On prediction of turbulent heat transfer in the framework of Improved Delayed Detached Eddy Simulation with Wall Functions

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Abstract. An investigation of Improved Delayed Detached Eddy Simulation (IDDES) with $\Delta y^+$-insensitive Near Wall Treatment (NWT) for prediction of turbulent heat transfer is performed in the framework of general-purpose CFD code ANSYS-Fluent for both fully attached and separated flows. The obtained results show that the considered approach is capable to predict the mean and RMS temperature with sufficient accuracy on the grids with the wall-adjacent step of about 1% of the velocity boundary layer thickness.

1. Introduction

Nowadays, hybrid RANS-LES methods (HRLM) are very promising for prediction of turbulent heat transfer at high Reynolds numbers typical for industrial applications [1,2], where the conventional RANS (Reynolds Averaged Navier-Stockes) models are not sufficiently accurate or informative, while LES (Large Eddy Simulation) is still beyond the capabilities of modern computers. Particularly, HRLM are widely employed on grids with the sufficient wall-normal resolution to integrate the governing equations down to the viscous sublayer to calculate the temperature pulsations [3–7], which are required for example for the thermal fatigue prediction [8]. However, generation of such grids could be a challenging task for complex industrial flows and, therefore, using of $\Delta y^+$-insensitive near wall formulations is required for more precise wall boundary conditions specification.

It should be mentioned that a comprehensive assessment of HRLM with WF has been recently performed in [9] for Shear Stress Transport based Improved Delayed Detached Eddy Simulation (SST-IDDES) [10] with the $\Delta y^+$-insensitive Near Wall Treatment (NWT) [11]. Particularly, it has been shown that using of grids with the wall-adjacent step of about 1% of the velocity boundary layer thickness allows accurate prediction of the mean and RMS velocity for a wide range of fully attached and separated flows.

However, it is not evident that the wall-normal grid requirements [9] are sufficient for prediction of the mean and RMS temperature fields since the temperature boundary layer thickness could be noticeably smaller than the velocity one depending on the considered Prandtl number. Therefore, the principal objective of this work is to estimate the accuracy of SST-IDDES with NWT for flows with turbulent heat transfer.

2. Assessment of SST-IDDES with NWT

Three test cases namely the periodic channel flow [12], the backward facing step [13], and the thermal mixing in the T-Junction [14] are considered to estimate the accuracy of SST-IDDES with
NWT for both attached flows and for flows with separation and reattachment. The employed computational setups are exactly the same as those in [9]. Particularly, two grids are considered throughout the paper. Mesh 1 utilizes the steps of 10% and 5% of the velocity boundary layer thickness in the streamwise and spanwise directions respectively, while the wall-normal step is changing from its minimum value corresponding to $\Delta y^+<1$ up to 5% of the velocity boundary layer thickness in the core-flow. Mesh 2 is exactly the same as Mesh 1 with the only difference for the wall-adjacent step, which is about 1% of the velocity boundary layer thickness.

It is worthwhile mentioning, that all simulations within the paper are performed in the framework of the general purpose CFD code ANSYS-Fluent [15]. Finally, the inlet content required for simulation of spatially developing flows is introduced with the use of Synthetic Turbulence Generator (STG) [16].

2.1. Periodic channel flow

The simulations of the periodic channel flow [12] (Figure 1) are conducted at the Reynolds number $Re=\rho u_\tau h/\mu=4200$ ($u_\tau$ is the friction velocity, $h=0.5H$ is the channel half-height, $\rho$ is the density, and $\mu$ is the dynamic viscosity) and at three Prandtl numbers $Pr=\mu/C_p/\lambda=0.07, 0.7, and 7.0$ ($C_p$ is the specific heat capacity and $\lambda$ is the thermal conductivity) corresponding to liquid metals, air, and water. The lower and upper channel walls are kept at constant temperature of $T_0$ and $T_0+\Delta T$ respectively.

![Figure 1. Computational setup for the periodic channel flow](image)

![Figure 2. Profiles of the mean ($T'$) and RMS ($T''$) temperature and the temperature power spectral density ($T_{PSD}$) for the considered Prandtl numbers](image)
To be able to estimate the grid effect on the heat transfer prediction the profiles of the mean and RMS temperature as well as the temperature power spectral density are shown in Figure 2. As seen, for all the considered Prandtl numbers Mesh 1 and Mesh 2 yield almost identical results. It should be noted, however, that Mesh 2 is not capable to capture a peak of the RMS temperature near the wall at \( Pr=7.0 \), which is observed on Mesh 1. However, it is still not clear if this peak could be properly predicted on Mesh 1 since in this region SST-IDDES is operating in the RANS mode due to the insufficient grid resolution and, therefore, a comparison of the RMS temperature on Mesh 1 with the DNS data is required, which is not available from [12].

Summing up, virtually identical solutions are obtained on Mesh 1 and Mesh 2 indicating that the grid with the wall-adjacent step of about 1% of the velocity boundary layer thickness is sufficient at small and moderate Prandtl numbers. At the same time, for large Prandtl numbers, for which the temperature boundary layer is typically thinner than the velocity one, some peculiarities of the heat transfer in the vicinity of the wall could be missing on Mesh 2, while in the core-flow both grids still yield almost identical solutions.

2.2. Backward facing step

The backward facing step test case (Figure 3) has been experimentally studied in [13] at \( Re=\rho U_0 H/\mu=28000 \) (\( U_0 \) is the inlet bulk velocity, \( H \) is the step height, \( \rho \) is the density, and \( \mu \) is the dynamic viscosity) and \( Pr=0.7 \) (the definition of \( Pr \) is the same as for the periodic channel flow). The lower wall is heated with the constant flux of \( Q_0 \), while the adiabatic condition is preserved elsewhere.

![Figure 3. Computational setup for the backward facing step flow](image)

To assess the performance of SST-IDDES with NWT the wall distributions are firstly shown in Figure 4. As seen, Mesh 2 yields higher Stanton number near the reattachment point and further downstream comparing to those on Mesh 1 (better agreement with the experimental data on Mesh 2 is likely due to the error cancelation). Consistently, the mean temperature is slightly lower near the reattachment point and further downstream and slightly higher within the separation zone. At the same time, the RMS temperature distributions are almost identical on the considered grids in the most part of the domain except the small region in the vicinity of the step, where Mesh 2 yields slightly higher RMS temperature.

![Figure 4. Distributions of the Stanton number (St) and of the mean \((T_w - T_0)/T_0\) and RMS \((T'_w/T_0)\) temperature along the bottom heated wall](image)

Similar conclusions could be drawn for the mean and RMS temperature profiles (Figure 5). Particularly, almost identical solutions are obtained on Mesh 1 and Mesh 2, however, in the vicinity of the reattachment point Mesh 2 seems to be insufficiently fine to properly capture the temperature gradients in several near wall cells.
Figure 5. Profiles of the mean \((T-T_0)/T_0\) and RMS \((T'/T_0)\) temperature at \(x/H=3.2, 5.9, \) and 9.5

Thus, SST-IDDES with NWT is able to provide a reasonably precise results on the considered grids not only for the attached but also for separated flows. However, coarsening of the grid in wall-normal direction results in slightly lower accuracy in the vicinity of the stagnation point likely due to the insufficient wall-normal grid resolution.

2.3. Thermal mixing in the T-Junction

The experimental setup for the thermal mixing in the T-junction [14] consists of vertical and horizontal pipes with inner diameters of \(0.7\cdot D\) and \(D\) (Figure 6). The bulk velocity is kept constant throughout the experiment and is equal to \(1.3\cdot U_0\) and \(U_0\) in the vertical and horizontal pipe respectively. The temperature of the water is \(T_0\) in the vertical pipe and \(T_0-\Delta T\) in the horizontal one with the adiabatic condition preserved on both horizontal and vertical pipes. These parameters correspond to \(Re=\rho\cdot U_0\cdot D/\mu=100000\) (\(\rho\) is the density and \(\mu\) is the dynamic viscosity) and to \(Pr=7\) (the definition is similar to those in sections 2.1 and 2.2).

Figure 6. Computational setup for the T-Junction flow

As seen from Figure 7, Mesh 1 and Mesh 2 provide almost identical mean and RMS temperature distributions along the horizontal pipe walls (the corresponding sections are depicted in Figure 6), which agree fairly well with the experimental data [14]. Particularly the peak of the RMS temperature, which is very important for the thermal fatigue predictions, is properly captured everywhere in the domain. Consistently, the profiles of the mean and RMS temperature are almost the same at all the considered vertical sections (Figure 8).
Figure 7. Distribution of the mean \((T_w-T_0)/\Delta T\) and RMS \((T'_w/\Delta T)\) temperature along the horizontal pipe

Figure 8. Profiles of the mean \((T_w-T_0)/\Delta T\) and RMS \((T'_w/\Delta T)\) temperature at \(x/D=1.6, 2.6,\) and 3.6

Summing up, the obtained results justify that SST-IDDES with NWT is capable to predict the heat transfer in case of three-dimensional separation and reattachment on grids with the wall-adjacent step of 1% of the velocity boundary layer thickness.

3. Conclusions

An assessment of SST-IDDES with NWT for the heat transfer prediction has been performed for several attached and separated flows.

It has been shown, that for small and moderate Prandtl numbers using of grids with the wall-adjacent step of about 1% of the velocity boundary layer thickness is sufficient to achieve almost identical mean and RMS temperature profiles with those on the conventional grids with \(\Delta y^+<1\). At the same time, for large Prandtl numbers, for which the temperature boundary layer is typically thinner than the velocity one, using of such coarsened grids results in the missing RMS temperature peak in the vicinity of the wall, whereas almost identical profiles are still obtained in the core-flow. Nevertheless, taking into account that SST-IDDES is operating in the RANS mode in that region it is not clear if the RMS temperature peak could be properly captured even on conventionally fine wall-normal grids.
Finally, it should be mentioned, that within the current work the energy equation is solved as a passive scalar and, thus, the flow physics is fully separated from the peculiarities of the heat transfer. However, when the energy and momentum equations are strongly coupled (e.g. for compressible flows) the abovementioned effect of high Prandtl numbers become more important and, therefore, the temperature boundary layer thickness should be also taken into account for the grid generation.

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