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EVALUATION OF FLOW STRUCTURES AND HEAT TRANSFER OVER DIMPLED SURFACES IN A NARROW CHANNEL FOR HIGH REYNOLDS AND PRANDTL NUMBER USING HYBRID RANS-LES METHODS

Johann Turnow*, **Nikolai Kornev**
Chair of Modeling and Simulation
Faculty of Mechanical Engineering and Shipbuilding
University of Rostock
Albert-Einstein-Str. 2
18059 Germany
*johann.turnow@uni-rostock.de

ABSTRACT

Numerical simulations using classical LES (Large Eddy Simulation) and hybrid RANS/LES methods as IDDES (Improved Delayed Detached Eddy Simulation) with improved wall modeling capability are applied to analyze flow structures and heat transfer of turbulent flow over structured surfaces for high Reynolds and Prandtl numbers. Based on the simulations of the turbulent channel flow up to $Re_\tau = 1024$ and $Pr = 3$, the LES and IDDES methods are validated, needed mesh sizes and its limited application for high Reynolds numbers are determined. The methods have been used to analyse mean values, high order statistics as well as vortex structures and secondary flow structures of a spherical dimple and further compared to experimental data. Hybrid methods reproduce mean quantities and the asymmetric flow structures with a changing orientation towards the main flow while reducing the computation time enormously with a satisfying accuracy. The heat transfer rates and the skin-friction factors of the IDDES are consistent with empirical correlations whereas LES show large differences for higher Reynolds numbers using moderate grid sizes

INTRODUCTION

Several turbulence generators like ribs, fins or dimples have been investigated experimentally and numerically in the last decades to enhance heat transfer at a minimum hydraulic loss. Analyzing the thermo-hydraulic efficiency by comparison of the different surface depressions, dimpled surfaces show the most compromised results. Dimples consist of regulary convex surface depressions which generate a heat transfer enhancement while keeping the pressure losses moderate. Main attention of papers published in the literature has been paid to the heat and mass transfer effects averaged in time whereas the important unsteady processes including the vortex formations and their role in the heat transfer enhancement, especially for high Reynolds numbers, have not been thoroughly investigated. The big challenge and its high computational ressources for numerical simulations to predict unsteady flow features, like reattachment of shear layers, asymmetric flow structures, as well heat transfer rates for higher Reynolds and Prandtl numbers leads to the Detached Eddy Simulation (DES), as a combination of RANS and LES approach. The hybrid methods are mostly applied for aerodynamics problems in order to use the advantages of RANS near the wall and to use LES far away from the wall when the turbulent length scales exceed the grid dimensions. The development of DES has been started by Spalart *et al.* (1997) introducing a characteristic length scale determined by the RANS model to account for switching between RANS and LES region. In the ongoing work, several variants of DES models in terms of conservative combination of LES and RANS region have been developed with rather different characteristics to address several kind of flow physics like flow separation or evolving near wall vortex structures. The Improved Delayed Detached Eddy Simulation (IDDES), to connect Wall Modeled Large Eddy Simulation (WMLES) and Delayed Detached Eddy Simulation (DDES), has been extended to the $k-\omega$-SST by Gritskevich *et al.* (2011). The model extension is used within this study to take the advantages of the near wall modeling of the $k-\omega$-SST model regarding vortex structures and heat transfer into account.

In addition SST-based formulation has a considerable advantage that the transition from RANS to LES regions does not only depend on the distance to the wall and the mesh resolution, but also on the solution. Previous work from Viswanathan & Tafti (2006) using classical DES formulation proposed by Strelets (2001) of the fully developed flow and heat transfer in a channel with normal ribs showed very good agreement in comparison to the experiments and LES results. It was reported, that the computation time were an order of magnitude less expensive than pure LES approach.

The objective of this study is to analyze the capabilities of LES and IDDES approach for high Reynolds and Prandtl flow over a single dimple and further to clarify the role of the vortex formations and its influence to the heat transfer and friction losses. The hybrid model is validated using turbulent channel flow testcase as well for the single dimple in a narrow channel to address higher Reynolds numbers up to $Re_D = 105000$ and Prandtl numbers up to $Pr = 3$. In our previous work (see Turnow *et al.* (2010)) vortex structures have already been investigated for a single spherical dimple. LES simulations revealed the formation of asymmetric structures with an orientation switching between two extreme positions. The study is conducted to prove the capabilities of the hybrid method IDDES using $k-\omega$-SST for the RANS regions to capture the characteristic flow structures and to identify vortex structures for higher Reynolds numbers including heat transfer.

COMPUTATIONAL METHOD

The governing equations are solved on a non-staggered Cartesian grid using implicit filtering within a finite volume method. The discretization in space and time of the quantities at the cell faces is of second order using central differencing scheme. The LES equations are obtained by filtering the continuity equation, the Navier-Stokes equations and the transport equation for the non-dimensional temperature θ at the filter width $\widetilde{\Delta}$.

$$\frac{\partial \widetilde{u}_i}{\partial t} + \frac{\partial \widetilde{u}_j \widetilde{u}_i}{\partial x_j} = -\frac{1}{\rho}\frac{\partial \widetilde{P}}{\partial x_i} + \frac{\partial}{\partial x_j}\left[\nu\left(\frac{\partial \widetilde{u}_i}{\partial x_j} + \frac{\partial \widetilde{u}_j}{\partial x_i}\right) - \tau_{ij}\right] \quad (1)$$

$$\frac{\partial \widetilde{\theta}}{\partial t} + \frac{\partial \widetilde{u}_j \widetilde{\theta}}{\partial x_j} = \frac{\partial}{\partial x_j}\left[\frac{\nu}{\mathrm{Pr}}\frac{\partial \widetilde{\theta}}{\partial x_j} - J_j^{SGS}\right]. \quad (2)$$

For classical LES the unclosed subgrid stress tensor $\tau_{ij} = \widetilde{u_i u_j} - \widetilde{u}_i\widetilde{u}_j$ and the subgrid contribution to the scalar dynamics $J_j^{SGS} = \widetilde{\theta u_j} - \widetilde{\theta}\widetilde{u}_j$ are modeled in terms of the filtered quantities $\widetilde{u}_i$ and $\widetilde{\theta}$, using a dynamic one equation eddy-viscosity model proposed by Kim & Menon (1995). The turbulent scalar fluxes are modeled using gradient diffusion approach. In Eq. 2 the non-dimensional temperature θ is defined as $\theta = T - T_{lowerwall}/(T_{lowerwall} - T_{upperwall})$ and further treated as a passive scalar without buoyancy effects. The molecular Prandtl number Pr was set to $\mathrm{Pr} = 0.71$ and to $\mathrm{Pr} = 3.0$ respectively, whereas the turbulent Prandtl number is set to constant $\mathrm{Pr}_t = 0.9$. Investigations revealed that the chosen SGS model shows fairly good agreement with measurements in respect to heat transfer and recirculating flows in contrast to other SGS models. The IDDES with $k-\omega$-SST approach uses a more extended expression for the turbulent length scales as rather than $\Delta = \Delta_{max}$ as in DES and DDES. This yields to a linear variation of the subgrid length-scale in the vicinity of the wall and becomes Δ_{max} off the wall. It was shown, that this choice is superior to either of the previously used subgrid length-scale definitions for LES (Δ_{max}, $\Delta = V^{1/3}$), with regard to wall-bounded flows. Gritskevich *et al.* (2011) proposed a modified version of the IDDES based on the $k-\omega$-SST model. The recalibration of the shielding function f_d show an improvement for several testcases compared to the previous version without damping of resolved turbulence. Thus, the IDDES approach proposed by Gritskevich *et al.* (2011) is used in this study to conduct hybrid RANS/LES calculations. The hybrid length scale is given by the following expression

$$l_{IDDES} = \widetilde{f}_d(1+f_e)l_{RANS} + (1-\widetilde{f}_d)l_{LES}, \text{ with} \quad (3)$$

$$l_{LES} = C_{DES}\Delta \quad (4)$$

$$l_{RANS} = \frac{k^{1/2}}{\beta\omega} \quad (5)$$

$$C_{DES} = C_{DES1}F_1 + C_{DES2}(1-F_2) \quad (6)$$

The subgrid length-scale is calculated as:

$$\Delta_{IDDES} = \min\{C_w \max[y, \Delta_{max}], \Delta_{max}\} \quad (7)$$

where $C_w = 0.15$, y_w – wall-Distance and Δ_{wn}-grid spacing in wall normal direction. The full description of the IDDES model can be found in Gritskevich *et al.* (2011). The LES and IDDES method have been evaluated using turbulent channel flow simulations up to $\mathrm{Re}_\tau = 1024$. In contrast to classical turbulent channel flow simulations, where the dimensions are set in reference to the non-dimensional channel height to $H = 2$, $L_x = 2\pi$ and $L_z = \pi$, the computational domain is down scaled and expanded since in the next step a dimple has to be placed at the lower wall. The channel height H is equal to $H = 0.015m$. The length in axial direction is set to $L_x = 12H$ and in spanwise direction to $L_z = 5.33H$. Thus, the ratio of channel length to channel height is fairly larger than $L_x/H = \pi$ as in the DNS computations. The expansion of the channel dimensions will require much more grid cells using LES method but ensures definitely the decrease of the autocorrelation functions to almost zero in streamwise and spanwise direction. A schematic sketch of the computational domain is presented in Figure 1. The dimple diameter is kept constant

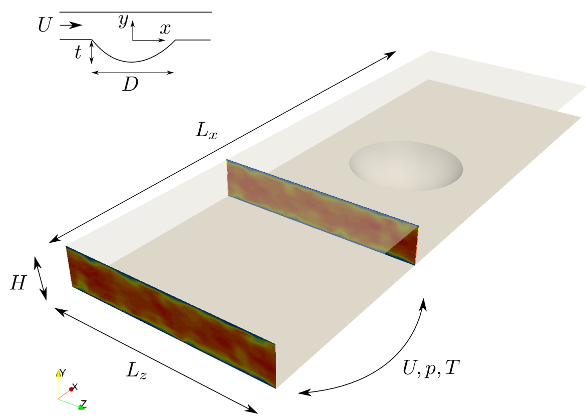

Figure 1. Sketch of the computational domain of the turbulent channel flow including the mapping plane for the recycling method.

with an diameter of $D = 0.046m$ and a ratio of dimple depth-to-diameter $t/D = 0.26$. The recycling method is applied to ensure correlated inflow conditions which copies the values from a given slice located downstream the inlet plane each timestep back to the inlet. No slip wall conditions were enforced on the lower and the upper solid walls for the velocity whereas the temperature was fixed at the lower (hot surface, $\theta = 1$) and the upper (cold surface, $\theta = 0$) channel wall. Three blockstructured grids up to 4 million cells are used for the turbulent channel flow (see Table 1). It should be noted, that the applied grid sizes are not sufficient for the expanded channel dimensions ($L_x = 12H$) and do not comply with the needed LES requirements.

Table 1. Different grid resolutions for LES of turbulent flow in a plane channel ($\mathrm{Re}_\tau = 1024$).

Mesh	$N_x \times N_y \times N_z$
C1	$116 \times 32(y^+ = 6.7) \times 88$
C2	$174 \times 48(y^+ = 5.8) \times 132$
C3	$272 \times 72(y^+ = 0.6) \times 208$

A grid stretching normal to the wall is used where the first grid point is located at a distance of $y^+ = 6.7$ (case C1), $y^+ = 5.8$ (case C2) and $y^+ = 0.6$ (case C3) for $\mathrm{Re}_\tau = 1024$. A small stretching factor of 4.5 (from the largest to the smallest edge length) normal to the wall was chosen for both cases to place several grid points into the viscous sublayer. The mesh is homogeneous in spanwise and streamwise direction for the plane channel flow.
A block structured curvilinear grid consisting of 1.591.296 cells was chosen on the basis of the turbulent channel flow calculations for further investigations of the dimpled channel.

RESULTS
Turbulent Channel Flow

For validation, reference and for establishment of the grid independency a series of turbulent channel flow simulations within a Reynolds number range from $\mathrm{Re}_\tau = 180$ up to $\mathrm{Re}_\tau = 1024$ have been carried out. Results for the skin-friction coefficient have been compared to empiric correlation from Dean

$$C_f = 0.073\ \mathrm{Re}^{-1/4}, \tag{8}$$

whereas the Reynolds number is based on the half channel height and bulk velocity. The heat transfer rates in terms of Nusselt number have been compared to empiric correlation of Petukhov-Gnielinski

$$\xi = (0.79\ln(\mathrm{Re}_H) - 1.64)^{-2} \tag{9}$$

$$\mathrm{Nu} = \frac{(\xi/8)(\mathrm{Re}_H - 1000)\mathrm{Pr}}{1 + 12.7\sqrt{\xi/8}\ (\mathrm{Pr}^{2/3} - 1)} \tag{10}$$

for the smooth channel (Figure 2). The results for the skin-friction coefficient show, that LES simulations underpredict the empiric values for the applied grid sizes. Up to a Reynolds number of $\mathrm{Re}_\tau = 1024$ IDDES underpredicts the friction coefficient about 6% compared to 51% for LES which show that LES in unemployable even using the fine mesh C3. In case of heat transfer it can be seen, that the Nusselt numbers are overpredicted in case of the IDDES and LES method compared to empiric correlations. The power spectra taken at the center of the channel

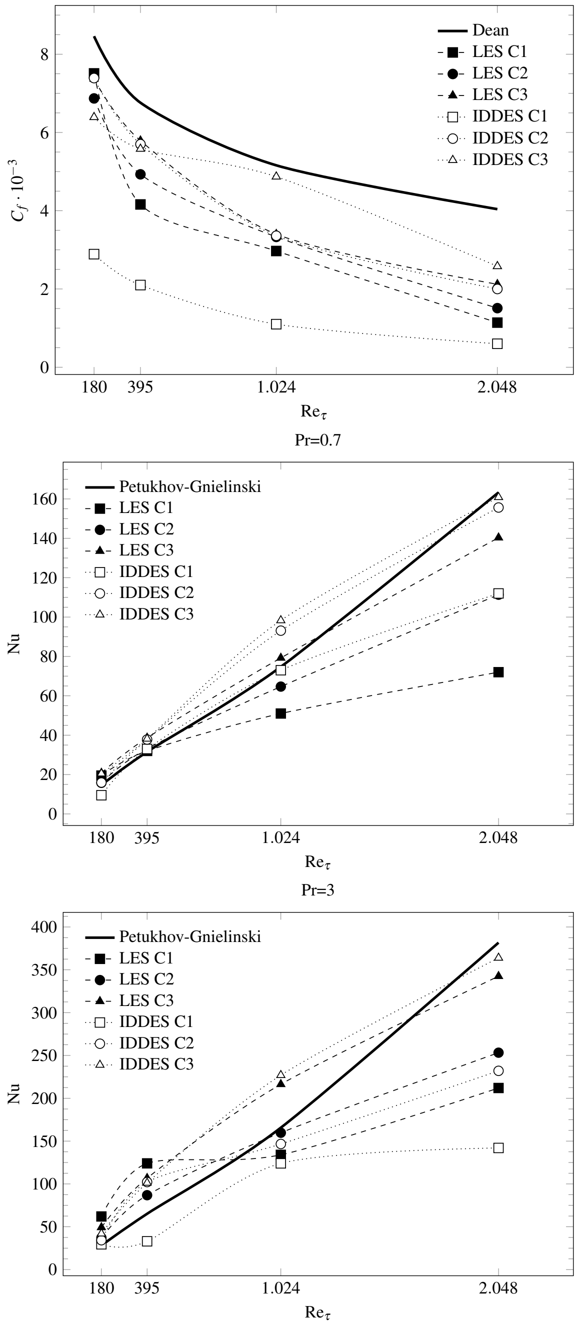

Figure 2. Friction factor C_f (left) and Nusselt number Nu for Prandtl number Pr = 1 (mid) and Pr = 3 for turbulent channel flow up $\mathrm{Re}_\tau = 1024$ using LES and IDDES method in comparison with empiric correlation.

at $y/H = 0.5$ and near to the wall at $y/H = 0.1$ for Reynolds number $\mathrm{Re}_\tau = 395$ show no differences within both methods. All scales are captured within the IDDES approach.t.

Heat Transfer and Flow Structures of a Single Dimple

Numerical simulations for turbulent flow over a single dimple at Reynolds number $\mathrm{Re}_D = 42000$ and $\mathrm{Re}_D = 105000$ have been carried out, which corresponds to the Reynolds number based on the friction velocity of $\mathrm{Re}_\tau = 395$ and $\mathrm{Re}_\tau = 1024$ for the smooth channel flow respectively. Figure 3 shows the LES (value 1.0) and RANS (value 0.0) regions inside the single dimple. The near wall regions are always resolved using RANS whereas the flow inside the channel and dimple is captured by LES. The results are in good agreement with experimental data. Since the choice of the region is determined using turbulent length scales, a smooth transition between LES and RANS takes place in dependence of the actual flow features. It can be seen, that the recirculation zone including the shear layer inside the dimple is captured by LES ensuring most accurate calculation. Hence, the IDDES model acts like a wall function in order to capture the high velocity and temperature gradients near the wall which is especially important for higher Prandtl numbers. The mean values of the friction

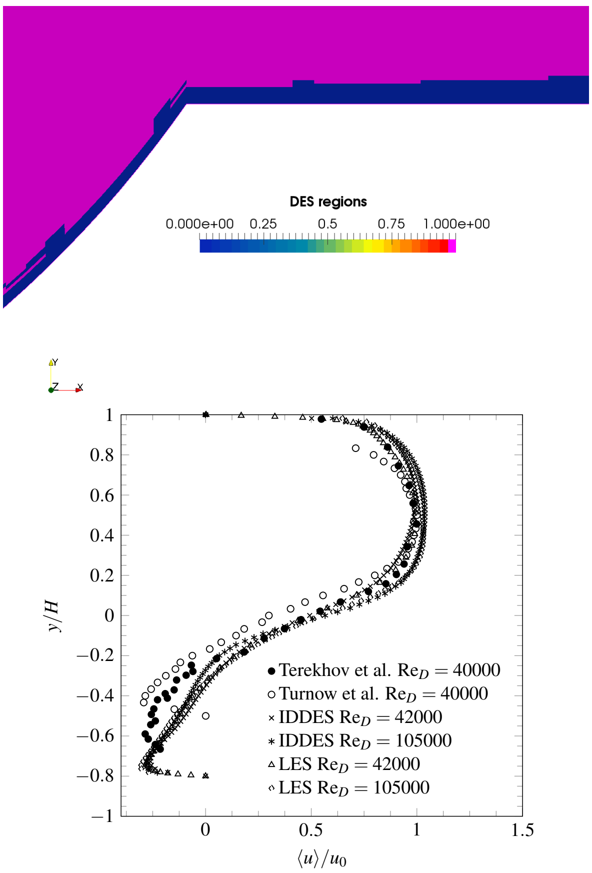

Figure 3. IDDES regions in the transversal center plane of the dimple ($Re_D = 42000$) (right), Streamwise velocity profiles for turbulent flow over a single dimple from the center of dimple to the upper channel wall in comparison to experimental LDV measurements for $Re_D = 42000$.

losses and heat transfer augmentation for the turbulent flow over a single dimple have been normalized by its values obtained for the smooth channel flow. The mean values for heat transfer are integrated around the dimple within a rectangular box of the dimensions $\pm x/D = 2.5 \times \pm z/D = 1.5$. The results are summarized in Table 2. Results of the skin-friction and heat transfer coefficient for the moderate Reynolds number $Re_D = 42000$ are in the same range for LES and IDDES method which are in good agreement of results published in literature. The values for heat transfer show differences for the investigated Reynolds number $Re_D = 105000$ since pure LES is not capable to resolve the gradients near the wall accruately. A difference of the heat transfer augmentation of 11% in case of LES and 18% in case of IDDES for the lower Prandtl number $Pr = 0.71$ is determined. Furthermore, a dramatically increase of heat transfer rates compared to a smooth channel while increasing the Reynolds number could not be observed for Prandtl number $Pr = 3$. Thus, the optimal thermo-hydraulic performance of the dimple determined for moderate Reynolds numbers and is lowered for higher flow velocities. Streamlines indicate the asymmetrical vortex structures switching its position from $\alpha = +45^\circ$ to $\alpha = -45^\circ$ periodically. As seen from instantaneous streamlines patterns in Figure 4, the fluid enters directly from the channel into the dimple and rotates within the recirculation zone and finally leaves the dimple at one side. For a dimple with a depth to diameter ratio of $h/d = 0.26$, numerical results from LES and IDDES confirm the generation of unsteady asymmetric monocore vortex structures with a predominant transversal direction. It has to be noticed, that LES and IDDES show the same asymmetric flow behavior for Reynolds number $Re_D = 42000$ and $Re_D = 105000$.

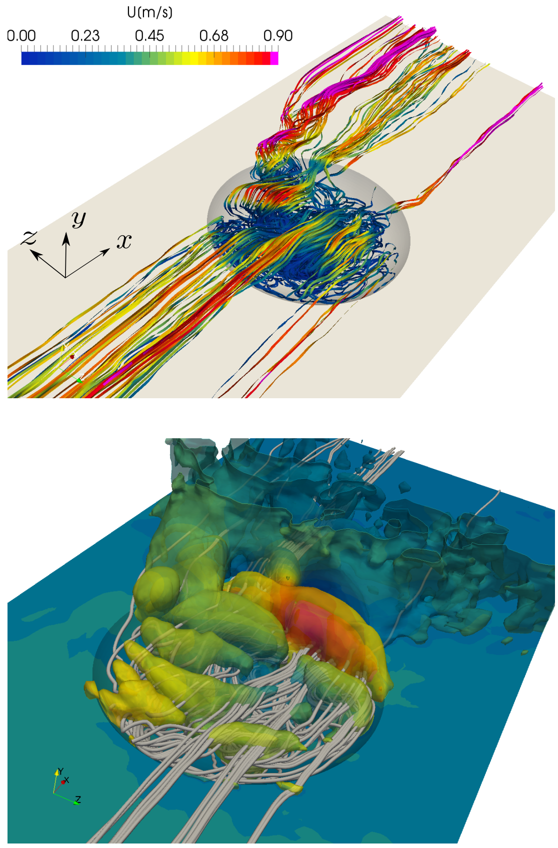

Figure 4. Streamlines (up) and pressure iso-surfaces (low) for a turbulent flow over single dimple at Reynolds number $Re_D = 105000$ using IDDES approach.

CONCLUSION

Comparison of numerical results obtained from LES and IDDES for turbulent channel flow up to $Re_\tau = 1024$ and the turbulent flow over a single dimple including a variation of the Reynolds number ($Re_D = 42000$, $Re_D = 105000$) and Prandtl number ($Pr = 0.71$, $Pr = 3$) with the experimental

Table 2. Skin-friction coefficient and Nusselt number for turbulent flow over a single dimple using LES and IDDES method in comparison to smooth channel flow simulations (denoted with 0) at up $\mathrm{Re}_D = 42000$ and $\mathrm{Re}_D = 105000$ for $\mathrm{Pr} = 0.71$ and $\mathrm{Pr} = 3.0$.

		$\mathrm{Re}_D = 42000$		$\mathrm{Re}_D = 105000$	
		$\mathrm{Pr} = 0.71$	$\mathrm{Pr} = 3$	$\mathrm{Pr} = 0.71$	$\mathrm{Pr} = 3$
LES	C_f/C_{f0}	1.057		1.32	
	$\mathrm{Nu}/\mathrm{Nu}_0$	1.32	1.36	1.11	1.40
IDDES	C_f/C_{f0}	1.144		1.36	
	$\mathrm{Nu}/\mathrm{Nu}_0$	1.35	1.42	1.18	1.45

data and empiric correlations confirmed, that the established hybrid method IDDES is capable of predicting flow physics and heat transfer rates with a satisfactory accuracy. Numerical simulations reveal the presence of self-sustained oscillations inside a single dimple. Analysis of flow structures using instantaneous streamline patterns and λ_2-structures show the presence of an asymmetric vortex structure which is inclined in respect to the incoming flow of $\alpha = \pm 45°$. With respect to heat transfer enhancement, the asymmetric vortex structures are preferable in terms of steadily driving the hot fluid out of the dimple. A significant increase of the heat transfer rates due to the long period oscillations could not be found since the time scale of the heat transfer mechanism is much smaller than shifting time of the asymmetric vortex structure. It can be concluded, that the IDDES predicts the physics of turbulent flow, as p.ex. shear layer induced secondary motions, inside the dimple and produces trustful results at a much lower computational costs than an equivalent LES simulations.

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