High-Fidelity Numerical Analysis of Highly Turbulent Corium Pool for In-Vessel Retention Strategy Feasibility Assessment

Numerical Analysis of Algebraic Flux Model Using OpenFOAM CFD

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Contents

2 Research Objective

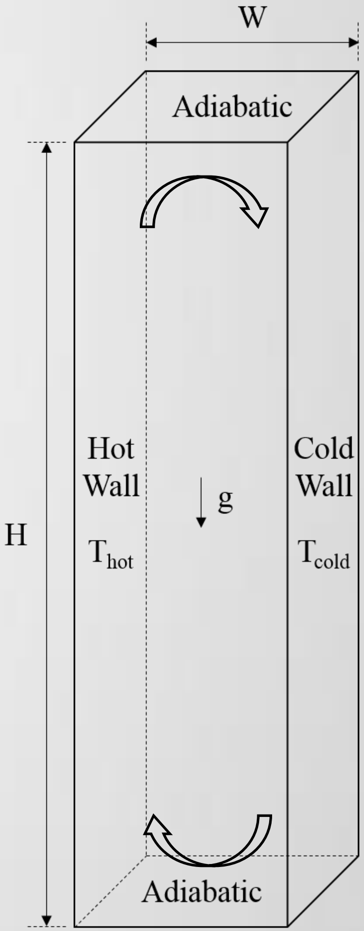
High-Fidelity Numerical Analysis of Highly Turbulent Corium Pool for In-Vessel Retention (IVR) Strategy Feasibility Assessment

- Goal 1 : LES-based Oxide layer Database (DB)
- Goal 2 : DL-based Advanced RANS model for Oxide layer (RANS+)
- Goal 3 : RANS+-based Oxide layer correlation (AIR+) and Evaluation of IVR SAMG

3 Purpose

- To implement the algebraic flux model in the CFD solver
- To validate it against experimental data[1]

Working Fluid	Air
Rayleigh Number	~ 10^{10}
Brief Results from the experiment	
A. Asymmetrical flows	
B. re-laminarization on the floor wall	
C. Transition to Turbulence location: 20%	



General flow observations in the exp.

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[1] Cheesewright, R.., King, K.J., Ziai, S., 1986. Experimental data for the validation of computer codes for the prediction of two-dimensional buoyant cavity flows. ASME Meeting, HTD, vol 60, pp. 75-81

4 Numerical Methodology (1/2)

- **Governing equations**

$$\frac{\partial U_i}{\partial x_i} = 0$$

$$\frac{\partial U_i}{\partial t} + U_j \frac{\partial U_i}{\partial x_j} = -\frac{\partial P}{\partial x_i} + \frac{\partial}{\partial x_j}\left[\upsilon\left(\frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_i}\right) - \overline{u_i u_j}\right] + \beta(T - T_o)g_i$$

$$\overline{u_i u_j} = \upsilon_T \frac{\partial U_i}{\partial x_j} + \frac{2}{3} k \delta_{ij}$$

$$\frac{\partial T}{\partial t} + U_j \frac{\partial T}{\partial x_i} = \frac{\partial}{\partial x_j}\left(\alpha \frac{\partial T}{\partial j} - \overline{\theta u_j}\right)$$

$$\overline{\theta u_i} = -\frac{\upsilon_T}{Pr_T}\frac{\partial T}{\partial x_i} = -\alpha_T \frac{\partial T}{\partial x_i}$$

- **TMF ($\overline{u_i u_j}$) & THF ($\overline{\theta u_j}$) model**
  - TMF model: EVM (**k-omega SST)**
  - THF model: EDM (**AFM**: Algebraic heat flux model) [1]

$$\frac{\partial \overline{\theta u_i}}{\partial t} + U_k \frac{\partial \overline{\theta u_i}}{\partial x_k} = P_{\theta i}^{T} + P_{\theta i}^{U} + G_{\theta i} + \phi_{\theta i}^{*} - \varepsilon_{\theta i} + D_{\theta i}^{\alpha} + D_{\theta i}^{t}$$

$$\overline{\theta u_i} = -C_0 \frac{k}{\varepsilon}\left(C_1 \overline{u_i u_j}\frac{\partial T}{\partial x_j} + C_2 \overline{\theta u_j}\frac{\partial U_i}{\partial x_j} + C_3 \beta g_i \overline{\theta^2}\right)$$

	C_0	C_1	C_2	C_3
Air[2]	0.15	0.6	0.6	1.5

$$\frac{\partial \overline{\theta^2}}{\partial t} + U_J \frac{\partial \overline{\theta^2}}{\partial x_j} = -2\,\overline{\theta u_j}\frac{\partial T}{\partial x_j} - 2\varepsilon_\theta + \frac{\partial}{\partial x_j}\left[\left(\upsilon + \frac{\upsilon_t}{\sigma_{\theta 2}}\frac{\partial \overline{\theta^2}}{\partial x_j}\right)\right]$$

$$\varepsilon_\theta = \frac{\varepsilon \overline{\theta^2}}{2Rk} \qquad R = \frac{\tau_{th}}{\tau_m} \approx 0.5$$

In this study: **SST-AFM**

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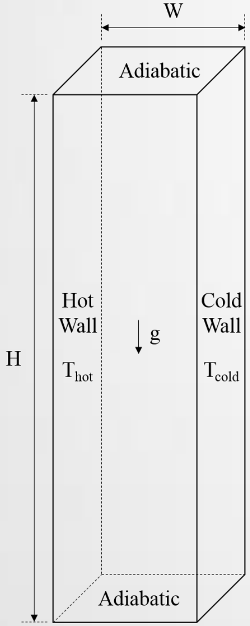
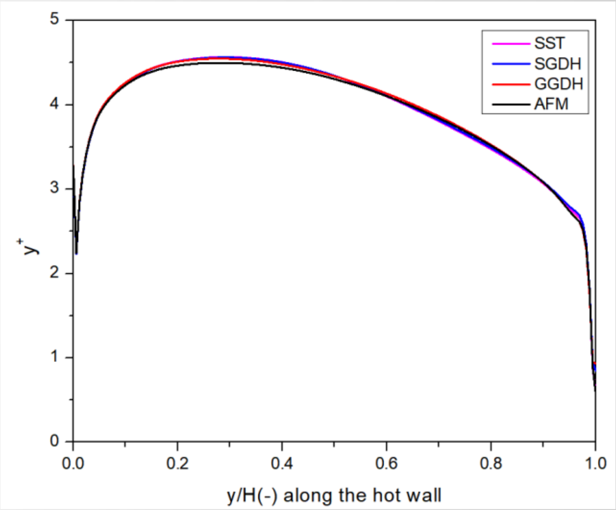
[1] K. Hanjalić, "One-point closure models for buoyancy-driven turbulent flows," *Annu. Rev. fluid Mech.*, 2002.

[2] Kenjeres, S. and K. Hanjalić. Contribution to elliptic relaxation modeling of turbulent natural and mixed convection, IJHFF, 26, pp.569-586

5 Numerical Methodology (2/2)



DHC	Air
Ra	5.2×10^{10}
Gr	7.4×10^{10}
T_{hot} / T_{cold} (dT)	341.15K/295.35K (45.8K)
ν	1.73×10^{-5}
β	3.15×10^{-3}
Pr	0.7
BC	No slip condition: $U_i = 0$ Reynolds stress: $\overline{u_i u_j} = 0$ Turbulent heat flux: $\overline{u_i \theta} = 0$ Temperature variation: $\overline{\theta^2} = 0$ Dissipation: $\varepsilon_w = 2\nu k / y^2$

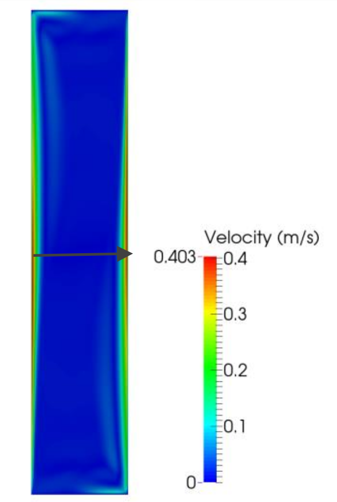


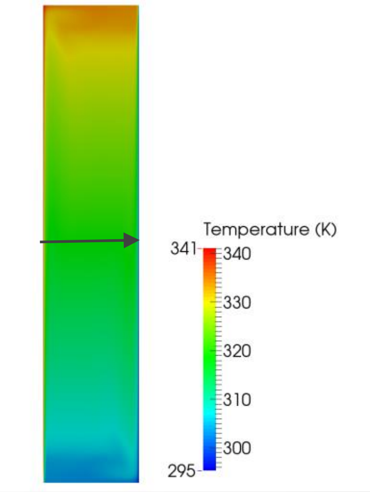
- In this study
Nodes: 160x160

- P-V coupling: SIMPLE (Steady)
- Gradient, Laplacian and TMF/THF terms - CD (2nd); Rest terms - Upwind (1st)

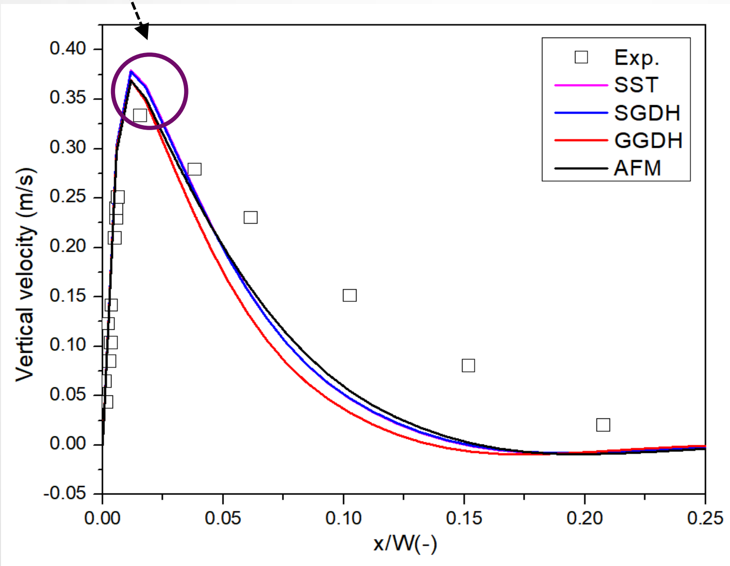
6 Analysis I:

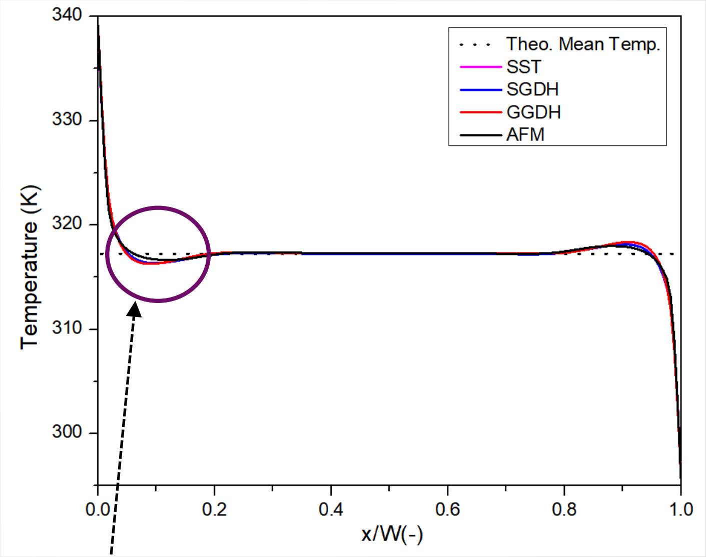
Velocity » Temperature





Sharp edged peaks

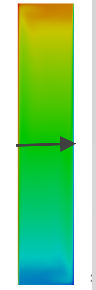


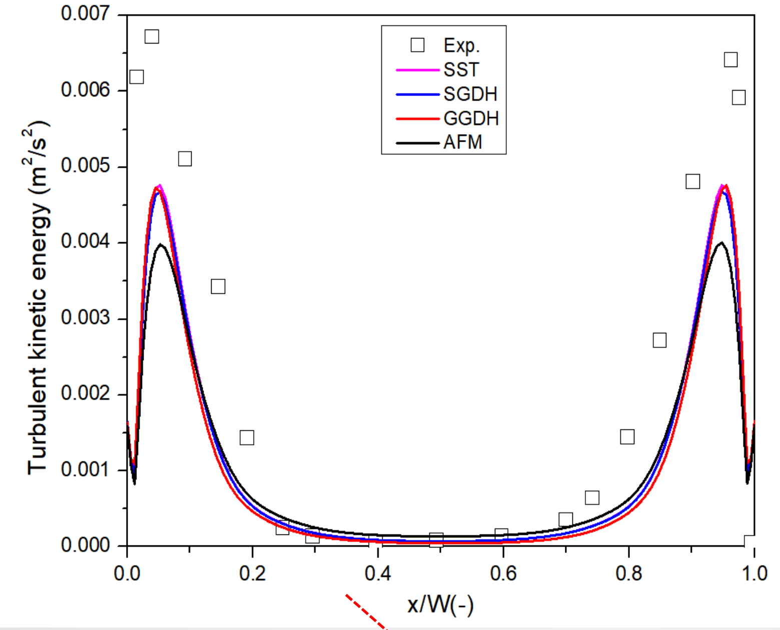


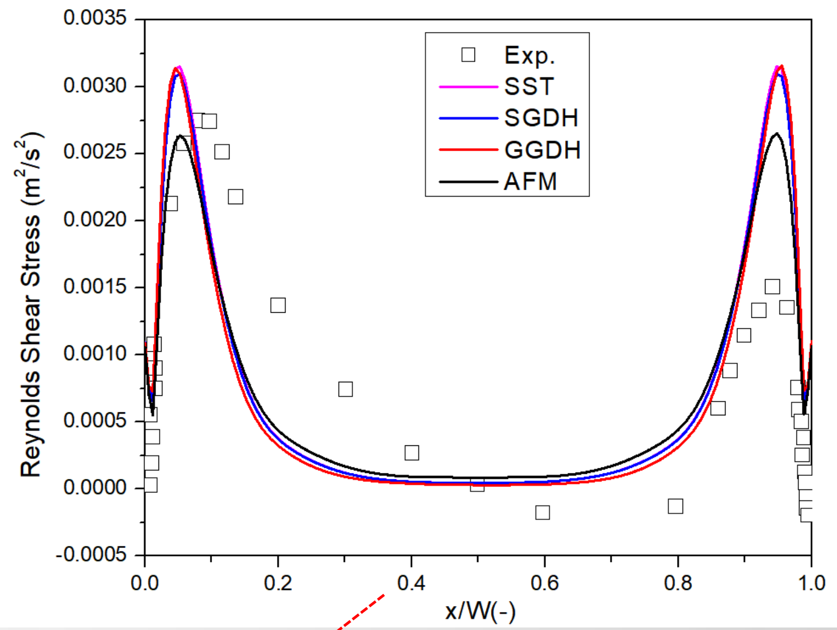
Other models are more deviated

7 Analysis I:

Turbulent KE » Shear Stress



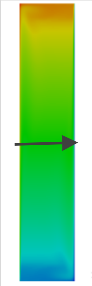




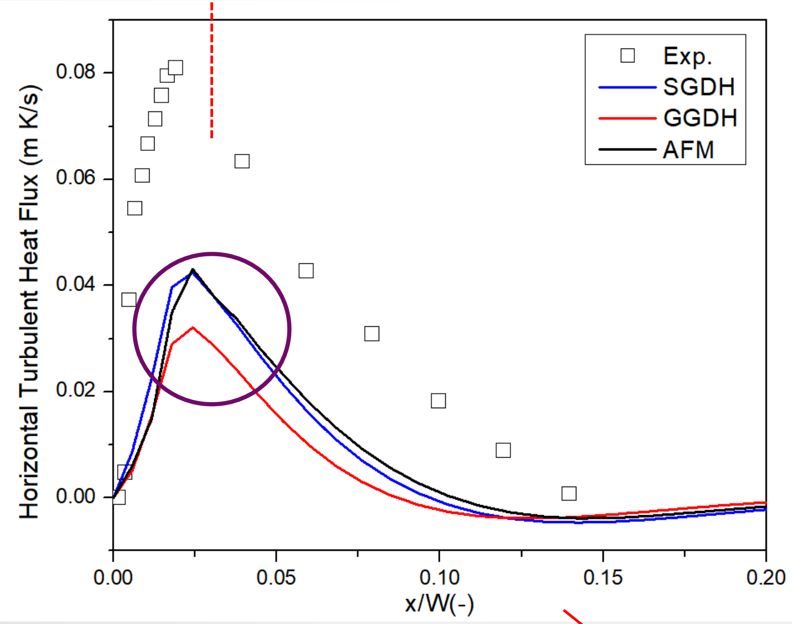
AFM is underpredicted due to fast dissipation of turbulence eddies that leads to lower turbulent intensity (Peng et al., 1998)

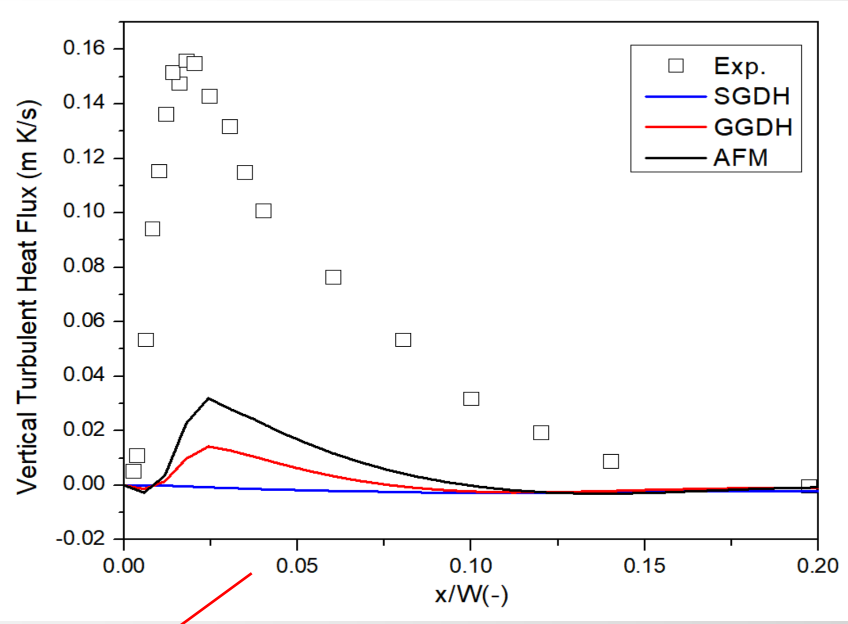
8 Analysis I:

Turbulent Heat Fluxes



Sharp edged peaks





- Gives hollow-like minima before reaching the midwidth[1]
- Among all the models, AFM has the highest peak

[1] Kenjeres, S. Numerical modeling of complex buoyancy-driven flows, Ph.D. These, Delft University of Technology, (1998).

Analysis II:

Sensitivity of Ct1 & Ct3 (Shams et al., 2014 & Shams, 2018)

$$\overline{\theta u_i} = -C_{t_o}\frac{k}{\varepsilon}\left(C_{t_1}\overline{u_i u_j}\frac{\partial T}{\partial x_j} + C_{t_2}\overline{\theta u_j}\frac{\partial U_i}{\partial x_j} + C_{t_3}\beta g_i\overline{\theta^2}\right) + C_{t_4}a_{ij}\overline{\theta u_j}$$

Model	C_{t0}	C_{t1}	C_{t2}	C_{t3}	C_{t4}	Applicability
AFM-2005	0.15	0.6	0.6	0.6	1.5	Unity Prandtl fluids
AFM-NRG[1]	0.2	0.053 ln(Re.Pr) -0.27	0.6	2.5	0	All flow regimes but with limited Ra range
AFM-NRG+[1]	0.2	0.25	0.6	See Eq. below	0	High Ra cases

$C_{t_3} = a_1 \cdot log_n(Ra \cdot Pr) + a_1$ with $10^0 < Ra \cdot Pr < 10^{17}$

where		
	a_1	-4.5×10^{-9}
	a_2	2.5
	n	7

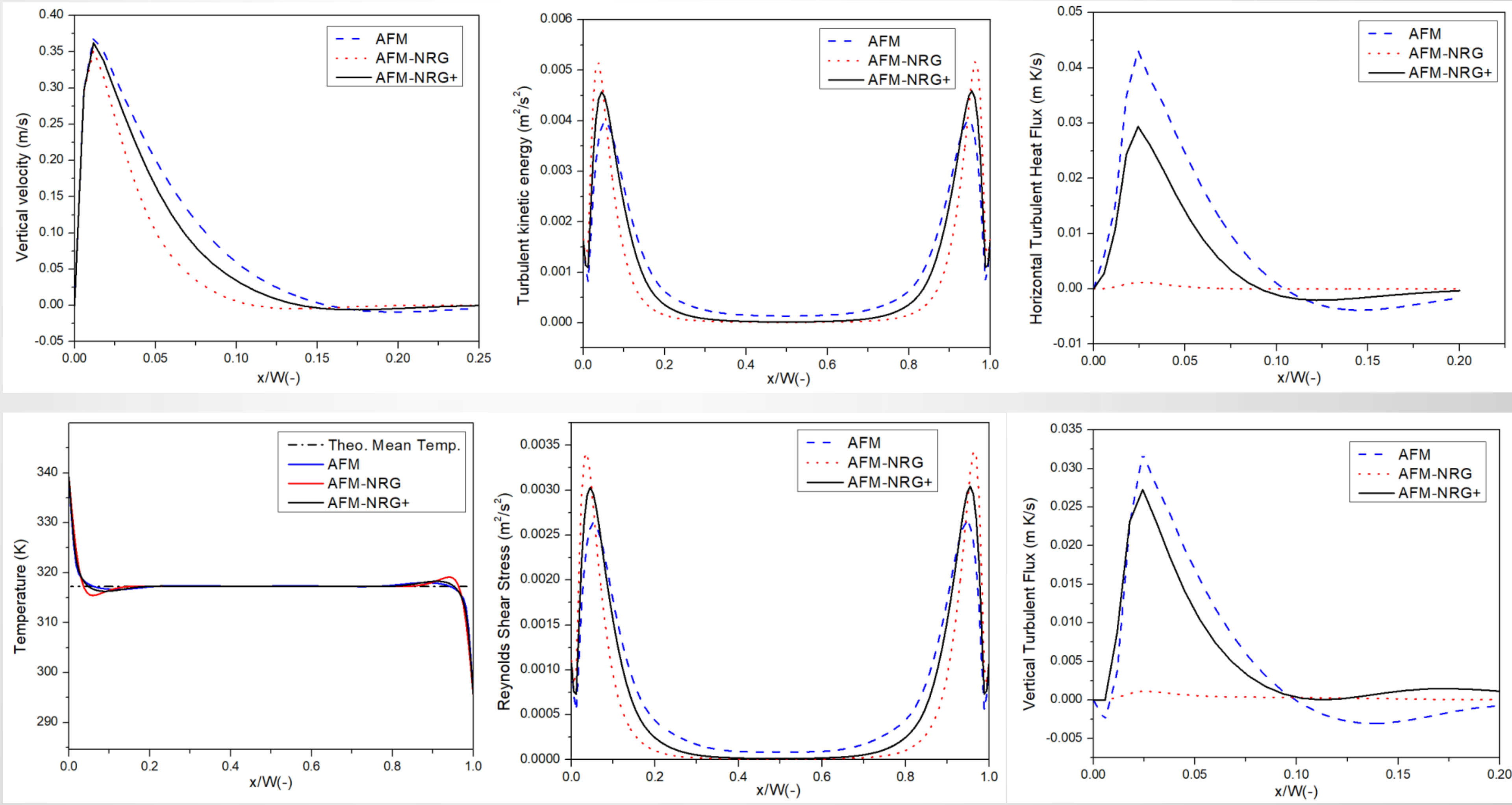
Based on the Re, Pr, and the limiting condition of natural convection (i.e. Re.Pr ≤ 180), $C_{t1} = 0.005$

Based on the Ra and Pr condition, $C_{t3} = 2.5$

[1] Shams, A. (2018). Towards the accurate numerical prediction of thermal hydraulic phenomena in corium pools. Annals of Nuclear Energy 117 (2018) 234-246

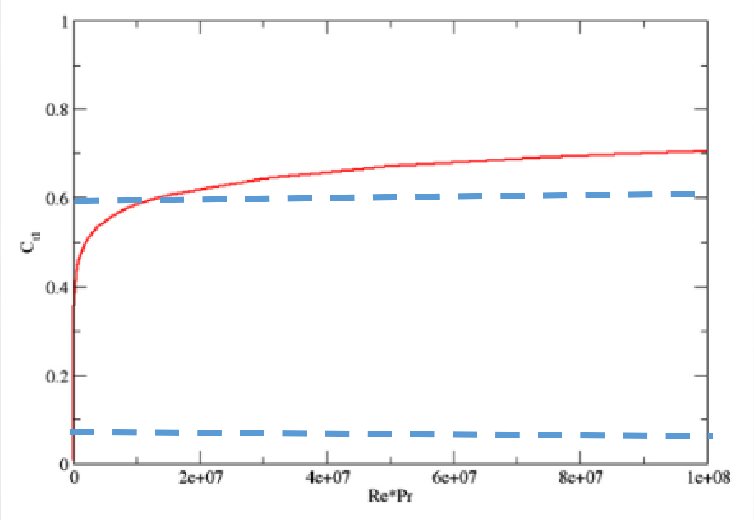
10 Analysis II:

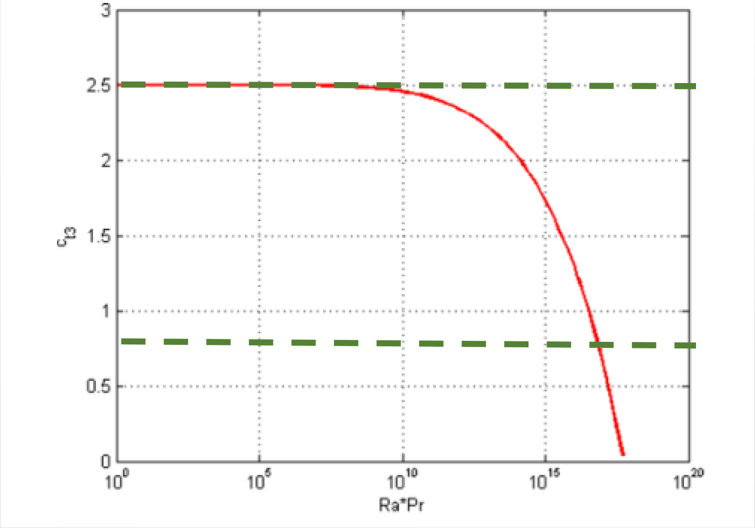
Coefficients adopted from Shams (2018)



11 Analysis III:

A. Sensitivity of Ct1 & Ct3





B. Forced versus Mixed/Natural

- **This follow-up study will incorporate wide range of values:**

C_{t1} from (0.005 to 0.60) with C_{t3} being fixed at 2.5

C_{t3} from (0.60 to 2.5) with C_{t1} being fixed at 0.25

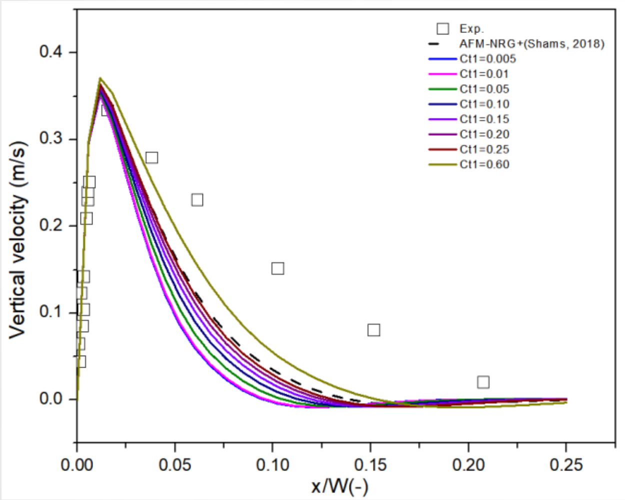
Ct0 & Ct1 being sensitive to forced convection

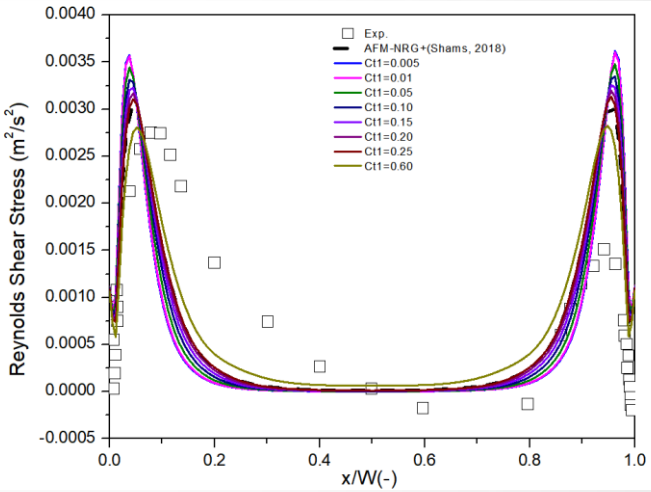
Ct2 & Ct3 being sensitive to mixed/natural convection

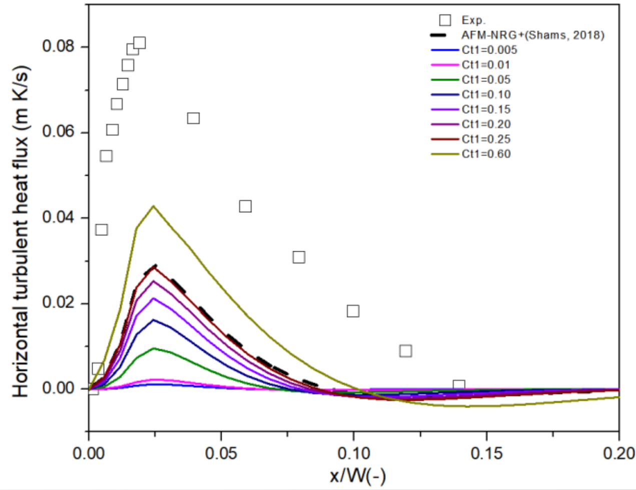
		C_{t0}	C_{t1}	C_{t2}	C_{t3}
Air	Optimum	0.2	1.0	0.6	1.5
	Case 1	0.1	0.2	0.6	1.5
	Case 2	0.1	0.6	0.6	1.5
	Case 3	0.3	1.0	0.6	1.5
	Case 4	0.2	1.0	0.4	0
	Case 5	0.2	1.0	0.8	2.5

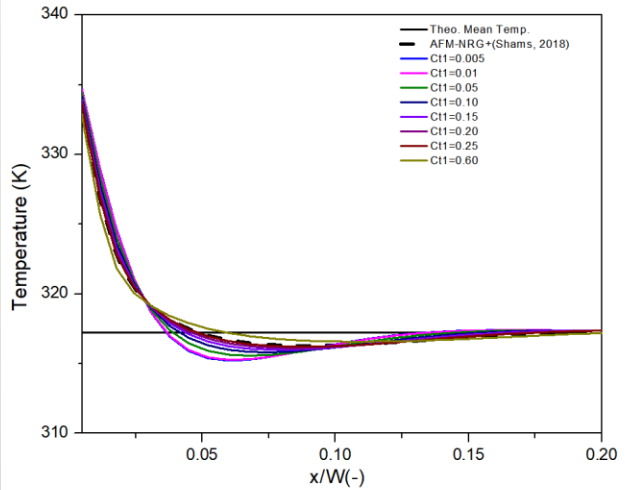
Analysis III:

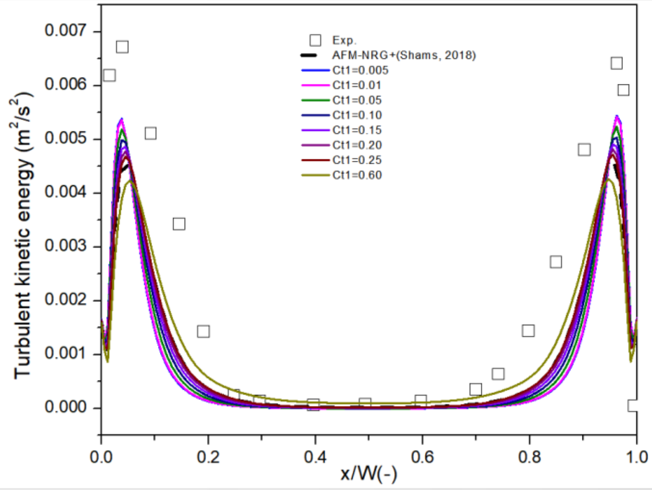
Sensitivity effect of Ct1

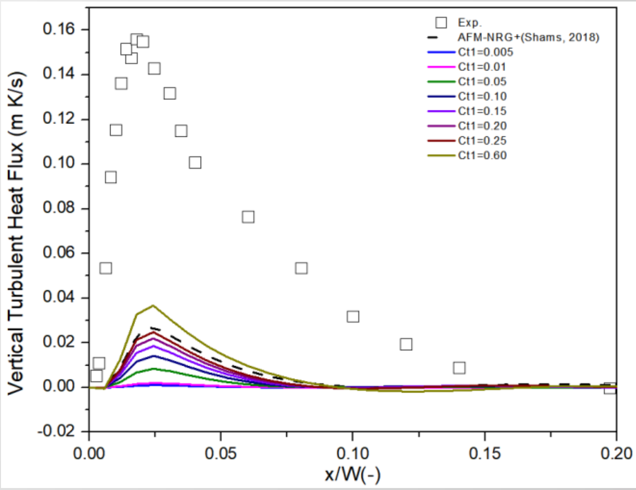






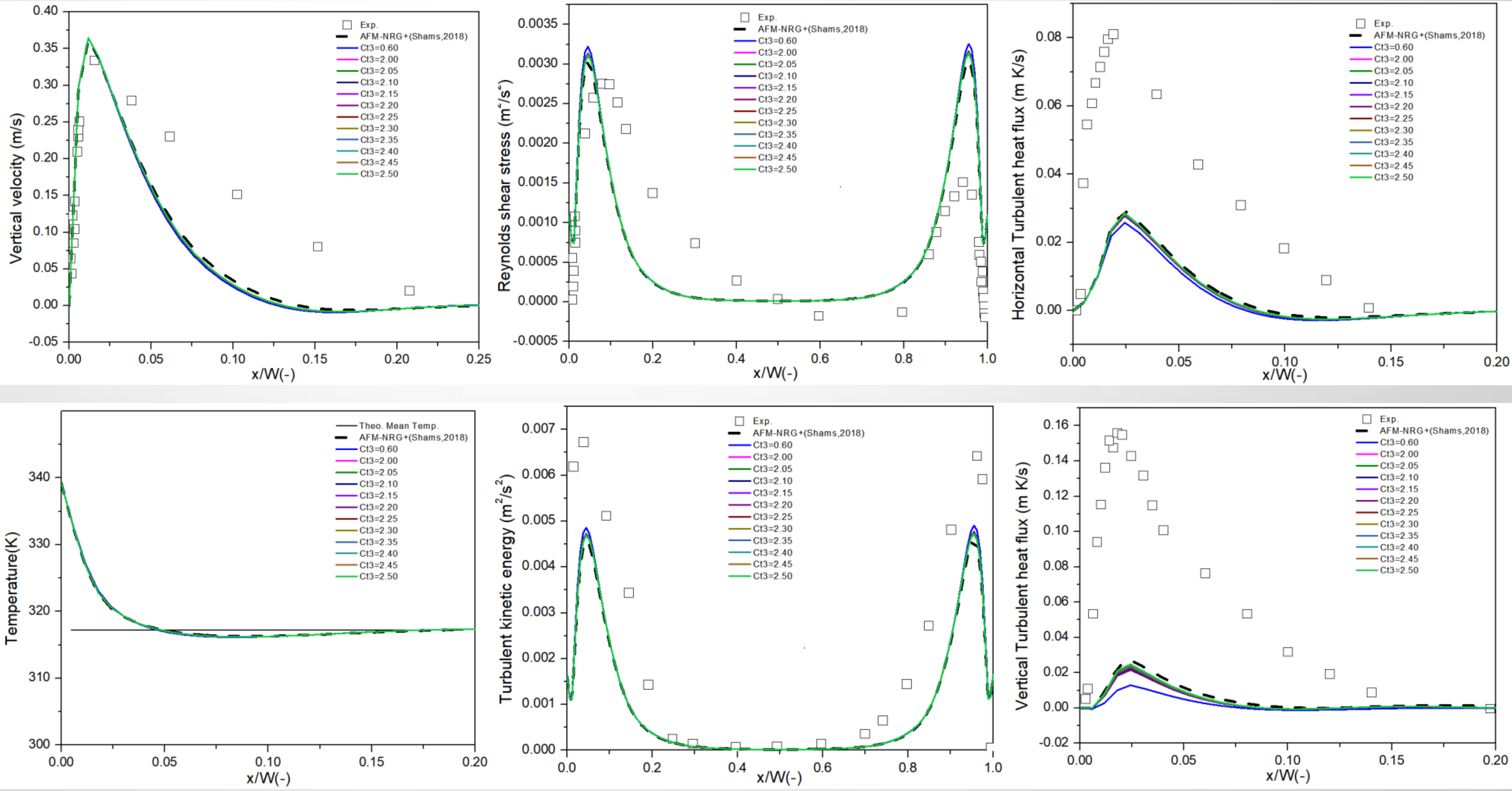






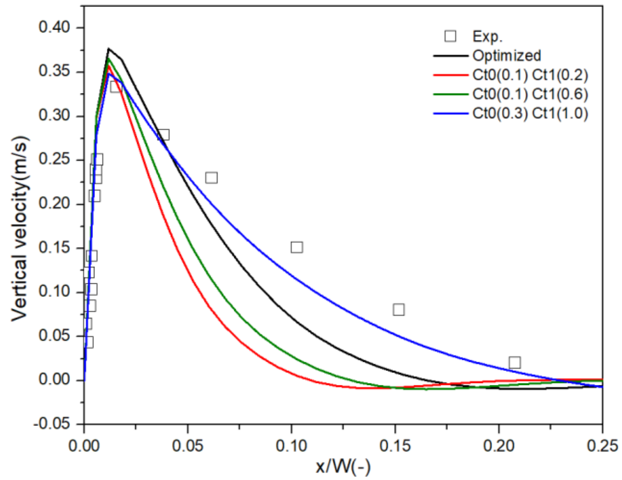
13 Analysis III:

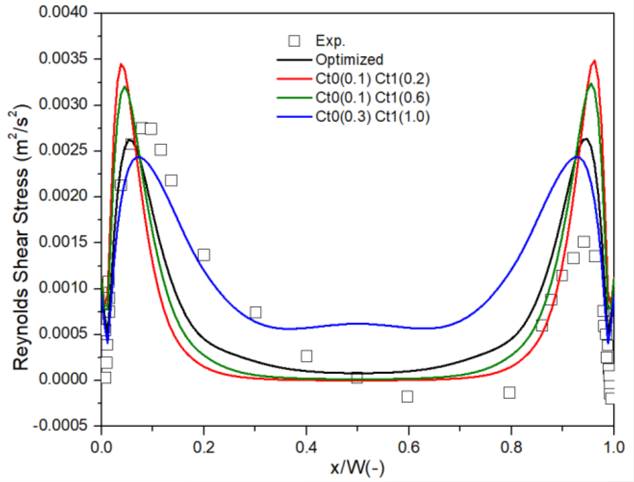
Sensitivity effect of Ct3

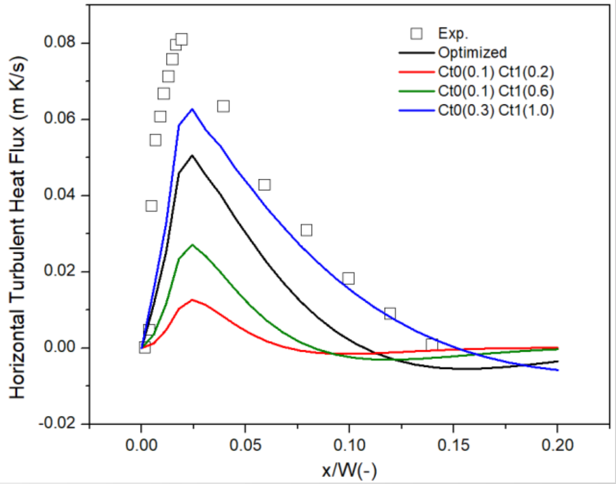


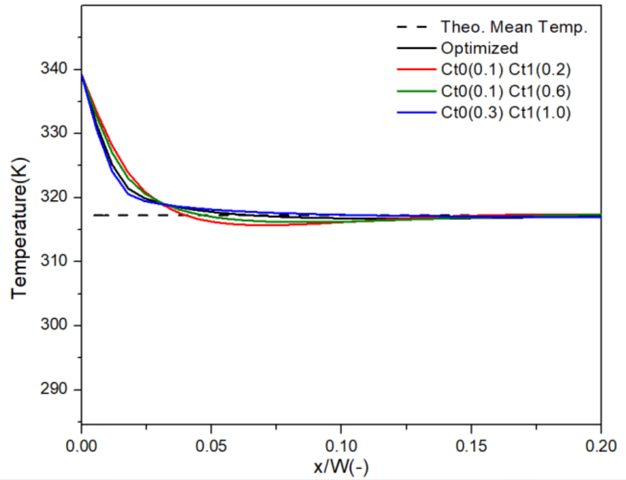
Analysis III:

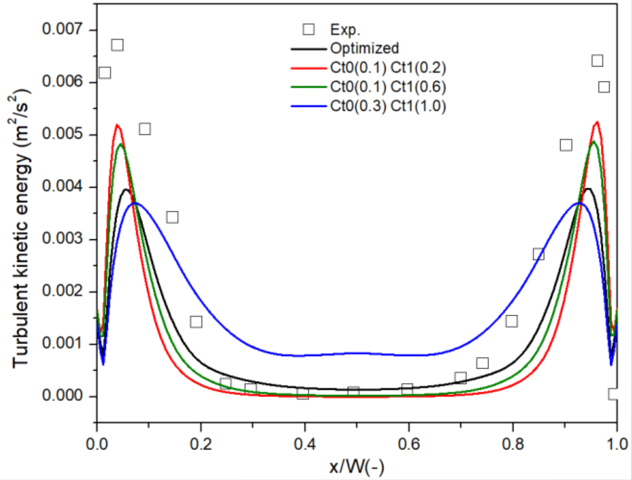
Effect of Ct0 and Ct1 (Forced Convection Emphasis)

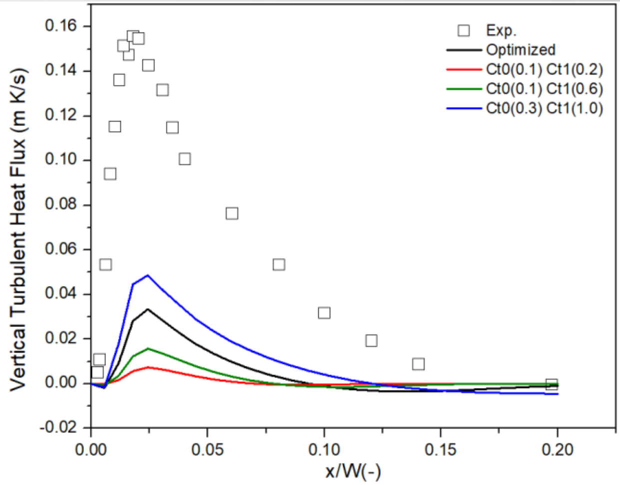






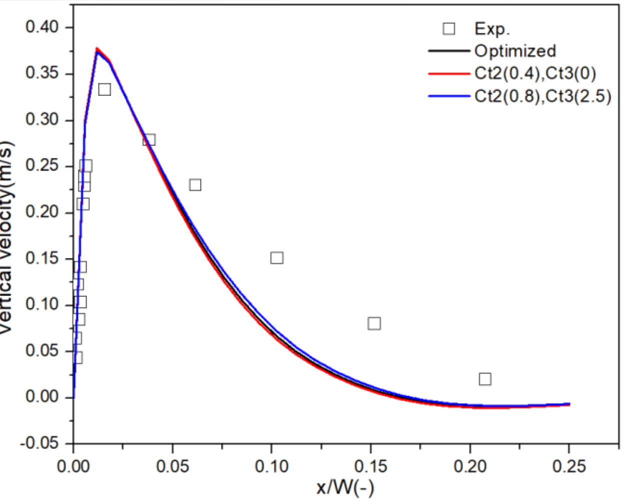


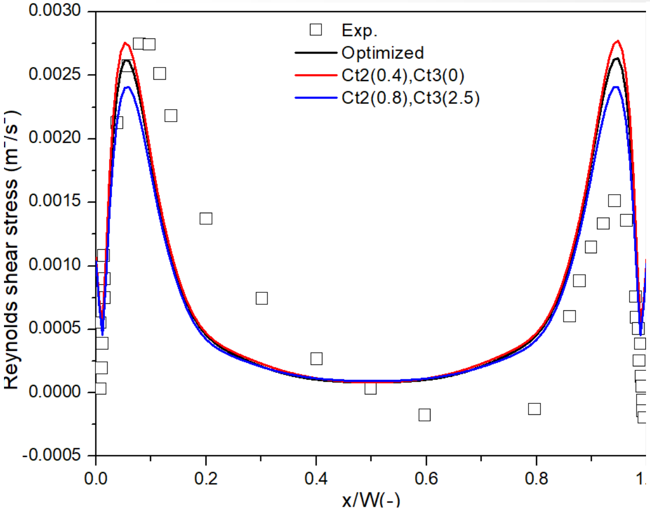


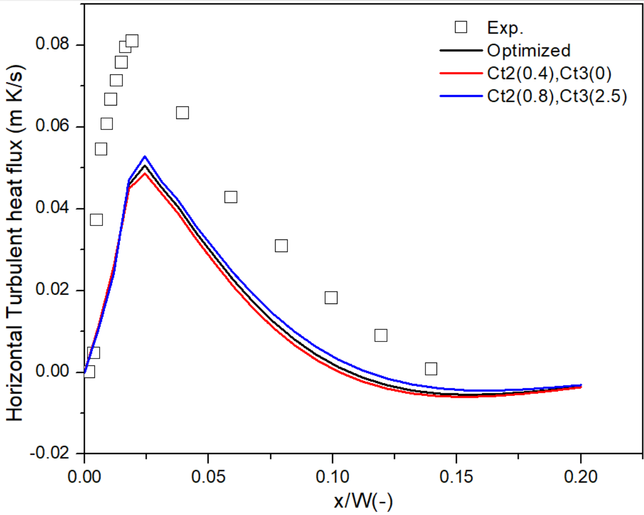


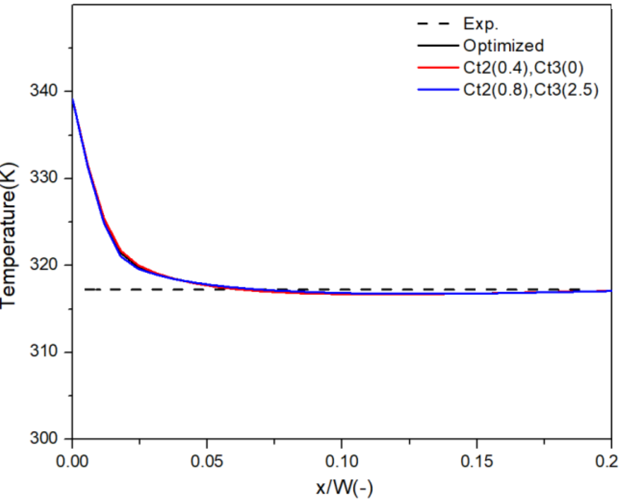
15 Analysis III:

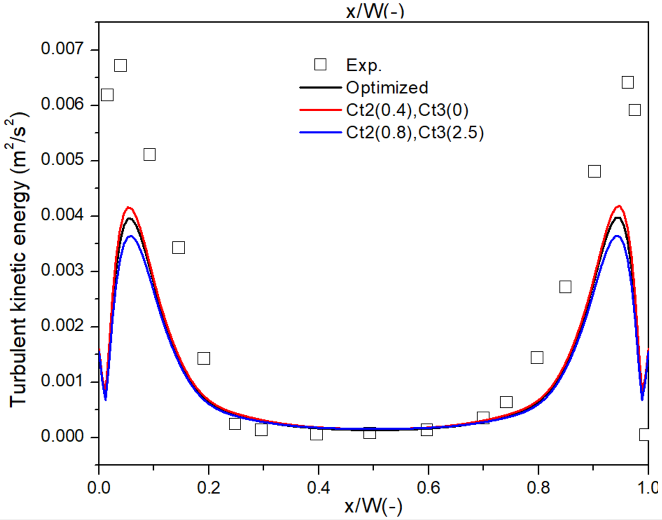
Effect of Ct2 and Ct3 (Mixed/Natural Convection Emphasis)

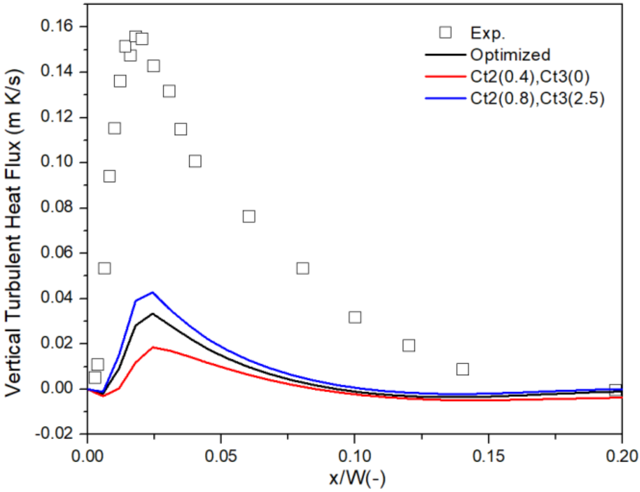










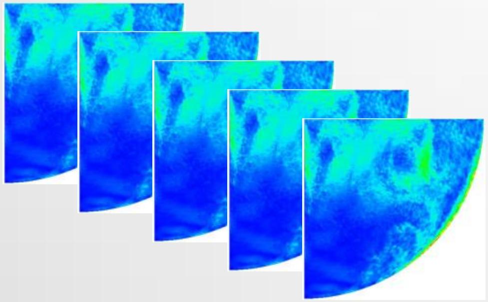


Conclusion

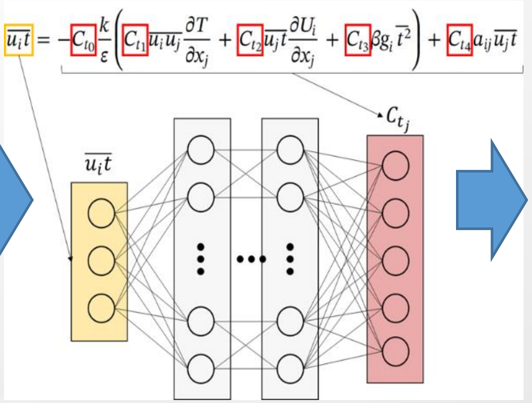
Validation of selected model (**SST-AFM**) for air (Pr=0.7) case

-Due to mesh grid dependence issues & RANS turbulence model selected, convergence is hardly achievable

-Coefficient Tuning has yet to be properly assessed once done with Large Eddy Simulation (LES)



Num. experiment data



$$\overline{\theta u_i} = -C_0\frac{k}{\varepsilon}\left(C_1\overline{u_i u_j}\frac{\partial T}{\partial x_j} + C_2\overline{\theta u_j}\frac{\partial U_j}{\partial x_j} + C_3\beta g_i\overline{\theta^2}\right) \;\&\; (\,\overline{u_i u_j}\,)$$

Impact of corium behavior on the evaluation