ME 420: Fluid Mechanics II

Project 3

March 26th, 2008

Introduction

The team recreated the experimental setup explained in the Project 3 description and shown in figure 1 in Vogel and Eaton. We created two different meshes, shown in figures 2 and 3 below, to check for grid independence. The team used a quad mesh. The meshes were then imported into Fluent where the calculations began. When we doubled the resolution, our results were very close to each other which indicated that the solution we obtained was grid independent.

We modeled the flow as 2-D because the aspect ratio of the channel is large. Air was used as the working fluid. We ran and compared the results using three k-epsilon models in FLUENT (standard, RNG, and realizable) used in conjunction with either standard or non-equilibrium wall functions. All runs were done using the same grid and a 2nd-order upwind scheme, as was stated in the project description.

Our 1st task was to compare the reattachment length to the experimental value which was reported to be 6.67 step heights by Vogel and Eaton. The 2nd task was to compare the variation of the Stanton number as a function of non-dimensional distance to figure 4 in Vogel and Eaton. The 3rd task was to show the comparison of the variation of the mean skin-friction coefficient as a function of downstream distance to figure 10 of Vogel and Eaton. Our last task was to show comparisons of the profiles of mean velocity, streamwise turbulence intensity, and mean temperature to figures 7, 8, and 9 in Vogel and Eaton.

Gambit

Using Gambit, we created a mesh based on the experimental setup shown in figure 1 and tried to recreate the mesh shown in the project description. Using Gambit, many different meshes were created and tested and the best single mesh is shown in figure 2. The type of mesh used was a uniform quad mesh inside of the boundary layers and a small ratio outside of the boundary layers. The ratio of length to height never exceeded 3:1. The boundary layer conditions can also be seen in figure 1.

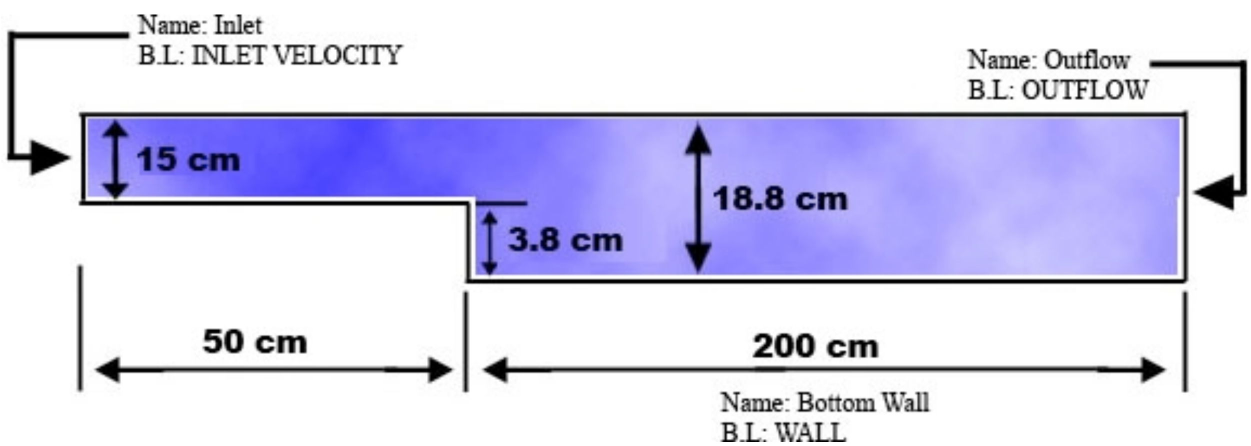


Figure 1: Experimental setup with dimensions and boundary layer conditions

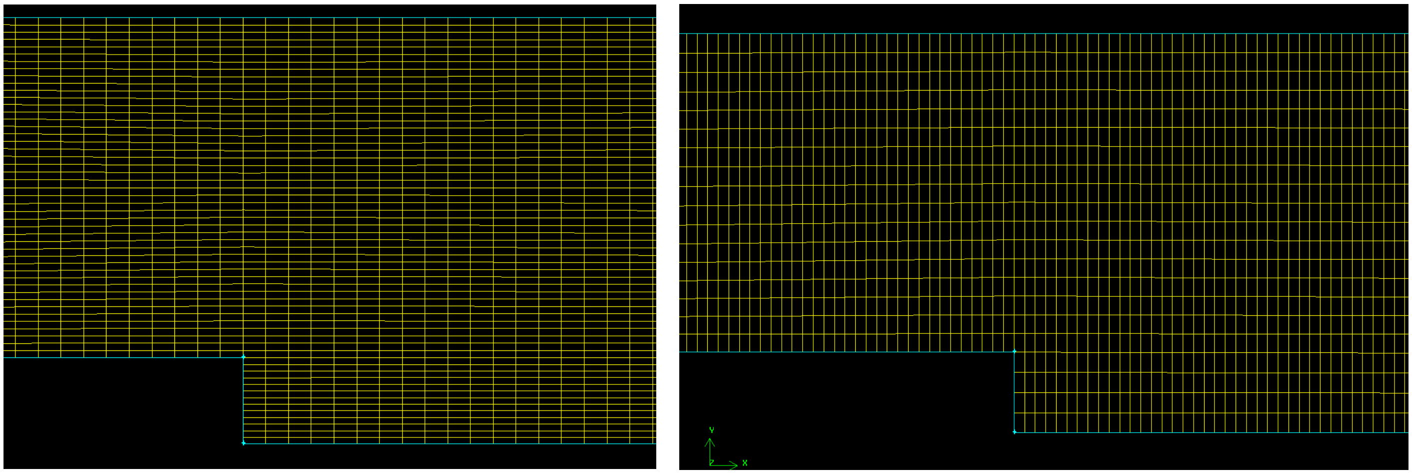


Figure 2 and 3: Single and double meshes used for calculations and to check for mesh independence respectively

Mesh Independence

In order to verify that we had mesh independence, we compared the values of the reattachment length for the two meshes we created in the most robust model (realizable k-epsilon with non-equilibrium wall functions) for the single and double mesh. In doing mesh independence, we kept the location of the first grid point the same and doubled the nodes on the horizontal walls. We found our double mesh to have a reattachment length 2.9% of that of the single mesh. We also calculated the reattachment lengths for the 6 different cases we ran and this is shown in table 1 below. For the single mesh, the realizable k-epsilon model with non-equilibrium wall functions compared best, as expected, to the experimental value of 6.67 step heights. For this case, the reattachment length is 6.73 step heights which is within 1% of the reference. The worst case was the standard k-epsilon model with standard wall functions which was off the reference by about 23.4%. The tests with different cases were run in Fluent.

To calculate the boundary layer thickness (BL) we used equation 2 below. We first had to calculate the Reynolds number (Re) which was found using equation 1. We made sure there was at least 10 grid points within the boundary layer when we doubled the mesh. L is the distance of the channel, longest wall, divided by 2, υ_k is the kinematic viscosity, C_f is the skin coefficient, u_τ is the friction velocity, and υ_d is the dynamic viscosity. The first grid point was placed according to equation 5, which was given in the Fluent software training PowerPoint slide.

$$\mathrm{Re} = \frac{U * L}{\upsilon_k} = 8.96E5 \qquad \text{(Eq. 1)}$$

$$BL = \frac{0.385 * L}{\mathrm{Re}^{0.2}} = 3.1E-2 \qquad \text{(Eq. 2)}$$

$$\frac{C_f}{2} = 0.0359 * \mathrm{Re}^{-0.2} = 2.3E - 3 \qquad \text{(Eq. 3)}$$

$$u_\tau = U * \left[\frac{C_f}{2}\right]^{0.5} = 0.54 m/s \qquad \text{(Eq. 4)}$$

$$2 * y_1 = \frac{50 * \upsilon_d}{u_\tau} = 3.4E - 3m \qquad \text{(Eq. 5)}$$

Upstream Length (m)	0.5	
Step Height (m)	0.038	
Vogel and Eaton reattachment length	0.25346	6.67 step heights

Case	Standard Standard	Standard Non-Equilibrium	RNG Standard	RNG Non-Equilibrium	Realizable Standard	Realizable Non-Equilibrium	Double Realizable Non-Equilibrium
	[illegible]	0.71013721	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
x	[illegible]	0.21013721	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Reattachment Length (m)	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
% difference to Vogel and Eaton	20.36%	17.08%	0.96%	2.67%	7.05%	[illegible]	7.4[illegible]%
					Percent difference single to double mesh:	[illegible]	

Table 1: Reattachment lengths for the 6 different cases and mesh independence results for single and double mesh at a velocity of 11.3 m/s

Fluent

In Fluent, we ran the 6 cases using air as the fluid at 300K. Table 2 below shows the parameters that were used in Fluent that correspond to this temperature. All runs were done using the single mesh and a 2nd order upwind scheme. The k-epsilon model under viscous model was also turned on and this is how the 6 different cases were calculated. One other parameter that was specified in the project description was a turbulence intensity reported at 0.5. We assumed the rest of the walls to be insulated.

x (m)	1.25
U (m/s)	11.30
Density (ρ) (kg/m^3)	1.1765
Dynamic Viscosity (kg/ms)	1.8538E-05
Kinematic Viscosity (m^2/s)	1.5757E-05
Specific Heat (Cp) (J/kgK)	1.0063E+03

Table 2: Parameters used in Fluent based on fluid temperature of air at 300K

We solved with an unsteady time and 2nd order implicit unsteady formulation. The energy equation was activated. The momentum and energy was changed to second order upwind and the absolute criteria of the residuals were changed to 1E-4 for all expect energy which was a factor of 1/10 smaller as well, 1E-7, to increase the accuracy of our results. The boundary conditions of the velocity inlets were set to have an x-velocity of 11.3 m/s shown in the table above, the bottom wall downstream of the step was given a heat flux of 270 W/m^2, and the model was initialized with zero initial conditions. We calculated the hydraulic diameter using the equation 6 below. A, is the cross sectional area and U, is the wetted perimeter of the channel.

$$HydraulicDiameter = \frac{4*A}{U} = \frac{4*0.51m*0.188m}{5.376m} = 0.071m \qquad \text{(Eq. 6)}$$

Comparison of the Variation of the Stanton number as a Function of Non-Dimensional Downstream Distance to Figure 4 of Vogel and Eaton

In order to calculate the Stanton Number (St), shown in equation 8, we first had to solve for h, the heat transfer coefficient. This was done using equation 7. The wall heat transfer rate per unit area, $\dot{q}''_o$, was given as 270 W/m^2 as stated in the project description. T_w, the local wall temperature, was obtained from Fluent as a function of length from the step height. T_∞, the free stream temperature, was assumed to be 300K. The other parameters used to calculate the Stanton number are given in table 2. The horizontal axis in the graph below is the non-dimensional stream coordinate x* calculated as equation 9. x is the streamwise coordinate measured from the step edge and x_R is the reattachment length.

$$h = \frac{\dot{q}''_o}{T_w - T_\infty} \qquad \text{(Eq. 7)}$$

$$St = \frac{h}{U*\rho*C_p} \qquad \text{(Eq. 8)}$$

$$x* = \frac{x - x_R}{x_R} \qquad \text{(Eq. 9)}$$

The Stanton number, downstream of the reattachment length is the same found under normal turbulent boundary layer. The curves are smooth for all 6 cases which means that it is safe to assume that the Stanton number is dependent on the heat transfer coefficient. Our figure closely matches that of figure 4 in Vogel and Eaton shown below in both shape and numerical values. The maximum heat transfer rate therefore occurs near the reattachment point and for the realizable and non-equilibrium wall functions case, which is approximately 0.26 m from the step.

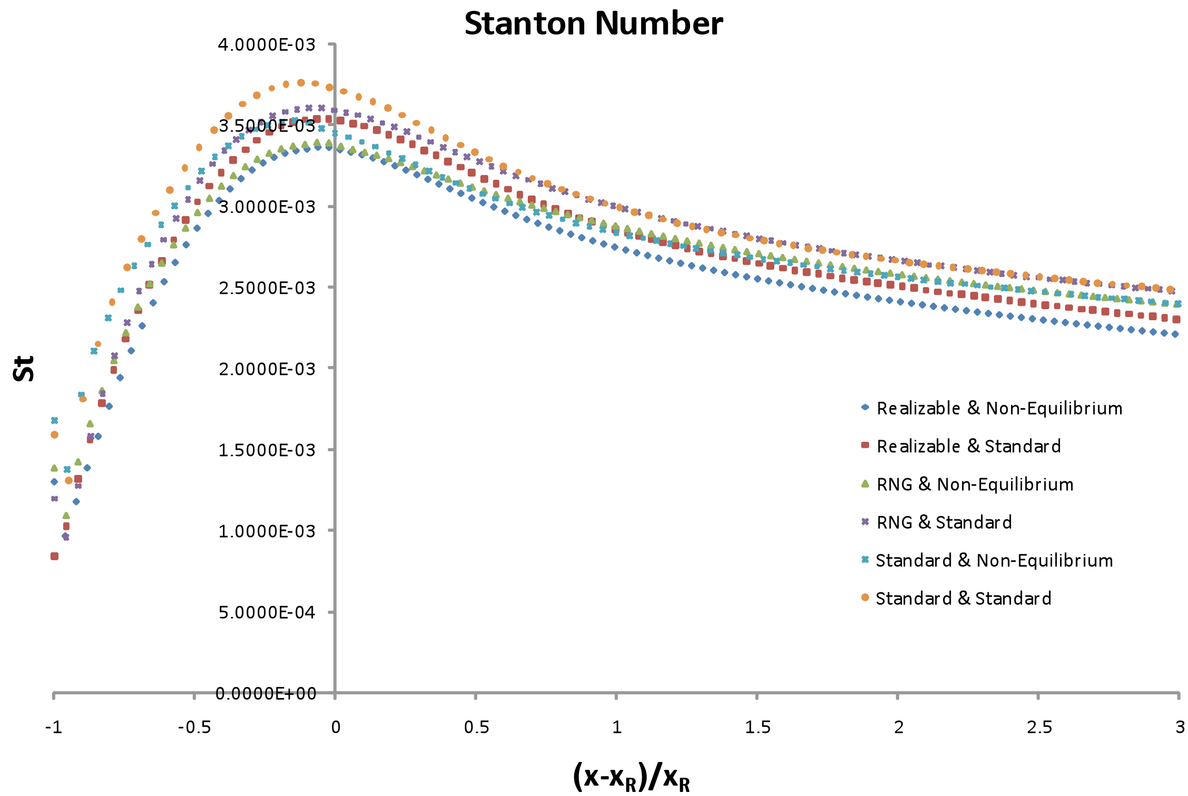


Figure 4: Stanton number profiles for all 6 different cases for air at a Re-8.96 E5

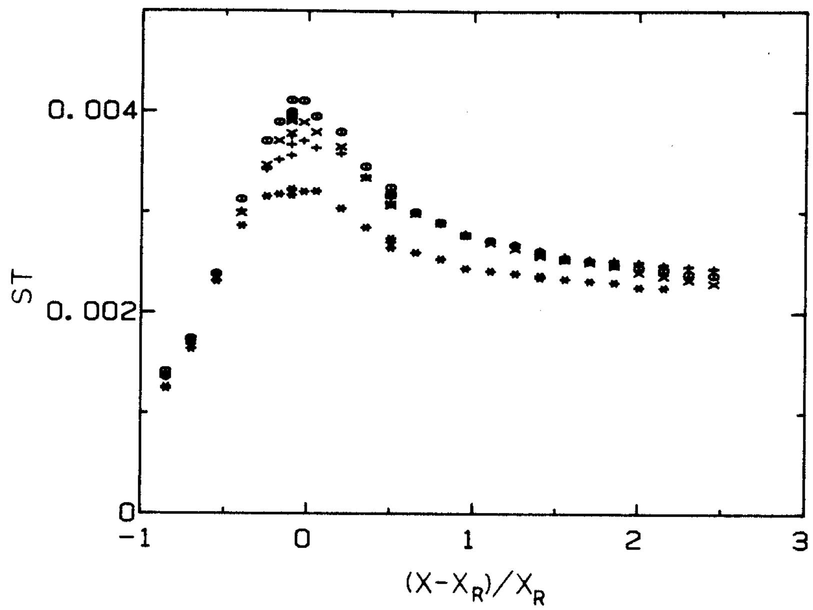


Figure 5: Figure 4 of Vogel and Eaton showing Stanton number profiles at Re=28,000

Comparison of the Variation of the Mean Skin-Friction Coefficient as a Function of Downstream Distance to Figure 10 of Vogel and Eaton

To examine the behavior of the near wall region, one must look at the mean skin-friction coefficient (C_f). Figure 6 below shows the mean skin-friction coefficient for all 6 cases. The mean skin-friction coefficient was found using equation 10. The local wall shear stress, τ_0, was found through the use of Fluent. The horizontal axis is the non-dimensional stream coordinate x* calculated as equation 9. For the figure below, one can see that at the reattachment length, C_f is approximately 0, and then it increases after this point. The C_f becomes negative in the backflow region of circulation. These observations relating to our data closely match that of Vogel and Eaton, shown in figure 7.

$$C_f = \frac{\tau_0}{\frac{1}{2}\rho * U^2} \qquad \text{(Eq. 10)}$$

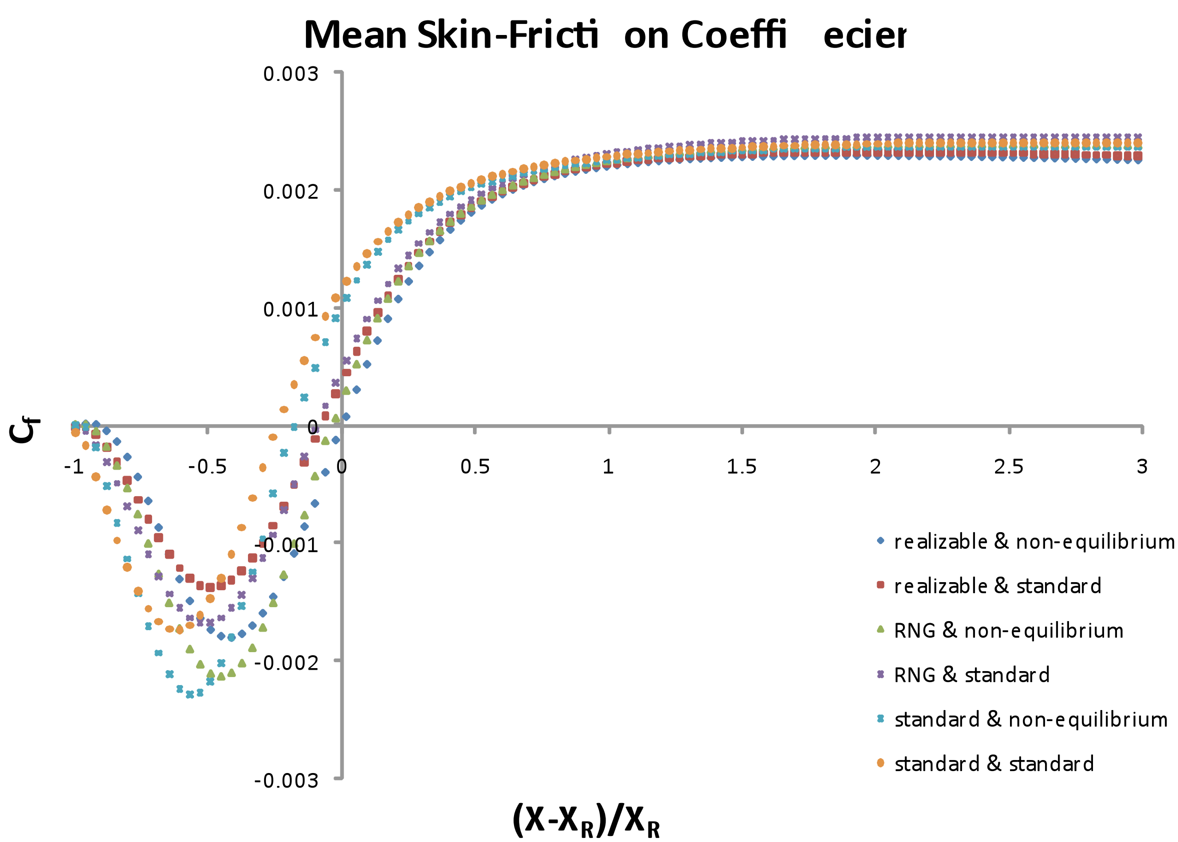


Figure 6: Mean skin-friction coefficient as a function of downstream distance for all 6 different cases for air at a Re=8.96E5

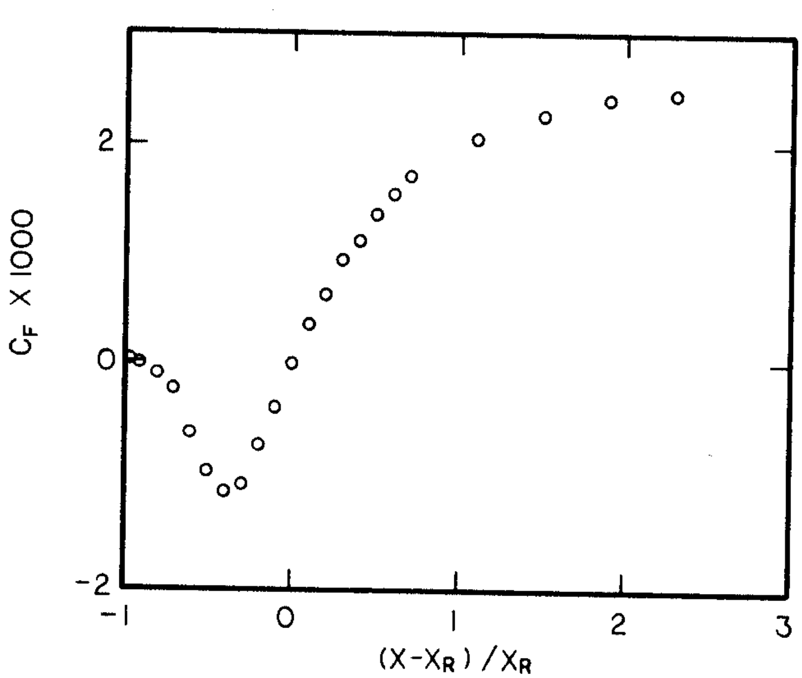
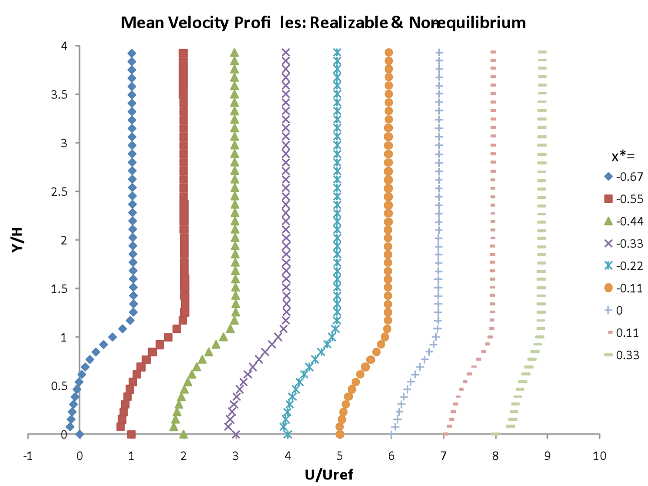
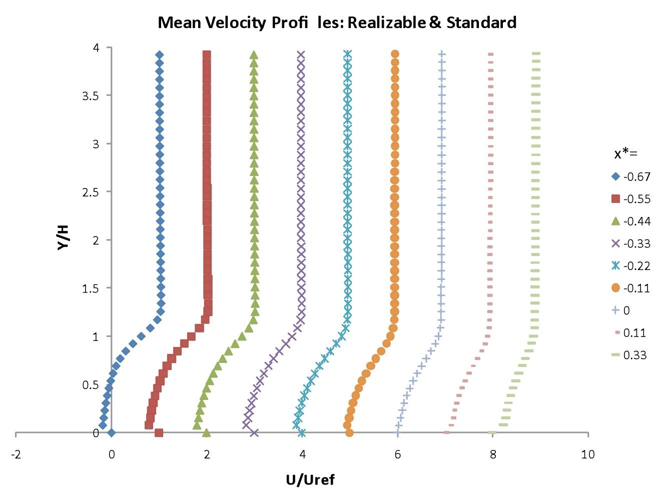
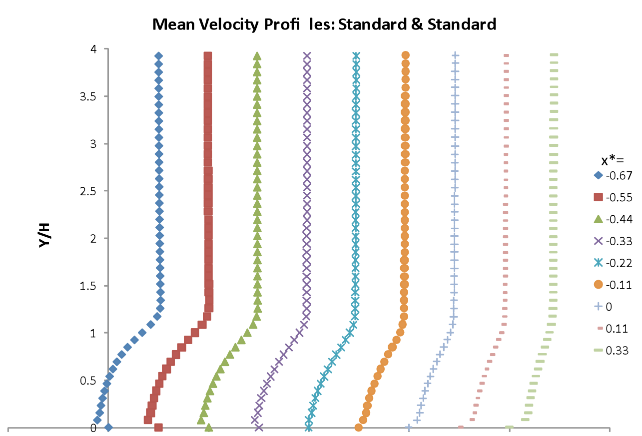


Figure 7: Figure 10 of Vogel and Eaton showing mean skin-friction coefficient downstream of the step

Comparisons of the Profiles of Mean Velocity to Figure 7 of Vogel and Eaton







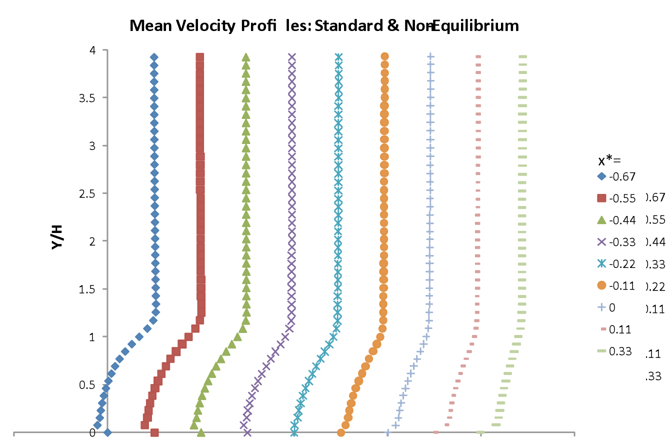


Figure 8: Mean velocity profiles for all 6 different cases for air at a Re=8.96E5

In order to find the mean velocity profiles, streamwise turbulence intensity profiles, and temperature profiles, at different lengths, down the channel, we created vertical lines at varying x* positions which matched Vogel and Eaton. U_{ref} was the uniform inlet velocity, 11.3 m/s, Y represents the vertical height from the bottom of the channel, H is the step height, and U was the x-velocity at x*. The graphs compare nicely to Vogel and Eaton and do not differ much between the k-epsilon equations and wall functions.

Comparisons of the Profiles of Streamwise Turbulence to Figure 8 of Vogel and Eaton

u' represents the wall shear stress along Y at x*. The graphs of steamwise turbulence closely compare to Vogel and Eaton and do not differ much between the k-epsilon equations and wall functions.

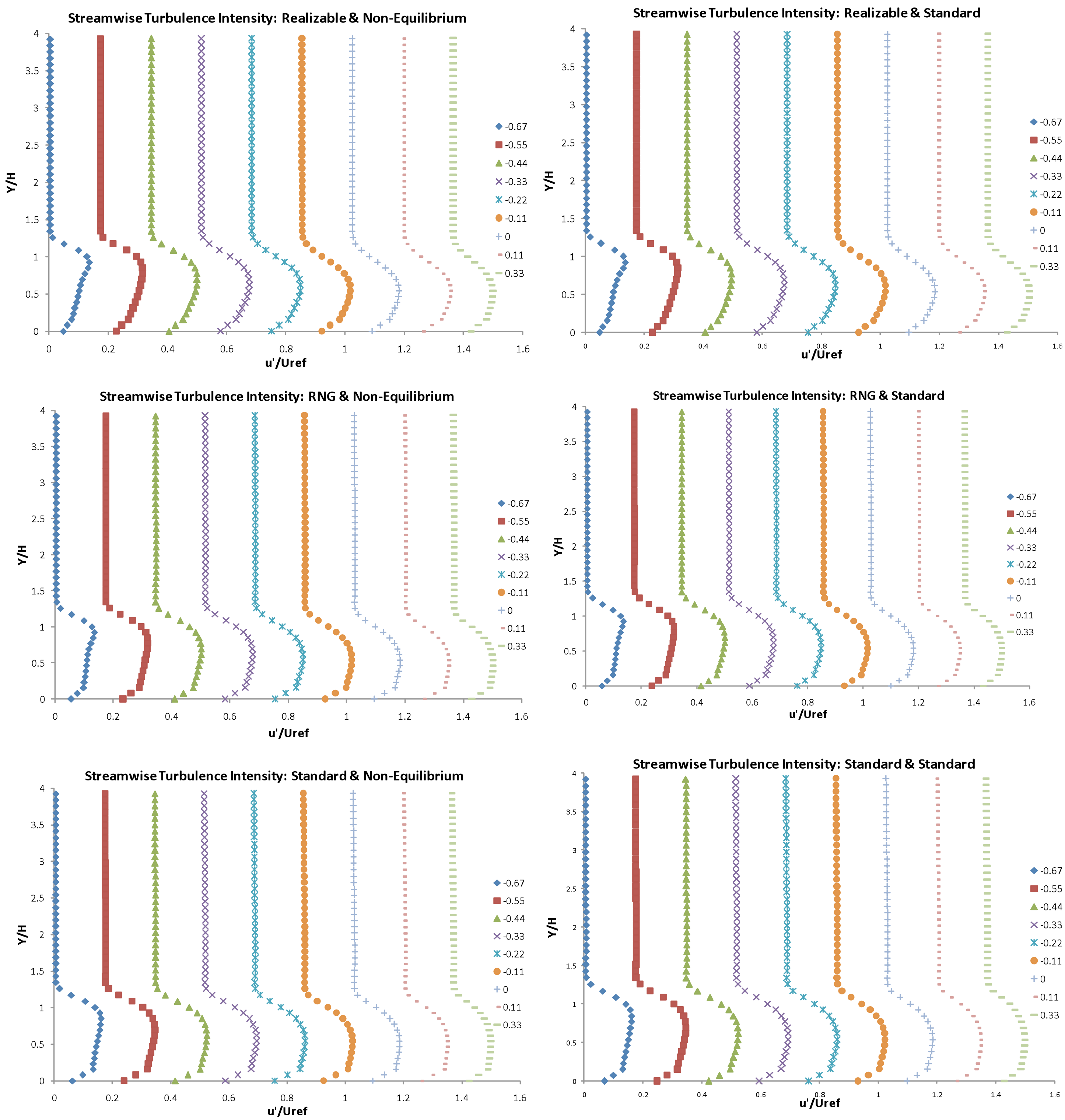
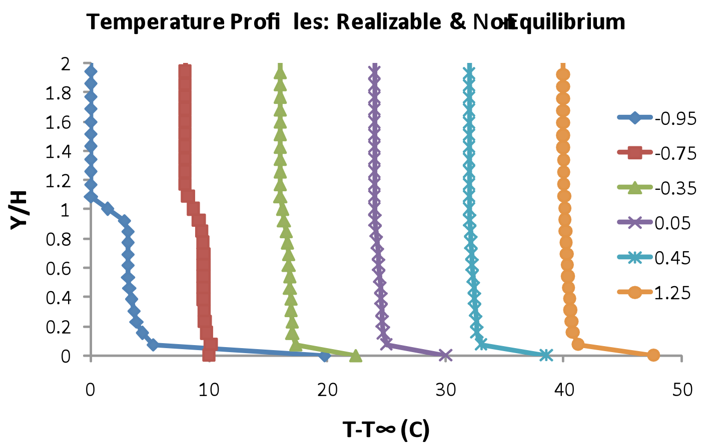
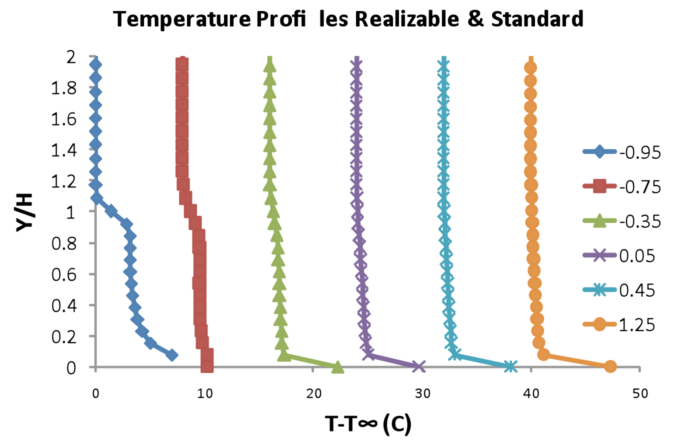


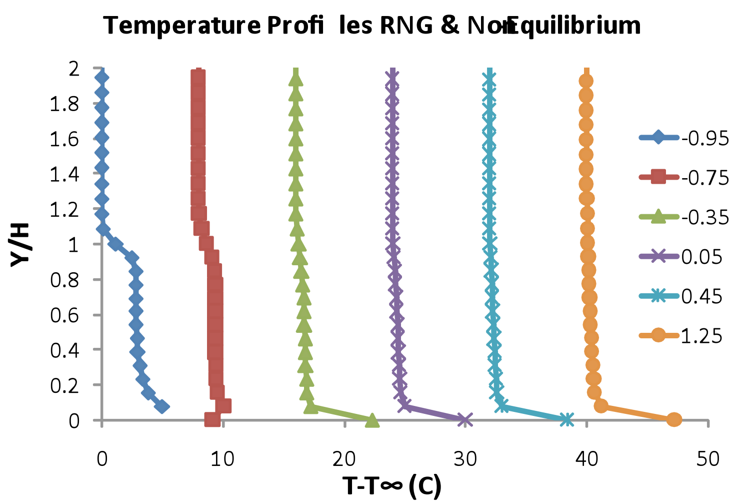
Figure 9: Streamwise Turbulence Intensity profiles for all 6 different cases for air at a Re=8.96E5

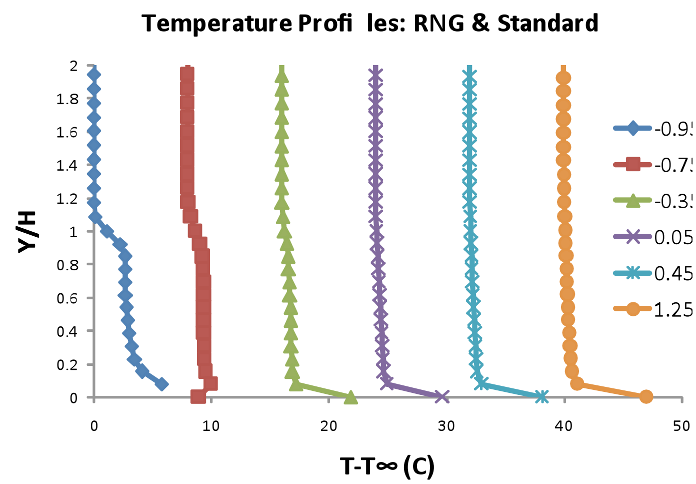
Comparisons of the Profiles of Mean Temperature to Figure 9 of Vogel and Eaton

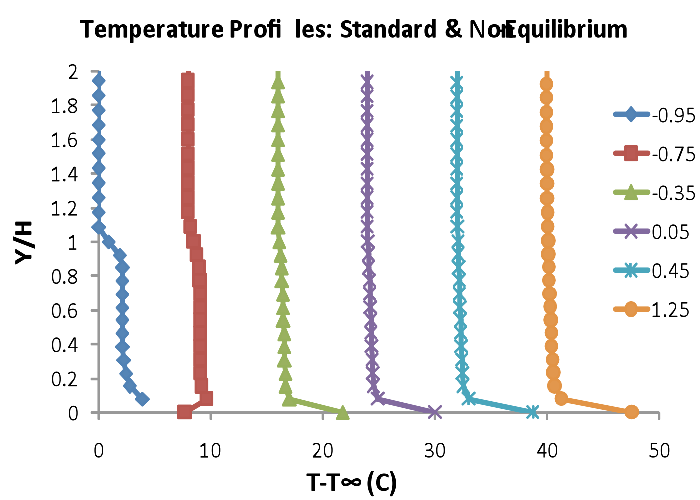
T represents the static temperature along Y at varying x* locations down the channel. T∞ is the ambient temperature, 300 K. The graphs of mean Temperature are similar to Vogel and Eaton and between the 6 different cases.











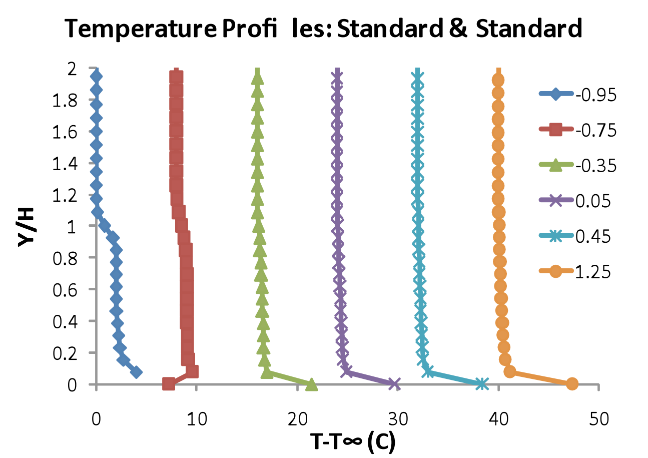


Figure 10: Mean temperature profiles for all 6 different cases for air at a Re=8.96E5

Conclusions

We have created a single and double mesh in Gambit and used our best single mesh to evaluate the performance of various k-epsilon models and near-wall treatments in Fluent. We have concluded that the realizable k-epsilon model with non-equilibrium wall functions is the best one. Our data for reattachment length for this specific model was within 1% of the reattachment length data for Vogel and Eaton. Also, our data for the variation of the Stanton number and mean skin-friction coefficient as a function of non-dimensional downstream distance closely matches that of Vogel and Eaton. Finally, our data for the mean velocity, streamwise turbulence intensity, and mean temperature closely matches that of Vogel and Eaton.