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Hot Water Layer and Thermal Stratification in an Open-pool type Research Reactor

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1. Introduction

In an open-pool type research reactor, a reactor is submerged in the lower part of the reactor pool to provide core cooling and reactor safety. Since the water in the lower part of the pool has high radioactivity, the water should be prevented from rising up to the pool surface to protect the workers and researchers around the pool top. In many open-pool type research reactors, a hot water layer is introduced in the upper part of the pool as a shielding layer to reduce the radiation level on the pool top. By maintaining the hot water layer in a properly higher temperature than the lower part of the pool, a thermally stratified region is developed below the hot water layer and the flows in the lower part of the pool is successfully isolated from the upper part of the pool. This reduces a mass transport from the lower part of the pool to the pool upper part and consequently the radioactivity level on the pool top is also diminished.

In this study, the characteristics of the hot water layer and the thermally stratified region in the pool of the KIJANG Research Reactor (KJRR) are investigated. Numerical simulation on a 3D simplified model of the pool of KJRR is conducted using the commercial CFD software ANSYS FLUENT 13.0. The results show initial time evolutions of the temperatures and the flow velocities in the pool toward each quasi steady state. The heat transfer rate from the hot water layer to the lower part of the pool is obtained from the results, which is needed to estimate the required heater capacity. The thicknesses of hot water layer and the thermally stratified region which are required for shielding analysis are also provided.

2. Pool Modeling

The KJRR consists of a reactor pool, a service pool, and a spent fuel storage pool. The pool is 12 m in height, 16.3 m in length, and 4 m in width. The reactor structure can be simply modeled as rectangular boxes at the bottom of the reactor pool. In-pool pipe lines of the Primary Cooling System (PCS), the Pool Water Management System (PWMS), and the Hot Water Layer System (HWLS) are included in the model. For the PCS, the inner wall temperatures of the PCS piping are only reflected since the PCS is a closed loop system. The PWMS piping has open ends in the lower parts of the pools which discharge and intake the pool water for chemical and temperature control. The flow rate and water temperature are given as boundary condition for the discharge ends and the flow rate is given as boundary condition for the intake end. The HWLS has two suction ends and one discharge end which is shaped as a T-shape distributor. The distributor is designed to slow down the water discharge velocity to enhance the thermal stratification.

3. Calculation Method

4.1 Mesh Modeling

For the numerical simulation, the geometries and meshes are produced by the Geometry and the Mesh in the ANSYS Workbench 13.0. The multi-zone and the patch conforming tetrahedrons methods are used for the mesh generation. The multi-zone method is adopted around the region where the thermal stratification is expected. Mesh sizing functions which consider the proximity and curvature of the geometry are used and the maximum cell size is restricted to 0.3 m. Number of generated mesh elements is about 4.8 million.

4.2 Calculation

The discharge flow rate, the intake flow rate, the discharge temperature, and the wall temperature of each piping are treated using the mass flow inlet, the out flow, and the wall boundary conditions implemented in the software. The discharge temperatures of the HWLS and the PWMS are set to be 50℃ and 34℃, respectively. The heat loss at the pool surface due to the evaporation is modeled using heat convection and the shear rates are set to be zero for the momentum condition. The initial pool temperature is set to be 34 ℃.

The calculation is done using a transient solver. RNG k-e model is adopted for the viscous model. For the pressure-velocity coupling, SIMPLE scheme is adopted with the spatial discretization of second order upwind for momentum, turbulence, and energy. The time step size is set to be 5 s and the entire calculation is conducted for up to 126 hours. The changes in the calculated flow and temperature distributions are shown to be almost trivial after 48 hours which indicates the establishment of quasi-steady state.

4. Results and Discussion

Fig. 1 shows time evolution of the depth-wise temperature profile at the center of the reactor pool. The temperature distributions in the early stage of the calculation show large changes until about 24 hours from the beginning. After 24 hours, the hot water layer temperature is nearly saturated but the thickness of the hot water is gradually increasing until about 48 hours. The profiles are saturating to a certain profile after 48 hours from the beginning. Similar trend is also observed from the time evolution of the heat transfer rates as shown in Fig. 2. The heat transfer rate from the HWLS (circles) indicates the heat supplied from the heater to increase the hot water layer temperature to the saturating temperature. It is rapidly decreasing at the initial stage and is converging to about 65 kW after 48 hours. The convergence means the hot water layer is going to be a saturated state. The heat transfer rate from the hot water layer to the lower pool (squares) is also converging to nearly zero after 48 hours. Therefore, the heat transferred to the hot water layer is mostly balanced by the evaporation heat loss on the pool surface. The small heat transfer rate from the hot water layer to the lower part of the pool indicates a large suppression of the energy and mass transport below the hot water layer by thermal stratification. Fig. 3 shows depth-wise flow velocity profiles at the center, north, south, west, and east positions in the reactor pool. Except the west position, the flow velocities are nearly zero in the depth from 2 m to 6 m. The increase of flow velocity below 5 m at the west position is affected by the nearby PWMS discharge end which has average discharge velocity of 2.3 m/s. From the flow velocity profiles, it can be deduced that the hot water layer thickness is about 2 m and the thickness of the thermally stratified region is about 3~4 m below the hot water layer.

For the shielding analysis in the pool which is required to estimate the radioactivity of the hot water layer, the mixing rate between the hot water layer and the lower part of the pool is important variable as well as the thicknesses of the hot water layer and the stratified region. In further study, the mixing rate will be estimated by post processing the obtained results.

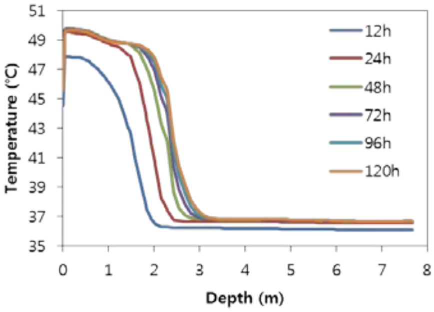

Fig. 1. Time evolution of the depth-wise temperature profiles at the center of the reactor pool.

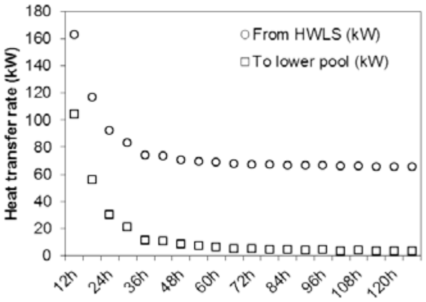

Fig. 2. Heat transfer rates of the hot water layer.

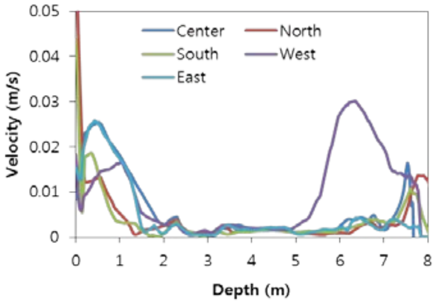

Fig. 3. Depth-wise velocity profiles at five positions in the reactor pool.

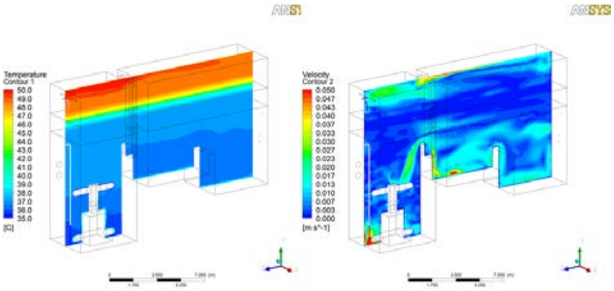

Fig. 4. Temperature and velocity distributions at the mid-plane of the pools.

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