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Preliminary Numerical Study of Hot Water Layer Temperature on Flow Stratification in Pool of Open-pool Type Research Reactor

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1. Introduction

A research reactor provides multi-purpose utilization of neutron sources such as radio-isotopes production, irradiation operation, and so on. In this type of research reactor, the reactor core is submerged in the lower part of the pool to provide core cooling and reactor safety. Therefore, the water in the lower part of the pool is highly radioactivated and is heated up by the core as well. If natural circulation occurs in the pool due to the heat from the core, the radioactivated water can rise to the surface of the pool where numbers of workers and researchers are nearby. To solve this problem, a Hot Water Layer (HWL) is often implemented in the upper part of the pool to reduce the radiation level on the pool top. The HWL is maintained at a sufficiently higher temperature than the lower part of the pool to produce a thermally stratified region in the middle part of the pool, which suppresses the natural circulation.

In this study, the flow and temperature distributions in the pool are investigated by preliminary numerical simulations. The effects of HWL temperature on flow stratification are further studied by changing the discharge temperature of the hot water in the upper part of the pool. The basic design of the on-going KIJANG research reactor (KJRR) project is considered in this study using commercial computational fluid dynamics software ANSYS FLUENT 13.0.

2. Hot Water Layer Model

In this study, the basic design of the KJRR is modeled for a hot water layer analysis. As shown in Fig. 1, the research reactor consists of a reactor pool, service pool, and spent fuel storage pool, which are connected in series. The height of the pool is 12 m and the total length is 16.3 m. The reactor structure is simply modeled as a rectangular box at the bottom of the reactor pool. In-pool pipe lines of the Primary Cooling System (PCS) are not included since the PCS is designed in a closed loop system. In-pool pipe lines of the Primary Purification system (PPS) and the Pool Water Management System (PWMS) are included in the model. The PPS maintains the quality and temperature of reactor pool water. The water from the PPS is discharged through the pipe in the lower part of the reactor pool. Then, the reactor pool water turns back to the PPS through the hole at the upper side of the reactor structure. The PWMS manages the quality and the temperature of the service pool and the spent fuel storage pool. The water is discharged through the pipes in the service pool and spent fuel storage pool and turns back through the pipes in each pool.

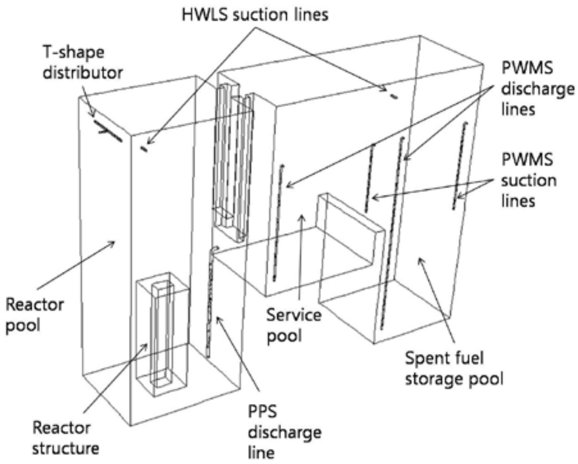

Fig. 1. Basic design of the on-going KIJANG research reactor.

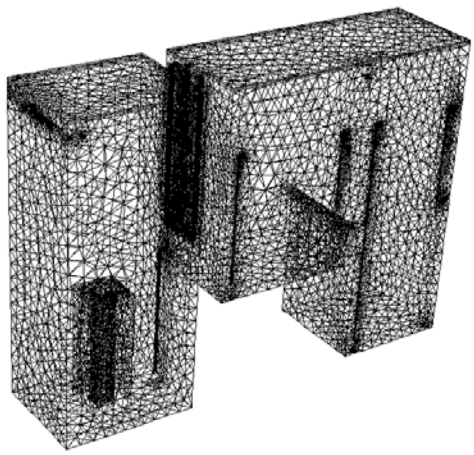

Fig. 2. Calculation domain and mesh.

The HWL is maintained by Hot Water Layer System (HWLS), which consists of pumps, ion-exchangers, and electric heaters. The water taken from the suction lines in the reactor pool and service pool is purified, heated, and then discharged to the upper part of the reactor pool through a T-shape distributor. The distributor is designed to slow down the discharge velocity of the hot water to reduce the disturbances, which are not favorable for the flow stratification.

3. Governing Equations

Governing equations and dimensionless parameters related to the natural convection and the thermal stratification are briefly reviewed. The steady state governing equations for the mass conservation, momentum and energy can be written as follows:

$$
\begin{aligned}
&\nabla \cdot \mathbf{V} = 0 \\
&\mathbf{V} \cdot \nabla \mathbf{V} = g\beta\left(T - T_\infty\right) + \nu \nabla^2 \mathbf{V} \\
&\mathbf{V} \cdot \nabla T = \alpha \nabla^2 T
\end{aligned} \tag{1}
$$

The Boussinesq approximation is introduced for the momentum equation where the thermal expansion coefficient is given by

$$\beta = -\frac{1}{\rho}\left(\frac{\partial \rho}{\partial T}\right)_P \approx -\frac{1}{\rho}\frac{\rho_\infty - \rho}{T_\infty - T} \tag{2}$$

The dimensionless parameters that govern the flow can be obtained by nondimensionalizing the governing momentum equation. Introducing

$$\nabla^* = L\nabla,\ \mathbf{V}^* = \frac{\mathbf{V}}{u_c},\ T^* = \frac{T - T_\infty}{T_H - T_\infty} \tag{3}$$

where L is a characteristic length, u_c is a characteristic flow velocity, and T_H is a hot water layer temperature. Then the momentum equation reduces to

$$
\begin{aligned}
\mathbf{V}^* \cdot \nabla^* \mathbf{V}^* &= \frac{g\beta\left(T_H - T_\infty\right)L}{{u_c}^2}T^* + \frac{1}{Re}\nabla^{*2}\mathbf{V}^* \\
&= \frac{Gr}{Re^2}T^* + \frac{1}{Re}\nabla^{*2}\mathbf{V}^*
\end{aligned} \tag{4}
$$

The dimensionless parameter in the first term on the right hand side of above equation is the buoyancy force, while the second term is the viscous force. In general, the buoyancy effects may be neglected when (Gr/Re^2) ≪ 1 and the buoyancy force dominates the flow when (Gr/Re^2) ≫ 1.

4. Calculation Method

4.1 Mesh Modeling

For this preliminary numerical study, the geometries and meshes are produced by the Geometry and the Mesh in the ANSYS Workbench 13.0. The patch conforming tetrahedrons method is used for the mesh generation with a minimum size of 0.01 m and the mesh sizing functions for proximity and curvature of the geometry. The number of generated mesh elements is 276,527 (Fig. 2).

4.2 Calculation

The flow rates of the HWLS, PPS, and PWMS are modeled reflecting the current status of the basic design. The inlet temperatures for the HWLS are varied at T_H = 35, 37.5, 40, and 45 °C for a case comparison. For the PPS and the PWMS, the inlet temperature is fixed to T_∞ = 35 °C. The flow rate and inlet temperature of each system are treated using the mass flow inlet and out flow boundary conditions implemented in FLUENT 13.0.

To simulate the formation of HWL, the calculation is made by a transient solver. A fixed time step of 5 s is used and the entire calculation is done for up to 20 hours. The changes in flow and temperature distributions are trivial after 20 hours. The initial temperature is set to 35 °C.

5. Results and Discussion

The flow velocity distributions at the mid-plane of the pool are presented in Fig. 3-6. When the HWLS inlet temperature T_H = 37.5, 40, and 45 °C, a HWL is developed at the upper part of the pool, and the average temperatures of the HWL reach 36.0, 37.7, and 40.9 °C, respectively. When T_H = 35 °C, the flows are widely distributed throughout the pools with a flow velocity range of over 0.02 m/s since there exists no temperature gradient in the pool. This indicates that the mixing of water in the pool may result in a significant increase of radiation level on the pool top since the water in the lower pool can reach the upper pool in several minutes. However, when T_H is increased to 37.5 °C, a stratified region is observed in the middle of the pool where the flow velocity falls below 0.001 m/s. The flows in the pool are separated to the upper and lower parts of the pool by the stratified region. It can be deduced that the mixing rate between the upper and lower pools may decrease and the pool top radiation level may also decrease. When T_H is increased more, the thickness of the stratified region is also increased.

The reason for the remarkable change in the flow distribution in spite of the slight temperature difference can be explained by the dimensionless parameter (Gr/Re^2). The characteristic flow velocity is assumed as the maximum velocity at the horizontal planes of 1.2 and 5 meters below the pool surface because the flow stratification is mainly affected by the flow velocities at the vicinity of the stratified region. u_c is found to be 0.02 m/s and the height of the pool, h = 12 m, is used as the length scale L. The value of thermal expansion coefficient is β = $0.4\times10^{-3}/K$. Then, the calculated values of the (Gr/Re^2) are 1.2×10^2 for ΔT = 1 °C and 7.0×10^2 for ΔT = 5.9 °C. Therefore, the flow in the pool is governed by the buoyancy force and the stratified region is formed very well. The values are noticeably high due to the large length scale and the small characteristic velocity. When we compare it to the currently operating research reactor HANARO, the characteristic velocity of KJRR is very small since the flow rates for the pool water purification are smaller than those of HANARO. This contributes to a more stable formation of the stratified region in KJRR. Moreover, the characteristic velocity can be further reduced by improving the distributor design of HWLS and the other systems. These imply that the operating temperature of the HWL in KJRR can be lower than that of HANARO, which is about 45 °C. If the temperature of HWL can be lowered, the electric power consumption required to maintain the HWL can be largely reduced.

Frankly speaking, the numerical calculations made in this study are not sufficient due to the relatively coarse mesh size, insufficient residual convergence, the large time step used in the transient solver, and so on. In a future study, the mesh size effects shall be confirmed and an accurate transient analysis shall be made to obtain more reliable information.

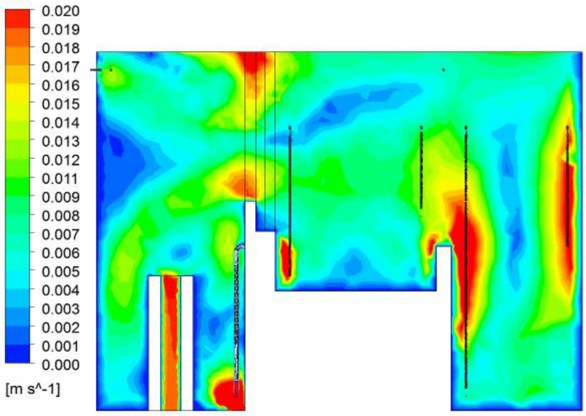

Fig. 3. Velocity distribution when HWLS inlet T_H = 35 °C.

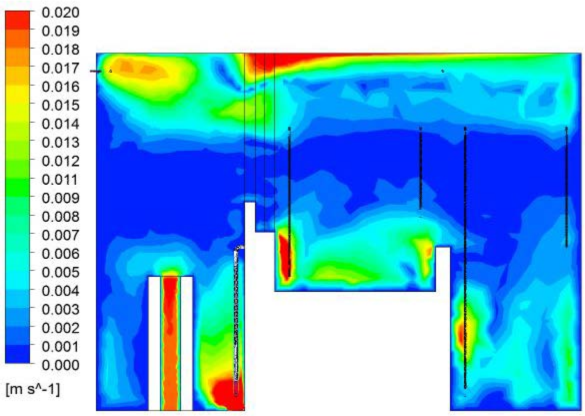

Fig. 4. Velocity distribution when HWLS inlet T_H = 37.5 °C.

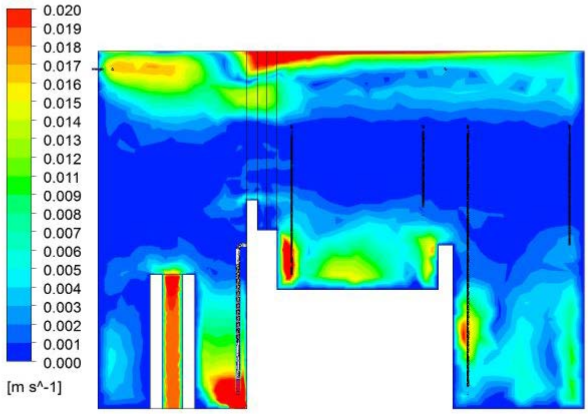

Fig. 5. Velocity distribution when HWLS inlet T_H = 40 °C.

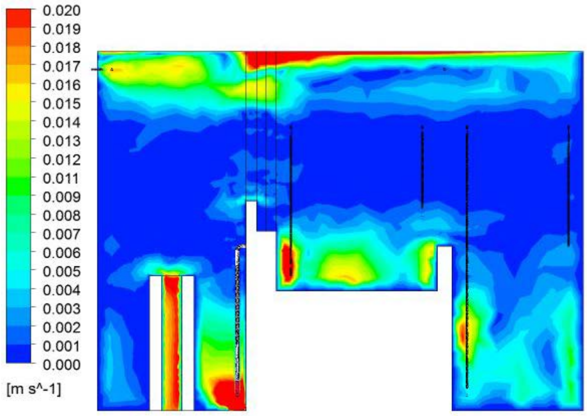

Fig. 6. Velocity distribution when HWLS inlet T_H = 45 °C.

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