ME-474 Numerical Flow Simulation

Comments on the exercise: turbulent backward-facing step

Fall 2021

In the tutorial, you observed that the inlet boundary conditions are very important in this turbulent flow: as shown in figure 1, the results are very different when using either (i) a uniform velocity and a uniform turbulent intensity (blue), or (ii) y-dependent profiles for velocity, turbulent kinetic energy k and dissipation rate ω, aimed at matching the experimental conditions (red). The agreement with the experimental measurements is much better in case (ii).

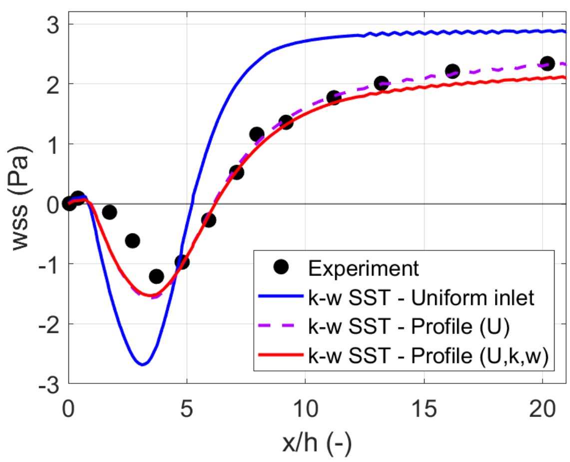

Figure 1: Streamwise component of the wall shear stress $\mu \partial u_x / \partial y$ on the downstream wall (distance x from the step, normalized by the step height h) obtained with the k-ω SST turbulence model and different inlet boundary conditions.

To determine which is more important among the profiles of velocity and turbulent quantities, it is possible to run an intermediate case, with a profile of velocity (like in case (ii)) but without profiles of k and ω (using instead a constant turbulent intensity, like in case (i)). The results (dashed line) suggest that the velocity profile has the strongest influence in this case. In the following, profiles of velocity, k and ω are used (case (ii)).

1 Turbulence models

Figure 2 (left) shows the streamwise wall shear stress obtained with 2 different variants of the k-ω models. The SST variant (default in Fluent) performs well in this flow. It is recommended in particular when there is separation. The standard k-ω model overestimates the recirculation length in this flow, and is not recommended in general when there is separation.

Figure 2 (right) shows the results obtained with the realizable variant of the k-ϵ model, and different near-wall treatments (standard wall function, scalable wall function and enhanced wall treatment). When the flow is separated, the standard variant is not recommended, and the realizable variant (like here) or the RNG variant should be preferred. Here, although the realizable variant is used, all the near-wall treatments underestimate the recirculation length. For the k-ϵ model, it is important to decide whether the near-wall flow should be explicitly resolved with a sufficiently fine mesh (which requires $y^+ \sim 1$), or modeled with a wall function (which requires $y^+ > 30$). It was observed in the tutorial that the mesh yields $y^+ \sim 5$ on

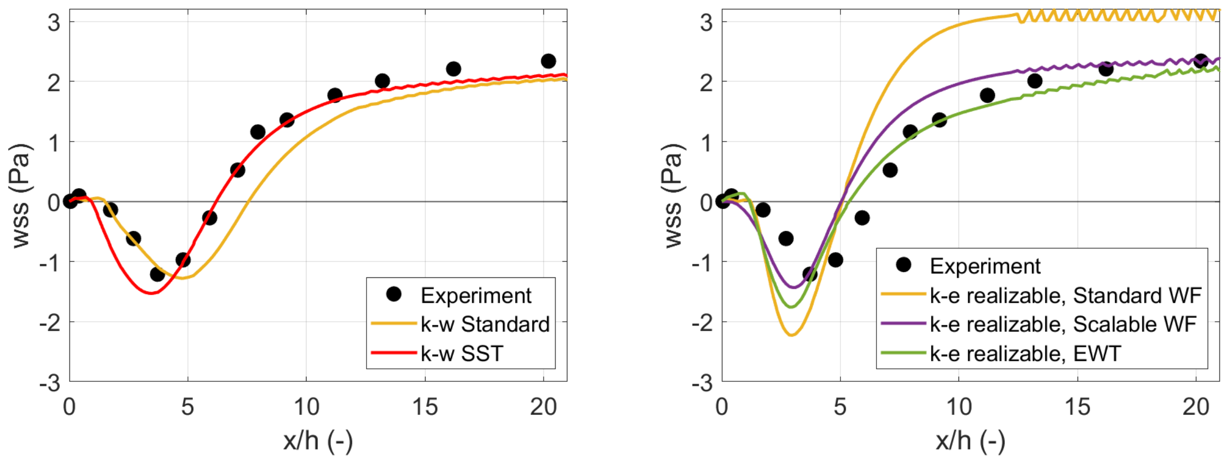

Figure 2: Streamwise component of the wall shear stress $\mu \partial u_x / \partial y$ on the downstream wall (distance x from the step, normalized by the step height h) obtained with different k-ω and k-ϵ turbulence models.

the downstream wall. The fact that $y^+ < 30$ explains why the results of the standard and scalable wall functions are not accurate. The enhanced wall treatment actually combines the explicit calculation of the viscous sublayer where the mesh is fine enough and a wall function where the mesh is coarser. Therefore, it performs better in this situation, where the mesh is neither fine enough to yield $y^+ \sim 1$ nor coarse enough to yield $y^+ > 30$.

Note that for all k-ω models, a so-called y^+-insensitive near-wall treatment is applied, which solves the flow explicitly if the mesh is sufficiently fine, and reverts to a wall function for coarser meshes.

2 Convergence study

For the convergence study, the k-ω SST model is used. Several strategies are available to refine the mesh: (i) a uniform refinement, i.e. all the elements of the mesh are made finer or coarser with the same ratio everywhere, (ii) a boundary layer refinement, i.e. only the inflation layer is made finer or coarser (for example varying the thickness of the first element, while keeping constant either the number of elements in the wall-normal direction or the total thickness of the inflation layer).

Figure 3 shows the results obtained for strategy (i) with the same mesh as in the tutorial (mesh 3), two coarser meshes (1 and 2) and two finer meshes (4 and 5). The ratio of element size between two successive meshes is $\sqrt{2}$. The number of elements ranges from 17'000 to 660'000. On the finest mesh, the wall y^+ is of the order of 2. Profiles of wall shear stress are very similar for meshes 3, 4 and 5. The recirculation length (distance between the step in $x = 0$ and the reattachment point in $x = x_r$ were the wall shear stress is zero) is well converged (relative variation between successive meshes of 2%, 1%, and then less than 1%). Also, the solution also gets closer to the experimental measurements as the mesh becomes finer.

Figure 4 shows the results obtained for strategy (ii) with the same mesh as in the tutorial (mesh 3), two coarser meshes (1 and 2) and two finer meshes (4 and 5). This time, only the inflation layer is refined or coarsened, while the size settings for the rest of the mesh are not modified. Consequently, the number of elements remains much smaller, from 57'000 to 104'000. Overall, results are comparable to those of figure 3, and the relative variation of x_r between successive meshes is of the order of 1% or less.

Note that, irrespective of the wall y^+ value, an important requirement to obtain accurate results is to have at least 10-20 elements in the inflation layer, and the inflation layer should be thicker than the boundary layer. (This also applies to free shear layers, i.e. shear layers not located near a wall.) Therefore, some care is needed if the number of elements is kept constant: when reducing the thickness of the first element, the whole inflation layer becomes thinner, possibly thinner than the boundary layer, and the accuracy may deteriorate.

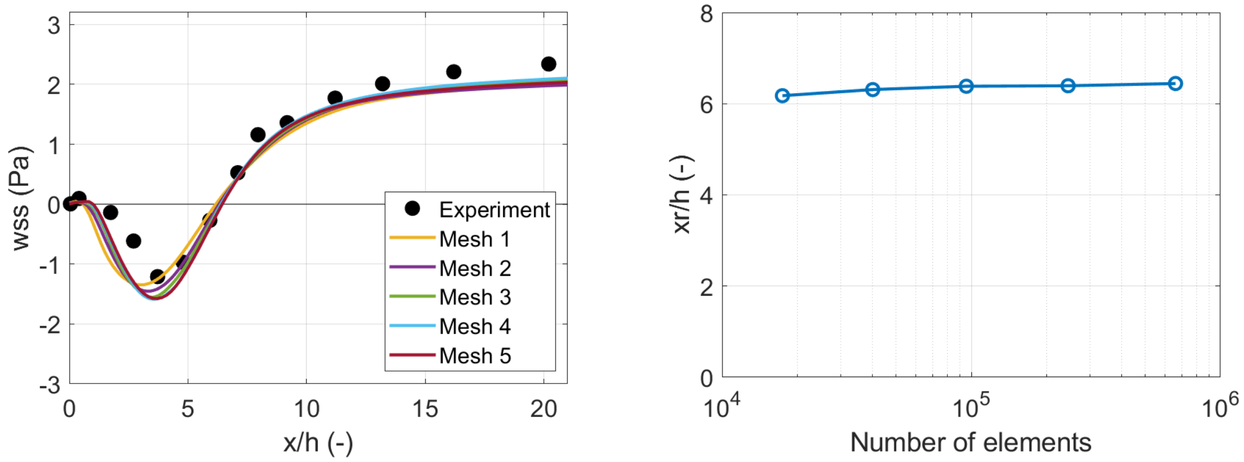

Figure 3: Convergence study with uniform refinement: streamwise component of the wall shear stress $\mu \partial u_x / \partial y$ on the downstream wall (left), and normalized recirculation length x_r/h (right).

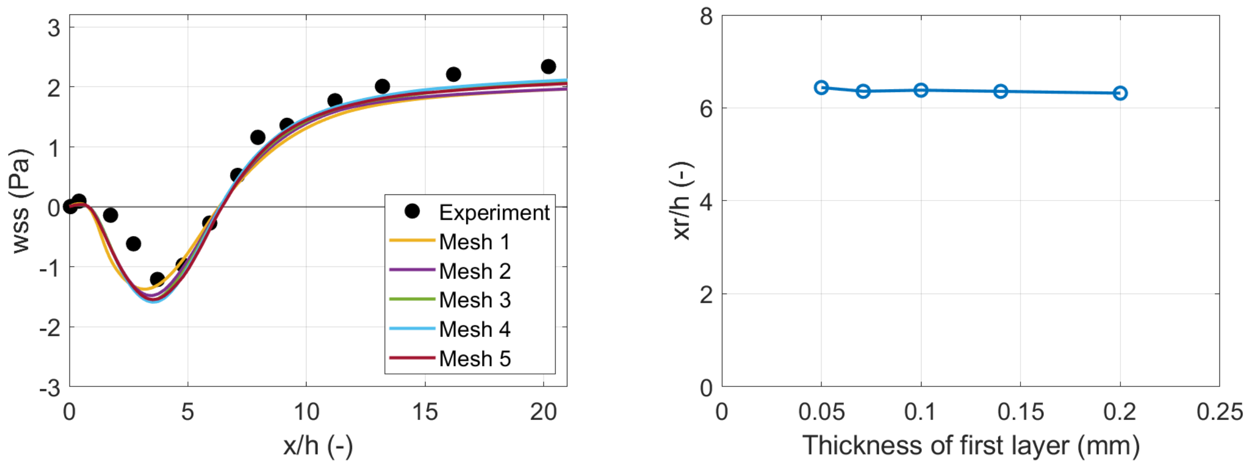

Figure 4: Convergence study with boundary layer refinement, using a constant number (15) of elements in the inflation layer.

For reference, figure 5 shows profiles of streamwise velocity in the recirculation region, obtained on the finest mesh. Recall that the step height is $h = 12.7$ mm, and the maximum inlet velocity is approximately 44 m/s. The free shear layer emanating from the step in $y = 0$ is initially very sharp and gradually becomes smoother downstream. The thin boundary layer and the strong shear stress on the bottom wall are also visible.

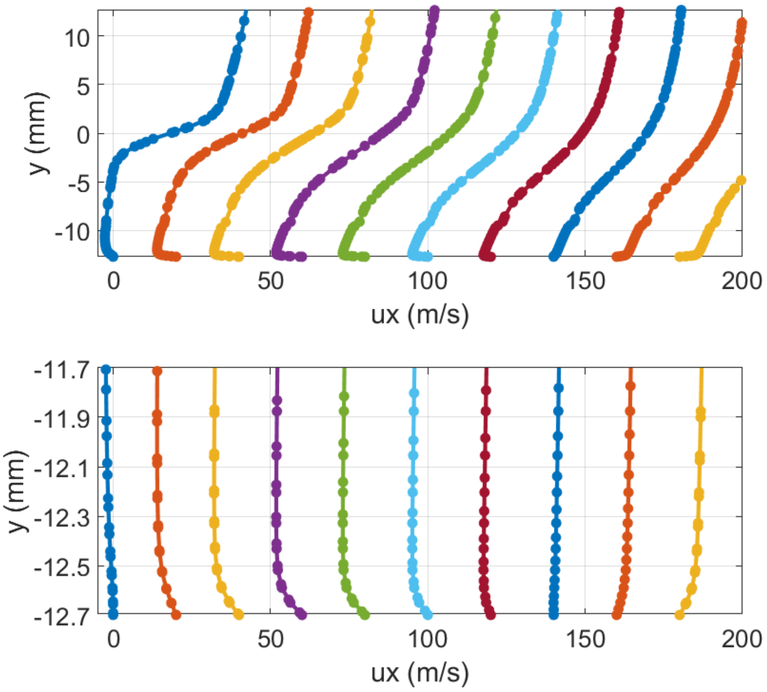

Figure 5: Streamwise velocity profiles in the recirculation region at $x = 10$ mm, 20 mm..., 100 mm (for clarity, profiles are successively shifted by 20 m/s). Top: global view $y \in [-h, h]$. Bottom: close up view on the region extending 1 mm from the bottom wall.