Hands-on session 7 – Turbulent Fully Developed Flow in a Squared Duct – Non-Linear Eddy Viscosity Model

Abstract

This session will show the application of the Non-Linear Eddy Viscosity Models (NLEVM) in Fluent, particularly the quadratic formulation of the Reynolds stresses. As explained in the lecture, the quadratic formulation in Fluent is available only in the k-ω model. For this reason, we will use it in this hands-on session in the k- ω SST version with the objective of predicting the secondary flows which establish due to the anisotropic behavior of turbulence close to the duct's corners. The student should have already created the geometry (refer to Hands-on Session 3) and the grid considering the size close to the wall to obtain a y^+ smaller than 1 (refer to Hands-on Session 6). For this exercise the Reynolds number is assumed to be equal to 40,000 and the fluid is air, which properties are the following: density 1.225 [kg/m^3] and dynamic viscosity 1.7894x10^{-5} [kg/m-s]. These are the default values in Fluent for air. The students will then compare the cross-stream velocity at two different locations and the wall shear stress.

Goal

The aim of this hands-on session is to apply the quadratic closure of the Reynolds stresses to predict the secondary flows of a fully developed turbulent square duct flow and to get familiar with plotting of the cross-stream velocities.

1 Introduction

Turbulence is fundamentally anisotropic, which means it behaves differently depending on the direction fundamentally because of geometric constraints. Anisotropy of turbulence can have an effect on the flow field which can have a non-negligible in the evaluation of the main values such as the pressure drop in a nuclear core. In this exercise we see the most classical example of geometry which generates secondary motions due to turbulence anisotropy, that is to say the fully developed turbulent square duct. CFD with the Non Linear Eddy Viscosity Model is capable to predict quite well the complex behavior associated to turbulence anisotropy.

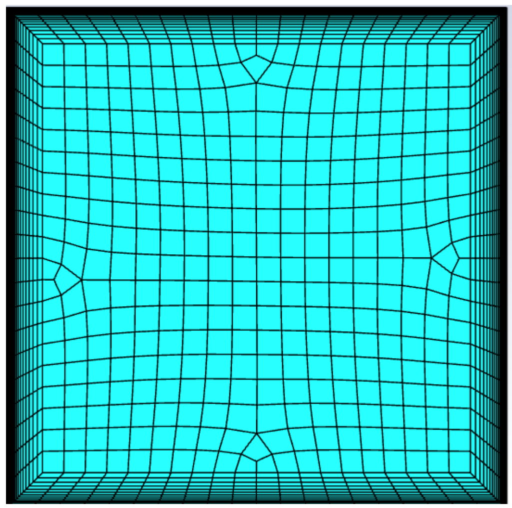
Note: *It is advised to prepare an excel file to summarize the fluid properties and boundary conditions for the resolved variables (pressure, x- and y-velocity, temperature). Some of these data may require calculation depending on the information given in the case description.*

2 Import the Grid

Read the case and save it in a new folder as “caseName_kwSST_quadratic”.

2.1 Visualize the grid

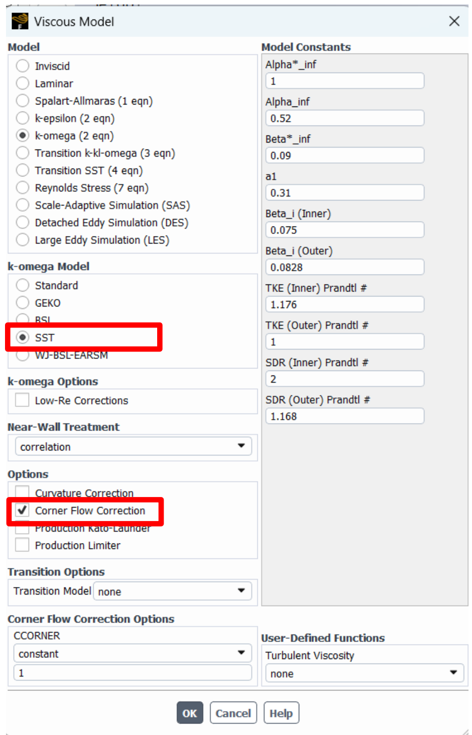
The grid should look like the picture below.



3 Define the Quadratic Model

To define the model, double click on “Viscous” and select “k-omega (2 eqn)” in Model. Select “SST” in “k-omega model” and “Corner flow corrections” in the “Options” below. Every other option should not be selected.

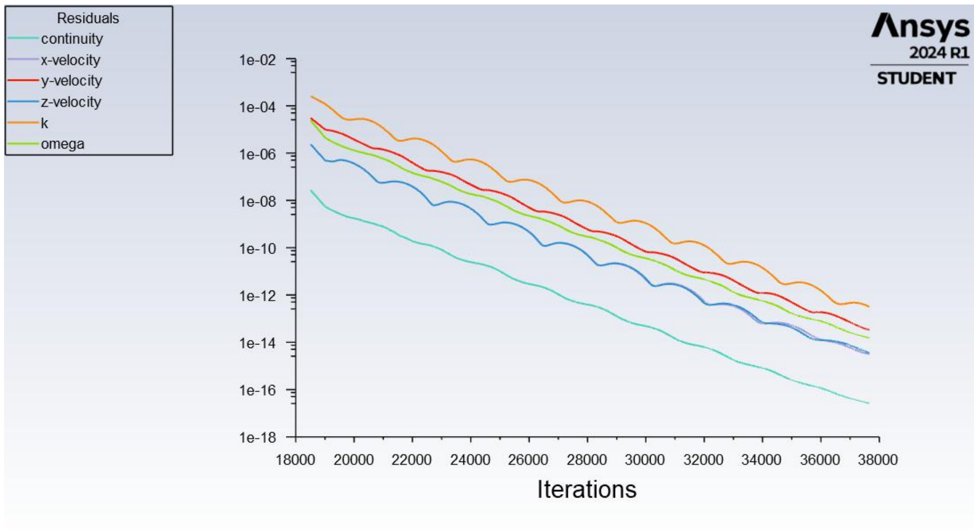
The selection should look like the picture below. Save and start the simulation.



4 Confirm the convergence

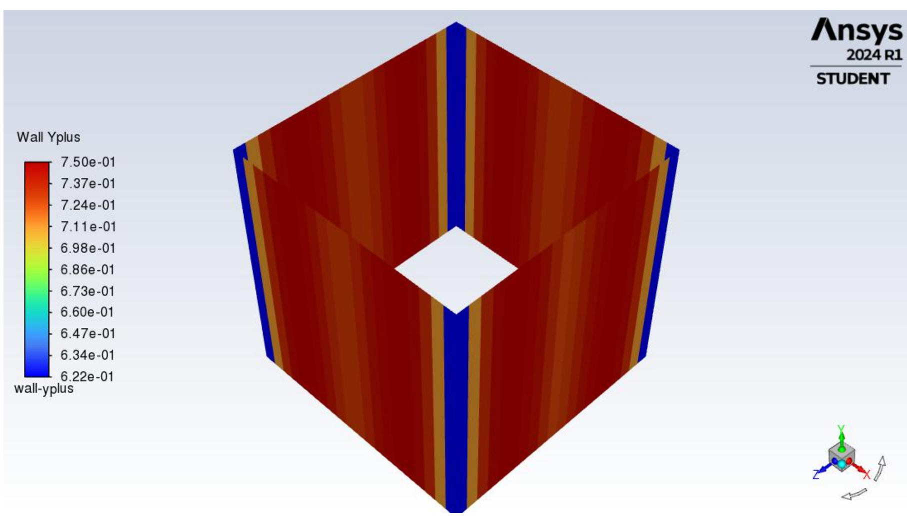
4.1 Plot the residuals

The plot below shows the residuals. The best practice would require waiting until the residuals reached a plateau value. However, for this particular case the value of residuals is so low that we can accept the results up to this point.

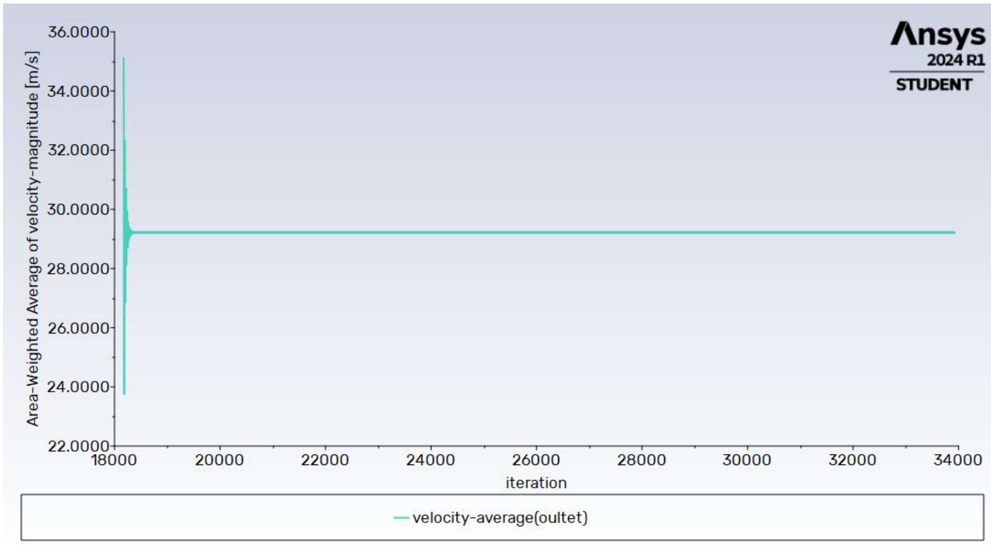


4.2 Show y^+ at the wall

The figure below shows the y^+ values at the wall. As expected from the analysis y^+ in each cell is below 1, indicating that we are solving the flow well below the viscous sublayer. The y+ in the corner is lower than in the center of the plane because the corner has a lower velocity due to the presence of both walls.



4.3 Plot monitors of main quantities

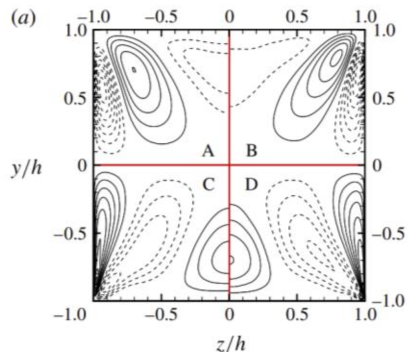


In this example only the average velocity at one of periodic boundaries is plotted and confirmed to be consistent with the analytical value evaluated.

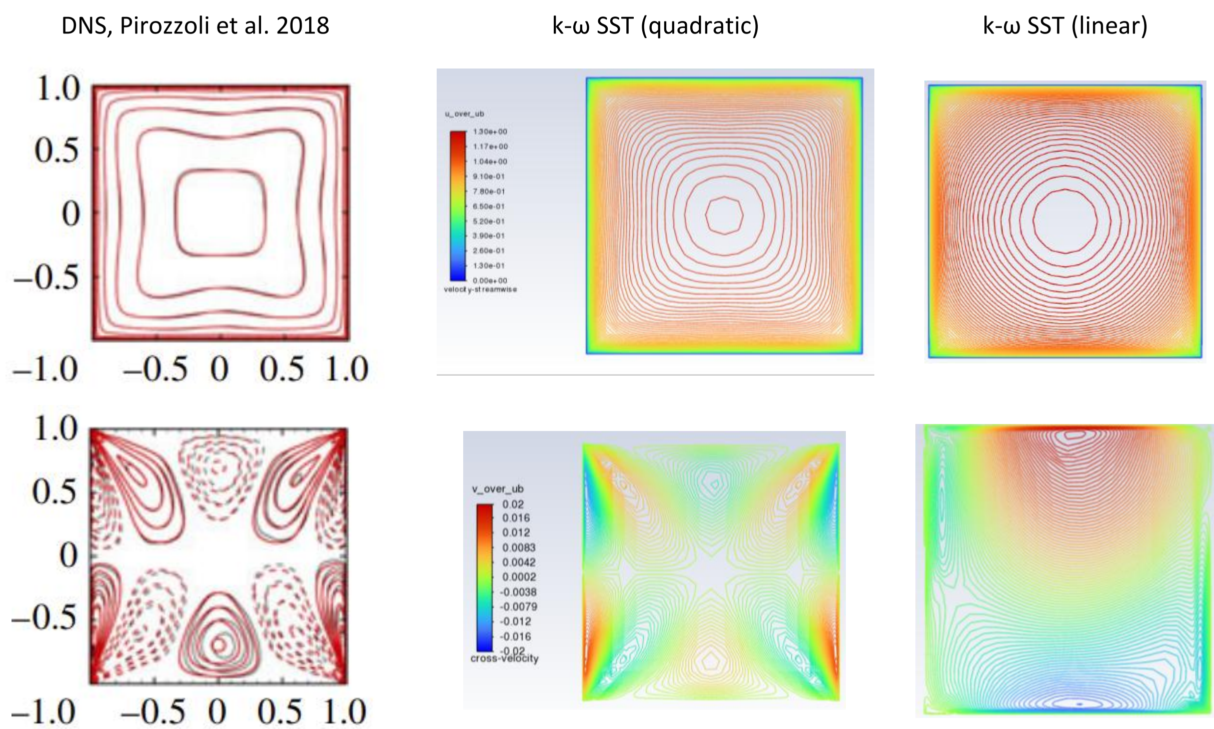
5 Results

5.1 Qualitative comparison of streamwise and cross-stream velocities

Qualitative comparison of the velocity contours shows the effect of the NLEVM on the streamwise velocity as well as on the cross-stream velocity in comparison to the linear models. It is interesting to note that the secondary flows are not symmetrical respect to the corner bisector, but they are symmetrical to the wall bisector. This is important during the comparison because it is important to rotate the duct according to the directions used in the paper of Pirozzoli et al. 2018.

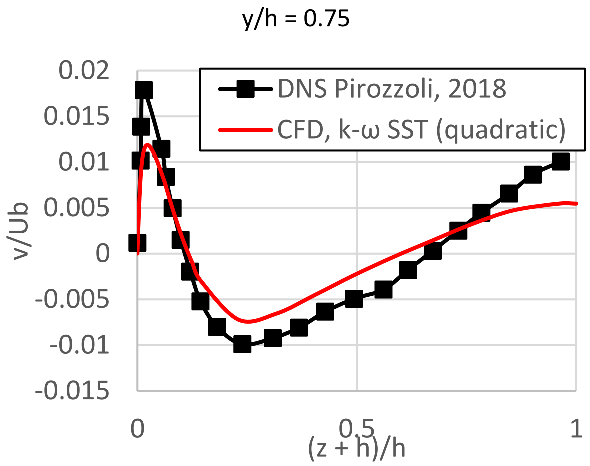


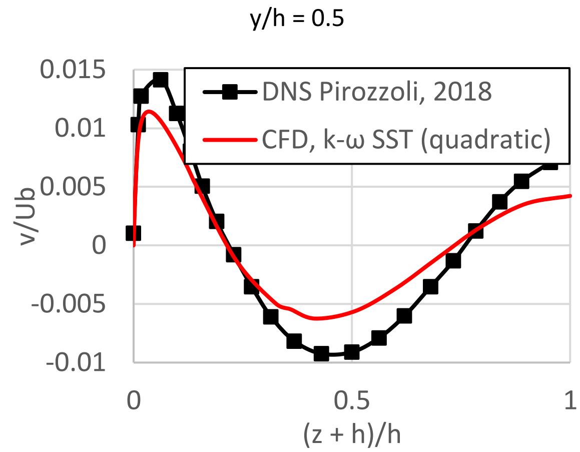
In their work the main flow is aligned in the x-direction. The positive secondary flows at the wall are located at the bottom. The cross-stream velocity provided is *v* which is the velocity aligned with the *y-axis* in their paper. To perform the comparison the student needs to pay attention to these details as the axis chosen during the definition of the geometry might not be the same as chosen in the DNS calculations.



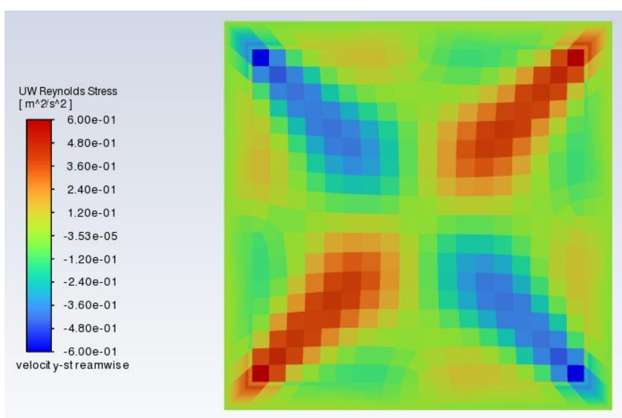
5.2 Quantitative comparison of cross-stream velocity v

Hereafter we report the comparison between the DNS data and the k-w SST quadratic closure. The DNS data have been provided in the Hands-on session 6. We can see that the secondary motion is in the order of magnitude of 1 to 2% the average flow velocity. The results of the linear closure are not introduced in the comparison because they would be simply zero everywhere. The quadratic closure gives a reasonable prediction of the secondary flows in the square duct. It is not our objective here to discuss possible improvements on the velocity profile.





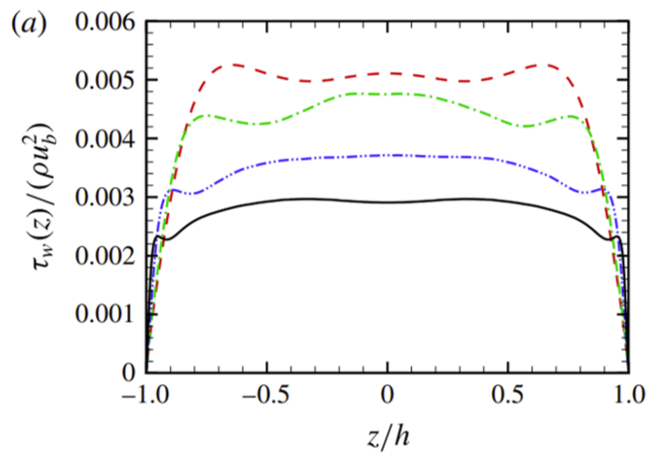
Below we can see the distribution of the Reynolds stresses $\overline{v'w'}$



5.3 Quantitative comparison of the wall shear stress

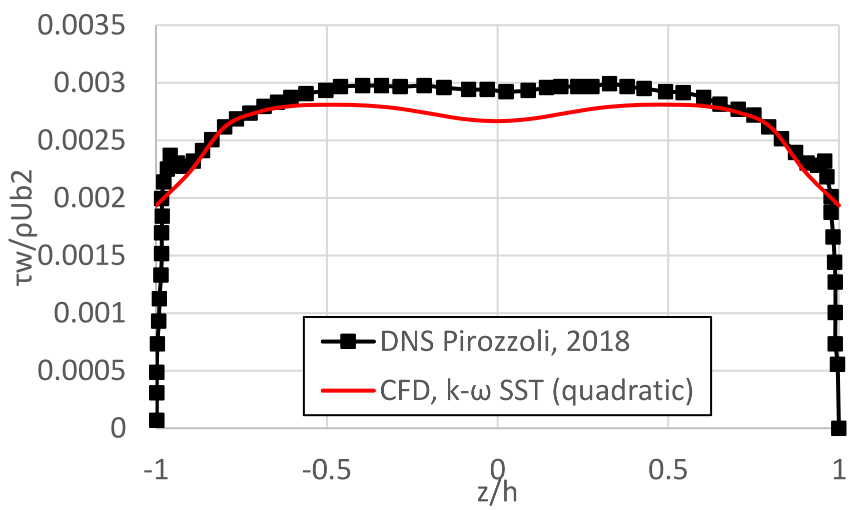
The DNS paper by Pirozzoli et al, 2018 provides also the wall shear stress on the bottom wall which is reported below. The student is requested to digitize the curve using any software available online such as:

- https://plotdigitizer.com/app
- https://web.eecs.utk.edu/~dcostine/personal/PowerDeviceLib/DigiTest/index.html



Local wall shear stress along the bottom wall, normalized with respect to the bulk dynamic pressure (a), for flow Re_b = 4410 (red dashed), Re_b = 7000 (green dash-dot), Re_b = 17800 (blue dash-dot-dot), Re_b = 40000 (black solid).

The results are shown below showing again a relatively good agreement with the DNS data.



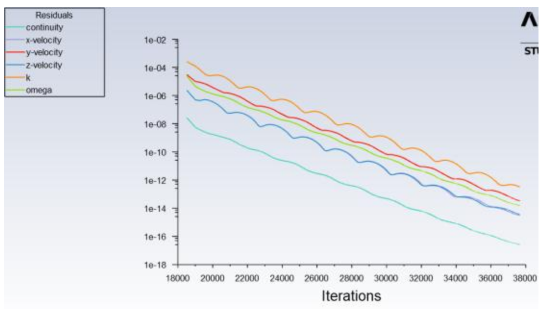
6 Simulation with a Coarse Grid at the Wall

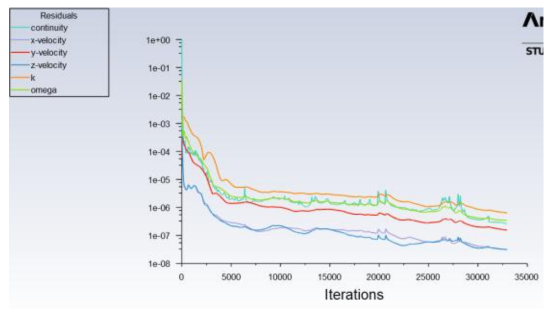
The k-ω model does not need a special requirement for the y^+ of the first cell close to the wall, as it is required in the k-ε model. Hence, one might expect that a coarse mesh close to the wall might be enough for the correct prediction of the secondary flows. The student should try to attempt the same simulation but employing the grid already generated with y^+ larger than 30, developed in "Hands-on session 5", compare and discuss the results which are reported below.

k-ω SST (quadratic) $y^+ < 1$

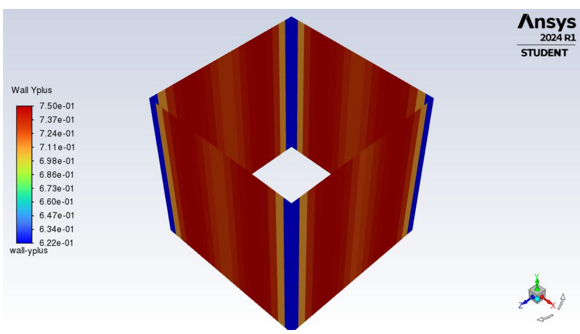
k-ω SST (quadratic) $y^+ > 30$

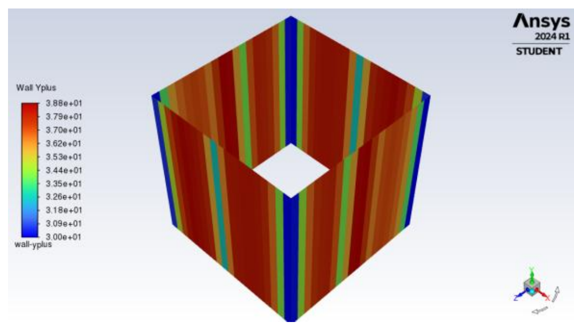
Residuals



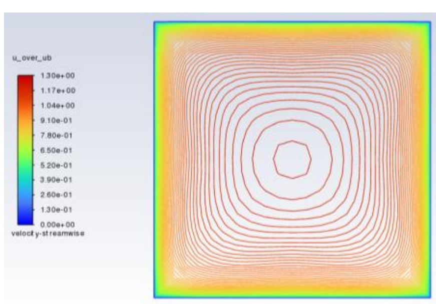


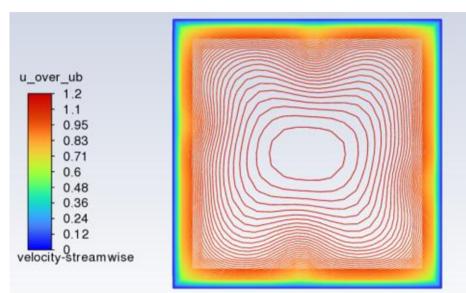
Wall y^+





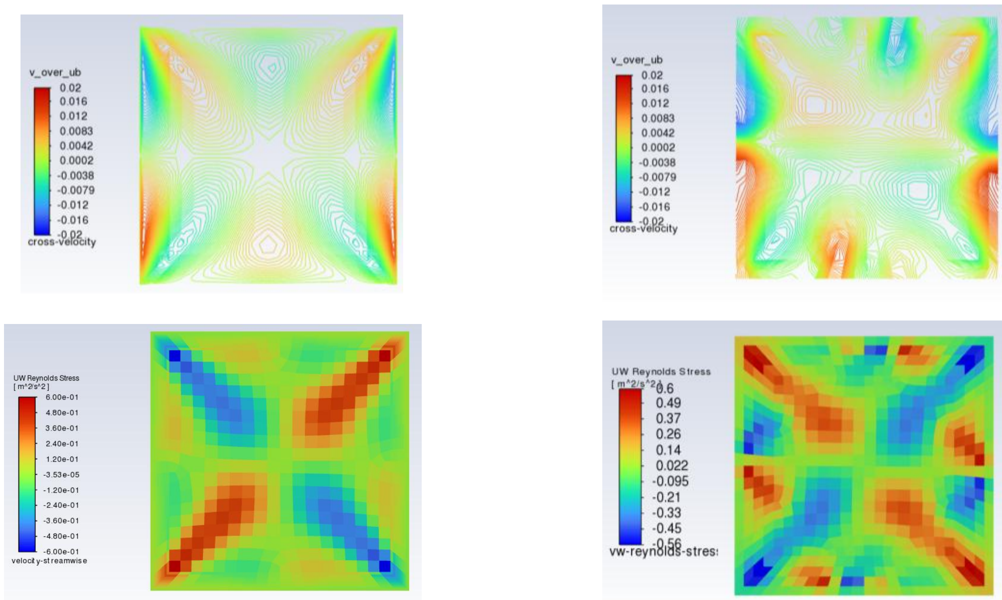
Stream-wise velocity



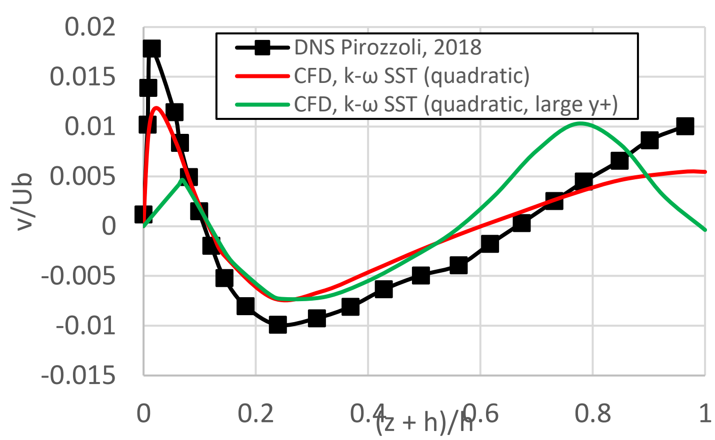


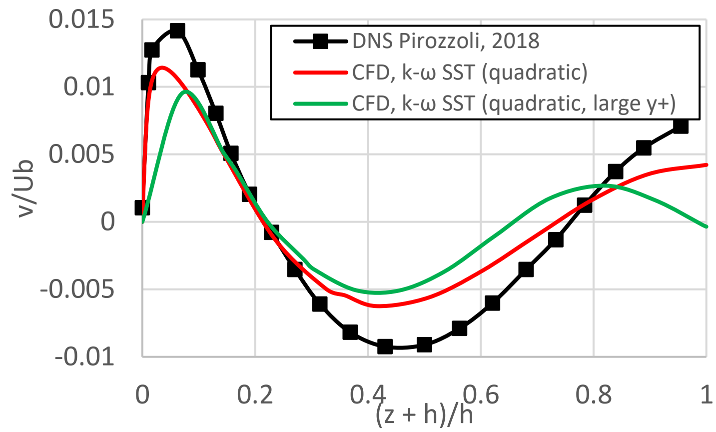
Cross-stream velocity

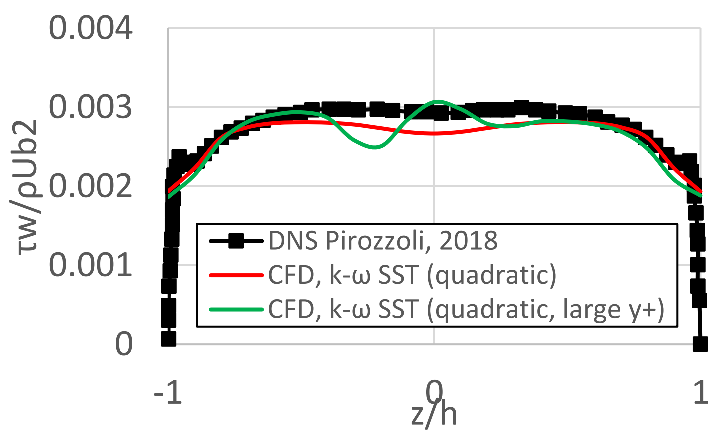
vw Reynolds stresses



Let’s also compare the cross-stream velocity profile as well as the wall shear stress.







Discuss the obtained results!

7 Conclusions

The quadratic formulation of the k-ω SST model is capable to predict relatively well the onset of secondary flows in the cross-stream direction. The qualitative comparison of the streamwise and cross stream velocity and the direct comparison with cross-stream velocity and wall shear demonstrate the robust formulation of the quadratic terms proposed by Pope in 1975 based on power series of tensor products of the mean rate of strain and mean vorticity.