Turbulent Flow Over Smooth Flat Plate

SmartNumerics Simulation Solutions Inc.

June 8, 2020

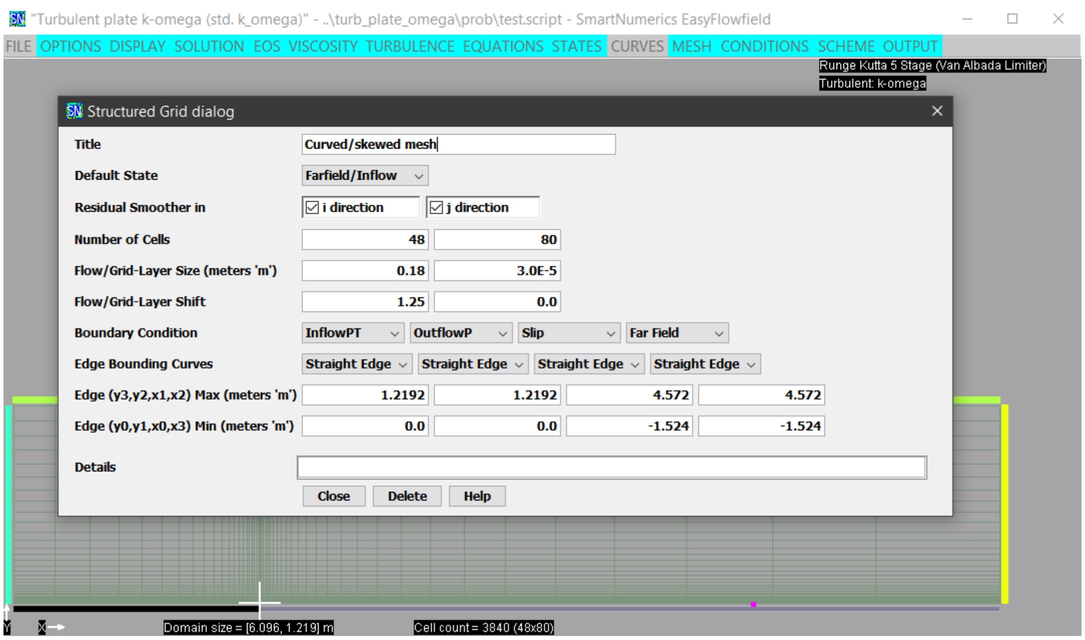

Fig. 1: Grid and k-ω turbulence model input for turbulent flow over flat plate.

Figure 1 displays the grid used to simulate turbulent flow of air over a flat plate using the ideal-gas equation of state. The k-ω turbulence model of Wilcox [1] is used without a wall function. The far-field conditions are Mach 0.2, 101325 Pascals, and 300° K. The Sutherland formula is used to compute molecular viscosity.

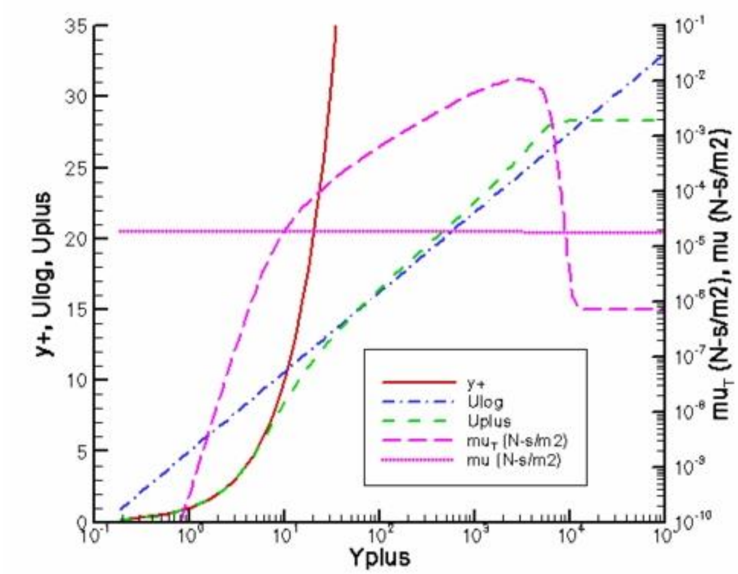

Fig. 2: Plot of viscosity and u^+ versus y^+ for turbulent flow over smooth flat plate.

Figure 2 displays a comparison of $u^+ = u/u^*$ to the incompressible log law

$$U_{\log} = \frac{1}{0.41}\ln\left(y^+\right) + 5.0$$

at a region downstream of the leading edge. As expected, the u^+ curve conforms to the y^+ curve near the wall. Also shown is the variation of molecular velocity and eddy viscosity. The simulation was solved using an explicit five stage Runge-Kutta solver with enriched w-cycle multigrid. The HLLC flux was used with the van Albada limiter.

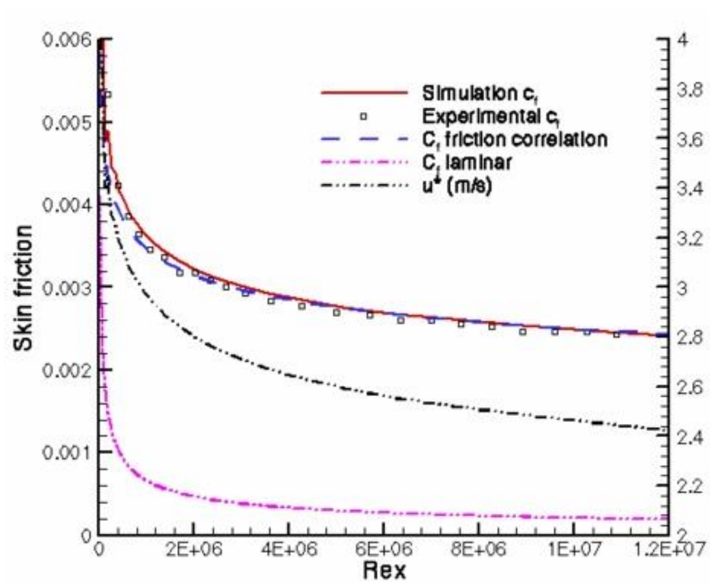

Fig 3: Plot of skin friction vs Reynolds number for turbulent flow over smooth plate.

Figure 3 displays the skin friction along the plate as a function of Reynolds number based on distance downstream from the leading edge. The skin friction velocity (u*) is also displayed. The skin friction coefficients are computed using

$$c_f = 2\frac{\rho_w (u^*)^2}{\rho_\infty U_\infty^2}$$

using the local friction velocity output by the solver. Here, ρ_w is the local density at the wall, ρ_∞ is the far-field density, and U_∞ is the far-field velocity.

The friction obtained from the simulation is a good match to the fully turbulent friction correlation

$$c_{f\ \text{fully turb}} = .025(\text{Re}_x)^{-1/7}$$

as well as to experimental points taken from Wieghardt and Tillman [2]. The friction curve for turbulent flow is well above the Blasius friction correlation for laminar flow

$$c_{f\ \text{laminar}} = \frac{0.664}{\sqrt{\text{Re}_x}} \quad .$$

Here

$$\text{Re}_x = \frac{\rho_\infty u_\infty x}{\mu_\infty}$$

is the Reynolds number a specified distance x downstream of the leading edge of the plate, where μ_∞ is the far-field molecular viscosity, u_∞ is the far-field velocity, and ρ_∞ is the far-field density.

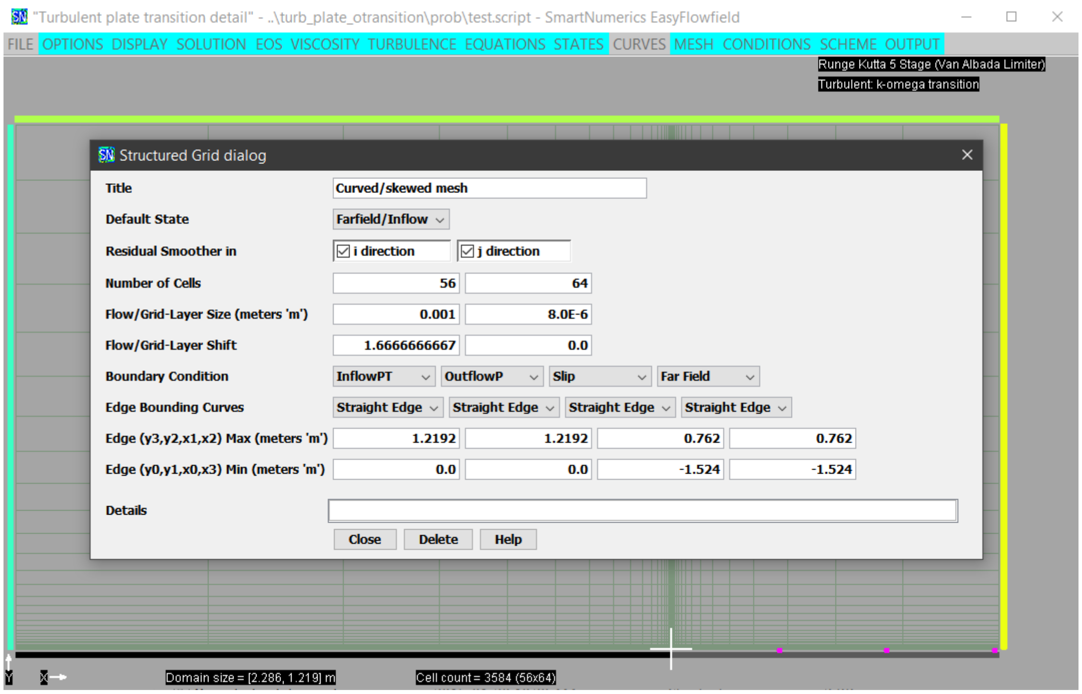

Fig. 4: Grid used for simulation of turbulent flow over plate at lower Re_x.

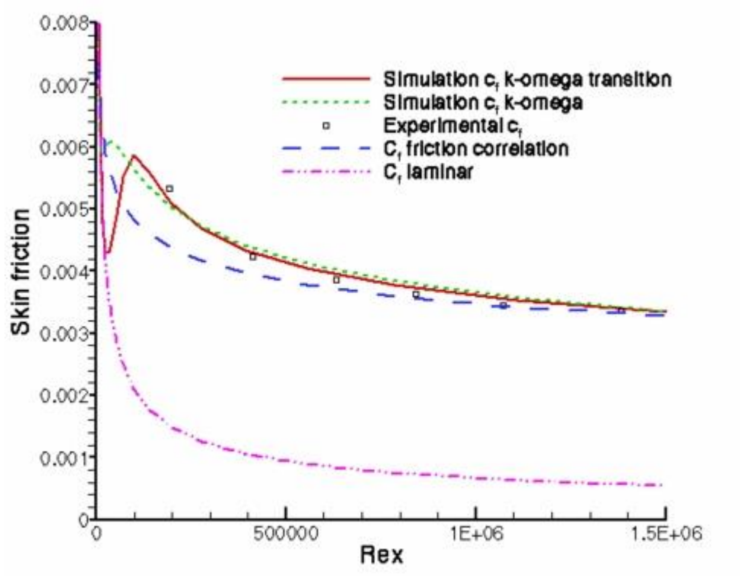

Fig 5: Plot of skin friction vs Reynolds number for turbulent flow over smooth plate.

All but one of the turbulence models currently implemented in EasyFlowfield assume fully turbulent flow and produce a friction curve similar to that produced by the k-ω model. The k-ω transition turbulence model of Wilcox [1] is tuned to model transition from laminar to turbulent flow near the leading edge of a smooth flat plate. As seen in Figure 5, the friction computed using the k-ω transition turbulence model on a shortened plate follows the laminar friction curve up to a certain point then moves upward as flow becomes turbulent further downstream. The friction computed using the k-ω turbulence model does not match the laminar friction curve. As one might expect, the fully turbulent friction correlation lies well under the experimental points until the Reynolds number exceeds 800,000.

References

[1] Wilcox, D. C., Turbulence Modeling for CFD, DCW Industries Inc., 1994.

[2] Wieghardt, K. and Tillman, W., On the Turbulent Friction Layer for Rising Pressure, NACA TM-1314, 1951.