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Effect of Bottom Blockage on Heat Transfer in Single Equivalent Cooling Channel of a Spent Fuel Pool

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1. Introduction

In recent years, numerous attempts have been made to study severe accident in a spent fuel pool (SFP) or dry storage system. System analysis codes are mainly used to analyze accident in SFP and to develop accident management guidelines or regulations for SFP.[1] 3-dimensional CFD method have been also used, for example, Hung et al.(2013) conducted CFD analysis on a SFP with modelling a spent fuel assembly as a porous medium.[2]

However, what seems to be lacking is database on local information of a partially uncovered spent fuel pool. Partial uncover of SFP can arise from the boil off scenario under long term large scale station black out, or leakage of coolant by accident. It is expected that deterioration of heat transfer in a partially uncovered SFP can cause dramatic change of temperature field. Schultz et al.(2013) conducted experiment on a BWR fuel assembly with bottom blockage condition, and they concluded that there is almost no convection near the bottom region.[3] Even though partial uncover of SFP are frequently simulated, modelling uncertainties on the case have been not sufficiently evaluated due to lack of experimental data.

In this study heat transfer in an equivalent fuel cooling channel was numerically studied to develop the basis for the study of a partially uncovered SFP. Transient characteristics of heating surface were analyzed under several boundary conditions.

2. Numerical Modeling

As shown in table I, 5 kinds of cases on single 1m fuel rod were investigated. Two heater geometry were used for this study, one is tube for its simplicity and other one is real fuel rod. Considering vertical and horizontal thermal resistance of a fuel assembly, following rough conjectures can be made: heat from side ones may be transferred in horizontal direction, and heat from core ones may be transferred in vertical direction. Both heat transfer direction were treated here. Based on such configuration of problem, effect of bottom blockage are investigated.

Geometry of a PWR 17x17 assembly was used for the prototype of this study.[4] Dimensions and properties of components in test section of case 1~4 are summarized in table II. Properties of air were varied by temperature change as the data of Incropera et al.(2013).[5] For case 5, diameter of air channel was reduced to 14.2mm, and properties of real fuel rod were used.[6,7]

Table I: Classification of cases

Case #	Geometry of heater	Direction of heat transfer	B.C. at bottom of test section
1	Tube	Horizontal	Open
2			Closed
3		Vertical	Open
4			Closed
5	UO_2 Rod		Closed

Table II: Properties used for case 1-4

	SUS	Air	Pyrex	Glass wool
I.D. [mm]	6.5	9.5	20.4	25.4
O.D. [mm]	9.5	20.4	25.4	80
Density [kg/m^3]	7854	Ref. [5]	2000	50
Specific heat capacity [J/kg K]	434		750	670
Thermal conductivity [W/m K]	15		1.005	0.04

2-dimensional mesh was constructed as shown in figure 1 under an axisymmetric flow assumption. Number of element in radial direction were 2 for heating tube, 8 for air, 2 for pyrex tube, 4 for glass wool. Axially 100 elements were made, and therefore total 1600 elements were used. In the case of vertical heat transfer, the adiabatic condition was applied on the outer surface of cooling channel, and only a heating tube or a fuel rod and gas region were analyzed.

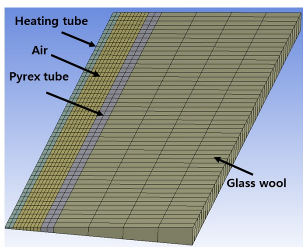

Fig. 1. The whole mesh of the test section.

ANSYS CFX 15.0 was used for this study. First backward Euler transient scheme with fixed time step 0.2 [sec] was used. In the fluid region, laminar model was used and discrete transfer model was used for the radiation heat transfer.(number of ray = 8, emissivity of SUS=0.3) No steam vapor or liquid were simulated. Oxidation model also was not used. Initial condition was set to 25˚C with stagnant atmospheric pressure.

In all the cases, boundary condition of upper surface was set to 25˚C, 0 Pa opening condition which means fluid can come in and out without any restriction, and B.C. of inner side of SUS tube was set to adiabatic wall.

Constant heat was generated in the SUS tube or UO_2 rod homogeneously. Total heat generation from the heater is 40W. For instance, Wu et al.(2014) considered two different groups of spent fuel assemblies. One group is consists of last core discharged batches which produce 50370W/FA(fuel assembly). Other group is consist of older fuel assemblies which generates 1242W/FA. Therefore arithmetic mean of heat generation is 9392W/FA. If we assume the number of fuel rod as 264, the arithmetic mean of heat generation per single fuel rod is 35.57W. Considering the reduced length scale of the test section here, it is corresponding to some large amount of decay heat.[8]

3. Results and discussions

3.1 Temperature distributions

The vertical distribution of temperature was computed as shown in figure 2. First, the direction of heat transfer result in huge difference between them. The maximum temperature on a heating surface of case 1 and 2 are 270.3˚C and 285.3˚C, respectively. However, case 3~5 show over 700˚C for the maximum temperature. Note that oxidation is not calculated here.

Second, cases which have open bottom of test section result in smaller axial temperature gradient at bottom due to fast gas flow. Therefore overall temperature of these cases are lower than that of cases which have blocked bottom.

Third, there is some difference between case 4 and 5. Cases of tube heating (case 1~4) show steady state at almost t = 2 hr. However steady state of case 5 is obtained at almost t = 8 hr. (maximum temperature 1836 ˚C) Maximum value and shape of temperature distribution have also some difference between them.

In order to explain the characteristics of these resultant temperature profiles, simple thermal circuit analysis is conducted in following section.

3.2 Theoretical considerations

Because the annular test section is too narrow, it can be conjectured that the internal natural convection may have conduction regime. Based on such assumption, following convective heat transfer model can be obtained.

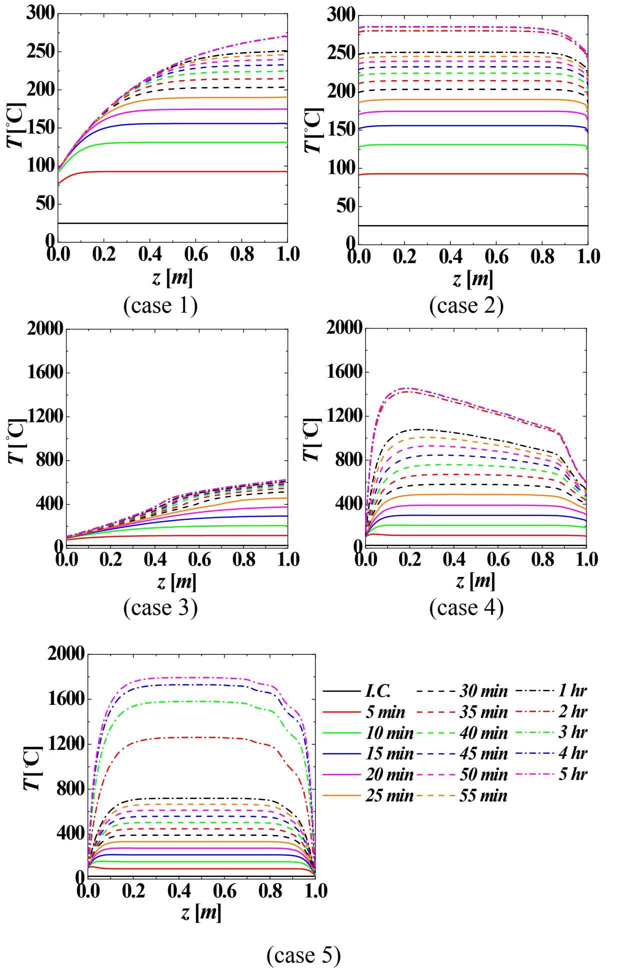

Fig. 2. Vertical profiles of temperature on a cladding surface.

$$Nu = \frac{h_c\left(r_2 - r_1\right)}{k_A} = \frac{r_2 / r_1 - 1}{\left(\ln\left(1+\left(r_2/r_1\right)\right) - \ln 2\right)} = 2.530 \qquad (1)$$

where h_c is convective heat transfer coefficient, k_a is thermal conductivity of air, r_1 and r_2 is radius of a fuel rod and cooling channel, respectively.

In the case of horizontal heat transfer, following thermal circuit model can be constructed for steady state temperature distribution of test section.

$$T_1 - T_2 = Q\left(\frac{R_c R_r}{R_c + R_r}\right) \qquad (2)$$

$$T_2 - T_\infty = Q\left(\frac{\ln\left(r_3/r_2\right)}{2\pi k_{23} L} + \frac{\ln\left(r_4/r_3\right)}{2\pi k_{34} L}\right) \qquad (3)$$

where T_1, T_2, and T_∞ is temperature of fuel cladding, fluid, and atmosphere. Q is heat generation from the fuel rod, and L is length of a fuel rod. R_c and R_r is convective and radiative thermal resistance, respectively. k_{23} and k_{34} is thermal conductivity of a pyrex and glass wool, respectively. r_3 and r_4 is radius of a pyrex and glass wool, respectively.

T_2 = 209.6 ˚C can be directly solved from equation (3). Then T_1 also can be solved through the 4th order algebraic equation and T_1 = -1291, -822.2, 275.9, 744.9 °C are obtained. The third and fourth solutions have physical meaning, and the third one is similar to the maximum steady state temperature of case 2.

If lumped parameter modeling is applied to the heating tube, following time constant can be obtained.

$$\tau = \frac{\rho V c}{h_c A_1} = \frac{\rho c}{h_c}\frac{\left(r_1^2 - r_0^2\right)}{2r_1} = 1724[\text{sec}] \tag{4}$$

Here only the convective one is used for the heat transfer coefficient. From this calculation, the time which is needed to reach the steady state is predicted to almost 5τ = 2.394 hours, and it is well supported by the result of case 1~4.

In the case of vertical heat transfer, it is difficult to explain that why such temperature profile is computed. As shown in figure 3, open bottom case show similar amount of convective heat transfer and radiative heat transfer on the cladding. However, in the case of blocked bottom case, dominant mode of heat transfer is radiation. Near top and bottom of test section, there is some abrupt change of heat flux, and it may be due to the vertical conduction in cladding. Because the thermal resistance of vertical conduction is very small near the heat sink, i.e. top and bottom of test section, conduction in cladding may be dominant at the region.

Based on this result, with an assumption of uniform temperature and heat flux, simple radiation equation can be made as following.

$$T = \left(\frac{Q}{\sigma A_\infty} + T_\infty\right)^{\frac{1}{4}} \tag{5}$$

where A_∞ is cross sectional area at top and bottom of gas region. Equation (5) generate solutions as 792.3°C for case 4 and 1119°C for case 5. These solutions are much smaller than the maximum temperature of CFD results of each cases. It seems that the reason is the assumption of uniform temperature distribution.

3. Conclusions

Considering a partially uncovered SFP, heat transfer in single equivalent cooling channel was numerically investigated. Thermal circuit analysis was accompanied to explain trend of CFD results. Most cases were analyzed for tube heater, and soundness of it were well supported by fuel rod case.

Bottom blockage hinders convective heat transfer. Therefore axially long and almost uniform hot zone is formed, contrary to developing temperature profile with low temperature gradient of opened bottom case. Moreover, if heat is vertically transferred, bottom blockage make dramatic increase of steady state temperature and temperature rising speed. As a result, for instance, amount of hydrogen generation can be largely varied by bottom blockage of spent fuel pool.

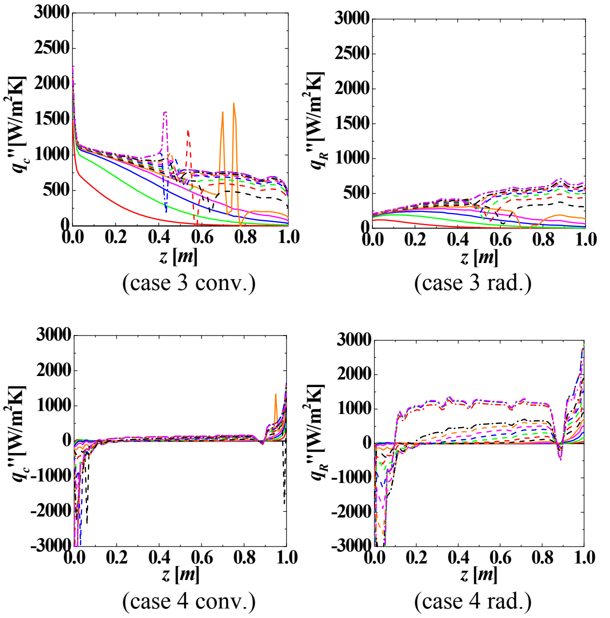

Fig. 3. Vertical distributions of heat flux on a cladding surface.

Extension of the methodology of this study to fuel assembly is needed to show the applicability of this single rod case. If the thermal circuit analysis can be applied to investigate local information of spent fuel pool, much insight may be obtained due to its simplicity and efficiency of analyzing time.

Acknowledgements

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