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Department of Physics
Lab 2

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Lab 2

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Turbulent Channel Flow

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1 Results and Discussion

After having imported the Direct Numerical Simulation (DNS) data for turbulence kinetic energy production P_k^+, turbulence kinetic energy dissipation ϵ^+ and turbulence kinetic energy k^+, we can graph a comparison between the Low-Re k-ϵ turbulence model with the DNS for channel flow, seen in Fig.(1).

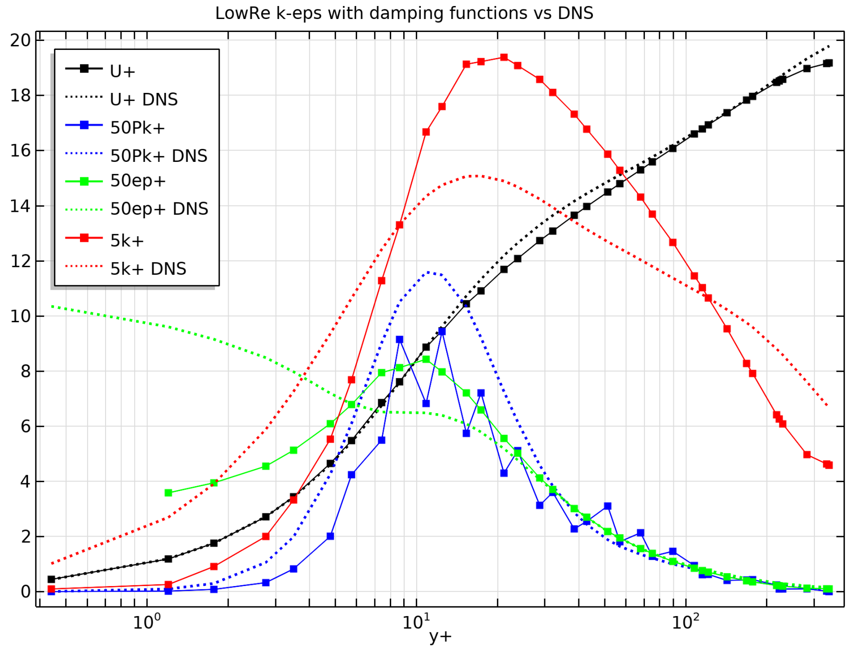

Figure 1 – Comparison between the Low-Re k-ϵ turbulence model and DNS for turbulent channel flow.

Right away one can note that the production P_k^+ seems to be quite jagged for the Low-Re k-ϵ model, but it still corresponds well to the general shape and position of the equivalent curve in the DNS data. The peak is at the same place, around $y^+ \approx 11$, and it trends as $P_k^+ \sim y^3$ in the viscous sublayer ($y^+ \leq 5$) and as $P_k^+ \sim y^{-1}$ in the log-layer ($y^+ > 30$), as expected if we perform a near-wall analysis in a 2D boundary layer, and a similar analysis for the general turbulence in the log-layer, assuming the flow is obeying the "law of the wall".

The reason for the jaggedness of the production term in the Low-Re k-ϵ model I would attribute to the dependence of the mean velocity gradient $\frac{\partial U}{\partial y}$. A fully developed turbulent flow in a channel will have a quite blunt velocity profile in the channel, yielding a small velocity gradient far from the wall. This in turn makes the production term very sensitive on small changes in the velocity gradient, which will combined with first-order polynomial solutions for velocity in Comsol result in the jaggedness displayed here.

For the dissipation term ϵ^+ of turbulence kinetic energy, we do not have as close of an correspondence between the Low-Re k-ϵ model and DNS as for the production term. Although the curves are overlapping closely in the log-layer ($y^+ > 30$), trending as $\epsilon\ y^{-1}$, and both having local extrema around $y^+ \approx 11$, similarly to the production term, the behaviour is quite different in the viscous sub-layer. While the DNS data displays a saddle point around $y^+ \approx 11$, the Low-Re k-ϵ turbulence model has a maxima around the same point. I'm not entirely sure on the interpretation of this, if it is due to an mistake on my part, or if it can be explained by a deficiency in the Low-Re k-ϵ model compared to the physically more correct DNS data. Alternatively, this could be due to a difference in the definition of the boundary values for ϵ at the the channel wall. I believe Comsol defines $\epsilon = \lim_{y\to 0} \frac{2\nu k}{y}$ for the Low-Re k-ϵ model while the DNS might have defined ϵ to something else at the boundary.

The turbulence kinetic energy k are also not matching as closely between the two models, but the general behaviour is still corresponding quite well. The turbulence kinetic energy grows as $k^+ \sim y^2$ close to the wall, and peaks around $y^+ \approx 20$ and stagnates somewhat in the log-layer.

Re-running the first Low-Re k-ϵ simulation while having shortened the channel to half the length used in the previous simulation, we can graph a similar comparison between to the DNS data, seen in Fig.(2).

Here we can see that the velocity profile U^+ of the Low-Re k-ϵ model does no longer match as closely to the DNS data, indicating that the flow in the channel is not fully developed. As such, the flows have not yet found its equilibrium velocity profile in the channel and still has a faint memory of the initial velocity profile at the inlet of the channel. However, the difference is not huge and the production P_k^+ and dissipation ϵ^+ still has the same general features described in the previous figure, although the production term does not have the same jaggedness as previously displayed. This is likely due to the velocity profile not having settled yet into its typical blunt shape for turbulent channel flow, and instead has a larger gradient of the velocity profile, which will lessen some of the sensitivity discussed earlier.

As one can see in both of the previous graphs, the production term P_k^+ equals the dissipation term ϵ^+ in most of the upper range of y^+, in particular for the log-layer $y^+ > 30$. This means that the rate of production and dissipation of turbulence kinetic energy are equal within this region, yielding a net zero change in turbulence kinetic energy. In other words, the rate at which kinetic energy is transported from the mean flow to the turbulence, equals the rate

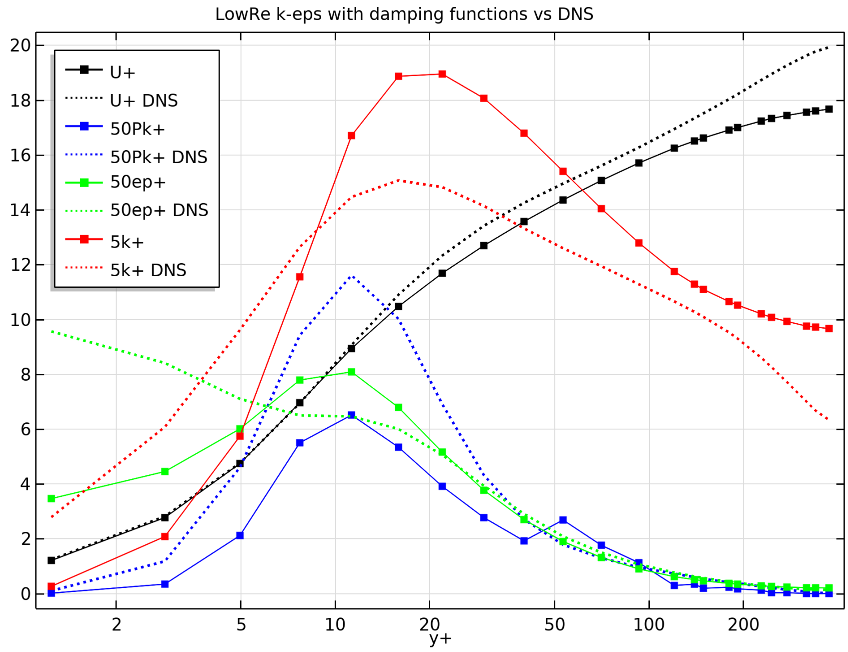

Figure 2 – Comparison between the Low-Re k-ϵ turbulence model and DNS for turbulent channel flow, where the channel have been shortened to half the length of the previous simulation detailed in Fig.(1).

at which turbulence kinetic energy is converted into thermal energy.

Next, we can try to smoothed the jaggedness of the production term P_k^+ in the graph for the Low-Re k-ϵ model. First, by simply using a finer mesh-preset in Comsol, as seen in Fig.(3), we can conclude that this did not improve the jaggedness of the curve, but it did however bring it closer to the DNS counterpart in the figure. The reason for general improvement in the shape, but not in jaggedness, I would explain as being due to the first-order polynomial solutions of velocity in Comsol. Since we are interested in the production P_k^+ which uses the first derivative of the mean velocity, we can only get constant estimates of the velocity gradient on each cell in the mesh. Combined with the overall sensitivity of the velocity gradient, this results in the P_k^+ curve still being jagged, while also having improved in its general shape due to the higher resolution mesh.

Further, if we manually tweak the mesh with custom user settings where we improve the mesh density along the boundaries, as seen in Fig.(4), we can further lessen the jaggedness of the production term. The reason for the improvement this time I would reason is due to the fact that we are better resolving the critical region $5 < y^+ < 100$, corresponding to the buffer layer and the log-layer in the turbulent boundary layer, where most of the

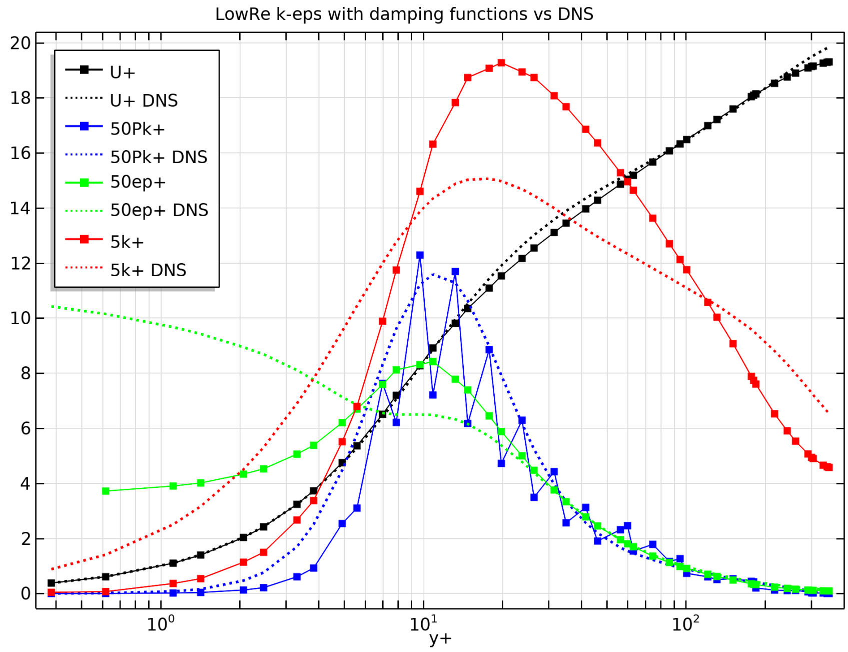

Figure 3 – Comparison between the Low-Re k-ϵ turbulence model and DNS for turbulent channel flow. Using a finer mesh-preset in Comsol than the initial Low-Re k-ϵ simulation in Fig.(1).

problem with this jaggedness occurs. We still only have first-order solutions of velocity, so the jaggedness still exists, although to a lesser degree due to the higher quality mesh of this simulation.

Lastly, we switch to using second-order solutions for the velocity, as seen in Fig.(5), which finally reduces most of the problems with the jaggedness. As discussed earlier, since we need the gradient of the mean flow velocity, we will now have linear, instead of constant, quantities for the velocity gradient on each cell in the mesh, which drastically improves on the general jaggedness.

2 Conclusion

This lab has concerned simulations of turbulent flow in a channel, where we have used available DNS data to assess the performance of the Low-Re k-ϵ turbulence model for RANS. Observing the behaviour and profile of the production and dissipation terms of turbulence kinetic energy, we have discussed its meaning and drawn conclusions from it. We have further tested and analysed how different mesh settings impact the simulation and quantities derived from it.

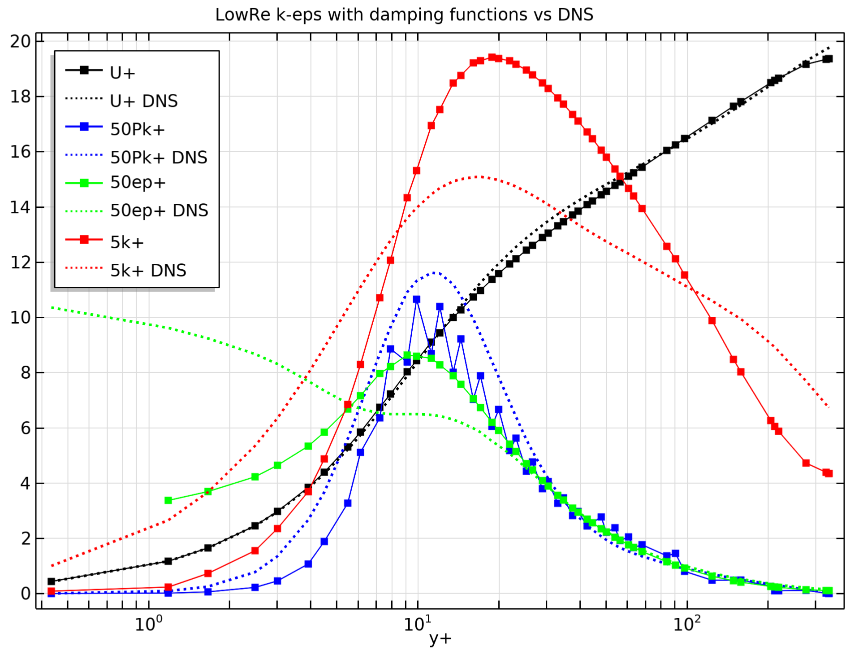

Figure 4 – Comparison between the Low-Re k-ϵ turbulence model and DNS for turbulent channel flow. Using a custom, user-defined mesh in Comsol which improves on the resolution around channel boundaries, compared to the initial Low-Re k-ϵ simulation in Fig.(1).

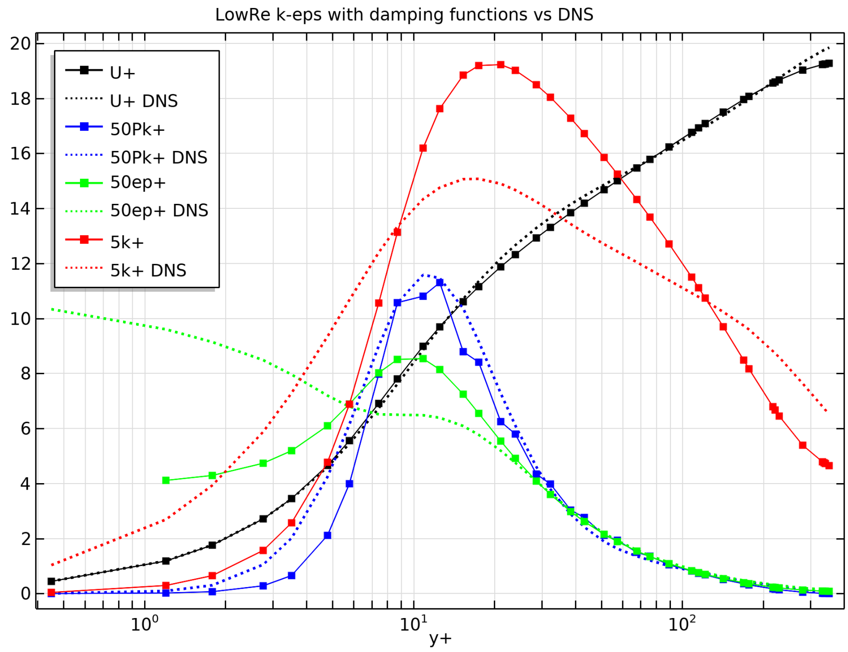

Figure 5 – Comparison between the Low-Re k-ϵ turbulence model and DNS for turbulent channel flow. Using a second-order discretization for mesh-elements in Comsol, compared to the first-order discretization used in the initial Low-Re k-ϵ simulation in Fig.(1).