CFD Analysis of Heat Transfer Phenomena with Phase Change in Molten Corium

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1. Introduction

The hypothetical scenario of a severe accident with core meltdown and formation of a molten pool in the lower plenum of the reactor pressure vessel (RPV) can result in the failure of the RPV and the discharging of the melt to the containment. Reactor vessel flooding is a one of the severe accident management to stabilize of the RPV by cooling the outside the vessel wall with water. (Fig. 1)

Heat transfer phenomena including the thermal mixing due to natural circulation in the multi-fluid stratified molten pool and the conduction in RPV structure must be investigated to evaluate the thermal and structural integrity of the RPV.

The aim of this study is to offer detailed information on thermal hydraulic phenomena in the molten pool and RPV structure. The conjugated heat transfer between the melt pool and the RPV structure is simulated using computational fluid (CFD) dynamics technique using phase change model for melt pool solidification.

2. Numerical Methods

In the present work, a two layer pool consisting of the metallic layer and the oxidic molten pool is considered. The Volume of Fluid (VOF) method is used for capturing the liquid-liquid interface between the two immiscible molten fluids. As using VOF method, the natural convection flow and heat transfer in both the two immiscible molten fluids.

Since the radiation and convection heat transfers occur on the top surface of metallic layer and on the outside boundary of RPV, The molten fluid can be solidified and formed to be crust. To achieve simultaneous computation of fluid flow, heat transfer and phase change, the enthalpy-porosity method introduced by Voller and Prakash (1987) which considers the solidification mushy zone as pseudo-porous medium.[1]

The calculation domain is divided into two region, fluid region representing molten fluids and solid region representing RPV structure. (Fig.2) The lower plenum of the RPV is almost hemi-spherical shape, the flow and axis-symmetric assumption is adopted for molten fluids heat transfer.

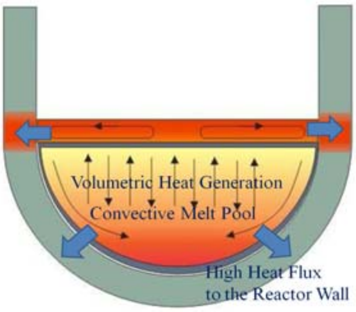

Fig. 1 Schematic of the Molten Corium Relocation and Heat Load on the Reactor Wall

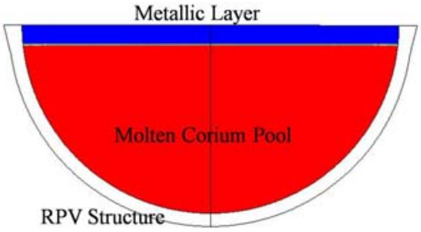

Fig. 2 RPV Lower Plenum Geometry and Two Layer Model

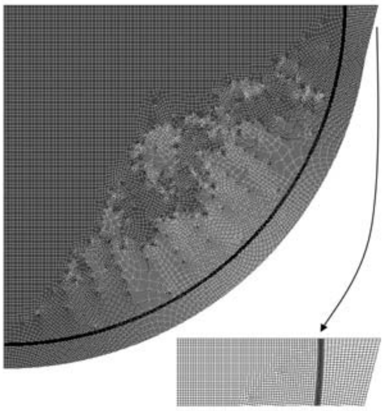

Fig.3 2D Computational Grid

Several conservation equations are numerically solved to obtain flow and temperature fields. A volume fraction equation is solved to track the interface between two immiscible molten fluid. The momentum conservation equation is solved to obtain velocity and pressure fields. To include turbulent effects in the flow domain, the standard k-ε model is adopted, and thus the turbulent kinetic equation and turbulent kinetic energy dissipation equation are solved together. The energy equation is solved to evaluate temperature distribution in the entire domain and the solidified crust formation in the lower oxidic molten pool. The two dimensional computational grid is shown in Fig. 3. About 50,000 hexahedral cells are generated.

Volumetric decay heat generation is applied at all computational cells of fluid. The ANSI-79 equation is used for the decay heat varied with time. For heat transfer conditions to remove the decay heat from the molten corium, radiation heat transfer condition is applied at the top surface of metallic layer and boiling heat transfer condition at outside wall of RPV with external cooling is applied. At all boundary surrounding fluid region, no slip conditions are applied.

3. Results

The temperature fields in the molten fluid and the RPV structure are shown in Fig. 4. Due to the external reactor vessel cooling, large temperature gradient appears and the temperature of molten corium near the RPV inner wall is much less than Solidus temperature. However, large portion of the molten corium have very high temperature above liquidus temperature of corium yet due to the decay heat generation.

The solidified region (corium crust) of the molten fluids is shown in Fig. 5. The thick crust is formed near the bottom of RPV. The crust thickness is decreased along the RPV wall with upward direction. If the solidified crust have a strength, the crust might affect RPV integrity because pressure boundary of reactor coolant system pressure is the top surface of the lower crust.

Fig.6 shows velocity field in the molten fluid. The natural convection flow is not activated in the lower region of the molten pool because the flow is restricted by the solidified region which can have porosity generating the momentum resistance. Also, because the thermal stratification in the molten pool is partly achieved, the molten fluid in the lower region could not have upward momentum. The local natural circulation flow pattern appears in both two molten fluid. But each natural circulation flow is separated by solidified upper crust.

The heat flux on the outer wall of RPV is plotted in Fig. 7. The heat flux near the bottom of RPV is relatively smaller than that of upper wall. The heat flux have peak near the interface between the metallic layer and the molten corium.

4. Conclusions

The natural convection and heat transfer phenomena in RPV have been simulated using a computational fluid dynamics. Temperature distribution in the RPV lower plenum and heat flux from the molten corium to RPV outside are obtained quantitatively. Also, the spatial crust formation is obtained.

The results of the present study show that CFD analysis results reflect physical phenomena in RPV lower plenum such as the natural convection and the crust formation properly. Therefore CFD can be broadly used for the severe accident analysis relate to core melt in a RPV lower plenum.

REFERENCES

[1] S.Alavi and M. Passandideh-Fard, Numerical Simulation of Droplet Impact and Solidification Including Thermal Shrinkage in a Thermal Spray Process, Frontiers in Heat and Mass Transfer, Vol.2, 2011

ACKNOWLEDGEMENT

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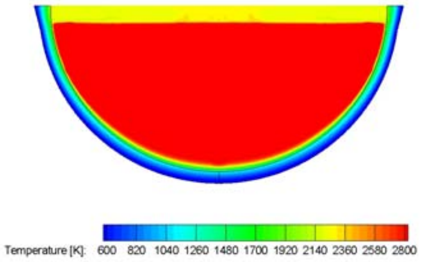

Fig.4 Temerature field in the Lower Plenum

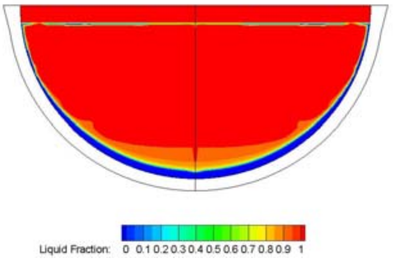

Fig.5 Solidified Crust Distribution

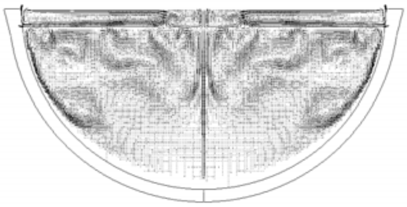

Fig.6 Velocity Field in the Molten Fluids

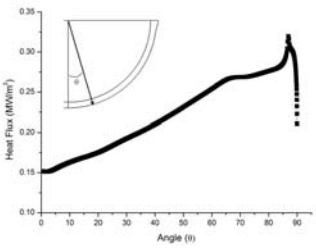

Fig.7 Heat Flux on the outer RPV wall