LES Study of Thermal Striping along the CRDM Guide Tube in the PGSFR

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1. Introduction

The Korea Atomic Energy Research Institute (KAERI) has performed a reactor design with the final goal of constructing the PGSFR (Prototype Gen-IV Sodium-cooled Fast Reactor[1]. The main objective of the PGSFR is to verify TRU metal fuel performance, reactor operation, and transmutation ability of high-level wastes.

In the PGSFR, each subassembly has an independent flow path and is separately assigned a flow rate. Therefore, outlet temperatures between adjacent subassemblies are different from each other. Coolant mixing with different temperatures causes temperature fluctuations in structure surfaces near the core exit. This phenomenon is called thermal striping, which can induce periodic thermal fatigues and deteriorate the integrity of the structures.

Figure 1displays a schematic diagram of the reactor core and upper internal structure (UIS) in the PGSFR. The thermal striping mainly occurs in the UIS located above the core exit. Previous studies have shown that thermal damage from the thermal striping increases as approaching the core. Since the bottom plate supporting the UIS is facing most of the core flow and mixing zone, it is designed to be sufficiently far from the core outlet. However, the control rod drive mechanism (CRDM) guide tubes and thermocouples to monitor the subassembly temperature are located near the core exit. In particular, the CRDM guide tubes may suffer the thermal striping due to the strong inflow of the surrounding fuel subassemblies.

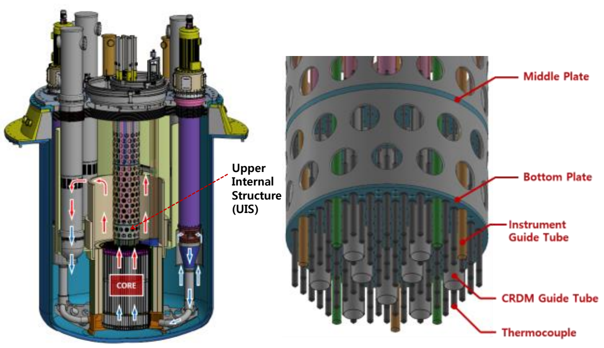

Fig. 1. Schematic diagram of the reactor core and upper internal structure

In this work, the numerical analysis has been developed to analyze the thermal striping phenomena in the UIS. A detailed evaluation was performed along the CRDM tube guide where the thermal striping may easily occurs due to the coolant mixing between the control rod subassembly and the fuel subassembly.

2. Numerical Simulation

2.1 Governing Equations

A Large Eddy Simulation (LES) turbulent model is applied to predict turbulent and temperature fluctuation of the thermal striping in the UIS. In general, the Reynolds Averaged Navier Stokes (RANS) model has been conducted for the turbulent simulation in complex structures with high computation efficiency. However, the RANS model is inappropriate for the thermal striping in which flow and temperature rapidly oscillate within a short time.

Unlike the RANS model, the governing equations for the LES model performs spatial filtering instead of taking a time average value for a special physical quantity. The solution ϕ consists of filtered value $\tilde{\phi}$ and sub-filtered value ϕ'. The fileted value $\tilde{\phi}$ can be written as follows:

$$\phi = \tilde{\phi} + \phi \quad (1)$$

$$\tilde{\phi}(t,x) = \iiint_{-\infty}^{\infty} G(x - x', \Delta)\phi(t,x')dx' \quad (2)$$

The fileted continuum and momentum conservations for the LES model are expressed by the following equations:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \tilde{V}) = 0 \quad (3)$$

$$\frac{\partial}{\partial t}(\rho \tilde{V}) + \nabla \cdot (\rho \tilde{V} \otimes \tilde{V}) = -\nabla \cdot \tilde{p} I + \nabla \cdot (T + T_t) + f_b \quad (4)$$

$$T_t = 2\mu_t S - \frac{2}{3}(\mu_t \nabla \cdot \tilde{v} + \rho k) I \quad (5)$$

where the turbulent stress tensor T_t represents a sub-grid scale stress and is obtained Boussinesq approximation. The turbulent viscosity parameter μ_t is defined based on the sub-grid-scale WALE model[2].

2.2 Numerical Methods

Numerical simulations were carried out using the finite volume CFD code, STAR-CCM+[3]. Three dimensional flow and temperature fluctuations were calculated under the unsteady condition. The data sampling was performed after the CFD analysis converged. The dependence on the sampling period from 1 to 5 seconds was evaluated, and the results showed that the sampling period more than 4 second did not reveal any difference. The main numerical parameters are summarized in Table I.

Table I: Main numerical methods

Physical Phenomena	Numerical Methods
Space	3-Dimensional
Time	Implicit Unsteady (dt=0.0001s, total=5.0s)
Flow	Segregated Flow Scheme (Bounded-Central Differencing)
Heat Transfer	Segregated Fluid Enthalpy Scheme (2nd Order)
Turbulence Model	LES with WALE Sub-grid Scale Model
Wall Function	All Y+ Wall Treatment
Buoyancy	Polynomial Density with Gravity

2.3 Computation Domain and Boundary Conditions

Since the LES model requires a huge computation capability, it is necessary to reduce the computation domain as much as possible without affecting the simulation results. The PGSFR core is approximately 120˚ symmetry along the azimuthal direction. Thus, the 120˚ region of the core, UIS and hot sodium plenum are only considered in this calculation as shown in Fig. 2. It contains two primary and one secondary control assemblies.

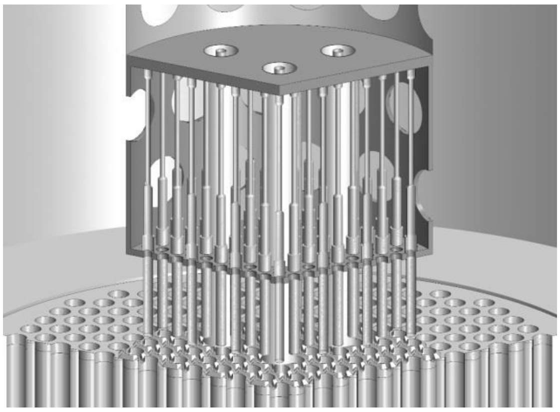

Fig. 2. Computation domain for the thermal striping analysis

Flow rates and temperatures from each subassembly are provided from the core thermal-hydraulic design[4]. Compared to the surrounding fuel subassemblies, the control assemblies for the thermal striping study reveals relatively low flow rates and temperature. The flow rate of the control assemblies is 2.11 kg/s, which is approximately 1/5 to 1/10 of fuel assemblies. The maximum temperature differences between two adjacent subassemblies are from 50 to 55℃ as shown in Fig. 3. The simulation flow outlet condition is the pre-calculated pressure boundary. Each outlet boundary region is mapped from the whole reactor simulation previously conducted in the steady state with the RANS model.

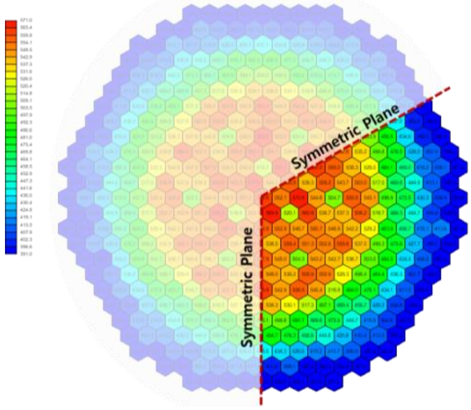

Fig. 3. Outlet temperature condition in each subassembly

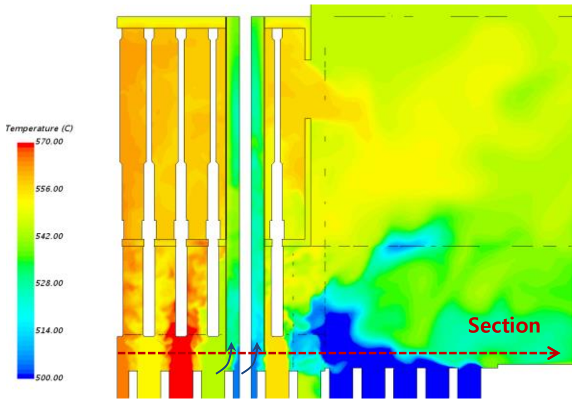

Fig. 4. Temperature distribution in the vertical section (CR #1)

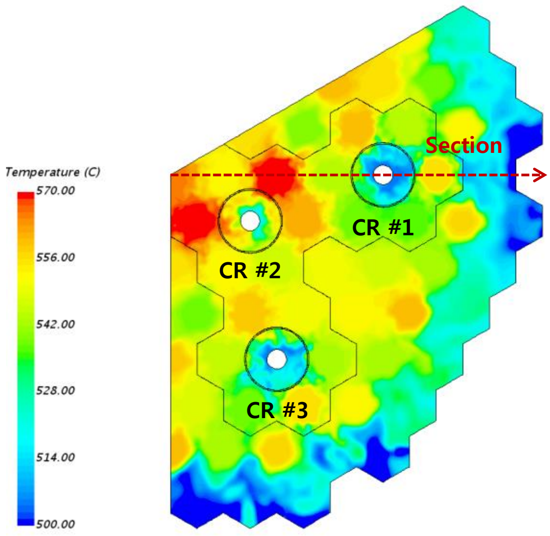

Fig. 5. Temperature distribution in the horizontal section (H=50.0 mm from the core exit)

3. Results and Discussion

Figures 4 and 5 display instantaneous temperature distributions during the thermal mixing in the vertical and horizontal sections, respectively. The vertical section is the plane from the core center to the CR #1. The horizontal distribution is depicted at a height of 50.0 mm from core exit, where the end tip of the CRDM guide tube is located. An irregular temperature pattern is formed along the mixing region between adjacent subassemblies. The turbulent flow and vortex generated from the core exit enforce this pattern to fluctuate in time and space. Since the flow rates of the control assemblies are much smaller than those of the fuel assemblies, there is an inflow into the CRDM guide tube.

The maximum temperature fluctuation on the solid surface is occurred at the end tip (H=50.0mm) of the outer CRDM guide tube (CR #1) as shown in Fig. 6. The turbulent vortex along a mixing region between two adjacent subassemblies induces the oscillating temperature on the surface of the CRDM guide tube. The oscillating amplitude is about 40 ℃ close to the maximum temperature difference of 51.1 ℃ between two adjacent subassemblies. The root mean square (RMS) of the temperature fluctuation is 9.39 ℃, which corresponds to 18.3% of the maximum temperature difference. Figure 7 reveals the fast Fourier transform (FFT) result of the temperature fluctuation. The temperature oscillations are observed over a wide range of frequencies from 0.1 Hz to tens of Hz. The main oscillation is at 15.4 Hz.

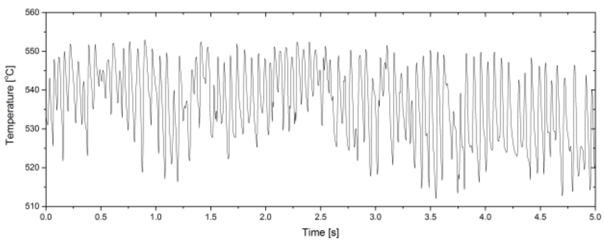

Fig. 6. Time history of the maximum temperature fluctuation at the CR #1

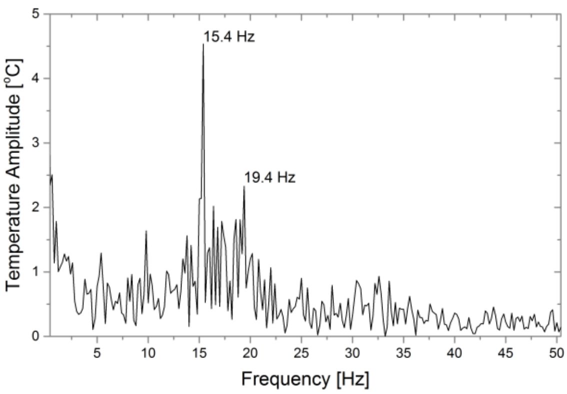

Fig. 7. FFT result of the maximum temperature fluctuation at the CR #1

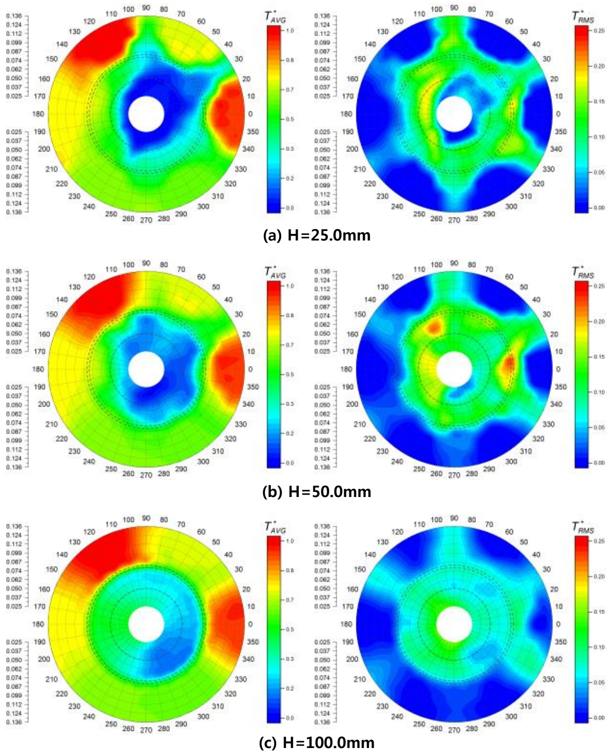

Fig. 8. Average and RMS temperature contours along the axial height near the CRDM guide tube

Figure 8 represents the detailed thermal striping phenomena near the outer CRDM guide tube (CR #1). The normalized average and RMS temperatures are calculated for a total of 5 seconds as follows:

$$T^*_{avg} = \frac{\sum\left(\frac{T - T_{min}}{\Delta T_{max}}\right)}{N} \quad (6)$$

$$T^*_{RMS} = \frac{\sqrt{\frac{\sum(T - T_{AVG})^2}{N}}}{\Delta T_{max}} \quad (7)$$

where ΔT_{max} and N are the maximum temperature difference between the control subassembly and adjacent fuel subassemblies and the number of time steps, respectively. T_{min} and T_{AVG} are the minimum and average temperatures during the whole simulation time, respectively. The temperature contours are depicted along the axial direction from the core exit.

Since the thermal mixing between adjacent subassemblies rarely proceeds near the core exit, the flow areas with different temperatures are clearly distinguished. Radial mixing proceeds along the axial direction and the temperature fluctuation gradually vanish from a height of 100 mm. The maximum RMS value is 26.3% of the maximum temperature difference (ΔT_{max}) near the core exit. The overall core radial flow moves the maximum fluctuation position in the core outward direction (0 degree). The temperature fluctuations on the solid surface from the flow mixing are evaluated at the CRDM guide tube of the outer control assembly, combining the core radial flow and the relatively high flow rate of adjacent fuel assemblies.

4. Conclusions

The thermal striping along the CRDM guide tube in the PGSFR is evaluated by the LES model. This model is employed to characterize small and fast turbulent vortices generated from the core exit. Temperature fluctuation is observed along a mixing region between two adjacent assemblies. The maximum temperature fluctuation on the solid surface occurs at the CRDM guide tube tip of the outer control assembly in the core outward direction. The RMS value of the temperature fluctuation is 18.3% of the maximum temperature difference. The present CFD analysis is employed to evaluate creep-fatigue damage due to the temperature fluctuation cycles in the UIS.

ACKNOWLEDGEMENT

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