Verification of Drag Measurements on a Laminar-Flow Body of Revolution

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1 Grid Generation and Setup

A coarse grid was constructed around the specified geometry using a wedge 2-D geometry using 8 blocks. Severe grading was used around the laminar-flow body in order to accurately capture the geometry and velocity gradients. A $k\omega{-}\mathrm{SST}$ turbulence model was used for an initial case using a Reynolds number Re_L of 1.2×10^6. The flow was considered incompressible and steady-state, so the **simpleFoam** solver was used. A inlet velocity U was set to $1(\mathrm{m/s})$, and all the other turbulence parameters are defined in Table 1. The equations used to calculate the turbulence parameters can be seen in Equations 1-4. The initial grid is shown in Figure 1. The convergence plots for the three grids can be seen in Figure 2.

After running three cases using the Reynolds number Re_L of 1.2×10^6, the final iterations of the three grids were mapped to empty folders and the kinematic viscosity was altered to simulate a new Reynolds number. These kinematic viscosity values are shown in Table 2.

$$\mathrm{Re}_L = \frac{VL}{\nu} \tag{1}$$

$$\nu = \frac{VL}{\mathrm{Re}_L} \tag{2}$$

$$k = \frac{3}{2}(UI)^2 \tag{3}$$

$$\omega = \frac{C_\mu k}{\nu\left(\frac{\nu_T}{\nu}\right)} \qquad (C_\mu = 0.09) \tag{4}$$

Table 1: Setup parameters for $k\omega{-}\mathrm{SST}$ turbulence model for a Reynolds number Re_L of 1.2×10^6

Parameter	Value
ν	2.54×10^{-7}
ν_T	1.27×10^{-6}
k	3.75×10^{-3}
ω	265.75

Table 2: Kinematic viscosity ν values for each Reynolds number Re_L used.

Re_L	ν $\left(\frac{m^2}{s}\right)$
1.2×10^6	2.54×10^{-7}
1×10^6	3.48×10^{-7}
8×10^5	3.81×10^{-7}
6×10^5	5.08×10^{-7}
4×10^5	7.62×10^{-7}

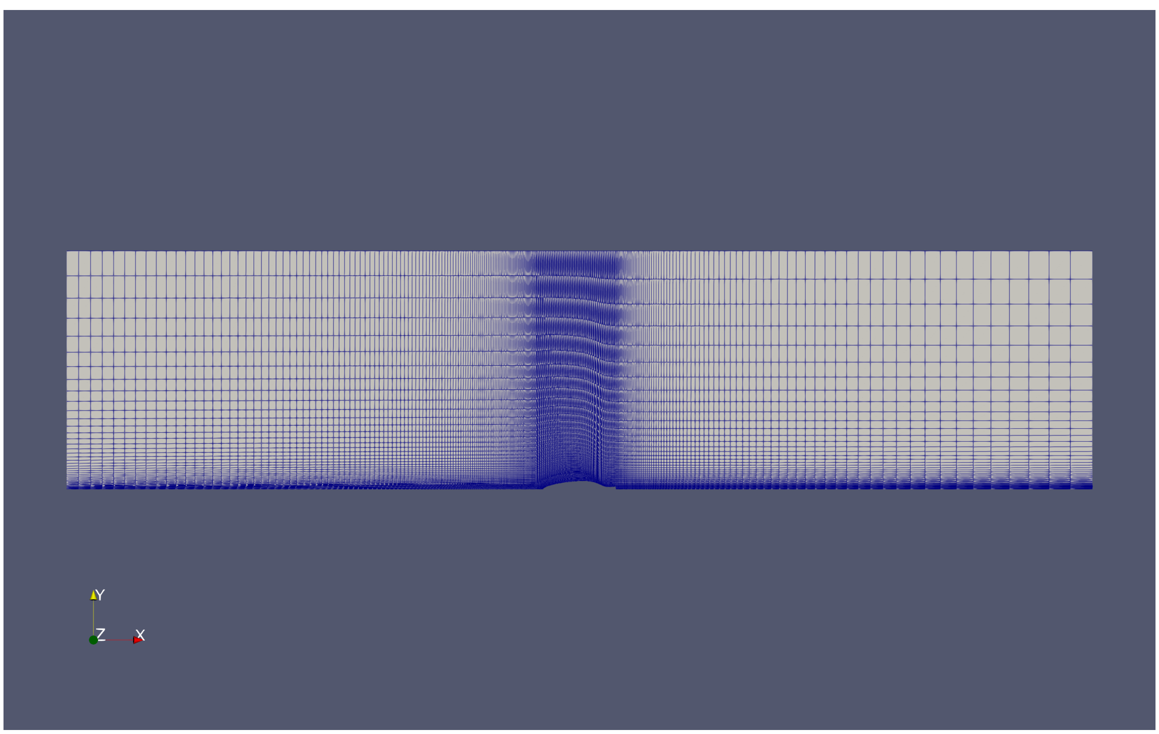
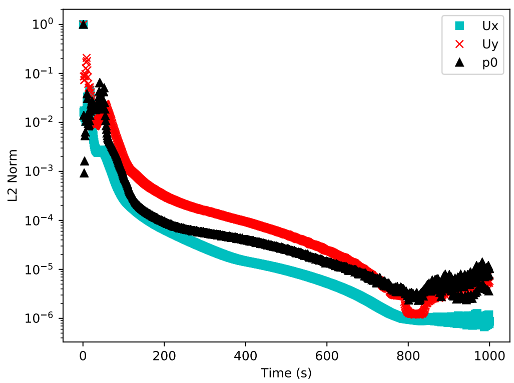
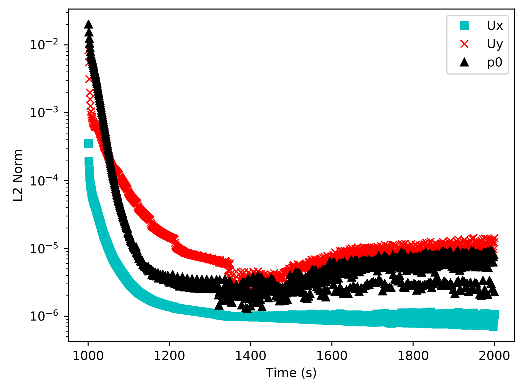


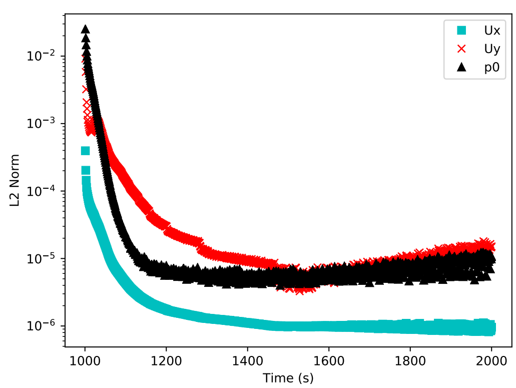
Figure 1: Initial Coarse Grid using 23,600 cells, with two refined grids using a grid refinement of $r = 1.22$.



(a) Coarse Grid



(b) Medium Grid



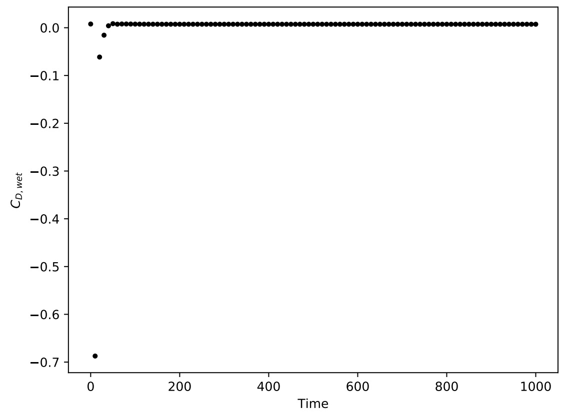
(c) Fine Grid

Figure 2: Convergence plots for all three grids for Reynolds number Re_L of 1.2×10^6

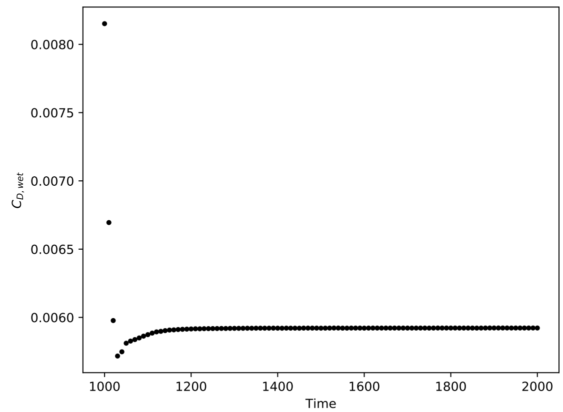
2 Validation and Verification

Figure 3 shows the drag coefficient based on wetted area $C_{D,wet}$ for the three grids using a Reynolds number Re_L of 1.2×10^6. All three grids gave an asymptotic or steady-state value for the drag coefficient, and so it is assumed that all three cases reached convergence. The drag coefficient plots for all the subsequent Reynolds numbers were similar, all reaching a steady-state value. The f values in Table 3 represent the steady-state drag coefficients for each grid, and f_{exact} is the value calculated using the Richardson extrapolation (see Equation 9. The p values calculated were quite high, over 6 in most cases, and over 8 for the $\mathrm{Re}_L = 4 \times 10^5$ case. This raises a little suspicion for the accuracy of the solution and the real verification of what the solver is approximating. The exact values and their corresponding error (calculated using $f_{exact}\,\mathrm{GCI}_f$) were plotted along with the free and fixed transition drag coefficient values measured are shown in Figure 4.

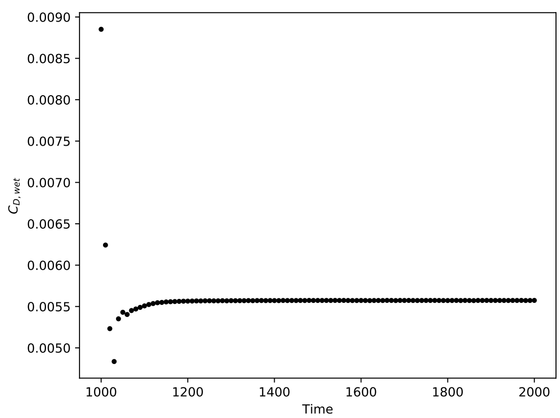
The fixed transition values were found when measuring the drag on the same body, except the boundary layer was tripped at $x/L = 0.17$. The free transition values had a transition point much farther down the body than the fixed transition values. The calculated values using **simpleFoam** matched the fixed transition values much better than the free transition values. This can be accounted for by recognizing that **simpleFoam** and the wall functions used assumed a turbulent boundary layer for the entire length of the body instead of transitioning from laminar to turbulent. Overall, the CFD simulations matched the fixed transition boundary layer much better than the free transition boundary layer due to the nature of how the software treats the boundary layers.



(a) Coarse Grid



(b) Medium Grid



(c) Fine Grid

Figure 3: Drag Convergence based on wetted area $C_{D,wet}$ versus iterations for all three grids.

$$\varepsilon = \frac{f_2 - f_1}{f_1} \tag{5}$$

$$p = \frac{\ln\left(\frac{f_3 - f_2}{f_2 - f_1}\right)}{\ln r} \tag{6}$$

$$\mathrm{GCI}_f = F_s \frac{\varepsilon}{r^p - 1} \tag{7}$$

$$\mathrm{GCI}_c = F_s \frac{\varepsilon r^p}{r^p - 1} \tag{8}$$

$$f_{exact} = f_1 + \frac{f_1 - f_2}{r^p - 1} \tag{9}$$

Table 3: Validation and Verification calculations for drag coefficients based on wetted area $C_{D,wet}$ for the three different grids using a grid refinement ratio of $r = 1.22$

Re_L	1.2×10^6	1×10^6	8×10^5	6×10^5	4×10^5
f_3	7.325e-03	7.345e-03	7.403e-03	7.557e-03	7.879e-03
f_2	5.922e-03	6.107e-03	6.365e-03	6.749e-03	7.376e-03
f_1	5.573e-03	5.792e-03	6.088e-03	6.521e-03	7.283e-03
p	6.99	6.89	6.63	6.36	8.46
ε	6.268e-02	5.436e-02	4.563e-02	3.496e-02	1.282e-02
GCI_c	1.043e-01	9.112e-02	7.789e-02	6.087e-02	1.968e-02
GCI_f	2.598e-02	2.317e-02	2.086e-02	1.717e-02	3.659e-03
f_{exact}	5.457e-03	5.685e-03	5.986e-03	6.432e-03	7.262e-03

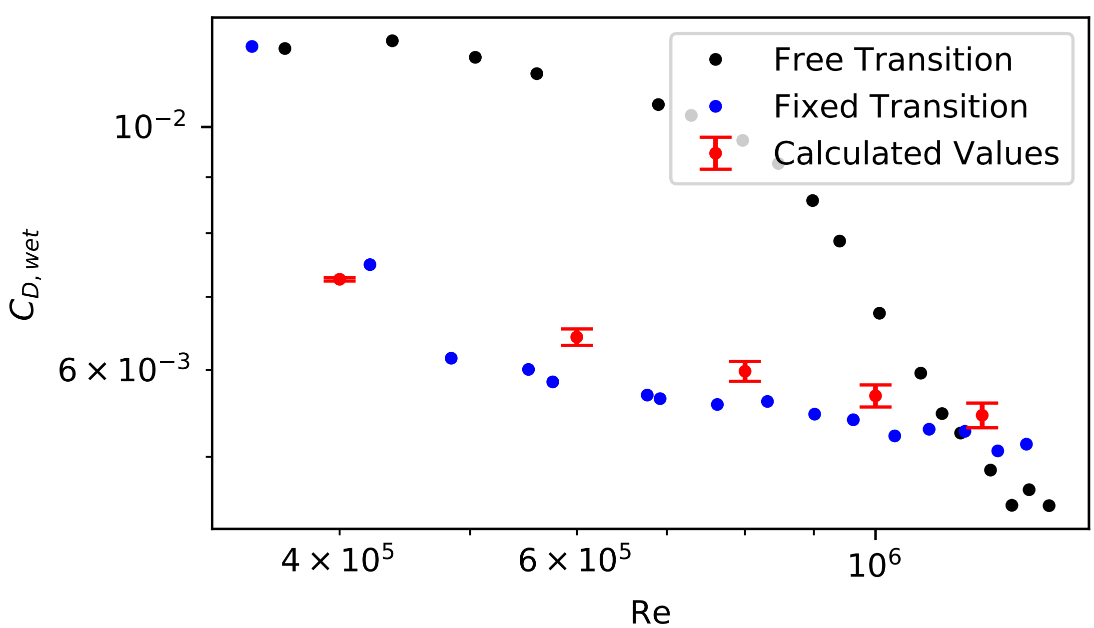


Figure 4: Drag Coefficient Based on Wetted Area $C_{D,wet}$ versus Reynolds number Re_L.