

Numerical Assessment of Turbulent Heat-Transfer Modeling in ANSYS Fluent for High-Rayleigh-Number Internally Heated Natural Convection

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1. Introduction

Molten salt reactors (MSRs) are among the Generation IV reactor concepts, offering high-temperature, low-pressure operation and inherent negative reactivity feedback associated with the thermal expansion of liquid fuel [1]. However, under accident conditions, molten fuel salt may be released from the primary fuel-salt system and form a pool in the lower region of the containment vessel, where the pool can be heated by decay heat.

In the containment geometry used in this study, the molten salt pool has a spherical-cap shape with a depth of 0.57 m and a horizontal radius of approximately 3.14 m. Its aspect ratio differs from that of the BALI configuration, and its internal Rayleigh number is approximately one order of magnitude lower, while still remaining in the high-Rayleigh-number regime.

A molten salt pool with volumetric heat generation can reach a very high internal Rayleigh number, depending on the thermophysical properties and geometric conditions. Under these conditions, strong buoyancy-driven natural convection develops within the pool and governs the power split among the pool boundaries as well as the local heat-flux distribution. Therefore, reliable prediction of the boundary heat loads requires an appropriate modeling approach for high-Rayleigh-number natural convection.

In a previous study, the boundary heat load of a molten salt pool was evaluated using RANS model. However, the prediction of turbulent heat transfer in strongly buoyancy-driven natural convection remains challenging. An advanced turbulent heat-flux model(AHFM) can better account for buoyancy effects and heat-flux anisotropy. Such a model has been implemented in OpenFOAM and applied to high-Rayleigh-number natural convection [2]. It is also available in STAR-CCM+ and has been used in related studies [3,4]. In contrast, this model is not built into ANSYS Fluent, and studies on its application remain limited.

In this study, an advanced turbulent heat-flux model was implemented in ANSYS Fluent using User-Defined Functions (UDFs). CFD simulations were performed for the BALI experiment, which represents high-Rayleigh-number internally heated natural convection, to assess the implemented model. The temperature distribution and upward and downward heat-transfer characteristics

were compared with experimental data and RANS results.

2. Methodology

The objective of this study is to assess an advanced turbulent heat-flux model implemented in ANSYS Fluent for high-Rayleigh-number natural convection.

2.1. Algebraic Heat Flux Model

In conventional RANS simulations, the turbulent heat flux is commonly modeled using the Simple Gradient Diffusion Hypothesis (SGDH), which relates the turbulent heat flux to the mean temperature gradient as

$$\overline{\theta u_i} = -\frac{\nu_t}{Pr_t} \frac{\partial \overline{\theta}}{\partial x_i} \quad (1)$$

where $\overline{\theta u_i}$, ν_t and Pr_t are the turbulent heat-flux, eddy viscosity and turbulent prandtl number respectively. This approach is simple and computationally efficient. However, this assumption may be insufficient for strongly buoyancy-driven natural convection, where the turbulent heat flux can exhibit significant anisotropy.

To account for these effects, AHFM was employed in this study. AHFM is derived from the turbulent heat-flux transport equation and algebraically accounts for the major mechanisms affecting the turbulent heat flux, including the Reynolds stresses, mean velocity gradient, buoyancy, and temperature variance.

$$\begin{aligned} \overline{\theta u_i} &= -C_{t0} \frac{k}{\epsilon} \left(C_{t1} \overline{u_i u_j} \frac{\partial T}{\partial x_j} + C_{t2} \overline{\theta u_j} \frac{\partial U_i}{\partial x_j} + C_{t3} \beta g_i \overline{\theta^2} \right) \quad (2) \end{aligned}$$

The first term($C_{t1} \overline{u_i u_j} \frac{\partial T}{\partial x_j}$) represents turbulent heat-flux production due to the mean temperature gradient through the Reynolds stresses. The second term($C_{t2} \overline{\theta u_j} \frac{\partial U_i}{\partial x_j}$) represents the effect of the mean velocity gradient on the turbulent heat flux. The third term($C_{t3} \beta g_i \overline{\theta^2}$) accounts for buoyancy-induced production associated with temperature variance. The

model coefficients used in the AHFM formulation are listed in Table I. The reference value of C_{t3} was 0.6. To examine its sensitivity, C_{t3} values of 0.3, 0.6, 0.8, and 1.4 were tested, while the other coefficients were kept constant.

Table I: AHFM coefficients [4]

	C_{t0}	C_{t1}	C_{t2}	C_{t3}
Model coefficient	0.12	1.0	0.6	0.6

2.2. BALI Experiment and CFD Model

The BALI experiment was selected to evaluate the applicability of the numerical model to high-Rayleigh-number internally heated natural convection[5]. The BALI experiment was conducted to investigate natural-convection heat transfer in an internally heated pool. The test section has a quarter-circular cross-section with a radius of 2.0 m and a thickness of 0.15 m.

Figure 1 shows the computational domain and boundary conditions. In this study, the BALI test section was modeled as a two-dimensional(2D) quarter-circular domain. The 2D model neglects flow and temperature variations in the depth direction. Therefore, possible three-dimensional effects are not captured. The 2D model is used here for heat-transfer-model assessment, while 3D analysis would be required to quantify these effects in detail. The nominal height of the test section is 2.0 m. For the single-phase flow simulation, the ice region was excluded, resulting in a fluid domain height of 1.85 m. Isothermal boundary conditions of 273.15 K, corresponding to the freezing point of water, were applied to the upper, lower, and curved boundaries, while the left vertical boundary was treated as adiabatic. A uniform volumetric heat generation of 33,316 W/m³ was applied throughout the fluid domain. Under these conditions, the internal Rayleigh number was approximately 2.5×10^{16} .

Table II summarizes the thermophysical properties of water used in the CFD simulations. Water was used as the working fluid, and its properties were evaluated at a reference temperature of 20°C. The buoyancy effect due to density variation was modeled using the Boussinesq approximation. Based on the mesh sensitivity test, a mesh consisting of 48,686 cells was used. The wall y^+ values were confirmed to remain below 1 over all wall boundaries.

The main numerical settings are given in Table III. For the SGDh case, the SST $k-\omega$ turbulence model was used with the SGDh turbulent heat-flux model. For the AHFM cases, the Standard $k-\epsilon$ model with Enhanced Wall Treatment (EWT) was employed, and the turbulent heat flux was calculated using the AHFM implemented through UDFs. The C_{t3} coefficient was varied as 0.3, 0.6, 0.8, and 1.4, while the other AHFM coefficients were kept constant. The PRESTO! scheme was used for

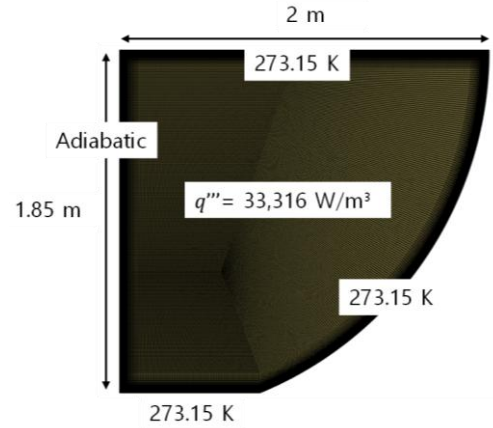


Fig. 1. Computational domain and boundary conditions.

Table II: Thermophysical properties of water for CFD

Properties	Values
β [1/K]	0.000207
ρ [kg/m ³]	998.3
C_p [J/kg·K]	4182
k [W/m·K]	0.6
μ [kg/m·s]	0.001003

Table III: Numerical conditions for SGDh and AHFM cases

Parameters	SGDH	AHFM
Dimension	2D	2D
Mesh cells	48,686	48,686
Volumetric heat generation	33,316 W/m ³	33,316 W/m ³
Internal Rayleigh number	2.5×10^{16}	2.5×10^{16}
Turbulence model	SST $k-\omega$	Standard $k-\epsilon$ with EWT
Turbulent heat-flux model	SGDH	AHFM
C_{t3}	-	0.3, 0.6, 0.8, 1.4
Pressure interpolation	PRESTO!	PRESTO!

pressure interpolation because of its suitability for high-Rayleigh-number natural convection.

3. Results and Discussion

3.1. Evaluation Parameters

The upward and downward heat-transfer characteristics were evaluated using the Nusselt number. The Nusselt number obtained from the CFD results was calculated as

$$Nu = \frac{q''H}{k(T_{\text{bulk}} - T_{\text{wall}})} \quad (3)$$

where q'' is the average boundary heat flux, H is the pool height, k is the thermal conductivity, T_{bulk} and T_{wall} are the bulk and wall temperatures, respectively.

For comparison with the BALI experiment, the reference upward and downward Nusselt numbers were calculated using the following correlations:

$$Nu_{up} = 0.383Ra'^{0.233} \quad (4)$$

$$Nu_{dn} = 0.116Ra'^{0.25} \quad (5)$$

where Ra' is the internal Rayleigh number. The CFD results were then compared with these experimental correlations.

3.2. Analysis Results

Figure 2 compares the temperature distributions predicted by the SGD case and the reference AHFM case ($C_{t3} = 0.6$). The AHFM case predicts a lower overall temperature than the SGD case and shows a more pronounced thermal stratification in the lower region.

Figure 3 also shows the effect of C_{t3} on the temperature prediction. As C_{t3} increased, the predicted temperature decreased and became closer to the experimental data. For $C_{t3} = 1.4$, the average temperature difference was reduced to approximately 13°C.

Figure 4 compares the bottom heat-flux distributions. All AHFM cases reproduced a similar overall distribution to the experimental data. As C_{t3} increased, the predicted bottom heat flux generally decreased, while the overall shape remained similar.

Table IV compares the upward and downward Nusselt numbers. As C_{t3} increased from 0.3 to 1.4, the upward Nusselt number increased from 1,563.2 to 1,960.5 and became closer to the experimental value of 2,478. The corresponding error decreased from 36.9% to 20.9%. In contrast, the downward Nusselt number remained nearly unchanged at approximately 1,114–1,118, with an error of about 21.5–21.7%.

However, the improvement in the temperature and upward Nusselt number did not lead to the same improvement in the power split. Table V shows that the experimental value of Q_{top}/Q_{total} was 0.50. The error was only 2% for $C_{t3} = 0.3$ and 0.6, but increased to 4% and 8% for $C_{t3} = 0.8$ and 1.4, respectively. These results show that increasing C_{t3} improves the temperature and upward heat-transfer predictions, but does not improve all heat-transfer characteristics in the same way. Therefore, the sensitivity of the other AHFM coefficients should also be examined.

Table IV: Comparison of upward and downward Nusselt numbers.

	Nu_{up}	Error (%)	Nu_{dn}	Error (%)
Experiment	2,478	-	1,424	-

SGDH	1,567	36.8	909.8	36.1
AHFM $C_{t3}=0.3$	1,563.2	36.9	1,117.2	21.5
AHFM $C_{t3}=0.6$	1,686.2	32.0	1,116.9	21.6
AHFM $C_{t3}=0.8$	1,776.4	28.3	1,118.1	21.5
AHFM $C_{t3}=1.4$	1,960.5	20.9	1,114.3	21.7

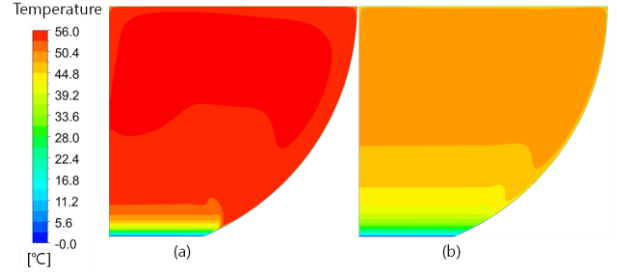


Fig. 2. Comparison of temperature distributions predicted by (a) SGD and (b) AHFM($C_{t3} = 0.6$).

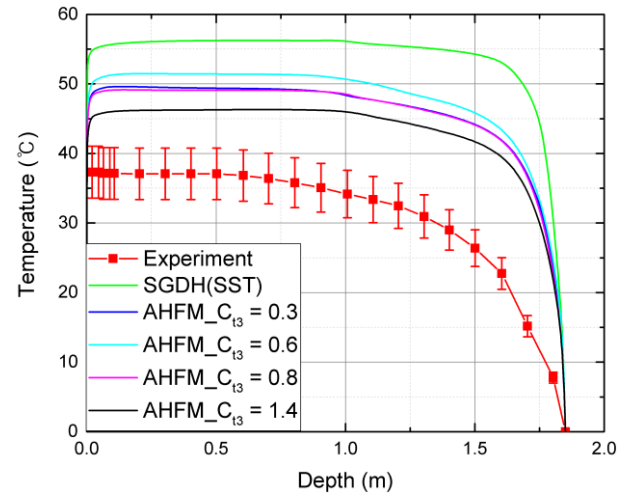


Fig. 3. Temperature profiles predicted by SGD and AHFM with different C_{t3} values.

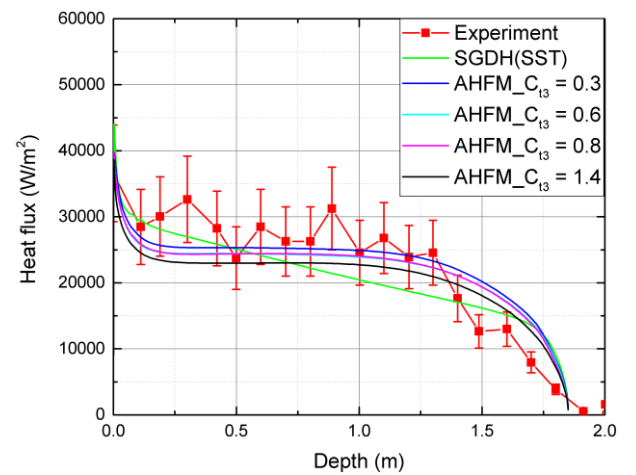


Fig. 4. Bottom heat-flux distributions predicted by SGD and AHFM with different C_{t3} values.

Table V: Comparison of top power fraction.

	Q_{top}/Q_{total}	Error(%)
Experiment	0.50	-

SGDH	0.53	6
AHFM_ $C_{t3}=0.3$	0.49	2
AHFM_ $C_{t3}=0.6$	0.51	2
AHFM_ $C_{t3}=0.8$	0.52	4
AHFM_ $C_{t3}=1.4$	0.54	8

4. Conclusion

The Fluent AHFM showed reasonable agreement with the BALI experiment and improved the prediction of pool temperature and boundary heat transfer compared with the SGDH case.

The sensitivity analysis showed that the results depend on C_{t3} . As C_{t3} increased, the predicted temperature and upward Nusselt number became closer to the experimental values. However, the downward Nusselt number changed only slightly, and the power split did not improve consistently. This asymmetric response is consistent with the direct buoyancy contribution of the C_{t3} term in the AHFM. Further analysis of the circulation structure and the sensitivity of the other AHFM coefficients is needed to explain the heat redistribution between the upper and lower boundaries.

The original AHFM was developed with the Launder–Sharma Low-Re $k - \varepsilon$ model, while the present study used the Standard $k - \varepsilon$ model with EWT. This difference may affect the results. Therefore, the AHFM should also be tested with the Launder–Sharma Low-Re $k - \varepsilon$ model.

For future application to molten salt pool, the AHFM coefficients should be evaluated against relevant experimental data. A term-by-term analysis is also needed to identify the dominant mechanisms under internally heated natural convection.

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