Transactions of the Korean Nuclear Society Spring Meeting
Jeju, Korea, May 10-11, 2007

An application of the modified turbulent model for analyzing supercritical heat transfer phenomena in a nuclear system

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1. Introduction

For understanding the characteristic of a supercritical fluid heat transfer, we proposed a new parameter [1], a global Froude number (Fr), dependent on the heat and mass flux, to determine under what conditions the buoyancy effect is dominant and the reduction of the heat transfer rate. In the region of the global Fr>0.01, variable property effects, which may occur at a high heat flux, and buoyancy effects, which could occur at a low mass flux, make the existing standard turbulent model such as the standard wall function not suitably accurate to calculate the heat transfer in supercritical fluid, needed for a reactor thermal-hydraulics simulation and design [2, 3, 4]. Therefore, the turbulence model, especially near the wall, the wall function for a momentum, applicable for a range of supercritical fluid conditions was modified [1, 5]. The modified models deal with a buoyancy, acceleration, and the variable property effect for supercritical conditions.

$$u^* - c_2 = \frac{1}{\kappa}\ln\left(\frac{y^*}{c_1}\right) - \frac{\Delta\tilde{\rho} g \tilde{\mu}}{\tau_w \tilde{\rho} C_\mu^{1/4} k^{1/2} \kappa}\left(y^* - c_1\right) + \frac{G^2 \mu}{\tau_w \rho C_\mu^{1/4} k^{1/2} \kappa}\frac{d\upsilon}{dx}(y^* - c_1)$$

where, $u^* = \dfrac{u C_\mu^{1/4} k^{1/2}}{\tau_w / \tilde{\rho}}$,

$$y^* = \frac{\tilde{\rho} C_\mu^{1/4} k^{1/2} y}{\tilde{\mu}},$$

$$\Delta\rho = \rho_\infty - \tilde{\rho},$$

$$\overline{\rho u}\frac{\partial \bar{u}}{\partial x} \cong \overline{G}^2 \frac{\partial\left(\overline{1/\rho}\right)}{\partial x} = \overline{G}^2 \frac{\partial\left(\overline{\upsilon}\right)}{\partial x} \qquad (1)$$

Where, the effective sublayer thickness (c_1) and $u^*_{y^*=c_1}$ at the thickness are unknown for the supercritical fluids. Let $u^*_{y^*=c_1}$ become c_2 at the effective sublayer thickness ($y^*=c_1$). In this study, the effective sublayer thickness for the modified momentum wall function is reconsidered. User-defined functions (UDFs) in FLUENT, which are employed to apply the above modified momentum wall function for analyzing supercritical heat transfer phenomena in a nuclear system, are used to estimate the cell field macros employed in UDFs and the sensitivity result of c_1 value.

2. Estimation of UDFs for the modified wall function

UDFs with the pre-defined macro in FLUENT, DEFINE_WALL_FUNCTIONS (udf_name, f, t, c0, t0, wf_ret, yPlus, Emod), are used to apply the modified momentum wall function that was developed. DEFINE_WALL_FUNCTIONS is the one of the DEFINE macros, which are the functions that can be programmed with a C programming language, access data from FLUENT solver and dynamically loaded within the FLUENT solver for a new momentum wall function. This macro is applied to the wall and the cell near the wall using thread and index which are variables passed into the function from the FLUENT solver.

First, it is necessary to access the thermo-physical properties (density and molecular viscosity) and other variables from the FLUENT solver for applying equation (1) to the UDFs. These variables can be obtained by the cell field variable macros such as C_R(c0,t0), which is the density in the wall function region, C_MU_L(c0,t0), which is a molecular viscosity in the wall function region, and C_R_G(c0,t0) [0], which is the density gradient in the x-direction in the wall function region. A macro, DEFINE_ON_DEMAND, which can be executed on demand by using the Get_Domain utility for retrieving the domain variables in FLUENT, is used to evaluate the cell and face field variable macros in UDFs. Density, molecular viscosity, and turbulent kinetic energy obtained from the macro are compared with those solved by FLUENT. The second step in an implementation of the UDFs is accessing the cell-averaged density and the wall shear stress added inside the UDFs. The values are also compared and verified by obtaining those from a C programming for accessing the values and the averaged value calculated in the UDFs. For a simple supercritical condition case, Figures 1 and 2 indicate that density and wall shear stress among the properties and the variables obtained in the two different ways show a good agreement with each other. This verifies that the cell field variable macros are used well in the UDFs

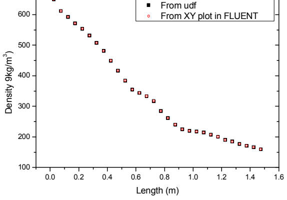

Figure 1. The comparison of the density

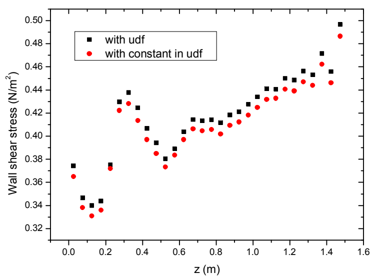

Figure 2. The comparison of the wall shear stress

3. Consideration of the effective sublayer thickness

As shown in a previous study [1], the effective sublayer thickness in the modified momentum wall function was a critical variable for the supercritical fluids. It is necessary for the sensitivity test of the effective sublayer thickness to estimate the effect on the FLEUNT results such as a wall shear stress and wall temperature.

Figures 3 and 4 show the results of a sensitivity test conducted on the simple supercritical case with various effective sublayer thickness, c_1 in the following equation when the effective thickness of standard wall function is not fixed.

$$u^* = \frac{1}{\kappa}\left[\ln\left(\frac{e^{\kappa c_1}}{c_1} y^*\right)\right] \quad (2)$$

The graph shows that the wall shear stress along the tube decreases and the wall temperature increases as the c_1 value increases. In addition, the trends of the wall shear stress and wall temperature profiles were similar for each case. By equation (2) and the definition of u^*, it is explained that u^* increases, the wall shear stress decreases and the wall temperature increases as c_1 increases.

Therefore, this sensitivity calculation shows that the wall shear stress and wall temperature of the FLUENT results are affected by the value of c_1. It is necessary to measure and evaluate the value of c_1 for the supercritical fluids experimentally.

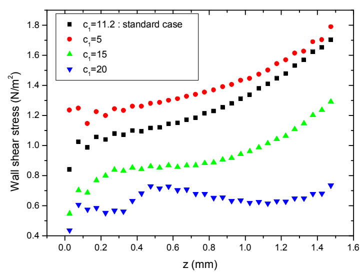

Figure 3. The comparison of the shear stress with the change of c_1

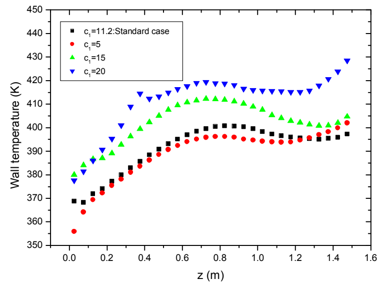

Figure 4. The comparison of the wall temperature with the change of c_1

4. Conclusion

The turbulence model near the wall, the wall function for a momentum applicable for a range of supercritical fluid conditions was modified. For applying the function to FLUENT, UDFs with the pre-defined macro, DEFINE_WALL_FUNCTIONS, are employed. The cell field variable macros such as the thermo-physical properties and other variables were verified to be used well in the UDFs for the momentum wall function. Since the effective sublayer thickness in the modified momentum wall function was a critical variable for the supercritical fluids, sensitivity tests were performed to verify the applicability of the UDFs for the modified momentum wall function. This sensitivity calculation showed that the FLUENT results when applying UDFs are affected by the value of c_1. Therefore, it is necessary to measure and evaluate the value of c_1 for the supercritical fluids experimentally.

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