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A Study on Heat Transfer Phenomena of Reactor Vessel with Structural Heat Source

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1. Introduction

The RVI of APR1400 operates in harsh conditions, such as long term exposure to neutron irradiation, high emperatures, and other operating loads. Even though they are mainly made of Type 304 austenitic stainless steel which is well known to have good mechanical properties and corrosion resistance, these operating conditions, especially neutron irradiation, cause them to age[1,2].

The present study is to evaluate temperature distributions of core structures in the conservative fuel cycle whether or not irradiation effect on structures and effective thermal conductivity (ETC) in relation to isotropic and anisotropic conductivity of porous media for APR1400 Reactor Vessel.

2. Methods

2.1 Configuration of Geometric Model

The APR1400 reactor vessel internals (RVI) consist of two major structures, the core support structures and internal structures. The RVIs are composed of core support barrel (CSB) assembly, the lower support structure (LSS) and in-core instrumentation (ICI) nozzle assembly, and the core shroud (CS). The general arrangement of the APR1400 reactor is shown in Fig. 1.

2.2 Boundary Condition and Simulation Parameters

The numerical analysis is performed for the normal operation condition. In this study, a thermal porous media methodology is used for the actual analysis for the reactor core.

The flow rate at the inlet flow of the reactor has a fully developed profile with a temperature of 290.6 °C and a pressure of 15.51 MPa in the RV and the water is discharged with a temperature of 323.9 °C. All of the outside walls were treated as adiabatic smooth walls obeying the no-slip conditions. A symmetry condition is adopted for the both sides of a quarter model. Thermal power, 996 MWth, and inlet flow, 5,231.2 kg/s, are the amount of heat generation and flowrate from one quarter core model as shown in Table I.

The irradiated heat amount with conservative fuel cycle obtained by MCNP neturon analysis[3] is mapped into solid grid structure using interpolation scheme.

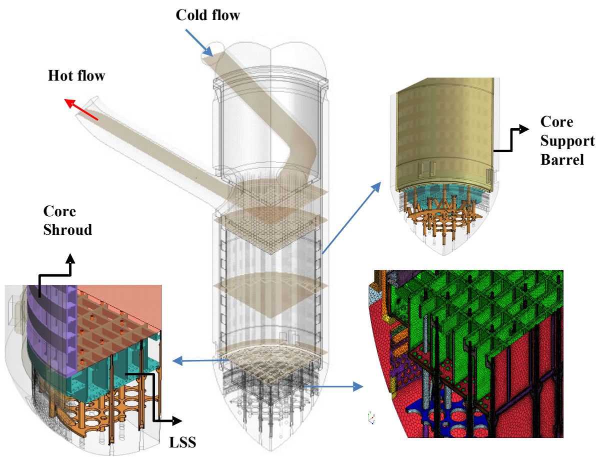

Fig. 1 Geometry model of the RVI and Computational Grid

Table I. Simulation Parameters

Parameters		Value	Unit
Thermal power		996	MWth
Operation pressure		15.51	MPa
Temperature	T_{Cold}	290.6	°C
	T_{Hot}	323.9	
Mass flow rate		5,231.2	kg/s

2.3 Numerical Methods

For treatment of porous media in STAR-CCM+[4], the flow passage is simplified as a channel flow governed by Darcy's law with pressure drop, and superficial velocity. Pressure gradient of porous media is given by the following equation.

$$-\nabla P = \frac{\mu}{k_p} v \tag{1}$$

v : superficial velocity (m/s)
μ : viscosity (Pa·s)
k_p: permeability factor (m^2)

For the flow solver, porous source term appears in the momentum equation as tensor and given by the below equation.

$$P = P_v + P_i |v| \tag{2}$$

P_v , P_i: viscous (linear) and inertial (quadratic) resistance tensor

The effective thermal conductivity of the porous region is defined as the ratio of the open area to the total volume of the porous medium. This value is mainly used to mix the thermal conductivity of the solid and fluid materials[5]. Here it is assumed that heat conduction in the solid and fluid phases takes place in parallel so that there is no net heat transfer from one phase to the other. The energy equation for solid-fluid phase is as follows.

$$\rho_s c_{ps}(1-\varepsilon)\frac{\langle T\rangle^s}{t} = k_s(1-\varepsilon)\text{�}^2\langle T\rangle^s \ \text{�} \ \frac{\text{殞}}{\text{湧憲}V}\ \text{窒}_s Tds \quad \frac{1}{V}\ {}_s k_s Tds \quad (3)$$

$$\left(\rho c_p\right)_{sf} = (1-\varepsilon)\rho_s c_{ps} + \varepsilon\rho_f c_{pf}$$
(4)

ETC (isotropic tensor):

$$k_{sf,xx-yy-zz} = (1-\varepsilon)k_s + \varepsilon k_f$$
(5)

ε *: Porosity*
k_s, k_f *: Thermal conductivity of solid and fluid*
$xx-yy-zz$ *: coordinate direction*

3. Results

For accuracy of calculation, grid sensitivity was examined. Three different mesh sizes were chosen ~ 15 10^6, ~21 x 10^6, and 37 x 10^6, which are generated with a polyhedral mesh.

A polyhedral mesh is that they have many neighbors (typical of order 10), so gradients can be better approximated (using linear shape functions and the information from nearest neighbors only) than is the case with tetrahedral or hexahedral cells. Even along wall edges and at corners, a polyhedral cell is likely to have a couple of neighbors, thus allowing for a reasonable prediction of both gradients and local flow distributions[4].

The appropriated grid size was determined by comparing the results of the pressure loss and temperature distribution in various regions of flow path and internal solid structure in these three grid cases. Three results of temperature and pressure loss are shown in Fig. 2 and 3 for ��� �and Realizable ����

Fig. 2 and Fig. 3 show that there are no significant difference in the temperatures and the pressure drop (RV exit temperature, fuel core temperature, 324 °C, 326 °C and deviation between pressure drops (CS-CSB) ≈2 %). The deviations in the grid test corresponding to the number of cells are expected to result in a relatively uniform level (within 2% difference), suggesting that the ��� �turbulence model and medium mesh case used in this study.

Fig. 4 is a result for isotropic ETC whether or not irradiated structure heat source on various part of the RVI. Without solid heat source, the maximum temperature was found on fuel (325.8 °C), whereas with solid heat source the hot spot appeared on CSB (341.8 °C).

The highest difference of temperature was found on the CS, which was over 20 °C. On the fluid, however, the effect of solid heat source seems to be ignorable. The temperature difference was 0.1 °C on fluid.

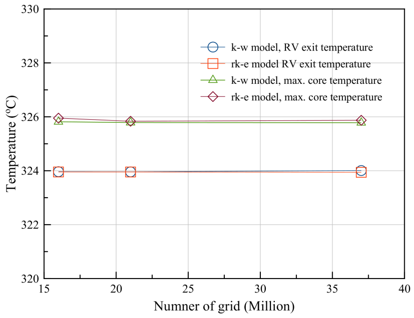

Fig. 2 Results of temperature for grid/turbulence test

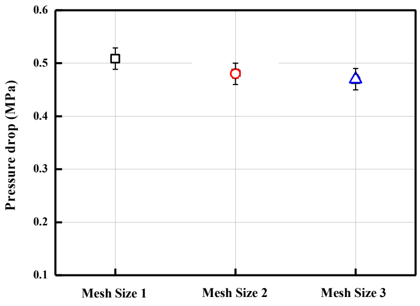

Fig. 3 Pressure Drops (CS-CSB) in the Grid Test/Turburence

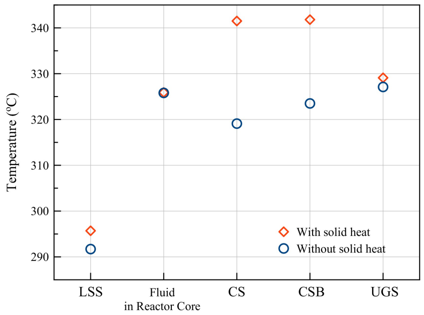

Fig. 4 Maximum temperature on each part of RVIs

3. Conclusions

The work presented in this study assesses the temperature distributions and the maximum temperature in the RVIs whether irradiated structure heat source is considered or not. Isotropic effective thermal conductivity was assumed with conservative fuel cycle condition.

In respective of using irradiated structure heat source, it is evident that the effect of the neutron irradiation is significant on the CS and the CSB. Otherwise there is no effect to fluid temperature.

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