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Effects of coefficients of algebraic heat flux model on turbulent natural convective flow simulation in BALI configuration (21A-322)

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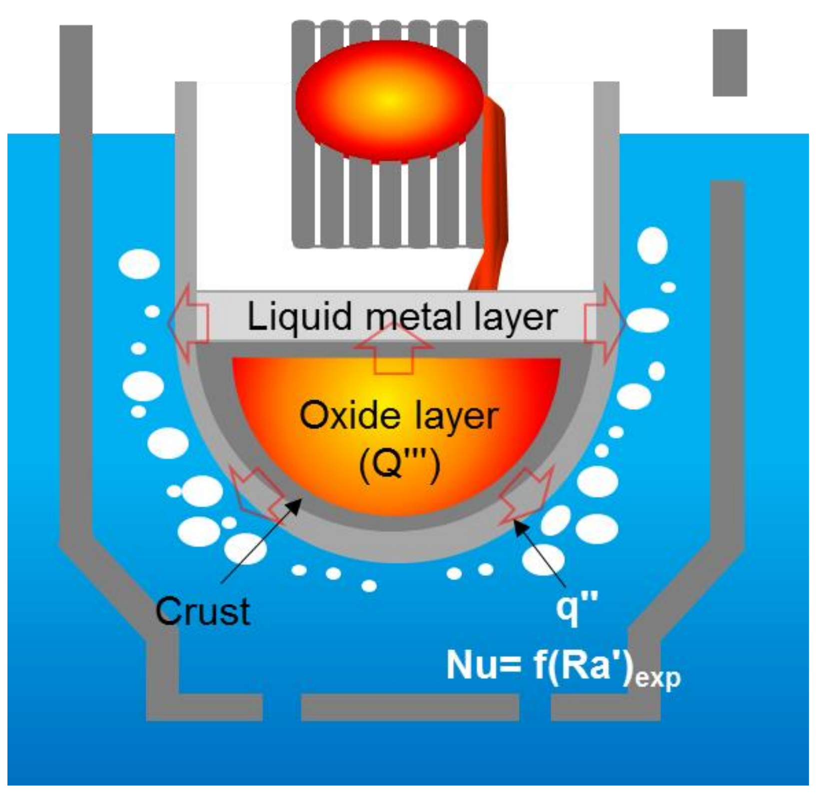
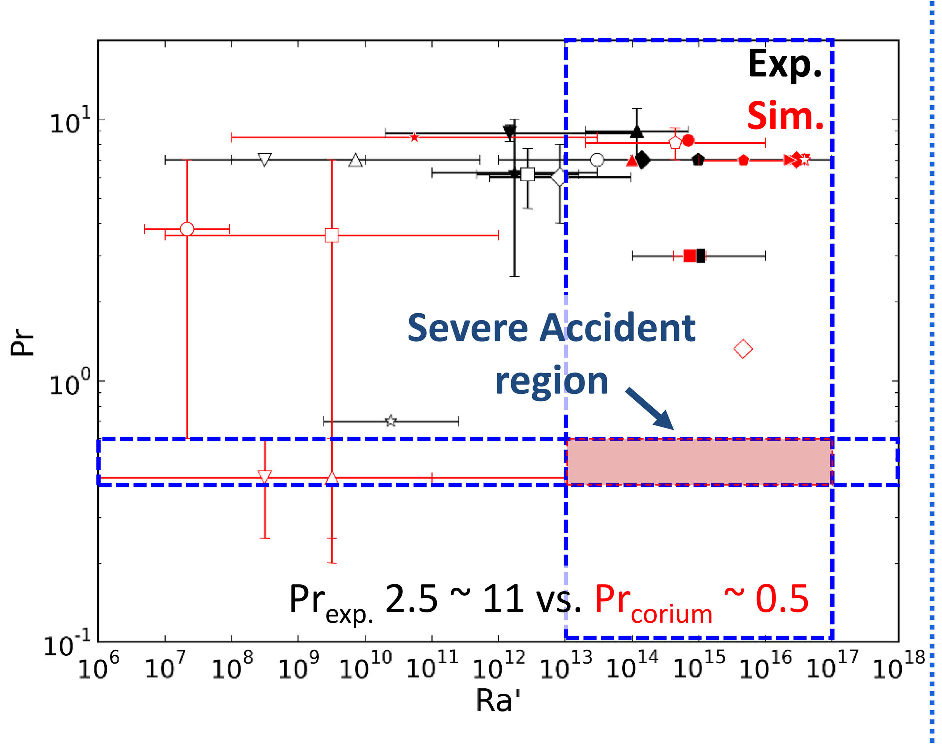
Introduction

- **Severe accident**
  - Partial or complete 'melt-down' of the reactor core
- **In-Vessel Retention by External Reactor Vessel Cooling (IVR-ERVC)**
  - Safety evaluation: Thermal failure criterion
    - Internal heat flux vs. Critical heat flux.
  - Complex phenomena determining thermal behavior of the oxide layer
    - Turbulent natural convection, crust formation, mushy zone, etc.
    - Rayleigh number of oxide layer is up to 10^{17}, which means strong turbulence

$$Ra = \frac{g\beta H^3 \Delta T}{\alpha \upsilon} \qquad Ra' = \frac{g\beta Q''' H^5}{\alpha \upsilon k}$$

- **Advanced** turbulence model is needed to simulate turbulent natural convection of oxide layer





Methodology

- **Buoyancy-driven natural convection of the single phase with a volumetrically heat source**
  - RANS equation (Energy equation)
    - Incompressible & Boussinesq approximation

$$\frac{\partial T}{\partial t} + U_j \frac{\partial T}{\partial x_j} = \frac{\partial}{\partial x_j}\left(\alpha \frac{\partial T}{\partial x_j} - \overline{\theta u_j}\right) + \frac{q'''}{\rho C_p}$$

- **Turbulent heat flux model**

1. **Eddy diffusivity model (EDM)**

$$\overline{\theta u_i} = -\frac{\nu_t}{Pr_t}\frac{\partial T}{\partial x_i} = -\alpha_t \frac{\partial T}{\partial x_i}$$

- **Limitation** of EDM reported in simulating complex phenomena such as **buoyancy flow**

2. **Algebraic heat flux model (AFM)**

$$\frac{D\overline{\theta u_i}}{Dt} = \boxed{P_{\theta i}^T + P_{\theta i}^U + G_{\theta i} + \Phi_{\theta i}^*} - \varepsilon_{\theta i} + D_{\theta i}^\alpha + D_{\theta i}^t$$

$$\overline{\theta u_i} = -C_0 T\left[C_1 \overline{u_i u_j}\frac{\partial \overline{\theta}}{\partial x_j} + C_2 \overline{\theta u_j}\frac{\partial \overline{u_i}}{\partial x_j} + C_3 \beta g_i \overline{\theta^2}\right]$$

$$P_{\theta i}^T \qquad P_{\theta i}^U \qquad G_{\theta i}$$

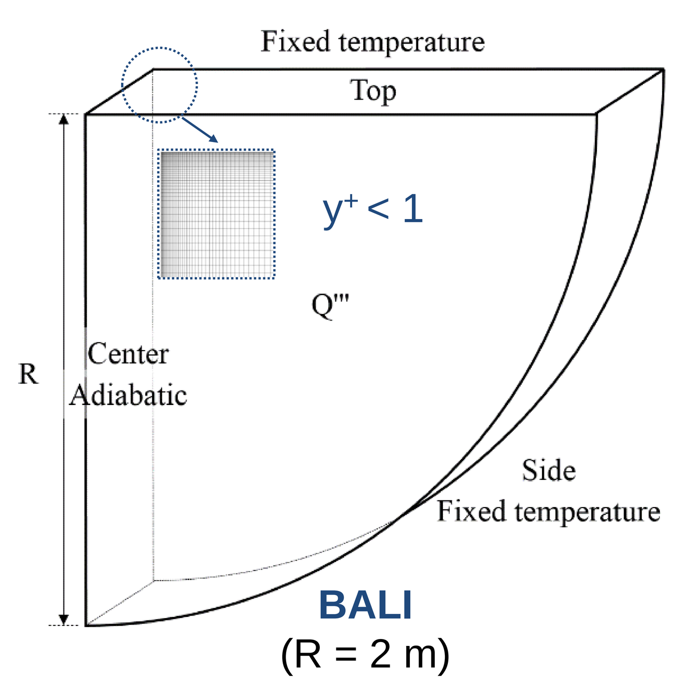
- **Temperature variance**

$$\frac{D\overline{\theta^2}}{Dt} = \frac{\partial}{\partial x_k}\left[\left(\frac{\nu}{Pr}\delta_{kl} + C_{\theta\theta}\overline{u_k u_l}\tau\right)\frac{\partial \overline{\theta^2}}{\partial x_l}\right] + P_\theta - \varepsilon_\theta$$

- Constant time scale ratio, R

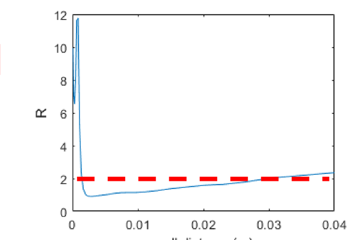
$$R = \frac{\overline{\theta^2}/\varepsilon_\theta}{k/\varepsilon} \longrightarrow \varepsilon_\theta = \frac{1}{R}\frac{\varepsilon}{k}\overline{\theta^2}$$

- **Validation cases**
  - **BALI:** 1/4 circular slice shape (radius = 2m)
    - Ra' ~ 10^{16}, Pr ~ 5.4



- **Grid generation**
  - Mesh sensitivity study for cell number and maximum y+
  - Number of two-dimensional cells ~20,000
  - Maximum non-dimensional wall-distance, y+ < 1
- **Numerical schemes and algorithms**
  - P-V coupling: PIMPLE
  - Time: Crank-Nicolson + Euler
  - Gradient, Laplacian and TMF/THF terms: Central difference; Rest terms: Upwind

- **Previous work [1]**
  - **Numerical database** using LES (Dynamic global-coefficient subgrid-scale model)
  - Notable results
    1. Dissipation model for temperature variance equation: $R \sim 2$
    2. Near top surface : $G_{\theta i} >> P_{\theta i}^T, P_{\theta i}^U$
    3. Along the side wall (wall-normal): $P_{\theta i}^U \sim 0$



Sensitivity analysis of the model coefficients

- **Algebraic heat flux model (AFM) coefficient:**

$$\overline{\theta u_i} = -\boxed{C_0} T\left[\boxed{C_1} \overline{u_i u_j}\frac{\partial \overline{\theta}}{\partial x_j} + \boxed{C_2} \overline{\theta u_j}\frac{\partial \overline{u_i}}{\partial x_j} + \boxed{C_3} \beta g_i \overline{\theta^2}\right]$$

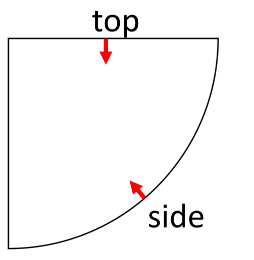
- **Time scale ratio for temperature variance**

$$\frac{D\overline{\theta^2}}{Dt} = \frac{\partial}{\partial x_k}\left[\left(\frac{\nu}{Pr}\delta_{kl} + C_{\theta\theta}\overline{u_k u_l}\tau\right)\frac{\partial \overline{\theta^2}}{\partial x_l}\right] + P_\theta - \frac{1}{\boxed{R}}\frac{\varepsilon}{k}\overline{\theta^2}$$

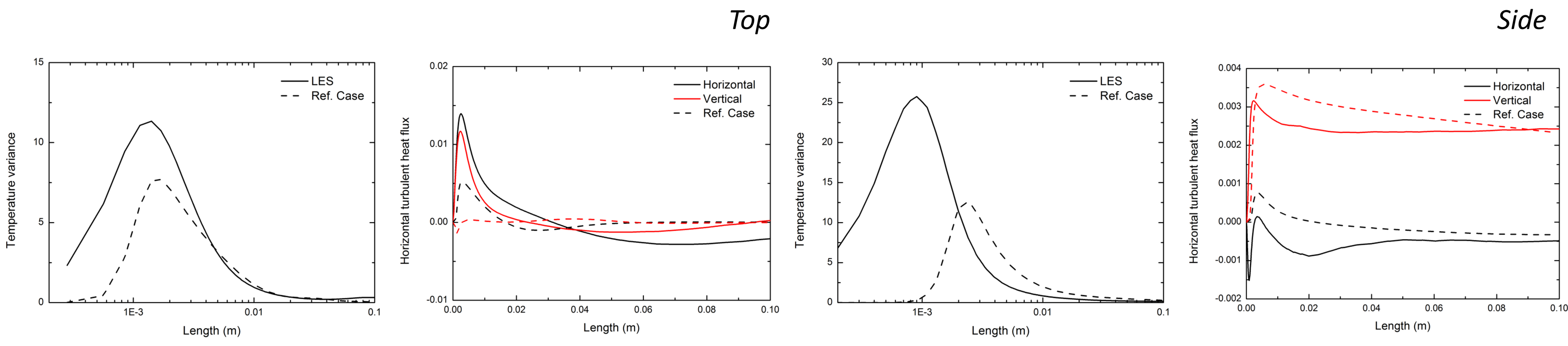
In this study, the impact of **R** and **C_3** was investigated

AFM	C_0	C_1	C_2	C_3	R
Ref. [2]	**0.2**	**0.25**	**0.6**	**0.385**	**0.5**
Case 01	0.2	0.25	0.6	0.385	1.0
Case 02	0.2	0.25	0.6	0.385	1.5
Case 03	0.2	0.25	0.6	0.385	2.0
Case 04	0.2	0.25	0.6	0.2	0.5
Case 05	0.2	0.25	0.6	0.55	0.5

- **Temperature variance** & **turbulent heat flux** behavior near wall is compared.
- Probe locations: top & side (as denoted in the right figure)

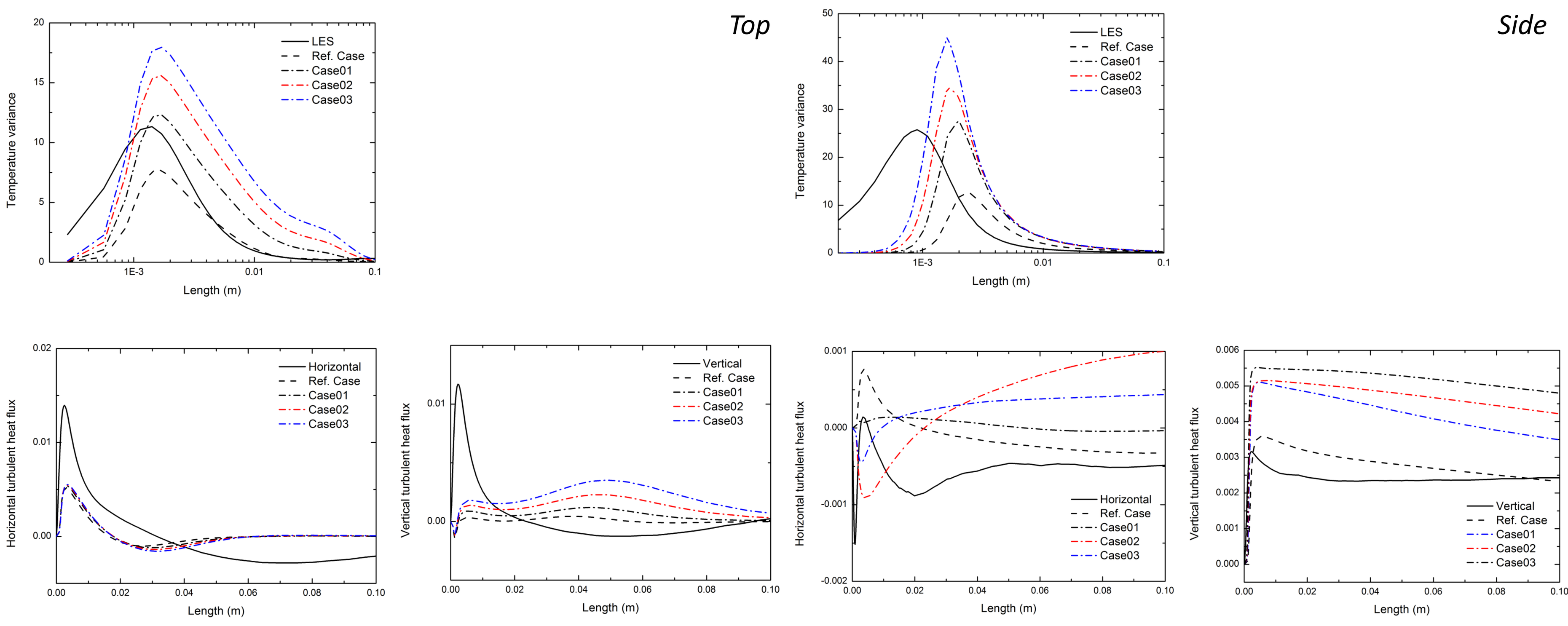


- **LES and reference case**

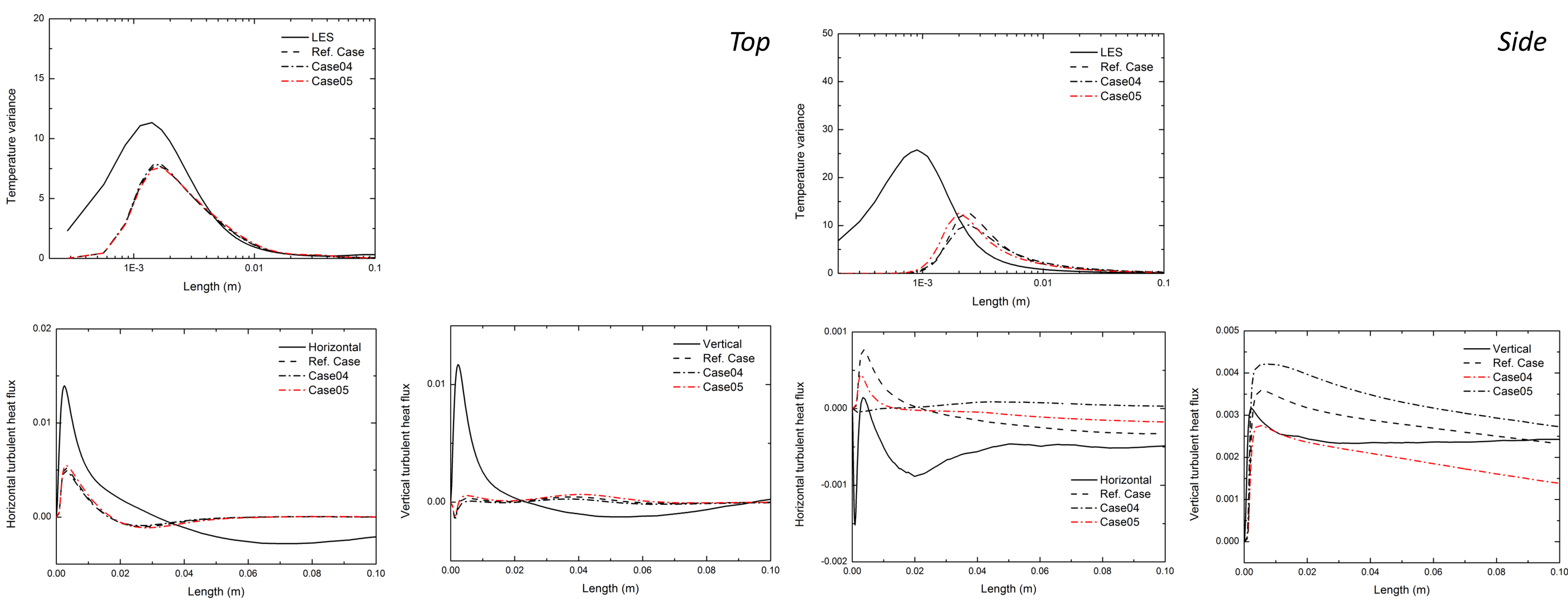


- The result of reference case
  - $\overline{\theta^2}$: the peak location of side wall is delayed, and the maximum value is underestimated
  - $\overline{\theta u_i}$: well-predicted except the vertical turbulent heat flux along the top surface.

- **Effect of coefficients (R & C_3)**
  - Time scale ratio (R)



- AFM coefficient (C_3)



Conclusion and Future plan

- According to the previous work, the influence of coefficients, **R** and **C_3** among the model coefficients was evaluated in this study.
- By adjusting the **R** value, it was possible to predict the maximum value of $\overline{\theta^2}$ (Case 01), and it was confirmed that THF behavior varies greatly depending on the **R & C_3**.
- It is expected that a model that can predict the physical behavior of major parameters can be proposed through sensitivity analysis including remain coefficients in the future work.

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This work was supported by KOREA HYDRO & NUCLEAR POWER CO., LTD (2019-Tech-05, "High-Fidelity Numerical Analysis of Highly Turbulent Corium Pool for In-Vessel Retention (IVR) Strategy Feasibility Assessment")

References

[1] Joo, D. et al., 2022. Validation of large-eddy simulation on turbulent heat transfer for highly buoyant flow in a corium pool, NURETH-19.

[2] Shams, A., 2018. Towards the accurate numerical prediction of thermal hydraulic phenomena in corium pools. Ann. Nucl. Energy 117, 234–246.

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