flow:** The inlet flow dominates and the central plume is moved toward the pool wall.

**Natural circulation:** The fluid motion is mainly due to the ascending central plume and the helical descending flow.
Forced vs natural circulation - Velocity

- **Forced circulation**: The inlet flow dominates and the central plume is displaced toward the pool wall.

- **Natural circulation**: The motion is mainly due to the ascending central plume.
In this work, the cooling capacity of the TRIGA-Mark I reactor was studied by CFD. Two operation conditions at full power were evaluated: forced circulation and natural circulation. The model allowed us to analyze the transition from forced to natural flow.

Steady-state forced circulation conditions were achieved after simulate around 7 hr of operation, getting a high mixing and quite complex flow pattern.

On the other hand, once the forced circulation shut down, an organized flow characterized by a central upwards plume was achieved. In this situation an almost constant heating rate of 5.2K per hour was obtained.

4- The heat exchange at the free surface was less than 5 kW, which was less than 5% of the total power in the core.
Thank you for your attention!

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