6.2 Analysis of Turbulent Natural Convection Heat Transfer in a Lower Plenum during External Cooling Using the COSMO Code

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ABSTRACT

The behavior of a large volumetrically heated melt pool is important to evaluate the feasibility of in-vessel retention by external flooding as an accident management. The COSMO (Coolability Simulation of Molten corium during severe accident) code has been developed at NUPEC to simulate turbulent natural convection heat transfer with internal heat source. The COSMO code solves thermal hydraulic conservation equations with turbulent model and can simulate melting and solidification process.

The standard k-ε model has a limitation to describe the turbulent natural convection in the very high Rayleigh number condition (10^{16}~10^{17}) assumed to occur in a lower plenum of RPV during a severe accident. This limitation results from the assumption of an analogy of momentum and energy transfer phenomena in the standard model. In this paper the modified turbulent model in which the turbulent number is treated, as a function of the flux Richardson number derived from the experiment, has been incorporated and verified by using the BALI experiments. It was found that the prediction of averaged Nusselt number became better than that of the standard model.

In order to extend the COSMO code to the actual scale analysis under the external flooding conditions, more realistic boundary condition derived from the experiments should be treated. In this work the CHF correlation from ULPU experiment or the heat transfer coefficient correlation from CYBL experiment have been applied. The preliminary analysis of an actual scale analysis has been carried out under the condition of the TMI-2 accident.

keywords: *natural convection, Nusselt number, turbulent model, external flooding, Richardson number, turbulent Prandtl number*

1. INTRODUCTION

It is important to relevantly assess heat removal from molten corium in a lower plenum in evaluating the feasibility of ‘in-vessel retention’ by external flooding as a severe accident management. Although level-2 PSA code like MELCOR or MAAP could analyze these phenomena, the incorporated models basically consist of simple modeling and empirical correlations. Hence, these models cannot apply to the conditions beyond the expected parameter ranges. To estimate heat removal from molten corium, it is necessary to develop the mechanistic thermal hydraulic code that could describe pertinently turbulent natural convection and crust formation.

2. TECHNICAL APPROACH

2.1 Governing equations

Mass, momentum and energy conservation equations are solved as the governing equations. Buoyancy term was treated by Bussinesq approximation. In high Rayleigh number condition, COSMO code can handle standard k-ε turbulent model. Whether the region is solidified or melted is calculated by simple heat balance equation.

2.2 Turbulent model

A high Reynolds number type k-ε turbulent model is incorporated in the COSMO code. Eddy diffusivity a_t is calculated by using the turbulent Prandtl number Pr_t and eddy viscosity ν_t. It means turbulent thermal field is assumed analogical with turbulent velocity field. However it is difficult to use fixed value as the turbulent Prandtl number in such system that stable and unstable stratified layer coexist. In a stable stratified layer, flow becomes laminarized then the turbulent Prandtl number should increase.

In this model, the flux Richardson number is utilized as the magnitude of buoyancy. In the transport equation of turbulent energy, two types of production term are observed in natural convection turbulence.

$$\frac{Dk}{Dt} = P + G + D - \varepsilon$$

$$Ri = G/P$$

One is the production term by shear stress (P), the other is the production term by buoyancy (G). The flux Richardson number Ri is defined as a ratio of these production terms. In a stable stratified layer, the flux Richardson number becomes minus, and flow becomes laminarized if the flux Richardson number decreases. In this model, the turbulent Prandtl number as a function of the flux Richardson number according to the experiments [1].

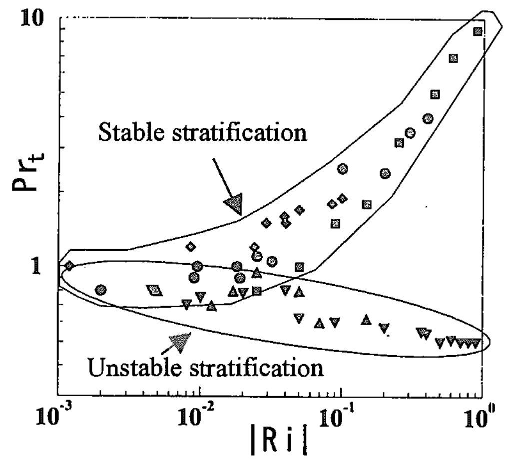

Fig. 1: Dependence of Pr_t on Ri

2.3 Boundary condition

Basically isothermal boundary condition is used for the experiment analysis like BALI. In order to extend the COSMO code to the plant scale analysis or under the external flooding conditions, more realistic boundary should be treated. At the upper surface of corium pool, film boiling or radiation model was installed. At the lower surface, on the other hand, heat conduction in lower head material and boiling heat transfer for downward facing curved wall derived from CYBL or ULPU experiment [2, 3] were installed.

2.4 Solution procedure

The fundamental scheme of the COSMO code is a conservation of finite volume method with staggered meshing in 2-dimensional cartesian coordinate system. The 2nd order QUICK scheme for convection term treatment, the semi-implicit time integral procedure and the SIMPLEST velocity-pressure coupling algorithm have been utilized. The curved wall or the solid obstacles and/or crust are simulated by porous medium approximation. The phase interface tracking method has been utilized. Each mesh has the fraction of solid phase, the direction of the phase interface and the distance to the phase interface. The calculations were carried out on the Compaq alpha workstations.

3. ANALYSYS

3.1 BALI simulation

BALI experiments were carried out at CEA/DRN in France in order to assess heat removal from reactor vessel during external flooding [4]. Test section modeled the lower plenum with full scale and the 2-dimensional slice model. Two electrodes were placed on the each side, and volumetric heating was achieved by direct current heating. The prototypical high Rayleigh number up to 10^{17} was achieved. The isothermal boundary condition was realized by ice crust formation along the cooled wall. The calculation mesh was showed as Fig. 3. Isothermal boundary condition was used. Nusselt number and maximum temperature were time averaged after reaching steady state. Two test cases, $Ra'=2.3\times10^{17}$ (case A) and $Ra'=7.3\times10^{17}$ (case B), were simulated.

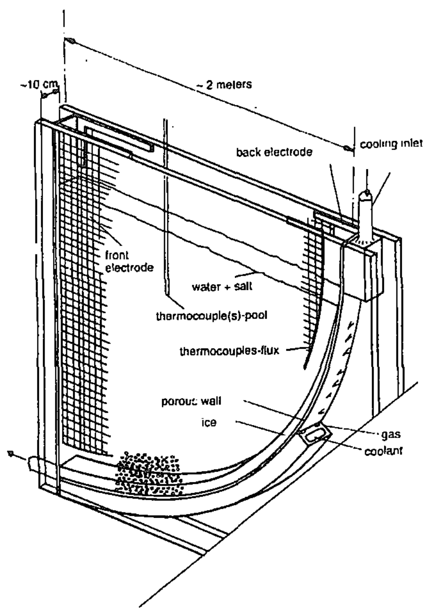

Fig. 2: Test facility of BALI

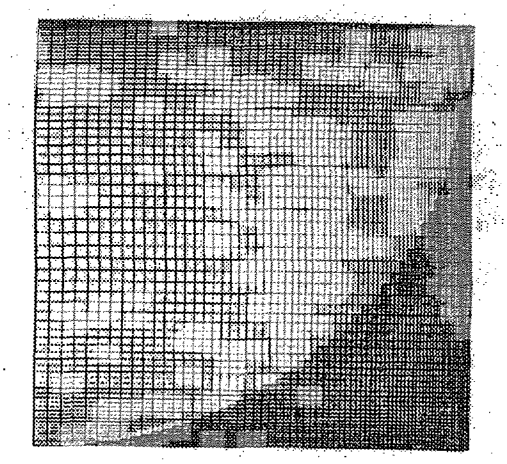

Fig. 3: Calculation mesh

3.1.1 Simulation by the fixed turbulent Prandtl number model

Three types of turbulent Prandtl number, one, point six or ten, were utilized. Figures 4 and 5 are the time averaged velocity and temperature fields in Case A, Pr_t=1. Stable stratification was observed in bottom region, and temperature in upper region was almost uniform.

According to Table 1, decrease in the turbulent Prandtl number resulted in increase in Nusselt number and decrease in maximum temperature, because turbulent energy transport was more enhanced rather than turbulent momentum transport. But, point six as the turbulent Prandtl number seemed to be too small especially for downward Nusselt number. Increase in the turbulent Prandtl number, on the other hand, resulted in laminarization. Anyway, to use fixed value as the turbulent Prandtl number in whole region is not appropriate.

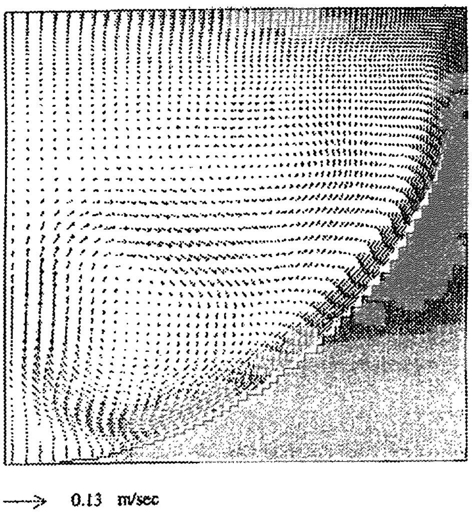

Fig. 4: Velocity Field

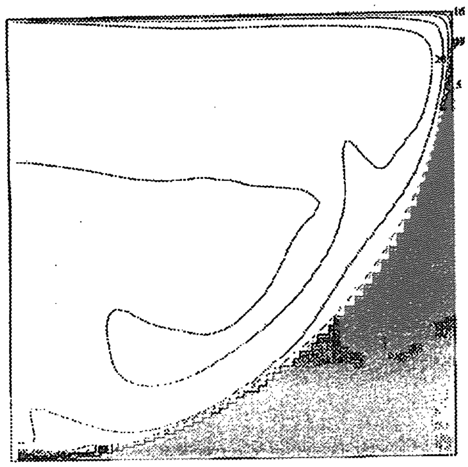

Fig. 5: Temperature Field

3.1.2 Simulation by modified model

The model in which the turbulent Prandtl number is as a function of magnitude of buoyancy should be considered. According to Table 1, predicted Nusselt number and maximum temperature became better than by the standard model with any turbulent Prandtl number.

Table. 1:Calculation Results

		Case A			Case B		
		T_{max} (℃)	Nu_{up}	Nu_{down}	T_{max} (℃)	Nu_{up}	Nu_{down}
Standard Model	Pr_t=1.0	36.4	2252	1633	63.3	2257	1811
	Pr_t=0.6	29.0	3750	2228	45.5	3939	2607
	Pr_t=10	108	494	331	192	490	352
Modified Model		40.0	2758	1526	62.8	2956	1748
Test results		37.4	2550	1430	54.6	3040	1832

3.2 Plant scale analysis

For the plant scale analysis, the various kinds of heat transfer model as the boundary condition were incorporated into the COSMO code. At the upper surface of corium pool, for example, film boiling or radiation could be utilized. At the lower surface, heat conduction in a lower head and boiling at outer surface could be simulated. In this model, the CYBL or ULPU experimental results were used. The material properties were modeled based on the MATPRO. After these models were incorporated, the preliminary calculation under TMI-2 accident condition was carried out.

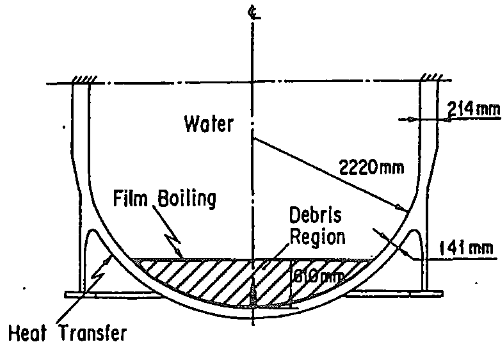

Fig. 6: Calculation region

The calculation region shows as the hatched area in Fig. 6. The debris component is 82% of UO_2 and 18% of ZrO_2. The initial temperatures and velocities condition of corium were 3000K and 0m/s, respectively. The upper surface was cooled by film boiling. At the lower surface, heat conduction in the lower head and nucleate boiling by external flooding based on CYBL were used. The uniform calculation mesh was used. The simulation was conducted during 2 hours for reaching steady state.

The velocity field and temperature field at the end of the calculation were shown in Fig. 7 and Fig. 8. Crust formation observed along the cooled surface. Maximum temperature of corium region was 2789K. Minimum temperature, on the other hand, was 865K. Minimum temperature of a lower head was 500K.

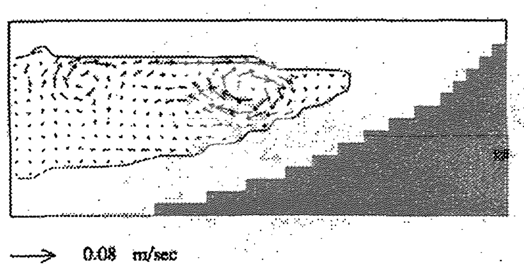

Fig.7: Velocity field (at 7200s)

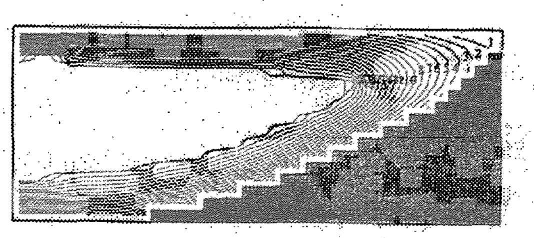

Fig. 8: Temperature field (at 7200s)

4. CONCLUSIONS

In BALI simulation, the standard turbulent model has a limitation to describe turbulent natural convection heat transfer in whole region under prototypical Rayleigh number. The experimental correlation for the turbulent Prandtl number based on the flux Richardson number was incorporated. In this model, the turbulent Prandtl number increases, if the flux Richardson number is negative and decrease. Predicted Nusselt number and maximum temperature by the modified model became better than by the standard model.

In the preparation of the plant scale analysis, the boundary conditions for external flooding were incorporated. And the preliminary calculation has been carried out under the condition of the TMI-2 accident.

ACKNOWLEDGMENTS

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