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Computation of turbulent natural convection with buoyancy corrected second moment closure models

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1. Introduction

IVR-ERVC is one of the severe accident strategies to mitigate or terminate the accident by holding the radioactive material which generates a decay heat in the lower head of reactor vessel. The understanding of thermal behavior of the molten oxide pool is important in terms of evaluation of IVR-ERVC. In the molten pool, it is expected a highly turbulent natural convection with volumetric heat generation. It is very difficult and expensive to investigate the phenomenon experimentally. It is even more challenging to simulate numerically since the turbulent intensity is extremely high. For the numerical analysis it has been reported that the Eddy Viscosity Model (EVM) or Eddy Diffusivity Model (EDM) fail to simulate those complicate phenomena (reference). Therefore, it is plausible option to adopt the Second Moment Closure (SMC) models for both Reynolds stress and turbulent heat flux (which is called "buoyancy corrected" in this study) to simulate the turbulent natural convection phenomena. Therefore, in this paper, the model validation to examine the major phenomena of the turbulent natural convection such as stratification, transition along the vertical wall and an anisotropy behavior near wall are performed with selected models. For the molten pool which has the low Prandtl number, it is simulated to analyze the fluid Prandtl number effect on the thermal behavior of the reactor case.

2. Development of Turbulent Natural Convection Models for In-Vessel Molten Pool

2.1 Turbulence Models applicable to Molten Pool Convection

In order to investigate the molten pool convection in highly turbulent conditions, turbulence in the pool convections plays important roles in momentum and heat flux. For the turbulent momentum flux models, Manceau et al. [1] proposed Elliptic Blending Reynolds Stress Model (EBRSM) which can predict the anisotropic behavior of Reynolds stress in the vicinity of the wall. In this model, the near-wall and the far-from-the-wall model of terms (such as pressure redistribution, ϕ_{ij}^* and dissipation, ε_{ij}) are blended with a single elliptic operator. The elliptic operator is zero at the wall and going to unity far from the wall. The models for near-wall and far-from-the-wall are followed by previous approaches [1-3]. For the turbulent heat flux models, Dehoux et al. [4-5] proposed Elliptic Blending Algebraic heat flux model (EBA) and Elliptic Blending Differential heat flux model (EBD) by applying the elliptic blending approach to the turbulent heat flux model; algebraic heat flux model [6] and differential heat flux model [7]. Later, Choi et al. [8] modified the turbulence model constants to simulate natural convection more accurately and it is used in the present study.

2.2. Numerical Algorithm and Discretization for the Present Simulation

All simulations were performed in OpenFOAM to implement the previously mentioned turbulence models. The blended second order Crank-Nicolson and the first order Euler schemes were employed to discretize the governing equations in time. The second-order differencing scheme was employed for space discretization. The SIMPLE and PIMPLE algorithms couple the momentum and pressure equations; the SIMPLE algorithm for the steady state calculation and the PIMPLE algorithms which is a combination of the PISO and SIMPLE algorithms for the transient simulation.

2.3. Validation of the Numerical Turbulent Models for the Molten Pool Convection

Differently Heated Cavity (DHC) [8] and the BALI [9] tests are chosen for the validation of the presently implemented turbulent models. DHC is for the natural convection test case in the differentially heated wall with ΔT of 43.8 ℃. It is a rectangular cavity with the height-to-width aspect ratio of 5 and the working fluid is air. The Rayleigh number is approximately 10^{10} in this case. The comprehensive turbulent characteristics can be obtained from the experimental result such as the anisotropy turbulent heat flux in the vicinity of the wall and the laminar-to-turbulence transition near the vertical wall.

The natural convection with an internal heat generating was investigated in the BALI test. The geometry of the facility is a 1/4 circular slice; the radius is 2 m which is a prototypical size of the reactor pressure vessel and the thickness is 0.15 m. The simulant fluid is water and the decay heat is simulated by direct current heating. The internal Rayleigh number is around 10^{16} which is a comparable value with the reactor case. From the experiment, the main phenomenon in a corium pool under the IVR condition and the local/averaged heat transfer correlations are suggested.

A steady state calculation was carried out for the case of DHC, and a transient calculation was conducted for the case of BALI and reactor application.

3. Simulation Results of the Validation of Turbulent Models for Molten Pool Convection

For the following description of the simulation results, simple notation is assigned for the simulation cases as shown in Table I. Turbulence model 'A/B' means that 'A' for turbulent momentum flux model (Reynolds stress model) and 'B' for turbulent heat flux model, respectively. The notation 'B' is omitted in case of EDM. The selected turbulence models are listed in Table I.

All models were implemented and converged for all cases, however, some calculation are in progress and those results will be added later.

Table I: Notation of the Turbulence Models in this study

Momentum/ Heat flux	Turbulence model
EVM/EDM	SST [10]
SMC/EDM	Reynolds Stress Transport Model (RSTM) [11]
	EBRSM
SMC/SMC	EBRSM/EBA
	EBRSM/EBD

3.1. Differently heated cavity: Natural convection in a rectangular cavity

Figure 1 shows that the profiles extracted along the horizontal axis at the center height and along the vertical hot wall in the cavity. The vertical mean velocity at y/H=0.5 near the hot wall is compared in Fig. 1 (a). The maximum value near the wall is well captured by all models. However, the predicted velocity far from the wall shows a slight difference among models.

The calculated local Nusselt number was compared with the experimental results as shown in Fig. 1 (b). Barhaghi et al. [12] studied the behavior of the turbulent natural convection including the transition from laminar to turbulent along the vertical wall by the Large Eddy Simulation (LES) method with the various subgrid scale models. The EDM-based model cannot capture the transition and under or overestimate the value. The buoyancy corrected models (EBRSM/EBA and EBRSM/EBD) are in good agreement with the experiment including the transition region (y/H is 0.2 to 0.4).

In Figs. 3 (c) and (d), it is observed that the anisotropic behavior of turbulent heat flux in the vicinity of the wall. The overall trend of horizontal turbulent heat flux is reproduced with all models. However, the vertical turbulent heat flux is not correctly reproduced by EDM-based model as shown in Fig. 3 (d). The anisotropic behavior of the turbulent heat flux in the vicinity of the wall is properly captured by the buoyancy corrected models.

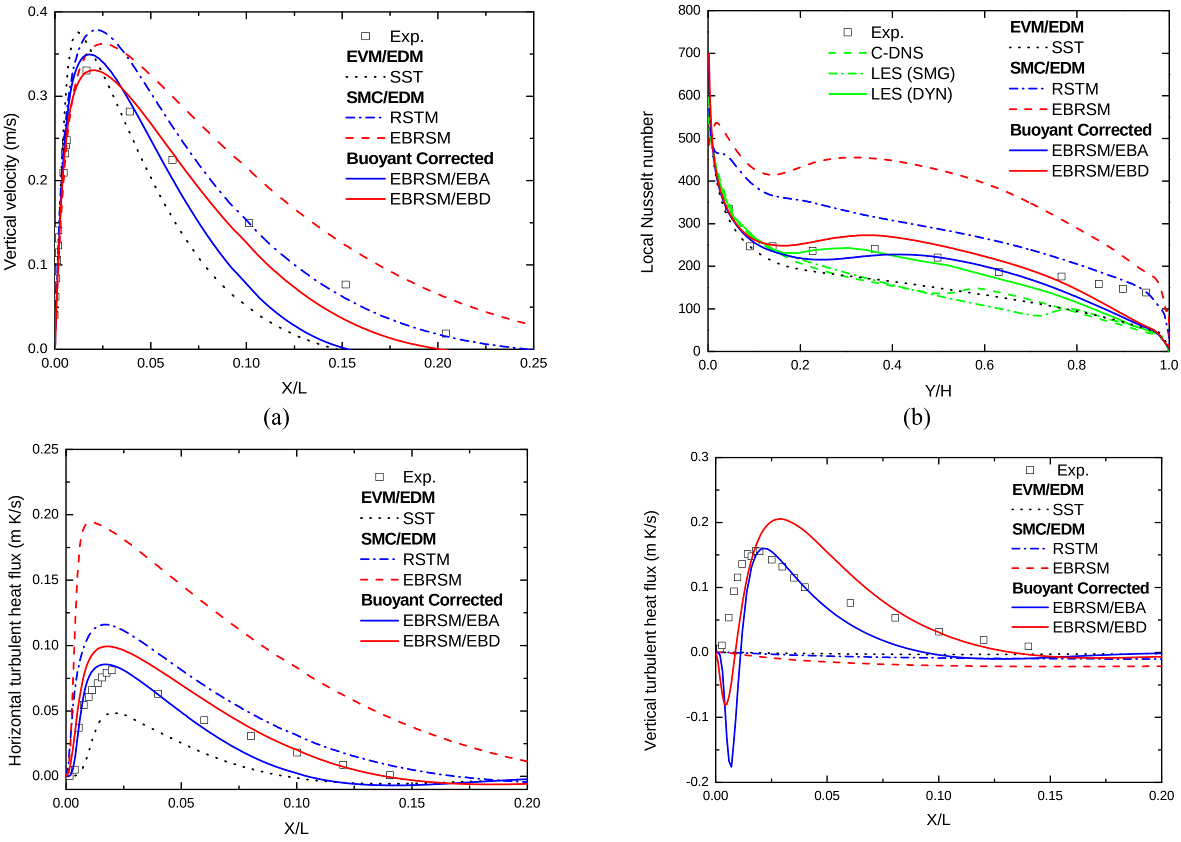
3.2. BALI: Natural convection with internal heat source

The mean temperature profile along the center depth direction at x = 0.1 m is shown in Fig. 2 (a). One of the characteristics of a mixing region or an unstable zone is the uniform temperature and the dimensionless depth of the mixing region is about 0.4 from the top as reported in the previous work [9]. The selected models well predict the mixing region depth. However, the deviations are observed in the stratified zone depending on the models.

Heat flux profiles along the curved wall also compared with the experimental results as shown in Fig. 2 (b). Different tendency is shown from the result; the heat flux decreases continuously from its peak value near top surface in EVM/EDM, while it shows almost uniform in the unstable zone which is a convection dominant region in the SMC/EDM model.

3.3. Reactor case: low Prandtl number effect ($Ra' \sim 10^{16}$)

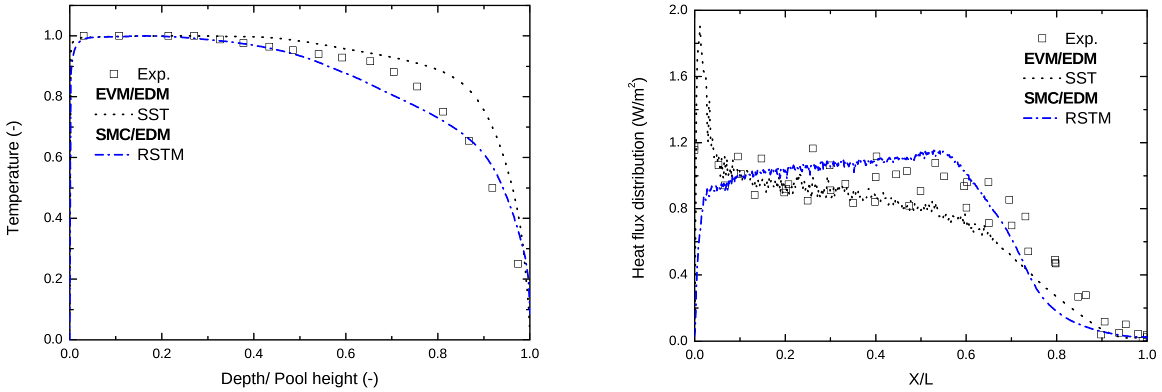
To simulate reactor case, corium properties which has low Prandtl number [13] are applied. Figure 3 shows the temperature distribution along the center line at x = 0.1 m (a) and heat flux distribution along the side wall (b). The length of an unstable zone is similar with the water case. However, the temperature of the stable zone is low in the corium case. This is probably due to the low Prandtl number effect which allows the intense descending cold flow to the stable zone (it is called υ-phenomenon as proposed in previous work [14, 15]). In the well-mixed convection dominant region, the similar heat flux profile is observed in Fig. 3 (b). It can be observed that high heat flux distribution in the stably-stratified zone in the low Prandtl number case. The heat transfer in the lower cavity is enhanced due to relatively high thermal diffusivity coefficient, so-called α-phenomenon [14, 15].



(a) (b)

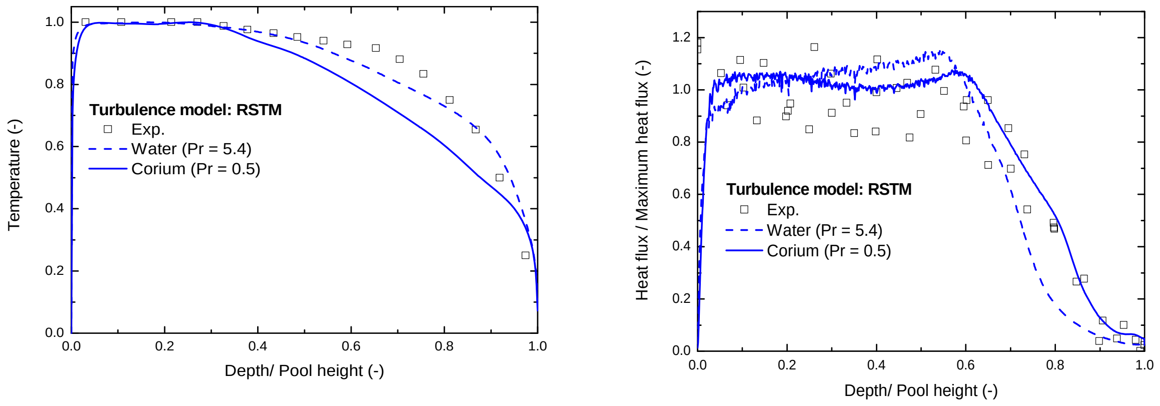
(c) (d)

Fig. 1 Natural convection in a rectangular cavity at Ra ~10^{10} [8].
(a) Mean vertical velocity profiles at y/H=0.5, (b) Local Nusselt number distribution along the hot wall,
(c) Horizontal turbulent heat flux at y/H=0.5, (d) Vertical turbulent heat flux at y/H=0.5



(a) (b)

Fig. 2 Natural convection with internal heat of BALI [9] with Ra'~10^{16}.
(a) Mean temperature profiles along the center line, (b) Heat flux profiles along the side wall



(a) (b)

Fig. 3 Comparison results between water (Pr = 5.4) and corium (Pr = 0.5) with same turbulence model (RSTM).
(a) Mean temperature distribution along the center line, (b) Heat flux profiles along the side wall

4. Conclusions

Turbulent natural convection is a key phenomenon to understand thermal behavior of the oxide molten pool, including stratification, laminar to turbulence transition and anisotropic behavior near wall. In this work, the buoyancy corrected SMC model was implemented in OpenFOAM and validated with experiments. The selected models well simulate the characteristics of natural convection and the anisotropic behavior in the vicinity of the wall reproduced properly by buoyancy corrected models. The analysis also investigates the fluid Prandtl number effect by applying the properties of the prototypical oxide melts into the models in the ranges of the modified Rayleigh number, Ra', of up to 10^{16}. Further simulations with the buoyancy corrected turbulence models and several geometries, such as 2D, 3D, slice, hemisphere are needed to understand the thermal behavior of the real reactor applications in near future.

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