# CFD study of dominant effect in combined DTHT by using hypothetical boundary conditions

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## 1. Introduction

KAIST MMR is a gas cooled fast reactor (GFR) using supercritical $CO_2$ as a working fluid of reactor core and power cycle without intermediate heat exchanger which operates in higher pressure and higher temperature conditions compared to PWR[1]. During a Loss of Coolant Accident (LOCA), MMR needs to relay on passive Decay Heat Removal (DHR) system by using natural circulation of gas since passive decay heat removal using conduction and radiation is not providing sufficient decay heat removal.

During an accident phase, a gas cooled systems might operate in the deteriorated turbulent heat transfer (DTHT) regime under high heat flux and low cooling flow environment. When the gas flow is in the DTHT regime, the flow will show unique behavior which will significantly affect temperature, velocity, turbulent momentum and heat transfer. There are two effects which induce DTHT phenomena: (1) buoyancy, (2) acceleration. Buoyancy induced DTHT or mixed convection regime is a region in which both free and forced convection affect the turbulent convective heat transfer with similar order of importance [2]. The acceleration induced DTHT or laminarizing flow regime is a region in which bulk flow will accelerate when the bulk density is decreased due to external heat source. Fig. 1 and Fig. 2 show the effect of buoyancy and acceleration, respectively, on turbulent heat transfer.

Apart from these two deteriorating effects, another unique behavior of fluid in the DTHT regime is that the convective heat transfer rate will continue to deteriorate until it reaches a certain point. The downstream of this point is known as recovery region, where the convective heat transfer rate returns back to the high values by recovering turbulence. This phenomenon is called as re-turbulization.

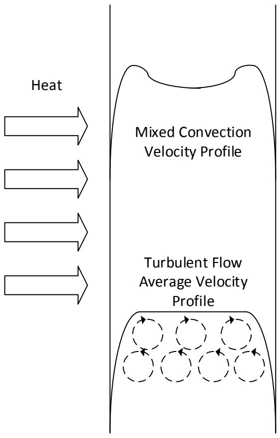

Fig. 1. Buoyancy effect on the turbulent flow.

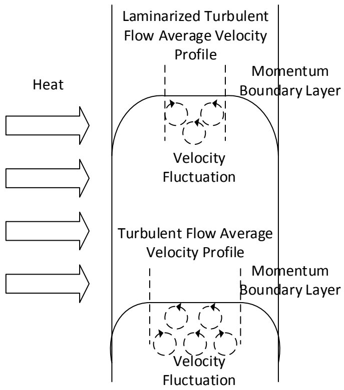

Fig. 2. Acceleration effect on the turbulent flow.

The most commonly used governing non-dimensional numbers among the researchers are the buoyancy parameter, which is defined in Eq. (1), and the acceleration parameter, which is defined in Eq. (2), for each regime. The threshold value for both effects to move from the forced convection turbulent heat transfer to DTHT regime are found to be $Bo^* \geq 2x10^{-6}$ and $K_v \geq 2.5x10^{-6}$ [3] in the previous works.

$$Bo^* = \frac{Gr_q}{\mathrm{Re}^{3.425}\,\mathrm{Pr}^{0.8}} \tag{1}$$

$$K_v = \frac{4q^+}{\mathrm{Re}} \tag{2}$$

Many experiments and simulation has been done to investigate this phenomenon and the boundary of the regime. However, very limited number of experiment was conducted in the regime where buoyancy effect and acceleration effect are in the same order of magnitude and high enough to cause DTHT (combined DTHT).

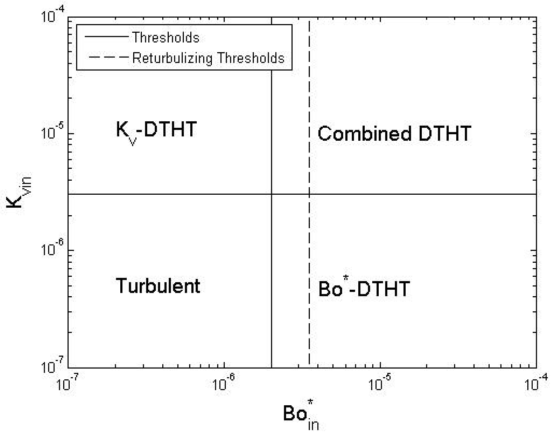

Fig. 3. Map of DTHT regime

Some important experimental research works that have been done in the gas DTHT regime are Lee et al. [3] who investigated the heat transfer of gas flow within range of buoyancy parameter from $3\times10^{-9}$ to $10^{-5}$ and acceleration parameter span from $6\times10^{-8}$ to $5\times10^{-6}$ and presented the behavior of Nusselt number ratio from the experiment as Fig. 4 and Fig. 5.

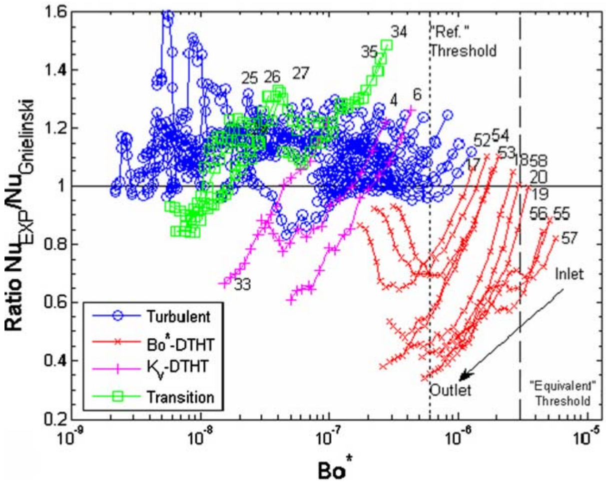

Fig. 4. Nu ratio-Bo plot [3]

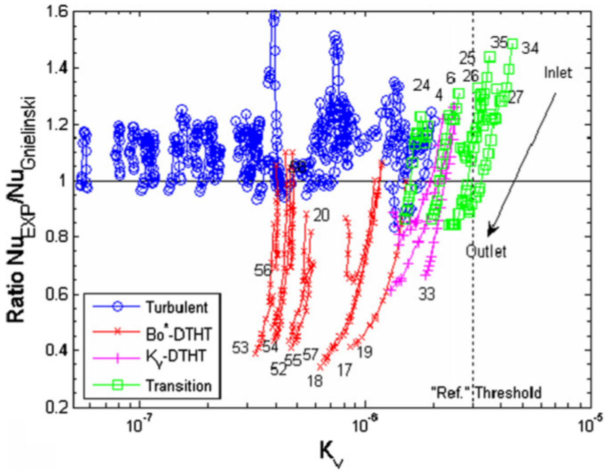

Fig. 5. Nu ratio-$K_v$ plot [3]

This paper will discuss a Computational Fluid Dynamics analysis by assuming hypothetical boundary conditions especially in the combined DTHT regime to see which effect is more dominant between buoyancy effect and acceleration effect.

## 2. Methods and Results

Numerical analysis was performed using a commercial computational fluid dynamics code ANSYS FLUENT 14.5 to model the mixed convection flow in a gas system. Coupled scheme is applied to solve the flow in a vertically oriented round tube by applying two-dimensional axi-symmetric model in a cylindrical coordinate system. In this section turbulence model, problem domain, and results will be described.

### *2.1 Turbulence Model*

The $v^2$-$f$ turbulence model is consisted of 4 equation model based on transport equation for turbulence kinetic energy ($k$), dissipation rate ($\varepsilon$), velocity variance scale ( $\overline{v^2}$ ), and elliptic relaxation function ($f$) shown in Eq. (1) to Eq. (4). Eddy viscosity was evaluated by using velocity variance scale and it has shown to provide the right scaling to represent the damping of turbulent transport near the wall which is not represented in the $k$-$\varepsilon$ model well. The anisotropic wall effects are modeled through the elliptic relaxation function $f$.

$$\frac{\partial}{\partial t}(\rho k)+\frac{\partial}{\partial x_i}(\rho k u_i)=P-\rho\varepsilon+\frac{\partial}{\partial x_j}\left[\left(\mu+\frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right]+S_k \tag{3}$$

$$\frac{\partial}{\partial t}(\rho\varepsilon)+\frac{\partial}{\partial x_i}(\rho\varepsilon u_i)=\frac{C'_{\varepsilon1}P-C_{\varepsilon2}\rho\varepsilon}{T}+\frac{\partial}{\partial x_j}\left[\left(\mu+\frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon}{\partial x_j}\right]+S_\varepsilon \tag{4}$$

$$\frac{\partial}{\partial t}\left(\rho\overline{v^2}\right)+\frac{\partial}{\partial x_i}\left(\rho\overline{v^2}u_i\right)=\rho k f-6\rho\overline{v^2}\frac{\varepsilon}{k}+\frac{\partial}{\partial x_j}\left[\left(\mu+\frac{\mu_t}{\sigma_k}\right)\frac{\partial\overline{v^2}}{\partial x_j}\right]+S_{\overline{v^2}} \tag{5}$$

$$f-L^2\frac{\partial f}{\partial x_j}=\left(C_1-1\right)\frac{\frac{2}{3}-\overline{v^2}/k}{T}+C_2\frac{P}{\rho k}+\frac{5\overline{v^2}/k}{T}+S_f \tag{6}$$

Where

$$P = 2\mu_t S^2, S^2 \equiv S_{ij} S_{ij}, S_{ij} = \frac{1}{2}\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right) \tag{7}$$

$$T' = \max\left[\frac{k}{\varepsilon}, 6\sqrt{\frac{v}{\varepsilon}}\right] \tag{8}$$

$$T = \min\left[T', \frac{\alpha}{\sqrt{3}} \frac{k}{v^2 C_\mu \sqrt{2S^2}}\right] \tag{9}$$

$$L' = \min\left[\frac{k^{3/2}}{\varepsilon}, \frac{1}{\sqrt{3}} \frac{k^{3/2}}{v^2 C_\mu \sqrt{2S^2}}\right] \tag{10}$$

$$L = C_L \max\left[L', C_\eta \left(\frac{v^3}{\varepsilon}\right)^{1/4}\right] \tag{11}$$

### *2.2 Problem Domain*

The problem domain is designed to match the operational geometry of GFR which is our domain of interest. The geometry of the problem domain was constructed and shown in Fig. 6. A developing length was provided to match the fully developed flow condition at the entrance of the test section. The test section was marked at 20 different locations to portray the process of the phenomena from inlet to outlet. The location of the marks is tabulated in Table. I. An adiabatic outlet section was attached after the test section in order to allow an outflow boundary condition and remove boundary condition effect on upstream. There are variations of inner diameter and heat flux to produce the conditions of buoyancy and acceleration parameters. The thermos-physical properties of gases were provided to FLUENT by using NIST real gas model mode.

Table I. Measurement Location

| Thermal Couple | L/D |
|---|---|
| TC01 | 2 |
| TC02 | 8.1 |
| TC03 | 14.1 |
| TC04 | 20.2 |
| TC05 | 26.2 |
| TC06 | 32.3 |
| TC07 | 38.3 |
| TC08 | 44.4 |
| TC09 | 50.4 |
| TC10 | 56.5 |
| TC11 | 62.5 |
| TC12 | 68.5 |
| TC13 | 74.6 |
| TC14 | 80.6 |
| TC15 | 86.7 |
| TC16 | 92.7 |
| TC17 | 98.8 |
| TC18 | 104.8 |
| TC19 | 110.9 |
| TC20 | 116.9 |

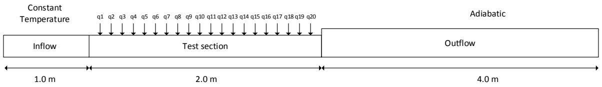

Fig. 6. Problem Domain

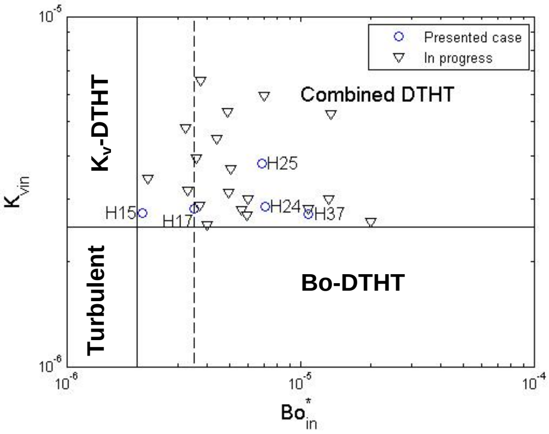

Fig. 7. Case Map

In the previous work, grid convergence was investigated and it was found that mesh system with 60 radial mesh was good enough to ensure good resolution of the near the wall flow (wall $y^+<1$). For the axial direction, axial mesh consist of 40 control volume was used in the test section. The validation of the CFD also has been done in the previous work.

### *2.3 CFD result in combined DTHT regime and discussion*

This paper will review the numerical analysis results to predict the threshold of the dominant effect in the combined DTHT regime by looking at the maximum axial velocity location as a parameter.

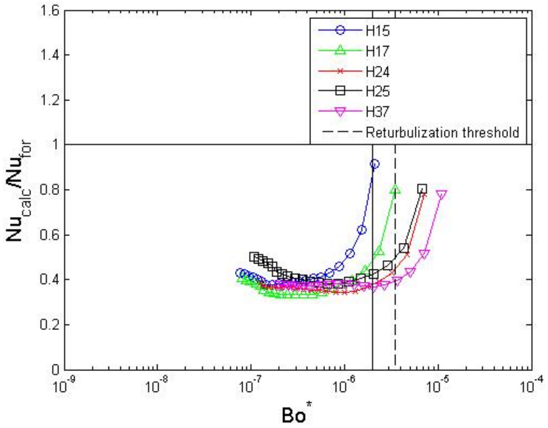

Fig. 8. Nu ratio vs. Buoyancy parameter.

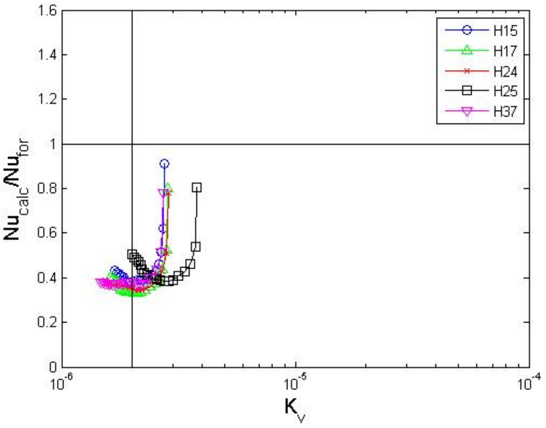

Fig. 9. Nu ratio vs. Acceleration parameter.

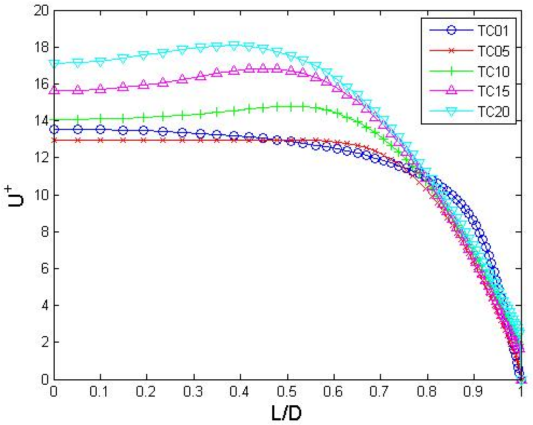

Fig. 10. Case H15 axial velocity profile

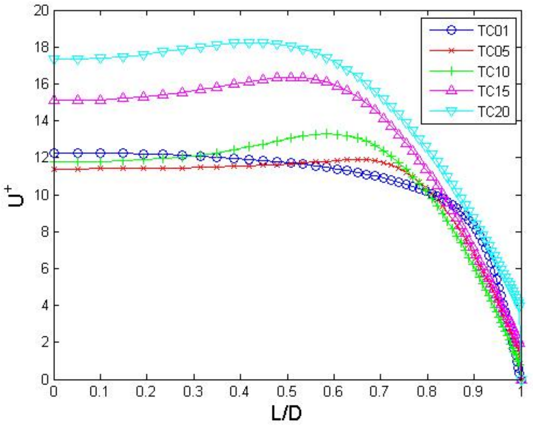

Fig. 11. Case H17 axial velocity profile

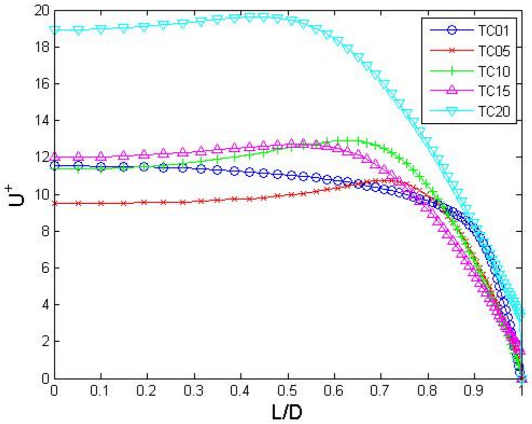

Fig. 12. Case H24 axial velocity profile

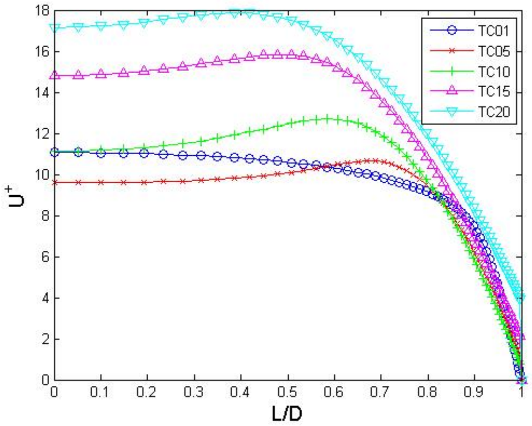

Fig. 13. Case H25 axial velocity profile

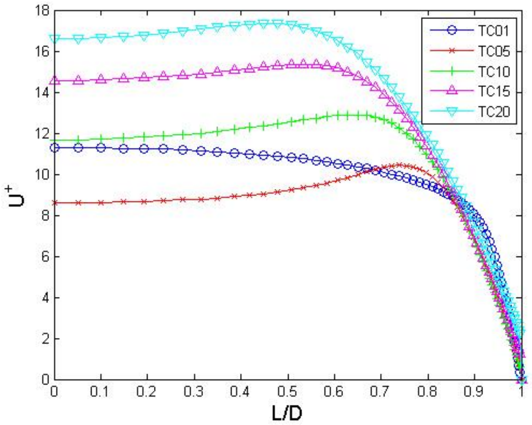

Fig. 14. Case H37 axial velocity profile

So far around 21% of the planned cases were calculated and even at this stage some interesting results are obtained. The axial velocity profiles which is shown in Fig. 10-14 tell us that buoyancy effect is more dominant than acceleration effect even when the acceleration parameter is greater than buoyancy parameter, such as case H15. More data is needed to confirm the thresholds where acceleration effect will start to dominate the DTHT phenomena. The other interesting result is even when case H15 condition is in the re-turbulization regime, there is no sign of the re-turbulization in the result, this result is due to the $v^2$-$f$ turbulence model over prediction of the buoyancy effect and thus it needs to be adjusted for more accurate result.

## 3. Summary and Further Works

It has been found that a gas cooled fast reactor has a tendency to operate in the Deteriorated Turbulent Heat Transfer (DTHT) regime as heat flux becomes higher under low cooling flow environment such as natural circulation operation in the past research works. Therefore, the unique behavior of the gas properties in the DTHT regime should be investigated. Previous researches have been done in either focusing on the buoyancy induced DTHT regime only or in the acceleration DTHT only. Very limited researches were conducted in the regime where both occur at the same time and in the same order of magnitude.

Numerical analysis is done with $v^2$-$f$ turbulence model to predict the physical phenomena for the future experimental work. The effects of buoyancy and acceleration were studied with CFD for designed cases to distinguish the dominant effect in the combined DTHT regime. Numerical results of the $v^2$-$f$ turbulence model show that the model can predict the buoyancy induced DTHT phenomenon even when the acceleration parameter is greater than buoyancy parameter but there is no data that shows that acceleration induced DTHT dominates the DTHT phenomena at this moment.

More numerical results in the combined DTHT regime will be obtained and studied to provide clearer view on strongly heated turbulent flow and its heat transfer deteriorating mechanism.

Adjustment for $v^2$-$f$ turbulence model to correct the prediction of buoyancy effect will be studied in the near future.

## REFERENCES

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