Analysis of a Molten Pool Natural Convection in the APR1400 RPV at a Severe Accident

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1. Introduction

During a hypothetical severe accident, reactor fuel rods and structures supporting them are melted and relocated in the lower head of the reactor vessel. These relocated molten materials could be separated by their density difference and construct metal/oxide stratified pools in the lower head[1]. A decay heat generated from the fuel material is transferred to the vessel wall and upper structures remaining in the reactor vessel by natural convection. As shown in Fig. 1 two-layered stratified molten pool is developed in the reactor lower vessel. The oxidic pool usually constructed by the mixture of uranium oxide and zirconium oxide. The melting temperature of the oxidic material is very high compared to the steel vessel and metallic layer. And highly turbulent natural convection generated by the decay heat enhances heat transfer to the boundary of the oxidic pool. By this thermal mechanism, oxide curst is developed around the oxidic layer as shown in Fig. 1. The oxidic pool is bounded thermally and fluid-dynamically by the developed crust. By this boundedness, the heat transfer structure in the stratified oxidic/metallic pool can be solved separately. The thermal boundary condition of the oxidic pool is isothermal with constant melting temperature of the oxidic material. The decay heat is transfer to side wall and upper interface between oxidic and metallic layer. Turbulent natural convection is dominant heat transfer mechanism in the oxidic pool. The heat transferred from the bottom oxidic layer is imposed to the upper metallic layer. This transferred heat in the metallic pool is removed through side and upper surface, which is augmented also by natural convection developed in the pool.

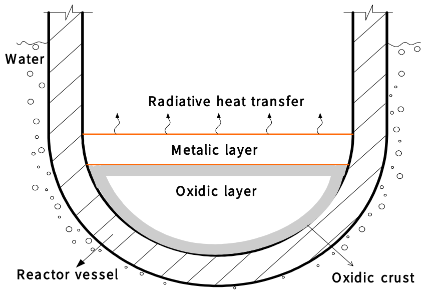

Fig. 1 Metal-oxidic stratified pool, reference[1]

In this study, a molten pool natural convection in the APR1400 RPV during a severe accident is simulated using the Lilac code[2] and the calculated heat flux distribution on the reactor vessel wall is compared with a lumped-parameter (LP) prediction.

2. Numerical models

LILAC is a multi-dimensional thermo-hydraulic analysis code that solves the Reynolds-averaged Navier-Stokes and energy equations as governing equations. Turbulent flows are modeled by two-equation turbulence models (κ-ε and κ-ω models) or large eddy simulation, and a molten pool crust is modeled using enthalpy-porosity method. A solution domain can be 2-dimensional, axisymmetric, and 3-dimensional. LILAC is based on the unstructured mesh technology to discretize a solution domain. The advantage of the unstructured mesh finite volume formulation is the ability to treat complex geometry and physics in a simple and clear fashion. To discretise the spatial domain in context with the unstructured grid finite volume method, the cell centered collocated scheme was employed.

In this study LP modeled is developed and used to analyze the thermal characteristics in the APR1400 reactor vessel during a chosen severe accident. For the hemi-spherical pool with natural convection, many experimental correlations for heat transfer coefficients are available. The upper and downward heat transfer coefficients can be obtained using the correlations[1] obtained from experiments. To calculate heat flux on upper and side walls, it is necessary to know bulk temperature of the oxidic pool. The bulk temperature is obtained by using the energy conservation equation. The metallic pool is heated from bottom wall and cooled from upper and side surfaces. The imposed heat flux on the bottom surface of the metallic pool is obtained from the lower oxidic layer.

3. Numerical Analysis

A 3″ LOCA was chosen to simulate natural convection heat transfer and to find heat flux distribution on the reactor vessel wall using the Lilac code. Masses of the molten materials relocated in the lower head during the 3″ LOCA was obtained from the SCDAP/RELAP analysis. Each mass of the materials is summarized in Table 1. In this study, it was assumed that the materials are mixed and form two separate mixtures, i.e. oxidic and metallic mixtures. Thermal properties of the oxidic and metallic mixtures are calculated using the correlations described in the MATPRO[3].

The thermal characteristics of the 3″ LOCA was analyzed using the LP model in order to compare with the CFD results. Table 2 is the results from the LP analysis. The expected Ra number of the oxidic layer is about 5×10^{15}, but it is about 7×10^{9} for the metallic layer, which means the turbulent natural convection regimes are different in the two layers. The main interesting point of the stratified two-layer molten pool is the heat flux distribution and thermal focusing effect by the molten pool stratification. The heat flux concentration factor is expected to be 1.8 by the LP model.

Table 1 Masses of the materials relocated in the lower head

material	UO_2	ZrO_2	steel	Zr
mass	1.01E+05	1.07E+04	5.00E+04	1.05E+04

Table 2 Thermal characteristics of 3″ LOCA from LP model

oxidic pool angle = 68.3 degree
Ra number of oxidic layer = 5.01E+15
Pool temperature = 3106.4 K
upward heat flux of oxidic layer = 1.16E+06 W/m^2
downward heat flux of oxidic layer = 7.03E+05 W/m^2
thermal splitting p_up/p_tot = 0.54

angle of upper surface of the metalic layer = 81.8 degree
Ra number of metalic pool = 6.9E+09
metalic pool temperature = 1775.0 K
side wall heat flux from metal layer = 2.05E+06 W/m^2
heat flux concentration factor = 1.80

In this study, the stratified molten pool is solved separately using the Lilac code. The oxidic pool was modeled in quasi 3-dimension with single computational cell in circumferential direction, and it was solved using a time-marching method instead of an iterative method because of a convergence problem which is originated from the very high volumetric heat source. After 2500 s, a quasi-steady solution was obtained. Fig. 2 depicts the calculated temperature distribution in the oxidic pool. A thermal boundary layer developed near the curved downward surface and thermal jet formed in the upper part of the pool are shown in the figure. The calculated upward heat from the oxidic pool is 1.23 MW/m^2 which is similar to the value from the LP model.

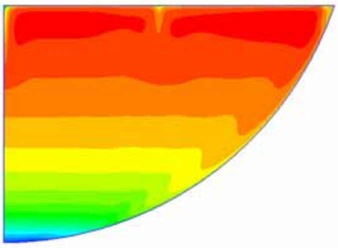

Fig. 2 Temperature distributions in the oxidic pool

The metallic layer was simulated with RANS-LES (Reynolds averaged NS with large eddy simulation) hybrid method. The mesh used for the calculation is shown in Fig. 3, where the number of computational cells is about 1 million. Fig. 4 is the instantaneous vector field at the center surface. The Calculated heat flux concentration factor using the Lilac code is 1.68 which is a little lower than the value expected using the LP model. The vector field looks like the Rayleigh-Benard convection. The side wall heat fluxes from the metallic layer calculated using the Lilac code were very scattered because of the unsteadiness of the flow structure. The side wall heat fluxes are fitted into a linear curve. The final heat flux distribution obtained by the Lilac code simulation is plotted and compared with the result from the LP model in Fig. 5. The discrepancy is found in the figure, but the pattern of the heat flux distribution is similar each other. In the LP model, the heat flux is assumed uniform at the upper layer, but it is linearly distributed in the Lilac results.

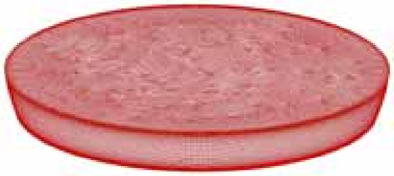

Fig. 3 computational mesh for the metallic pool

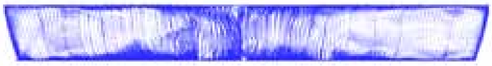

Fig. 4 Calculated velocity field in the metallic pool

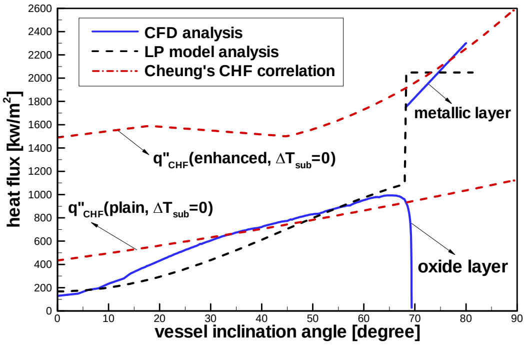

Fig. 5 Heat flux distributions from the LILAC code and LP model compared with CHF correlations.

The heat flux profiles obtained from the analyses were compared to the CHF on the outer vessel wall. It shows that the CHF enhanced by surface coating and vessel insulation structure proposed by Cheung[4] could overcome the thermal load from the 3″ LOCA.

4. Conclusion

In this study, the thermal load on the APR1400 reactor vessel from the molten corium during the 3″ SBLOCA severe accident was analyzed by CFD and LP methods and they were compared to the CHF correlations. It is concluded from the analysis that CHF enhancement is needed for the in-vessel retention.

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