CFD Simulations of Selected Steady-State and Transient Experiments in the PLANDTL Test Facility

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Abstract. In Sodium Cooled Fast Neutron Reactors natural convection flow and thermal stratification in the upper plenum may occur under emergency shutdown conditions. Thermal stratification phenomena have been examined experimentally in the PLANDTL facility of the Japan Atomic Energy Agency. This paper presents the results of numerical simulations of selected steady-state and transient experiments in the PLANDTL facility, using TrioCFD/MC2 code developed at CEA. CFD approach for the flow in large volumes and a sub-channel approach for the flow in the core region are used. Calculated results have been validated against experimental values. Validation of the upper plenum modelling has been also made based on CEA Sodium mixed convection experiments.

Keywords: Sodium Fast Reactors, PLANDTL, SUPERCAVNA, Thermal Stratification, CFD, TrioCFD.

1. Introduction

Fast Neutron Reactors are classified as Generation IV of nuclear reactors. They are more technologically advanced comparing to currently operated water reactors. In such reactor systems, liquid metal such as sodium, lead or lead-bismuth eutectic is used as a coolant. Fast reactors are characterized by more efficient fuel cycle and higher core power density [1].

Sodium Fast Reactors are most examined so far and they are considered to be most prospective in the future. Operation of Phenix and Superphenix provided a number of reactor-years of experience in Sodium Fast Reactors exploitation and maintenance. Currently there are few prototypes of Sodium Fast Reactors in use, mostly in Russia and China. Numerous experiments are also carried out using test loops including Plant Dynamics Test Loop (PLANDTL) owned by Japan Atomic Energy Agency.

It has been found that under emergency shutdown conditions, natural convection flow and thermal stratification in the upper plenum may occur. In order to better understand of these phenomena, Commissariat à l'énergie atomique et aux énergies alternatives (CEA) has developed a TrioCFD/MC2 code. This paper presents the results of numerical simulations of selected experiments related to thermal stratification issue in Fast Sodium Reactors, using TrioCFD/MC2 code.
2. Methodology

Calculations were performed using TrioCFD code, developed at CEA for scientific and industrial purposes. It is platform-independent CFD code, dedicated to transient thermal-hydraulics issues, especially for nuclear industry purposes [2]. Calculations on structured and nonstructured, large size, tetrahedral meshes (up to hundreds of millions of nodes) can be performed using TrioCFD [3].

In the sub-channel module of TrioCFD, called MC2, core region can be modeled, including wrapper tube, coolant, fuel pins and cladding. Thermal inertia of fuel and cladding is also taken into account. When forced convection is a dominant flow driver, velocity distribution in each sub-channel is uniform and calculated using the pressure drop correlations. If the natural or mixed convection regime is dominant, buoyancy force is applied as a primary mean of decay heat removal. Axial temperature growth is determined by the function of pin power, coolant flow rate and radial heat transfer coefficient [4]. Such coefficients result from specific correlations that are described in [5]. The sub-channel module is able to run standalone or may be coupled with CFD module.

2.1. Fundamental numerical scheme

Implicit time scheme was applied to simulate each experiment. Modeling of buoyancy force was performed using Boussinesq hypothesis. Turbulence effects were treated with \( k-\varepsilon \) model. 1\textsuperscript{st} order upwind scheme was applied to convection modeling, and 2\textsuperscript{nd} order centred scheme was applied for diffusion. Boundary layer was treated with logarithmic wall law.

| Table 1. Fundamental numerical scheme. |
|----------------------------------------|
| **General**                            |
| Dimension | 3D |
| Fluid | Sodium |
| Mesh | Tetrahedral |
| Discretization | P0/P1 for p |
| | P1NC for u, v, w, T, k, \( \varepsilon \) |
| **Time scheme** | Implicit |
| | Explicit for turbulence modeling |
| **Navier-Stokes equations** | |
| Convection | 1st order upwind |
| Diffusion | 2nd order centred |
| Pressure solver | Cholesky method |
| Thermal effects | Boussinesq approximation |
| Wall law | Logarithmic wall law |
| Turbulence | RANS |
| **Turbulence modeling** | |
| Turbulence model | High Reynolds \( k-\varepsilon \) |
| \( k, \varepsilon \) convection | 1st order upwind |
| \( k, \varepsilon \) diffusion | 2nd order centred |
| **Energy transport equation** | |
| Convection | 1st order upwind |
| Diffusion | 2nd order centred |
| Wall law | Kader wall law |
| Turbulence | Turbulent Prandtl Number \( \text{Pr}_t \) |

2.2. The RANS \( k-\varepsilon \) turbulence model

Two-equation \( k-\varepsilon \) turbulence model has been applied to all computational cases of the present study. This model is applicable for fully developed turbulent flows and treats buoyancy effects to a certain extent [6].
Conservation equations for turbulence kinetic energy $k$ and dissipation rate $\varepsilon$ are formulated as follows:

\[
\frac{\partial k}{\partial t} + \vec{u} \cdot \nabla k = \nabla \cdot \left( \frac{\nu}{\sigma_k} \nabla k \right) - \varepsilon + P + G
\]  

(1)

\[
\frac{\partial \varepsilon}{\partial t} + \vec{u} \cdot \nabla \varepsilon = \nabla \cdot \left( \frac{\nu}{\sigma_\varepsilon} \nabla \varepsilon \right) - C_{\varepsilon 2} \frac{\varepsilon^2}{k} + C_{\varepsilon 1} P \frac{\varepsilon}{k} + C_{\varepsilon 1} C_{\varepsilon 3} G \frac{\varepsilon}{k}
\]  

(2)

Turbulent viscosity $\nu_t$ is calculated using the following relation:

\[
\nu_t = C_\mu \frac{k^2}{\varepsilon}
\]  

(3)

$P$, which is the production of turbulence kinetic energy is calculated using:

\[
P = \left( \nu_t \left( \frac{\partial \vec{u}_i}{\partial x_j} + \frac{\partial \vec{u}_j}{\partial x_i} \right) - \frac{2}{3} k \delta_{ij} \right) \frac{\partial \vec{u}_i}{\partial x_j}
\]  

(4)

Buoyancy effects $G$ shall be treated as follows:

\[
G = -\frac{\nu_t}{Pr_t} \beta_T |\vec{g}| \cdot \nabla T
\]  

(5)

The empirical coefficients used in all equations listed above can be found in Table 2.

| $C_\mu$ | $\alpha_k$ | $\alpha_\varepsilon$ | $C_{\varepsilon 1}$ | $C_{\varepsilon 2}$ | $C_{\varepsilon 3}$ | $Pr_t$ |
|--------|------------|-----------------------|-------------------|------------------|------------------|--------|
| 0.09   | 1.0        | 1.3                   | 1.44              | 1.92             | f(T)             | 0.9    |

3. Validation of upper plenum modelling

Certain operating conditions of Sodium Fast Reactors may lead to thermal stratification of upper plenum. Thermal stratification effects in sodium cavity were investigated performing steady state and transient experiments. These experiments, called SUPERCAVNA, have been performed at CEA.

The entire installation consists of electromagnetic pump, electromagnetic flowmeter, test section cavity, expansion tank, sodium-air heat exchanger and valve and diaphragm system, in order to control the flowrate. In order to provide heating of the roof and vertical wall, there is installed a heating circuit consisted of electromagnetic pump, flowmeter, preheater, expansion tank and piping system [7]. Both systems are filled with sodium. Dimensions of the cavity are shown in Figure 1.

![Cavity dimensions](image)

Figure 1. Cavity dimensions (in mm).
In simulated steady-state experiment, heat has been transferring to the cavity through vertical wall. Sodium inlet velocity to the cavity was uniform and set to $0.69\text{ m/s}$. Sodium volumetric flow rate to the heating channel at the wall was $1.67 \cdot 10^{-2} \text{ m}^3\text{/s}$. Inlet velocity to the heating channel calculated using given flow rate was $0.6\text{ m/s}$. Inlet temperatures to cavity and heating channel were assumed to 251 °C and 302 °C respectively.

Three-step approach has been applied to verify mesh independent solution. The solution of the coarser mesh was interpolated and taken as initial conditions for refined one. Sequence of this procedure is as follows:

- initialization of the calculations on the coarse mesh, with ambient velocity equals to 0 m/s and uniform nozzle outlet velocity in order to achieve solution $S_C$
- initialization of the calculations on the fine mesh, with solution $S_C$ in order to achieve solution $S_F$
- initialization of the calculations on the very fine mesh, with solution $S_F$ in order to achieve solution $S_V$.

Mesh independent solution is indicated by comparable results of $S_F$ and $S_V$.

Simulation of SUPERCAVNA steady-state experiment shows that application of k-ε turbulence model with refined heat exchange region as well as cavity inlet and outlet region is sufficient to obtain satisfactory results on stable thermal stratification. Calculated results are acceptable comparable to experimental ones. Simulation was carried out in a reasonable CPU time. Figure 2 presents temperature distribution in cavity and heating channel. Calculated and experimental dimensionless temperature profiles are presented in Figure 3. Mesh independent solution on coarse mesh has been obtained.

![Figure 2](image1.png)  
**Figure 2.** Cavity temperature distribution.

![Figure 3](image2.png)  
**Figure 3.** Centerline dimensionless temperature profile.  
*T* – centerline temperature in cavity, $T_m$ – mean temperature in cavity channel, $T_{\text{max}}$ – maximum temperature in cavity

4. **Simulations of steady-state and transient experiments in PLANTDL Test Facility**

PLANDTL is a test loop used for experimental studies of steady-states and transitions occurring in Sodium-cooled Fast Neutron Reactors. In the primary loop, sodium from upper plenum feed the Intermediate Heat Exchanger (IHX), which is primary way of cooling process. Next sodium is directed
to the lower plenum with electromagnetic pump. Then coolant is pumped through three independent lines to the core region, where removes heat from the assemblies.

The secondary loop consists of Intermediate Heat Exchanger, pump and the main air cooler. In the IHX there is a heat exchange between coolant from primary loop and sodium in the secondary loop. Then sodium is cooled using Main Air Cooler.

Heat may also be removed in alternative way, using Reactor Auxiliary Cooling System. Such system consists of Primary Reactor Auxiliary Cooling System (PRACS) and Direct Reactor Auxiliary Cooling System (DRACS). Schematically, test section is presented in Figure 4 [8].

![Figure 4. PLANDTL flowchart.](image)

1. Upper plenum, 2. Core barrel, 3. Direct heat exchanger (DRACS), 4. Upper inner structure (UIS), 5. Center subassembly, 6. Outer subassemblies, 7. Interwrapper gap, 8. Lower plenum, 9. Electromagnetic flow meter, 10. Electromagnetic pump, 11. Intermediate heat exchanger (PRACS), 12. PRACS coil, 13. Main air cooler, 14. Air cooler.

Upper plenum is a cylindrical tank with internal diameter of 2 m. Its height is approximately 3 m. Sodium level may vary from 2.01 m to 2.61 m, measuring from the bottom of the tank. Diameter of the upper inner structure (UIS) is 0.4 m. Its bottom is located 0.91 m from the upper plenum tank bottom. DHX is located at distance 0.5 m from the UIS and its diameter is 0.318 m. Inside diameter of the core barrel is 1.8 m. Wall thickness of the upper plenum is 25 mm. Core barrel and UIS wall thickness is 6 mm. Core outlet is located at the height of 0.61 m from the bottom of the upper plenum tank. Core is consisted of 7 subassemblies: 1 center and 6 outer.

4.1. Simulation of steady-state experiment

Steady-state experiments were characterized by constant core power, coolant flow rate and core inlet temperature. CFD simulations were performed until the temperature distribution in the upper plenum and interwrapper gap were constant.

| Core power, kW | Coolant flow rate, m³/s | Coolant inlet temperature, °C | Cooling loop |
|----------------|--------------------------|-------------------------------|--------------|
| 170.5          | 8.13e-4                  | 296                           | Secondary Loop |
Temperature distributions in upper plenum and interwrapper gap are presented in Figure 5. In steady-state, upper plenum is negligibly stratified. Temperature difference between top and bottom of the tank is no more than 3 °C. Agreement between experimental and calculated results is acceptable. Temperature difference between calculations and experiment is about 5 °C. In the interwrapper gap, both center and outer regions, calculated temperature profile corresponds to experimental. Calculated temperature is however overestimated by approximately 20 °C.

4.2. Simulation of transient experiment

Transient experiments were carried out under varying power and flow conditions. At the beginning, core power decreased rapidly, then increased somewhat and followed the decay heat curve. Sodium inlet temperature and mass flow rate were time-dependent which is shown in the figure below. Transient experiment was being simulated for 5000 s. Coolant flow rate, power ratio and initial conditions were taken from [8].

![Figure 5. Temperature distribution in upper plenum and interwrapper gap.](image)

![Figure 6. Power and flow trends after emergency shutdown.](image)
Table 4. Thermal and flow initial conditions.

| Core power, kW | Coolant flow rate, m³/s | Coolant inlet temperature, °C | Cooling loop |
|---------------|--------------------------|-------------------------------|--------------|
| 1006.8        | 5.61e-3                  | 301                           | PRACS        |

Results of transient simulation are presented in figure below. At the beginning, temperature profile in upper plenum is uniform. There is no stratification in the tank. After shutdown, temperature gradient between top and the bottom of the upper plenum increases. Temperature variation in the bottom of the tank estimated by CFD model is in a good agreement with experimental data. The maximum difference between calculation and experiment is 5 °C. Sodium temperature at the top of the upper plenum is overestimated by approximately 20 °C, which will be investigated in future. Temperature distribution change in the upper plenum is presented in figure below.

Figure 7. Temperature distribution in upper plenum.

Figure 8. presents comparison between calculated and experimental values of core outlet temperature. Calculated temperature change is in a good agreement with experiment. There are two temperature peaks at the beginning of the transient. One of them is slightly underestimated, which requires future investigation.

Figure 8. Temperature variation at the core outlet.

Temperature change in selected horizontal cross-sections of interwrapper gap are presented in Figure 9. Temperature variations calculated in TrioCFD through the transient are with good agreement with experimental data. Peaks which appear roughly 800 s from the beginning of the transient are overestimated by approximately 30 °C. They are presumably related to coolant flow rate decrease and need to be investigated in the future.
5. Conclusions

Results obtained from presented validation cases may lead to the conclusion that steady-states in Sodium Fast Reactors can be numerically modeled preserving satisfactory accuracy. Discrepancies between experimental and simulated results are minor and acceptable. Numerical simulations of transients, where sodium is cooled outside the upper plenum show considerable differences with experiment in early stages of the simulation. Towards the end of the simulation, calculated results converge with experiment substantially. Therefore, further investigations are planned, including change of boundary conditions and variable level of sodium in the upper plenum as well as validation cases, where sodium is cooled inside the upper plenum.

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