Computational Fluid Dynamics Simulation of a Cylinder In Cross Flow

ME 541

March 25, 2024

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Tutorials

- Part of Dr. Ning's Incompressible Inviscid 2D Aerodynamic Simulation with StarCCM+
- Part of Dr. Ning's Incompressible Viscous 2D Aerodynamic Simulation with StarCCM+
- Part of Solution Recording and Playback: Vortex Shedding (Under Incompressible Flow on StarCCM+, this is a cylinder in unsteady cross flow)

Future Tutorials

- Adjoint Flow Solver: Wing Shape Optimization
- Simulation Operations: S-Bend Shape Optimization
- Multiphase flow: VOF: Tank Sloshing with Adaptive Meshing
- Motion: DFBI: Boat in Head Waves

Setup

It was desired to explore laminar flow over a cylinder at a Reynolds number of 20 and capture the unsteady effects. A cylinder diameter of 0.01m was arbitrarily chosen, and air was the fluid of choice. Using standard values of air, the freestream velocity was calculated to be approximately 0.313 m/s. Using a y+ value of 1 and following the method laid out in the Aerodynamics textbook by Dr. Ning[1] and using the laminar Blasius equations, it was found that the prism layer (boundary layer) thickness was approximately 0.00385m and only 3 (2.63) prism layers were needed. Knowing that in the author's past CFD simulations there have been many more prism layers, a safety factor of 10 was chosen and 26 prism layers were used. Following trial and error and discussion with Dr. Gorrell it was decided to reduce the prism layer total height to 0.0015m. This decision came due to issues in the convergence study, although it was found that constant density, instead of ideal gas, was used in the physics model, so it is likely that the original prism layer height, though large, would have been okay. The Implicit Unsteady, Partitioning, and Coupled Implicit solvers were used following a StarCCM+ tutorial[2].

Time Step Convergence

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[1] Ning, A. , Computational Aerodynamics, 2024, BYU, Section 7.1 "Sizing the Prism Layer Mesh"

[2] Solution Recording and Playback: Vortex Shedding (Under Incompressible Flow on StarCCM+)

As this was an unsteady simulation, it was necessary to verify that the solution converges in the time domain. The mesh was kept standard and the time step size was varied. Convergence of the coefficient of drag (the study's metric of interest) was achieved to less than 1%. Figure 1 shows the time step convergence plot as well as the Richardson Extrapolation estimation based off of the last four time steps studied. Each simulation was run for 15 seconds (largely steady state) and the value recorded and compared. All time steps studied, from 0.08 seconds to 0.05 seconds, were withing 0.1% of the Richardson Extrapolation value. To balance computational thoroughness with efficiency a time step of 0.4 seconds was chosen for the full simulation (although a smaller step size was chosen for the very unsteady portion, see the Results discussion). This time step size is less than 0.01% different than the Richardson Extrapolation value.

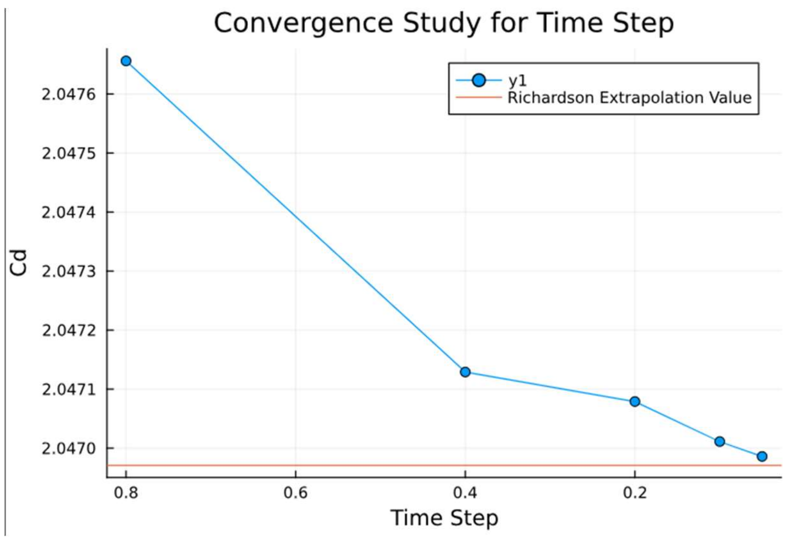

Figure 1: Time step convergence study showing the five points tested and their associated Coefficient of Drag.

<u>Grid Convergence</u>

For the convergence study the time step and grid (or mesh) can be thought of as independent. Thus, for computational efficiency, a time step of 0.5 seconds was chosen, and each grid (chosen by base size) was run for 30 seconds. Convergence was reached to less than 1%. Richardson Extrapolation could not be performed on the grid convergence study. It is assumed that this is because the relationship between the mesh base size and the number of cells or the coefficient of drag is non-linear or violates some assumption of the Richardson Extrapolation. Figure 2 shows the unusual behavior that was seen as the base size decreased. It can be seen that as the base size decreased the Coefficient of Drag seemed to drive towards a lower value, however at a base size of 0.005m and 0.0025m the coefficient of drag increased. While this appears to show that the mesh did not converge on a solution, a comparison of each solution to the finest mesh size shows convergence to less than 1% for all base sizes. A base size of 0.01m was chosen for the grid, which is closer than 0.3% to the finest base size value, as well as within about 0.3% of the average of all of the base size values. It should be noted that larger base sizes are closer to the finest mesh value (as can be seen on Figure 2) than the chosen 0.01m base size, however this was chosen to balance accuracy and efficiency as well as rule out any unseen errors that may have come from larger base sizes.

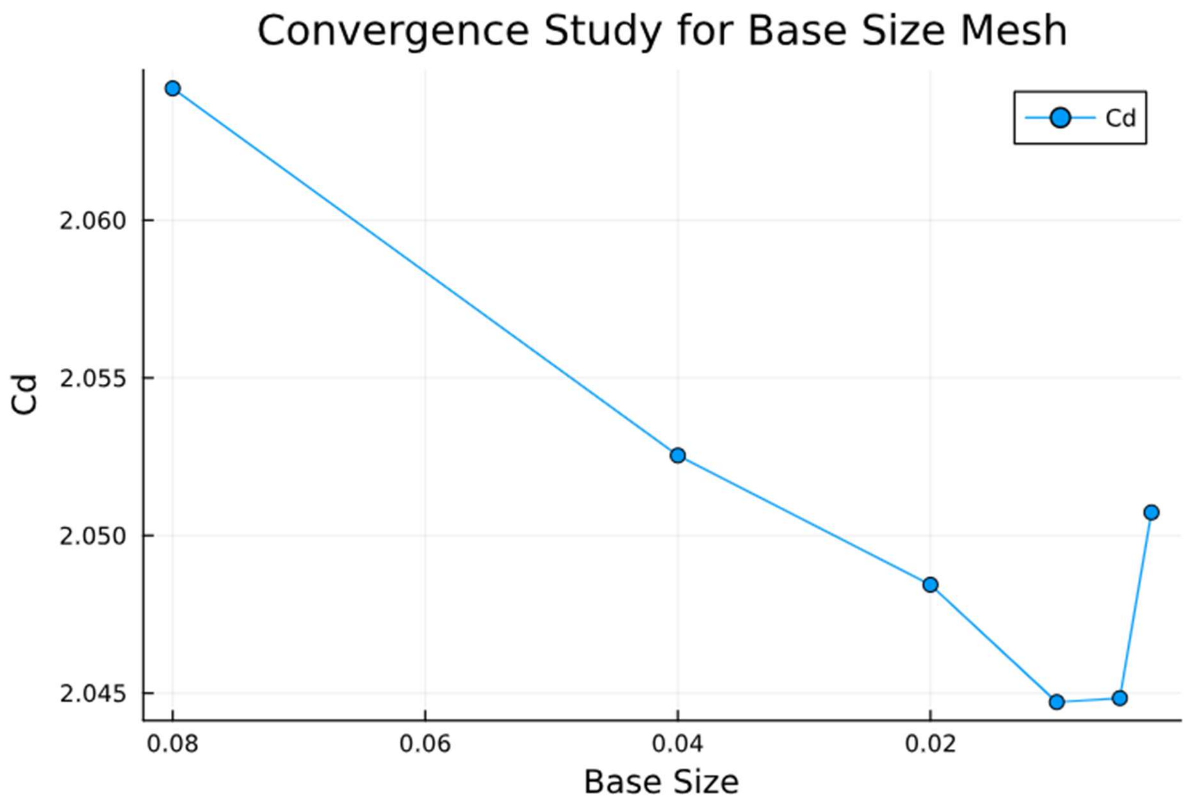

Figure 2: Mesh convergence study results based off of the base size for the mesh.

The resulting grid had 51970 cells and can be seen in Figure 3. As the resolution and development of the cylinder wake is closely related to coefficient of drag and thus convergence, the wake was refined significantly to 1.0m, or 100 diameters behind the cylinder. The overall grid was spaced with 40 diameters to either side of the cylinder, 25 diameters ahead, and 100 diameters behind the cylinder. To show that the spacing around the cylinder is adequate for a good solution, the simulation was run until steady state, whereupon the velocity contour was visually inspected to ensure that there was no gradient close to either the front or side boundaries. This result is satisfactory and can be seen in Figure 4. Verification is discussed in the last section.

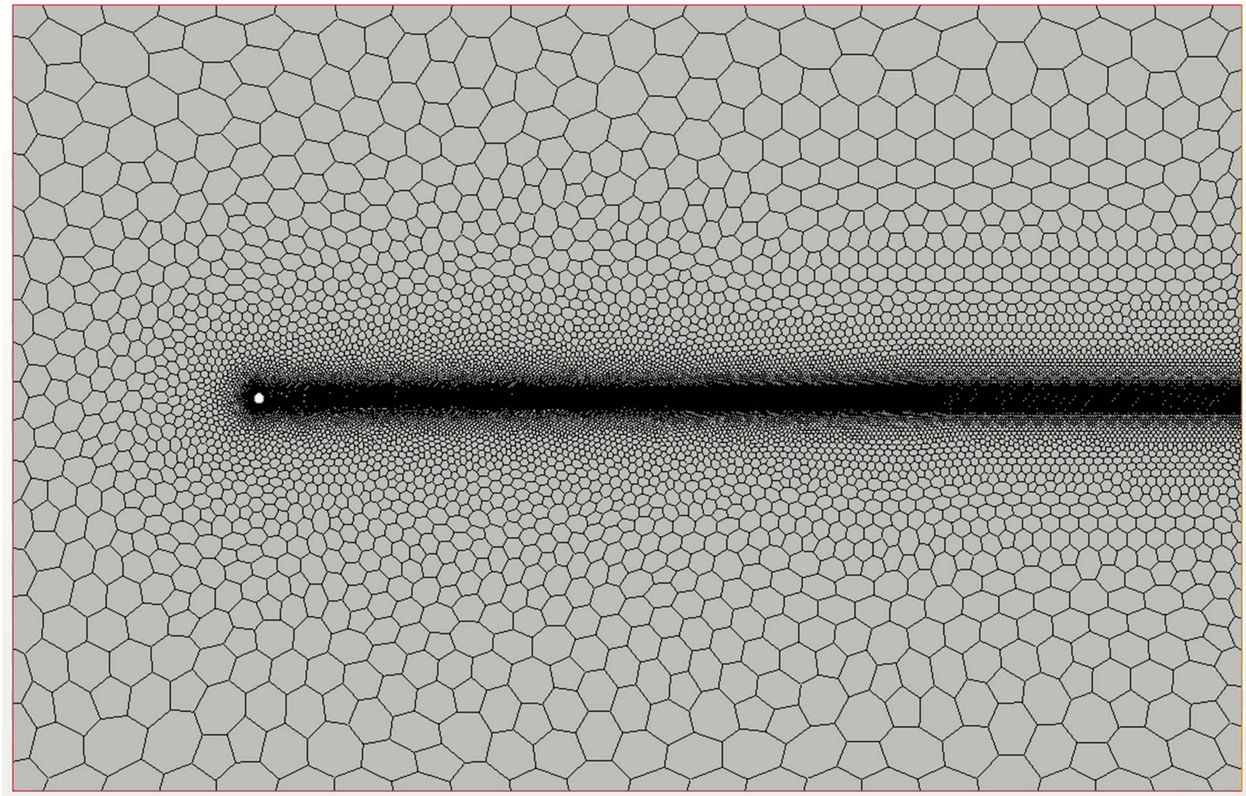

Figure 3: The final mesh with a base size of 0.01m (or one diameter) and 26 prism layers

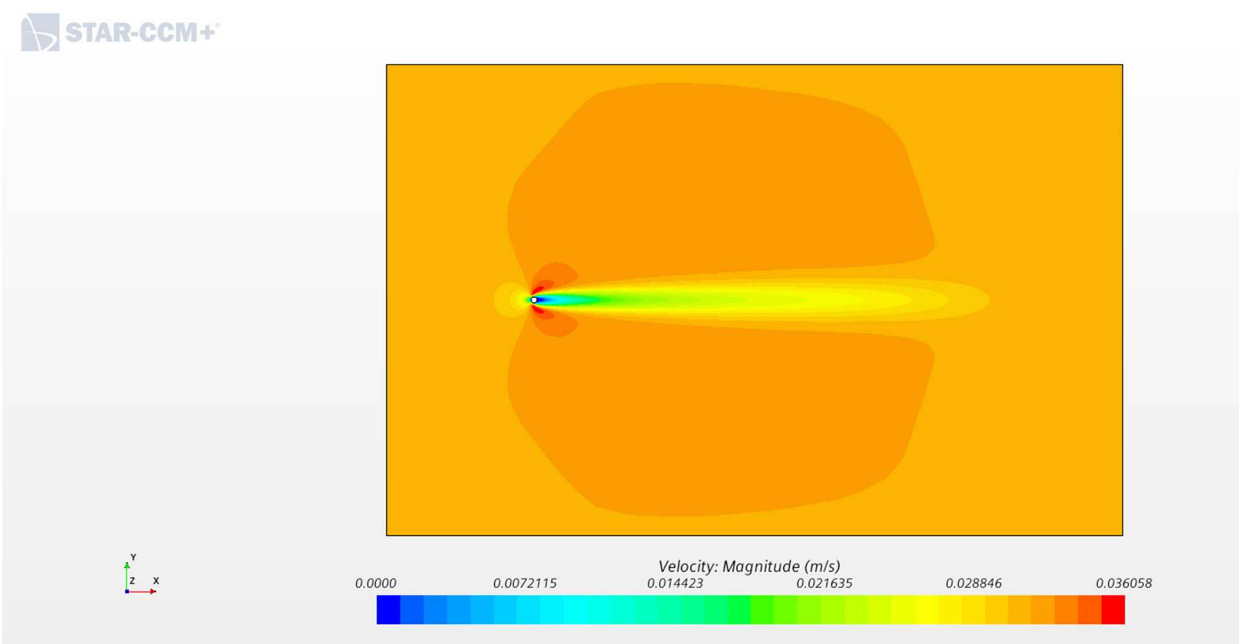

Figure 4: The velocity gradient after 25.6 seconds when fully steady state.

Results and Discussion

Drag Coefficient Over Time

The simulation was run with a 0.01m base size mesh and a time step of 0.4 seconds as was discussed above. It was run for 25.6 seconds until the coefficient of drag had reached steady state as well as the velocity and vorticity profiles as discussed below. The simulation reached a final coefficient of drag of 2.045. Figure 5 shows the Coefficient of Drag (Cd) over time with the y axis limits shortened so as to better show the convergence of Cd. There are dramatic unsteady affects until approximately 2 seconds, and then the coefficient of drag decreases quickly until about 5 seconds and then slowly decreases until leveling out around 20-25 seconds.

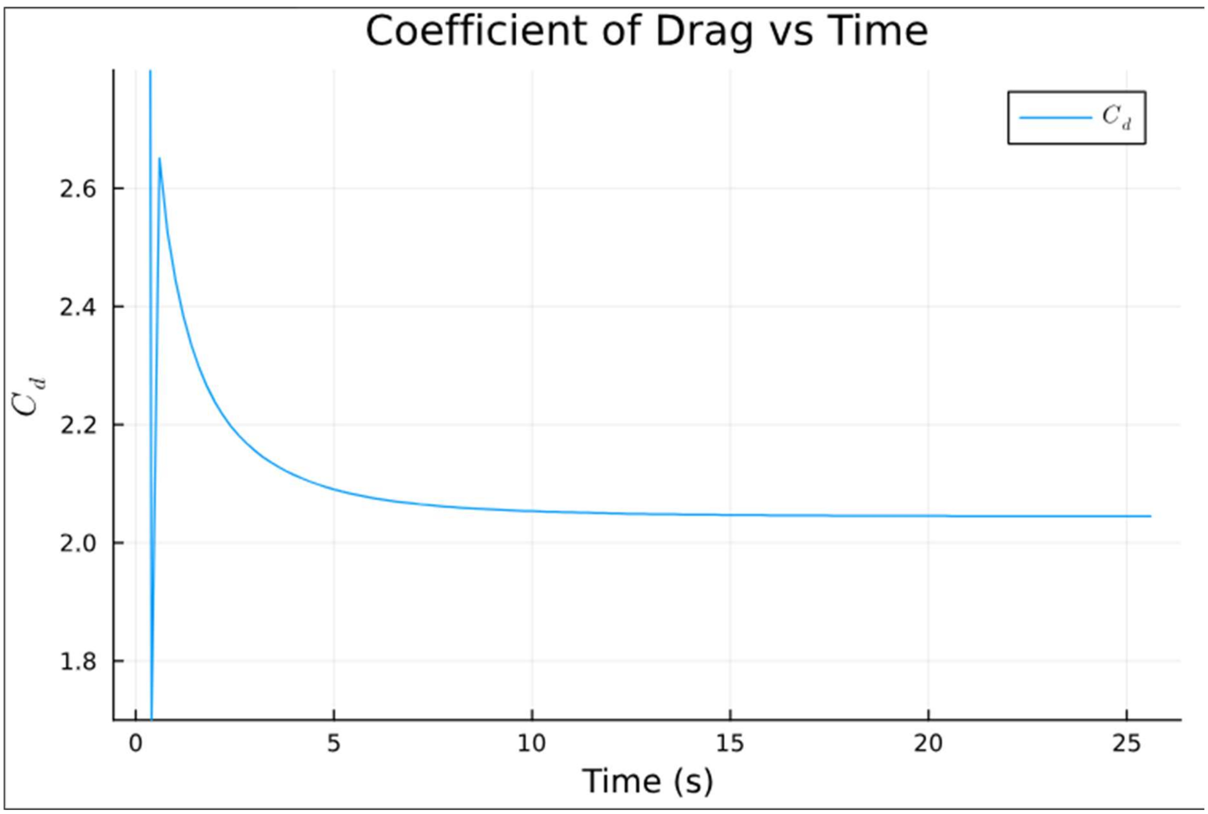

Figure 5: The coefficient of drag over time with the simulation settings discussed above.

In order to better understand the unsteady behavior of both the wake and the simulation solution the time step was decreased to 0.005 seconds and the simulation was run for 2 seconds. The results of the finer time step can be seen in Figure 6, with only one very large initial oscillation that quickly decreases within two seconds. To better understand how the "unsteady" portion of the solution fits with the larger time step and solution in Figure 5, the data was overlayed as shown in Figure 7.

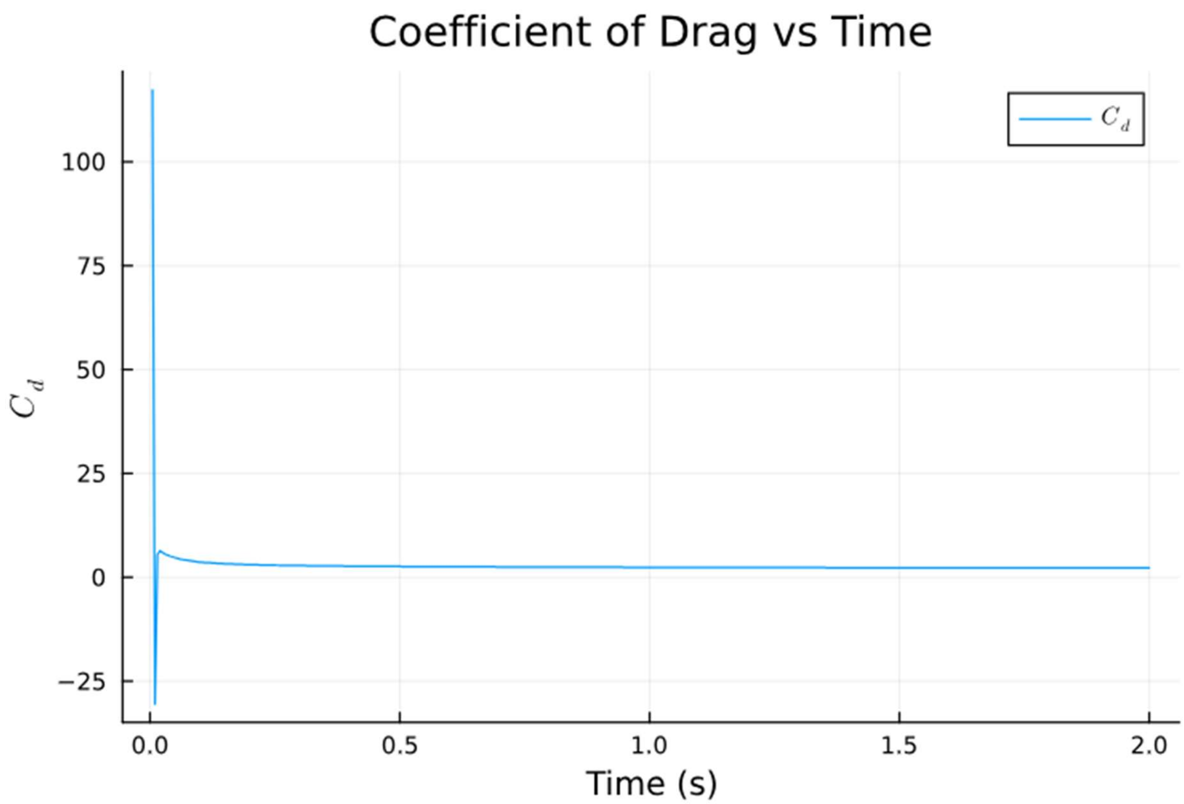

Figure 6: Unsteady portion of the coefficient of drag over time with a 0.005 second time step.

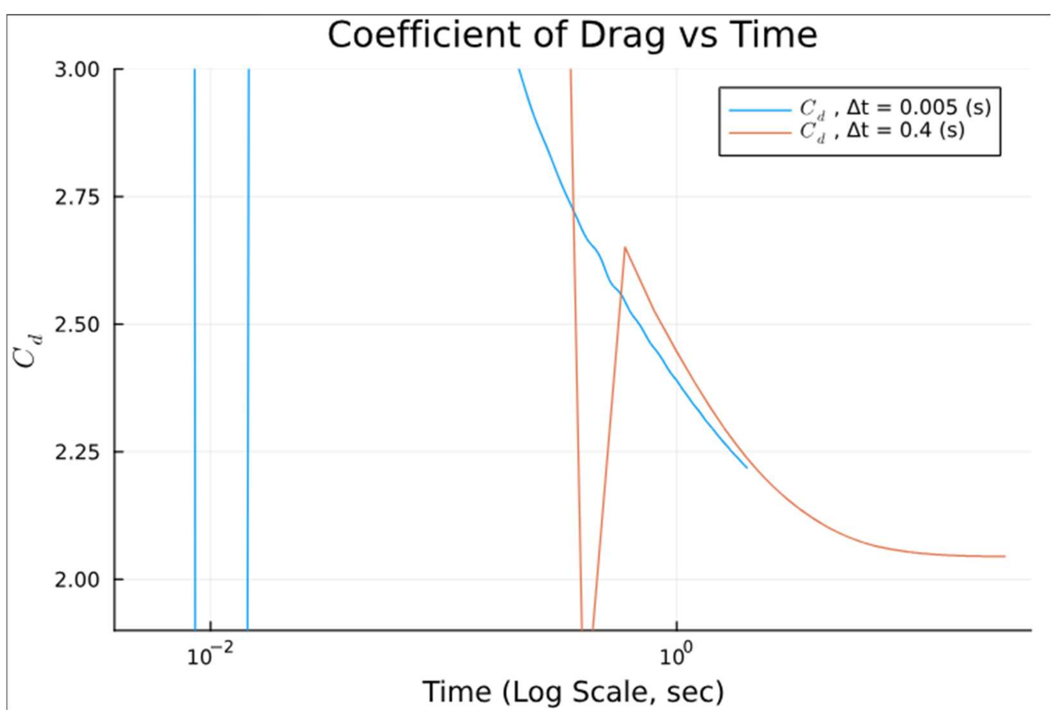

Figure 7: Combined small and large time step coefficient of drag. The small time step data ends very close to where the larger time step data continues after the jump.

It can be further seen in Figure 7 that the large oscillation is likely more of a numerical instability rather than a physical phenomenon as it occurs only once with both time steps, has a large amplitude but does not occur at the same time. In both cases it occurs within the first few time steps.

Velocity, Vorticity, and Pressure Development Over Time

As it takes several seconds for the coefficient of drag to steady, it is desirable to review the unsteady behavior of the flow. A large number of contour plots can be seen and compared in the appendix, for space and brevity only a few will be discussed here. It should be noted that the solution was initiated at the freestream velocity, 0.313 m/s, in all cells and then the simulation was run. At 0.4 seconds the velocity field around the cylinder is in the shape of a clover with higher velocities beginning to develop around the sides of the cylinder, see Figure 8. This is expected behavior as flow around the sides of a cylinder is expected to speed up. The wake deficit behind the cylinder is still quite small as well as the stagnation region in front of the cylinder. The pressure field at 0.4 seconds also appears similar, although a larger clover shape (plot in the appendix). The pressure is low on the sides of the cylinder and higher in front and behind as is expected. It should be noted that the pressure difference seems to propagate much further in the flow than the velocity difference does, although the gradient is very small.

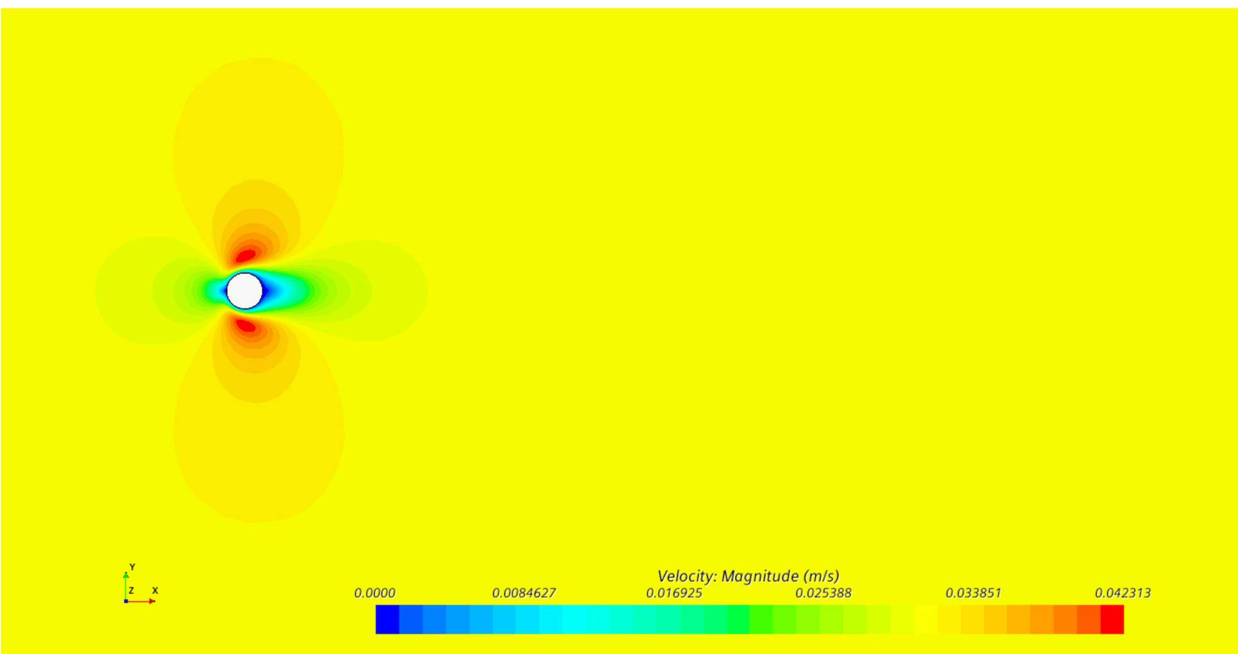

Figure 8: Velocity contour plot at 0.4 seconds.

At 0.4 seconds the vorticity (or particle rotation/spin) of the flow is just starting to grow as seen in Figure 9. The highest vorticity occurs closest to the mid front edge of the cylinder (about 46-60 degrees clockwise of the stagnation point) correlating to where the velocity is largest. It was surprising to see that the flow directly behind the cylinder is still at zero vorticity. This is likely because the wake is symmetrical and still not fully developed yet either, so the flow quickly returns to straightened out.

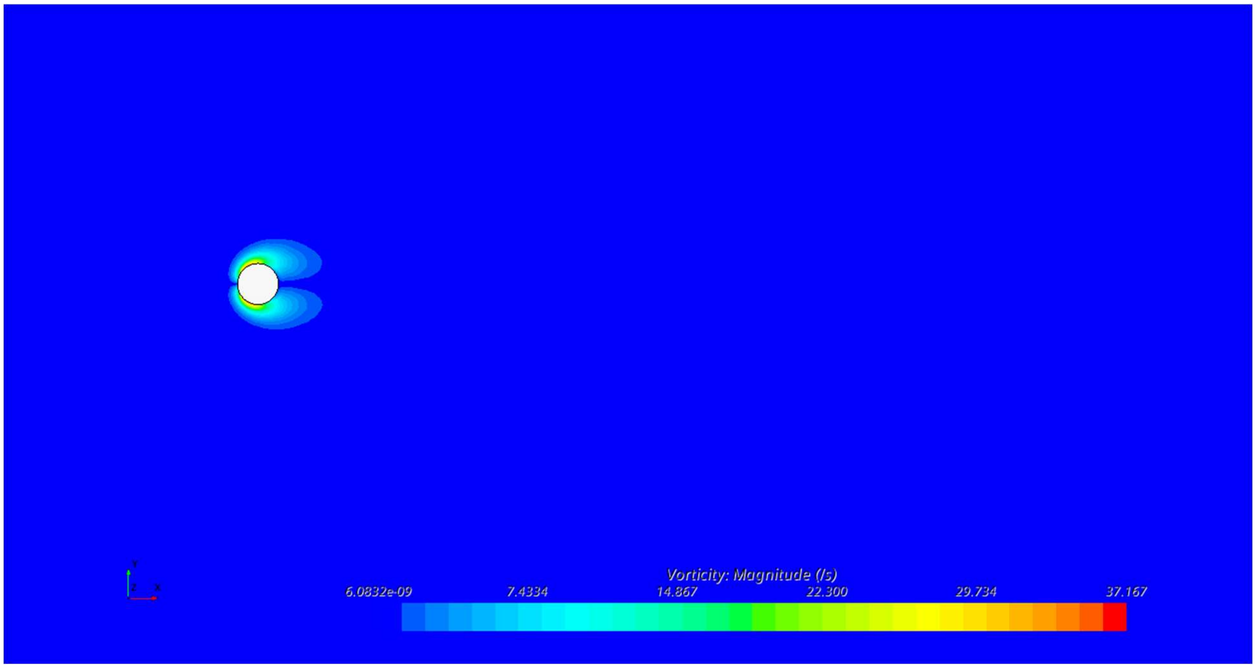

Figure 9: Vorticity plot at 0.04 seconds.

As the flow progresses to steady state at 25.6 seconds the velocity plot appears like a three leaf clover that is squashed and bent back until arriving at steady state as seen in Figure 10. There is a semi large wake deficit that begins to spread apart the further from the cylinder it gets (as expected due to turbulent mixing and breakdown). What was unexpected was the large portion of the flow that was accelerated (and or slowed down) at least slightly by the cylinder. A Reynolds number of 20 is very low, so the viscous forces play a large part in the flow behavior and thus the flow is accelerated in a large field around the cylinder, and a large half moon shape in front of the cylinder is slowed down. In contrast to the velocity field, the pressure field (seen in Figure 11) is quite consolidated, with most of the flow at atmospheric pressure and the flow on the sides and back of the cylinder at a lower pressure and high pressure at the front stagnation point.

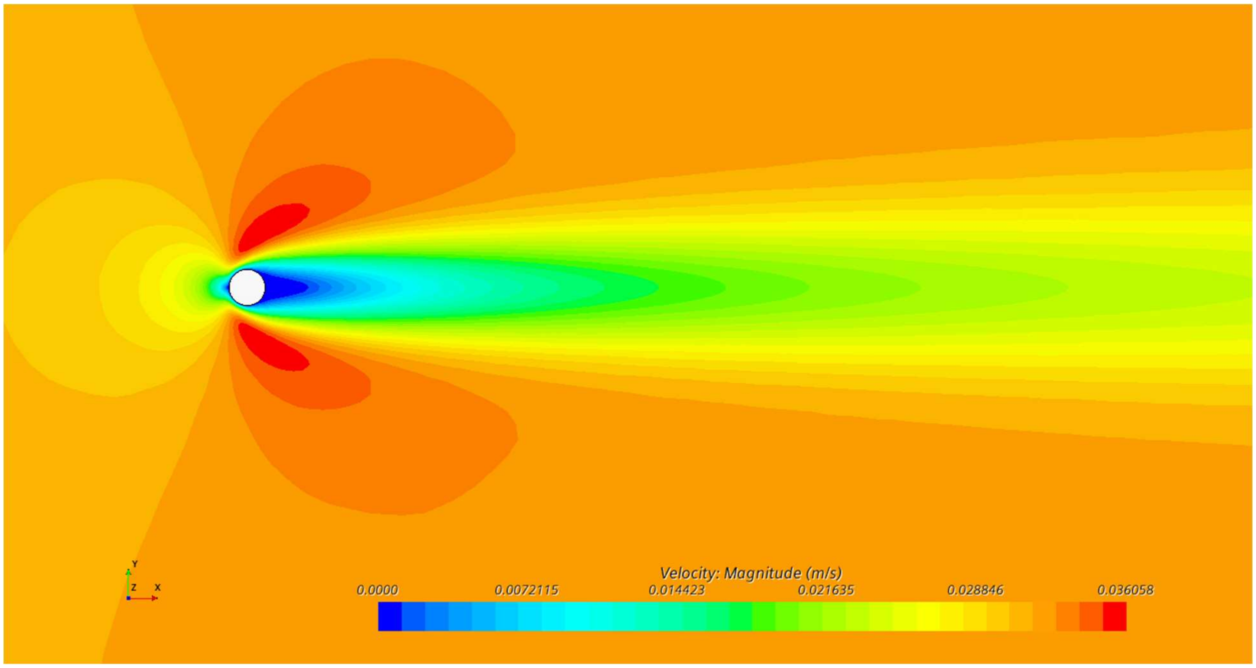

Figure 10: Velocity contour plot at steady state.

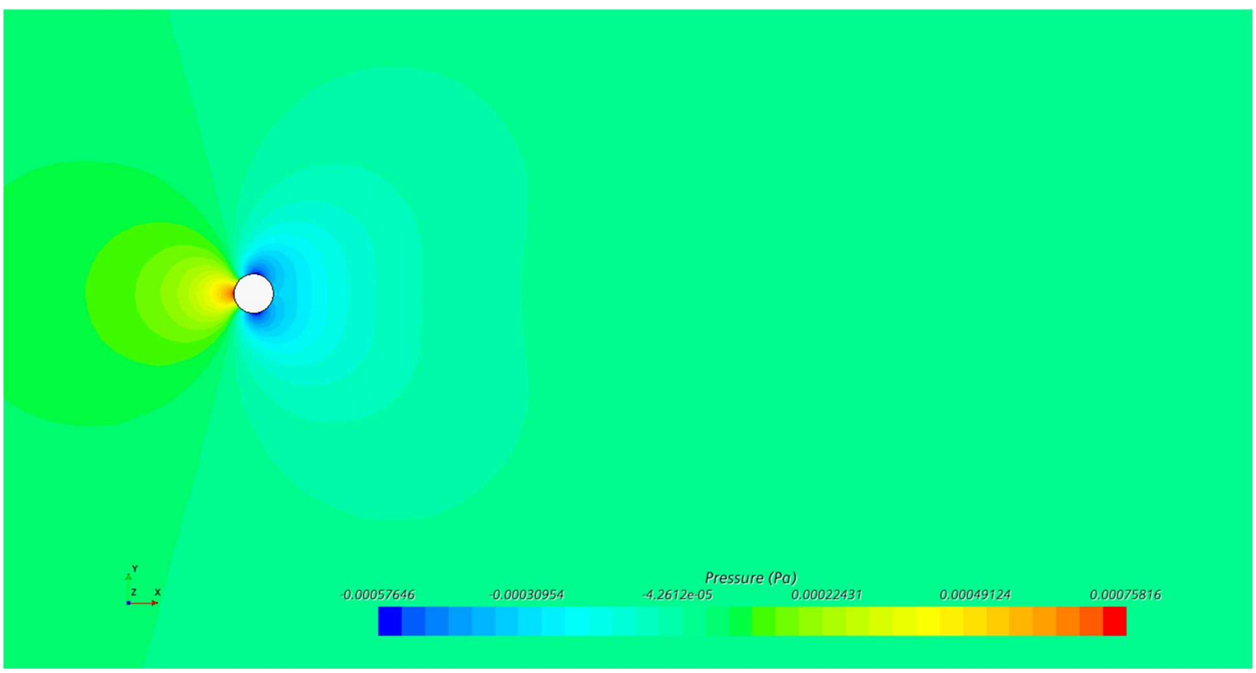

Figure 11: Pressure contour plot at steady state, 25.6 seconds.

The vorticity field is a similar shape to 0.4 seconds although quite elongated and grown slightly in width (as seen in the appendix). It surprising that a Karmen Vortex street doesn't form and/or that the vorticity doesn't propagate further behind the cylinder. This is also likely related to the low Reynolds number, the viscous effects of the flow are large enough to damp out a Karmen Vortex Street and large enough to dissipate the vorticity after 10 diameters. More in plots in between 0.4 seconds and steady state can be seen in the Appendix.

<u>Velocity and Vorticity Profiles Over Time</u>

The contour plots are helpful at understanding what is happening to the flow field as a whole. To better understand the specific profile of the velocity and vorticity fields over time a line probe was created one diameter (1 cm) behind the center of the cylinder and data recorded at the times shown in Figure 12 and 13. These profiles are another good confirmation of having achieved steady state. In Figure 12 there is very little change in the velocity profile between 12.8 seconds and 25.6 seconds. It can be seen that the wake directly behind the cylinder is not initially unmoving (0 m/s) due to the initial conditions of the mesh, however that quickly goes to zero. The portion close to the center of the cylinder wake is still moving faster than the freestream which is not what the author expected, then slows back down to the freestream speed the further from the cylinder wake it is. This shows that the portions of the flow that were sped up around the front edge of the cylinder actually stay that way for at least one diameter.

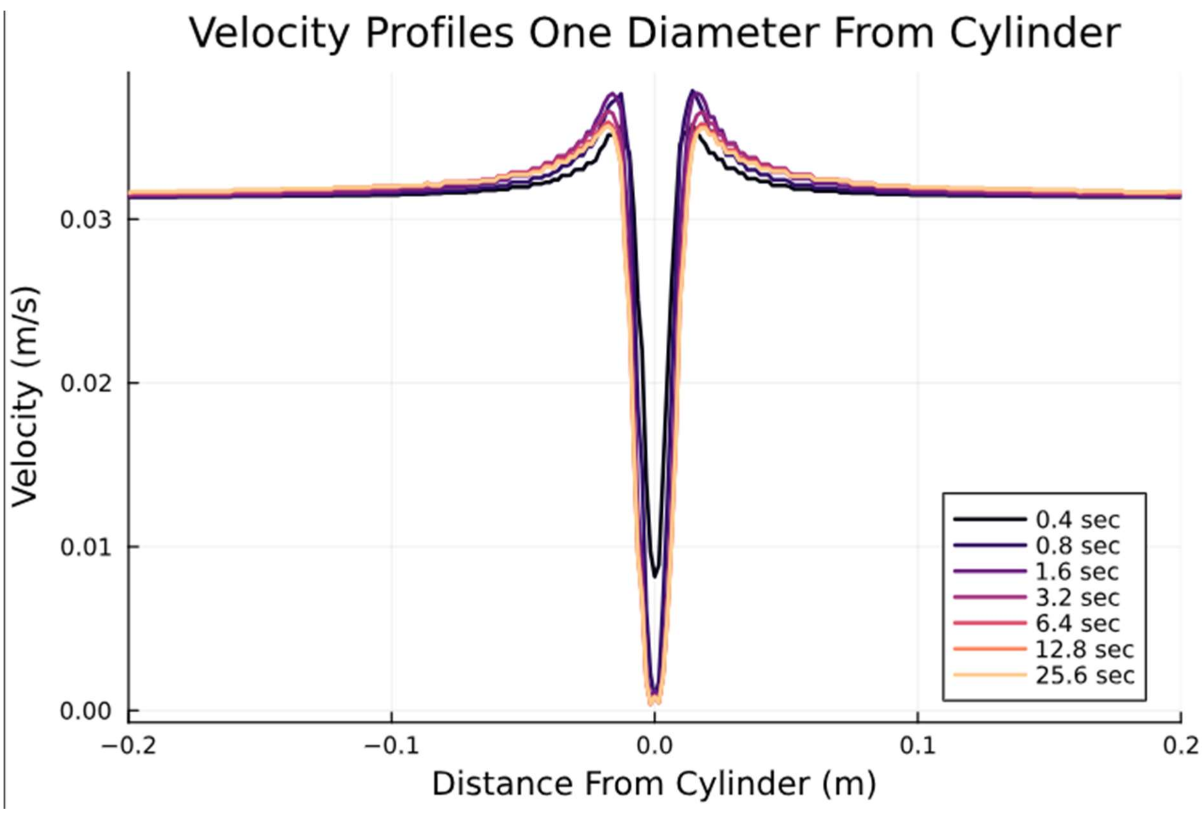

Figure 12: Velocity profile one diameter behind the cylinder over time. 0.0 is the center of the cylinder, and right and left on the plot is right and left of the center of the cylinder.

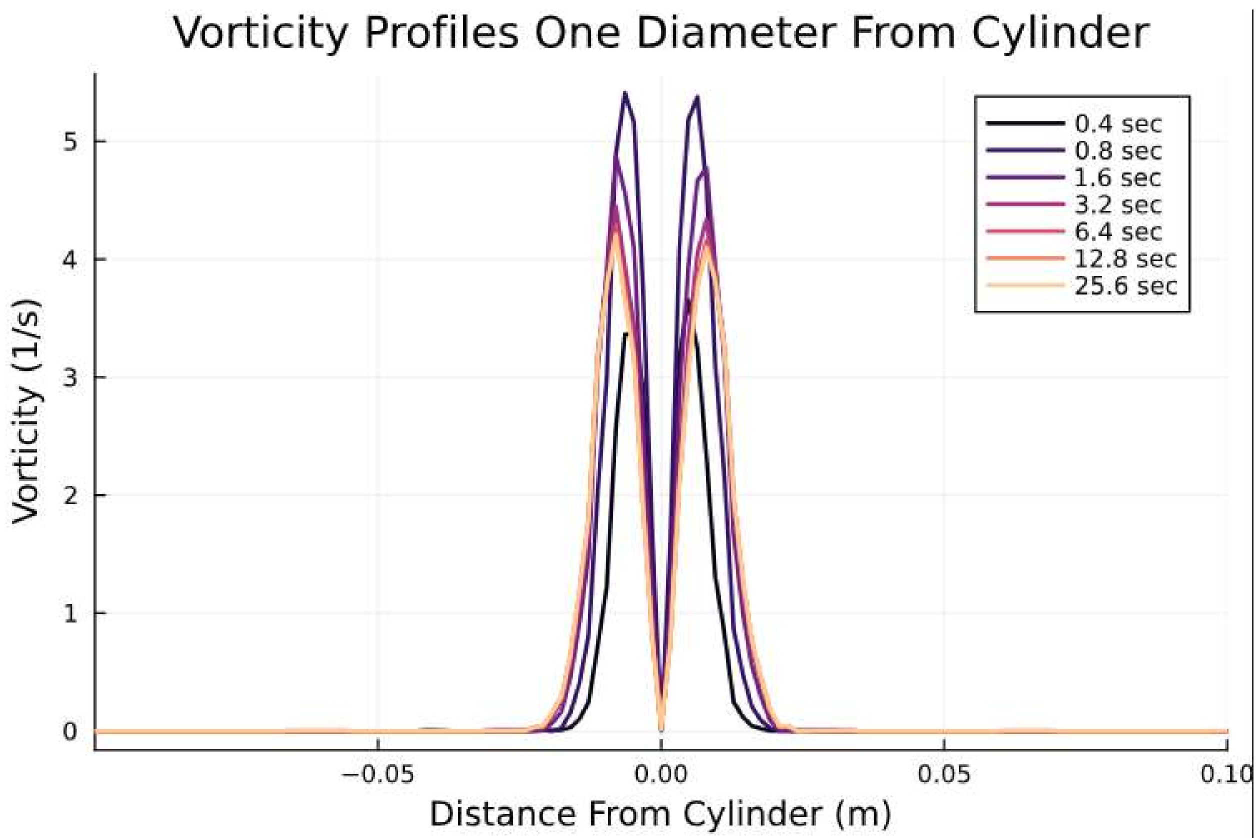

Figure 13: Vorticity profiles one diameter behind the center of the cylinder over time. 0.0 is the center of the cylinder and right and left on the plot is right and left of the center of the cylinder wake.

The Vorticity behind the cylinder does not just grow in magnitude or just decrease, but it appears to first increase and then decrease as time goes on and the flow develops. This was not seen in the contour plots due to not viewing the contour plots as often as the vorticity data was saved and/or a mistake in labeling the contour plots. The increasing and then decreasing of the vorticity must be an unsteady effect at low Reynolds numbers. As the flow begins vorticity increases which makes sense, as it begins to fully develop more flow around the cylinder is entrained and sped up causing the magnitude of the vorticity to stop growing and begin to decrease until reaching a steady value. It should be noted that while the magnitude of the vorticity went up and down, the width of the vorticity profile always grew. This makes sense as more and more of the flow would be entrained and begin to spin.

<u>Verification</u>

The final coefficient of drag found by the simulation was approximately 2.045. The author is used to coefficients of drag given by airfoils, which, when compared, make the coefficient of drag on the cylinder very large. The flow is at a low Reynolds number which leads to large skin friction drag, as well as pressure drag. Common Reynolds number versus Coefficient of Drag plots (both experimental and computational) place Cd of a cylinder in cross flow at a Reynolds number of 20 at approximately 2.0[3]. The vorticity plot/distribution and separation angle at steady state qualitatively appear to match the computational study done by Sen et al[4]. While values were not directly extracted and compared the combination of these two sources leads to confidence in the value of 2.045 as a viable coefficient of drag for a cylinder in unsteady Reynolds number 20 flow.

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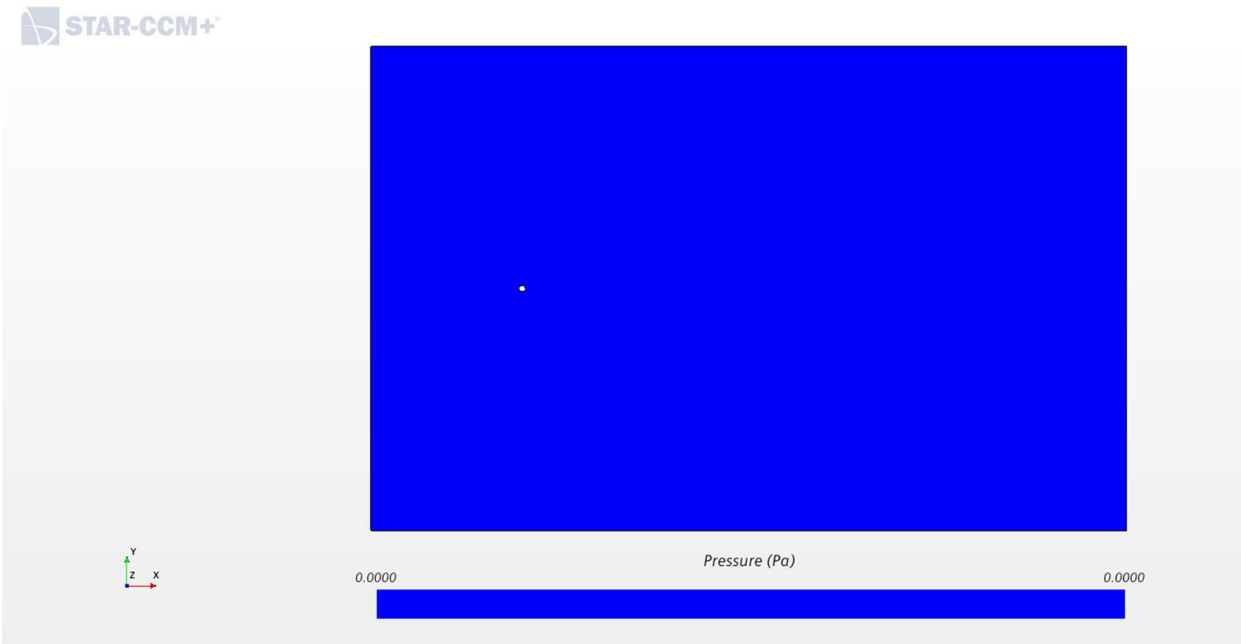
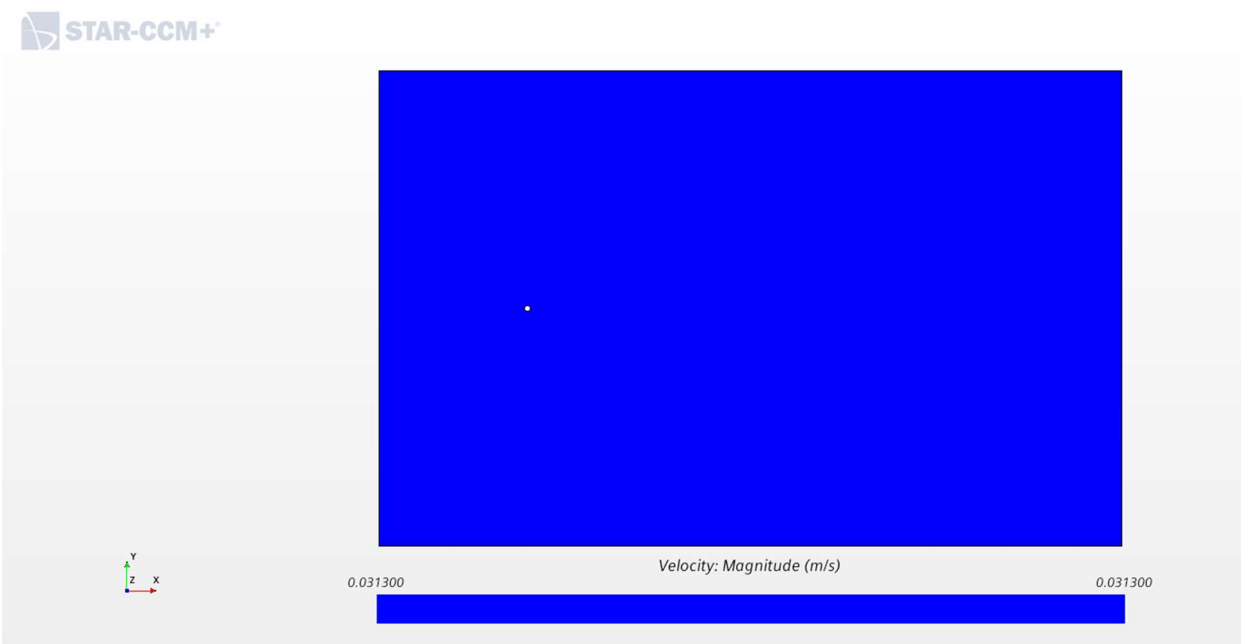
[3] See Mendez on ResearchGate, plot used by Florida State University, it should be noted that the Thor Fossen fluids textbook Cd vs Re for a cylinder plot seems to place Cd closer to 3-4, however it seems to be an outlier.
[4] Sen, Mittal, and Biswas, Steady separated flow past a circular cylinder at low Reynolds numbers, see Figures 9, 16 and 26.

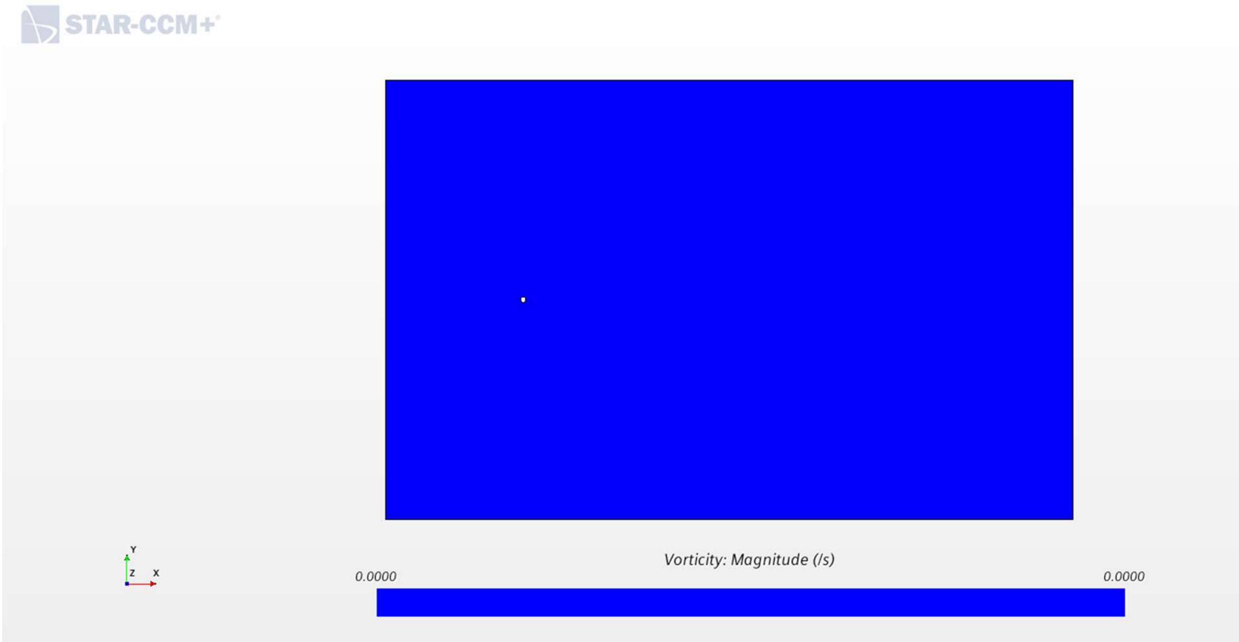
Appendix

Thanks to Dr. Gorrell for teaching and help debugging. Noah Cahill for help and advice, Thomas Andrews for wiggling the mouse and keeping the computer logged in when I left, and Christian Valencia for his help and validation of qualitative results.

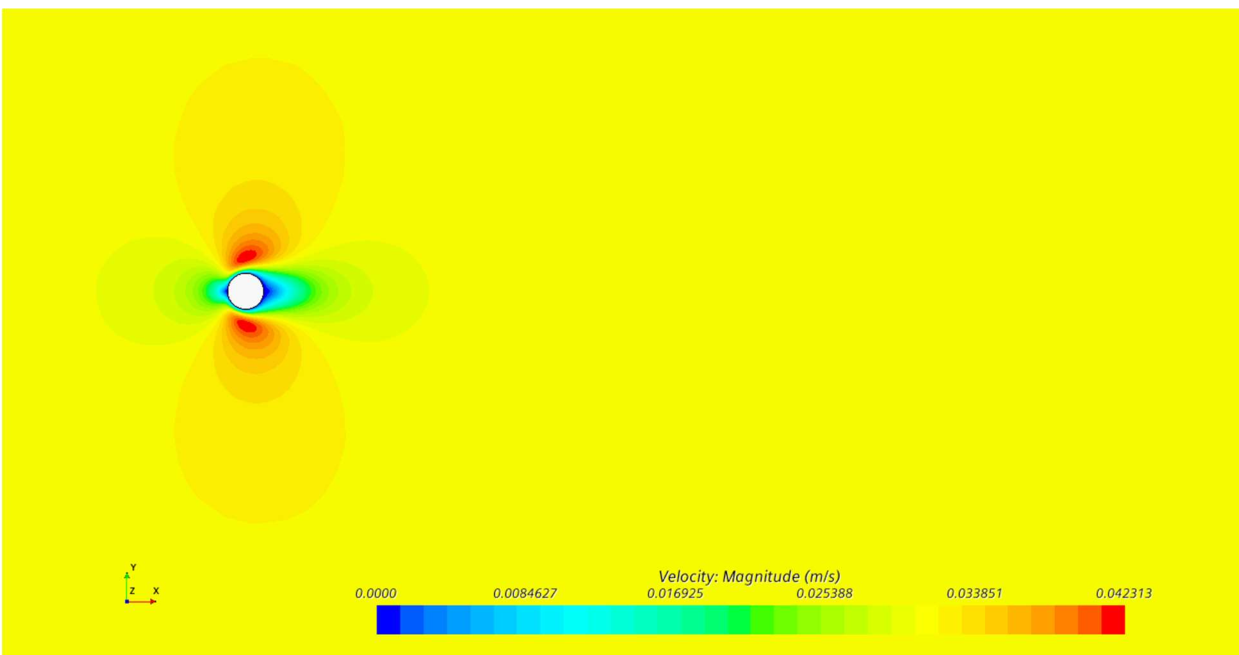
T=0






STAR-CCM+
Vorticity: Magnitude (/s)
0.0000
0.0000
Y
Z
X

0.4sec


Velocity: Magnitude (m/s)
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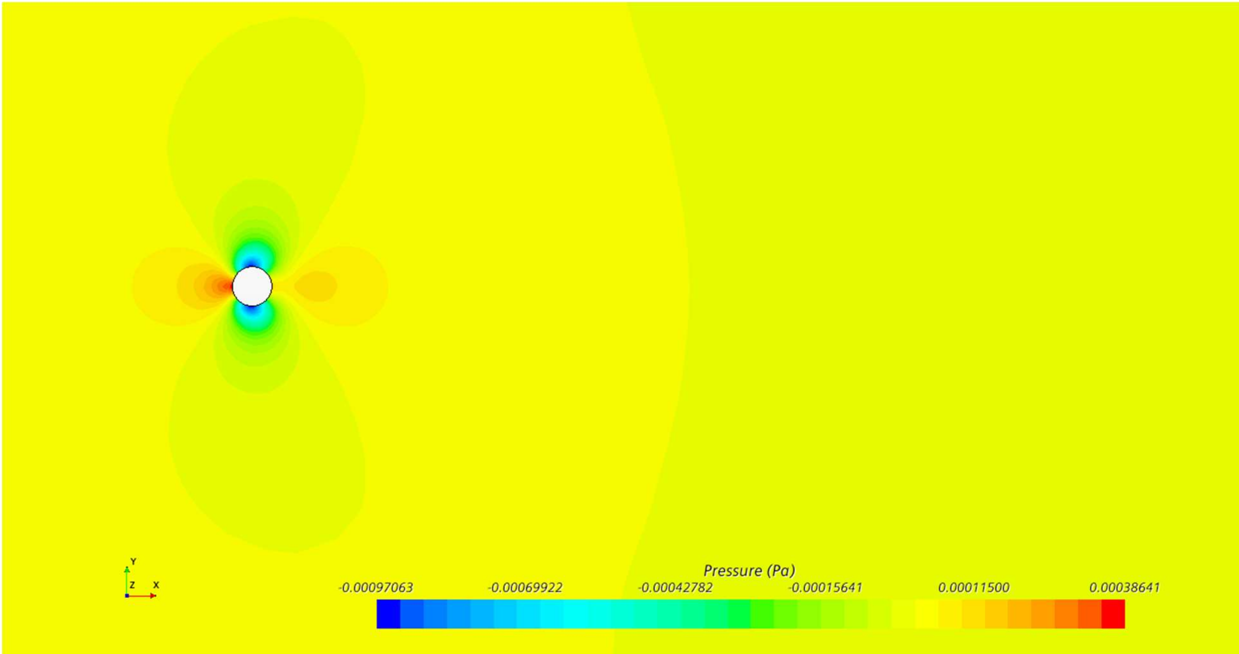
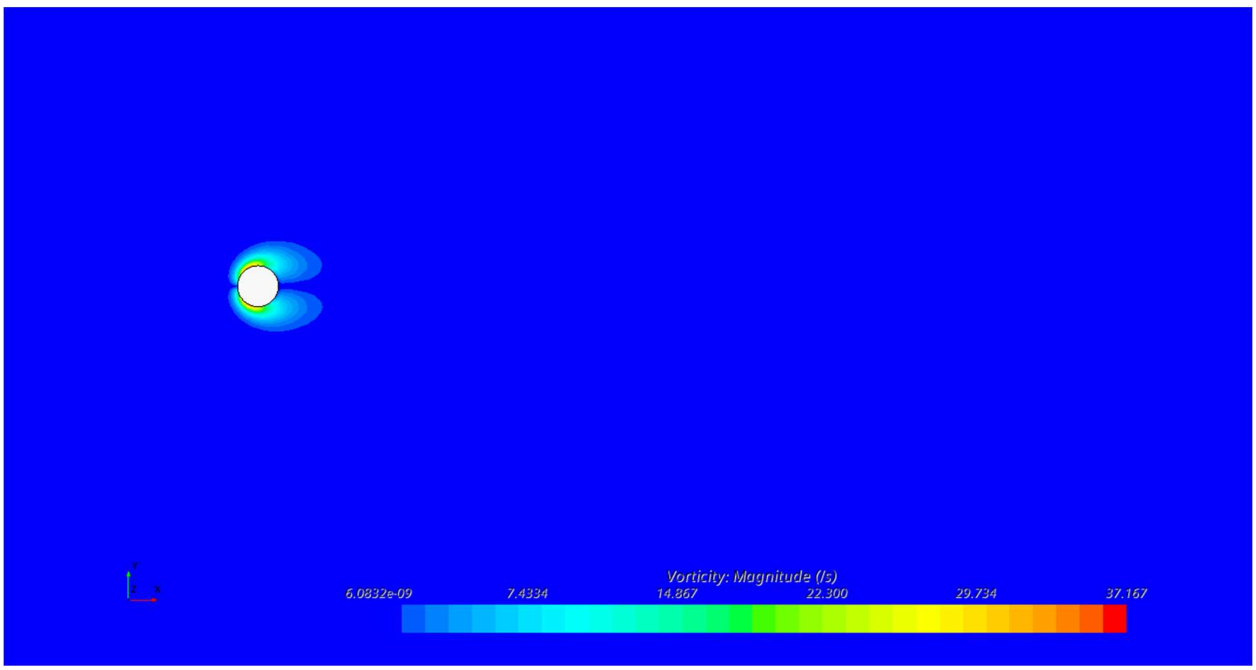
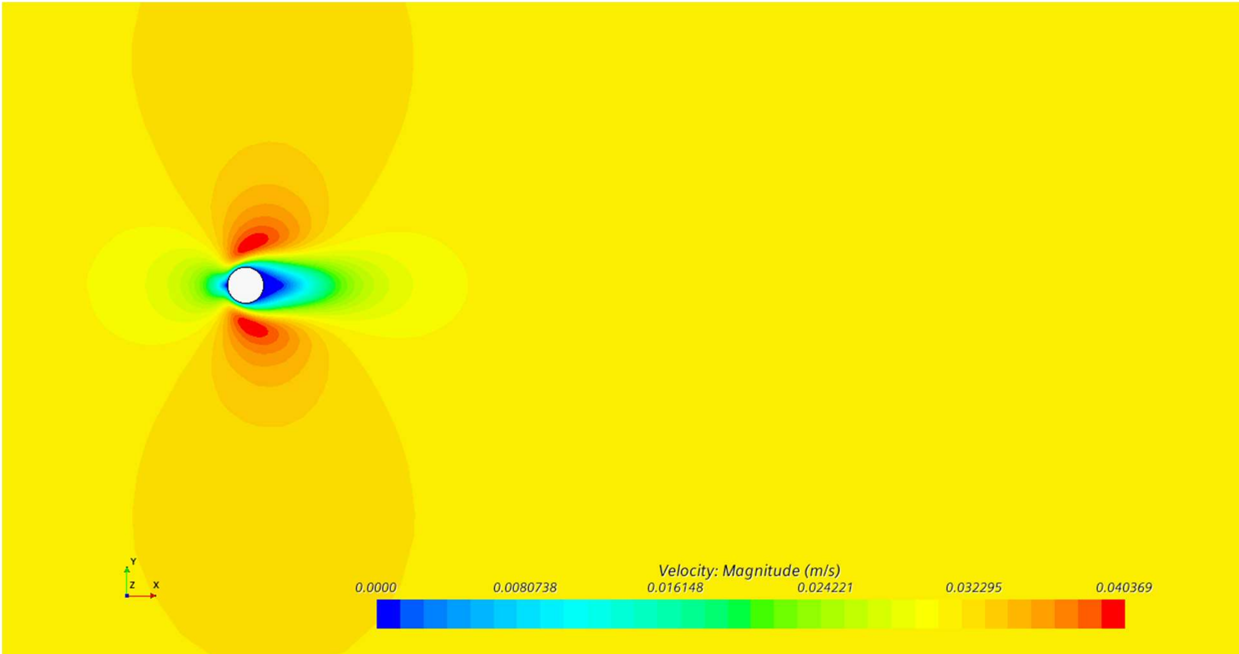
0.0084627
0.016925
0.025388
0.033851
0.042313
Y
Z
X


Y
Z X
Pressure (Pa)
-0.00097063 -0.00069922 -0.00042782 -0.00015641 0.00011500 0.00038641


Vorticity: Magnitude (/s)
6.0832e-09 7.4334 14.867 22.300 29.734 37.167

0.8sec


Velocity: Magnitude (m/s)
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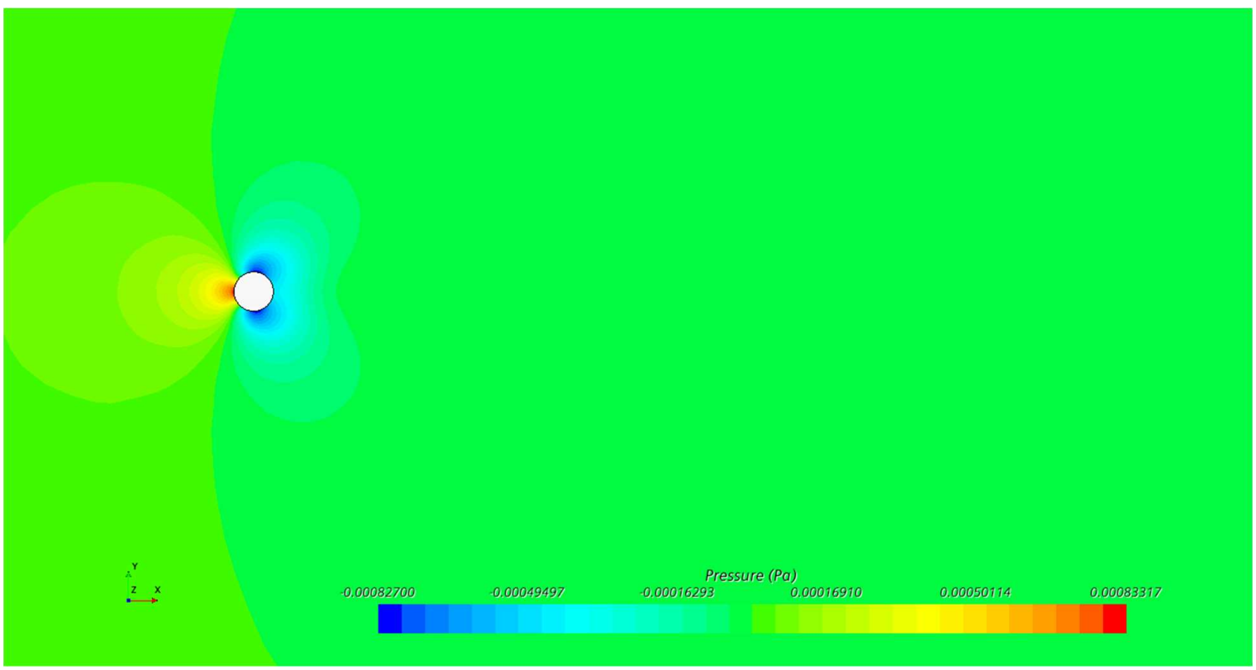
0.016148
0.024221
0.032295
0.040369
Y
Z
X


Pressure (Pa)
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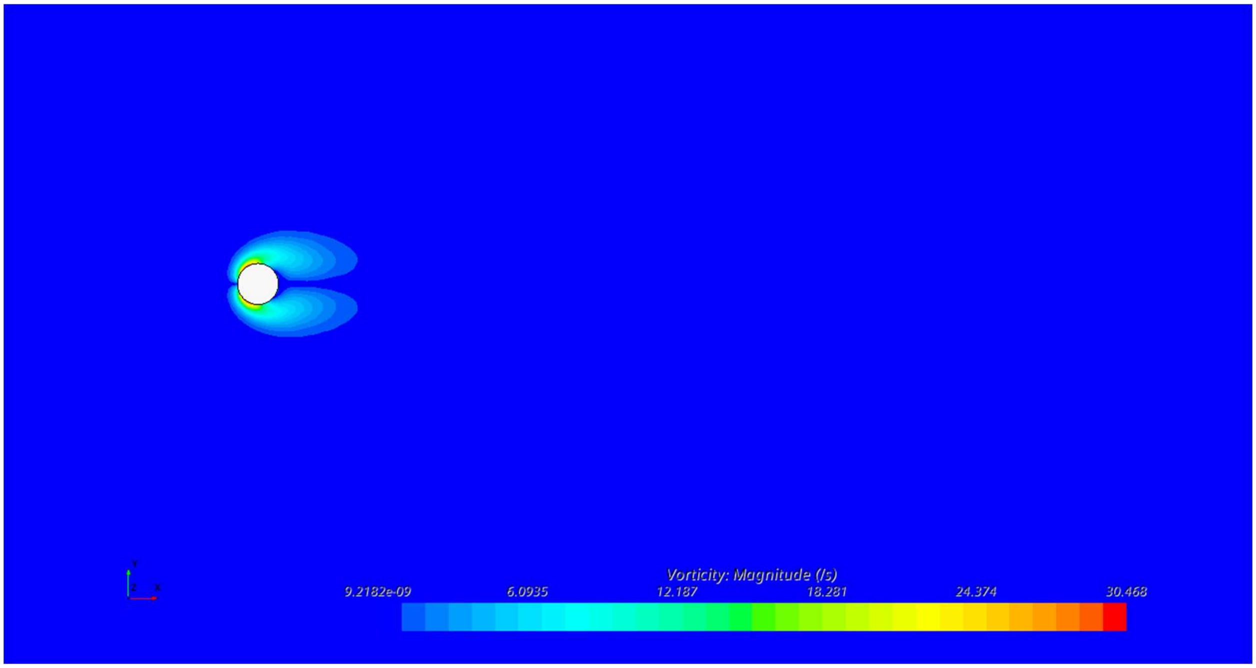
0.00016910
0.00050114
0.00083317
Y
Z
X



Vorticity: Magnitude (/s)
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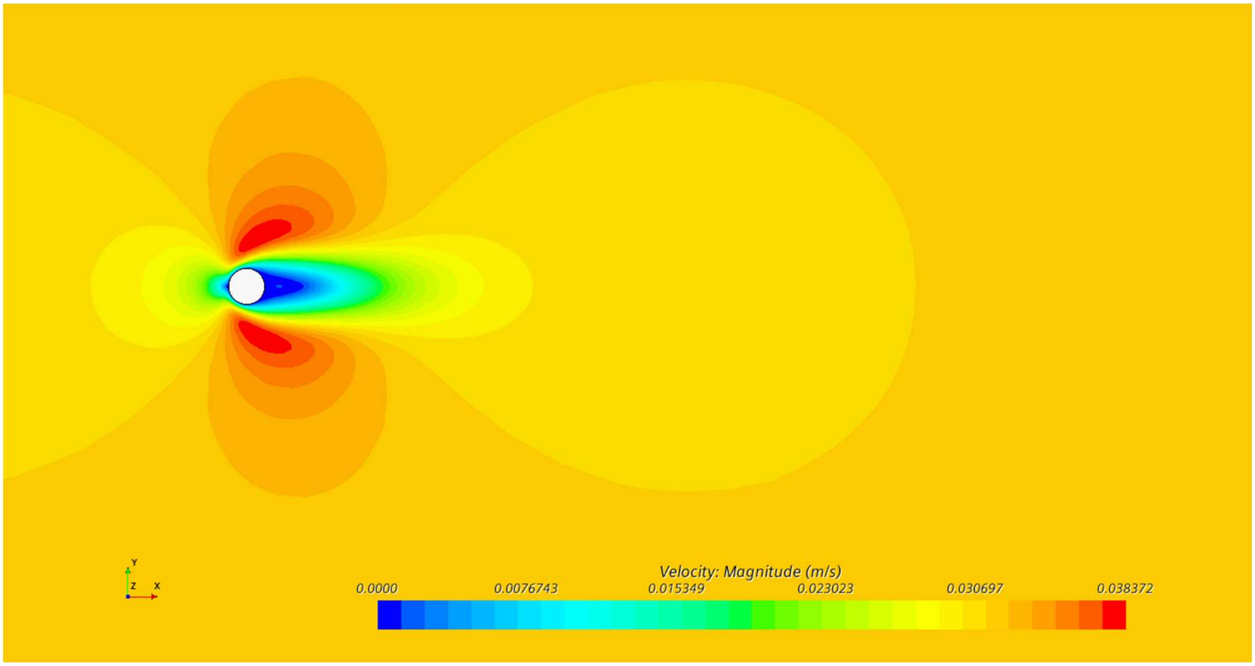
6.0935
12.187
18.281
24.374
30.468

1.6 sec



Velocity: Magnitude (m/s)
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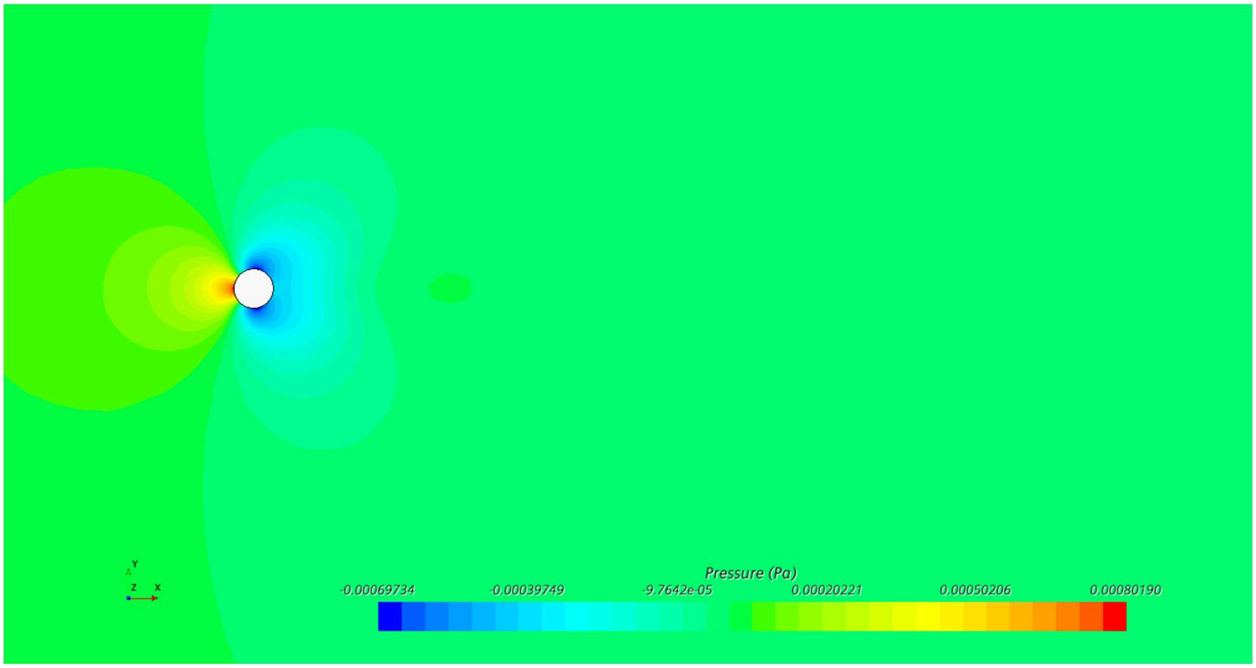
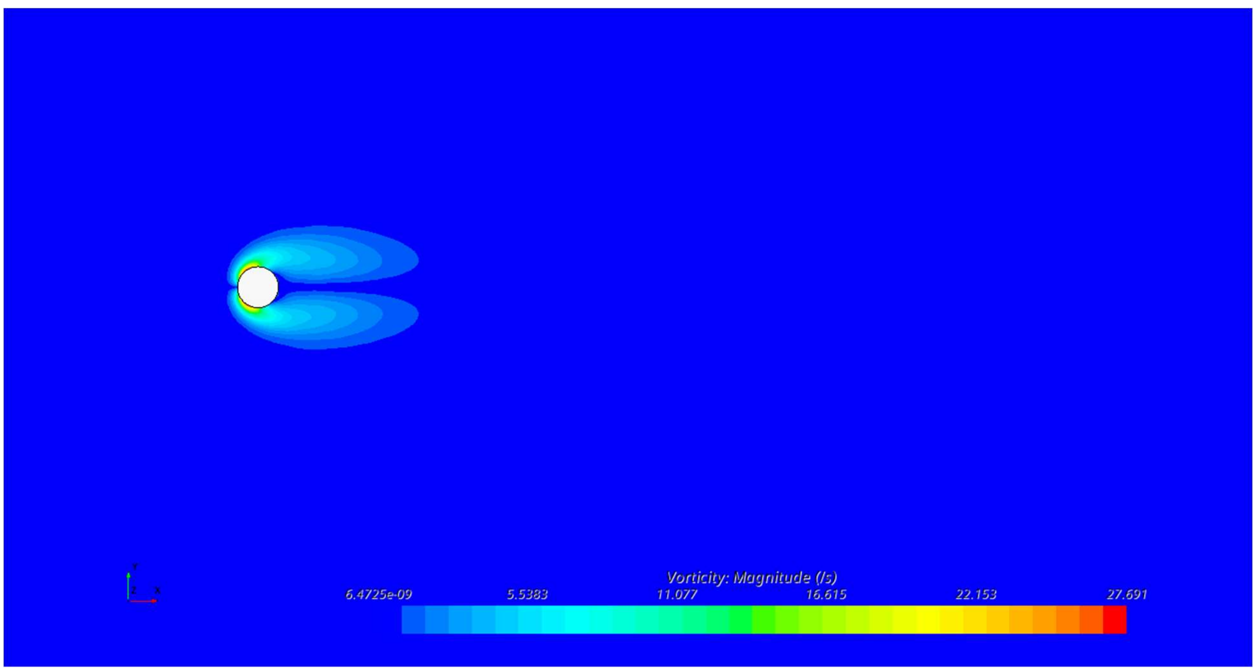
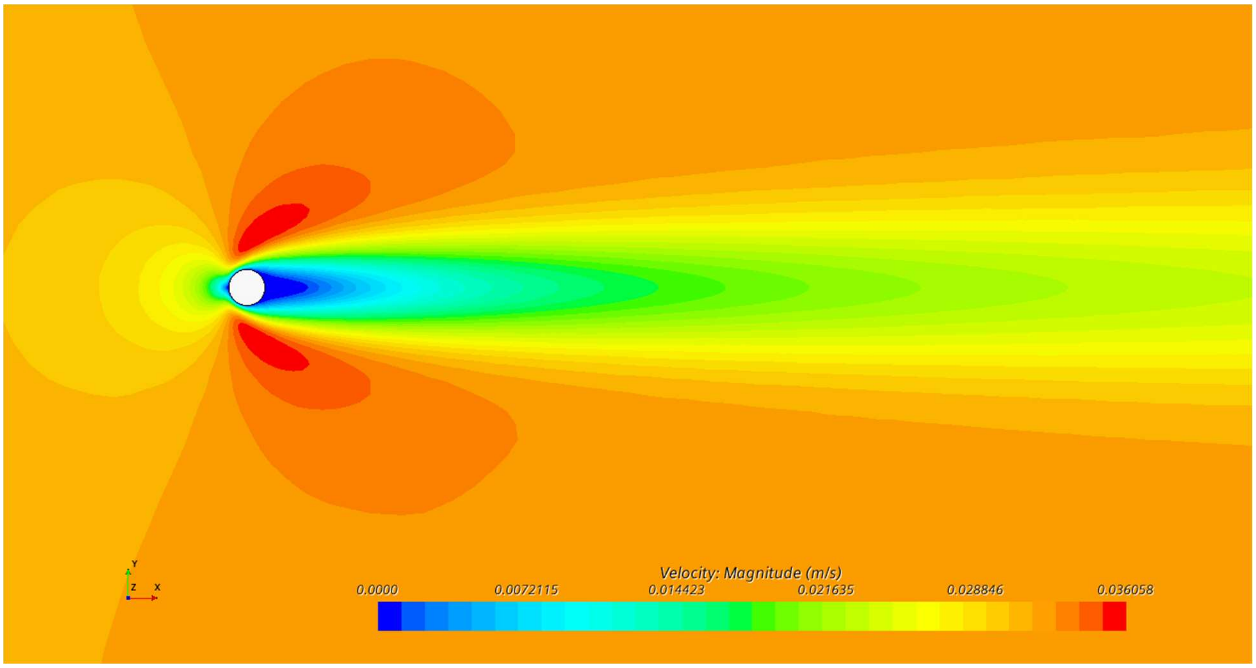
0.023023
0.030697
0.038372





25.6 steady state


Velocity: Magnitude (m/s)
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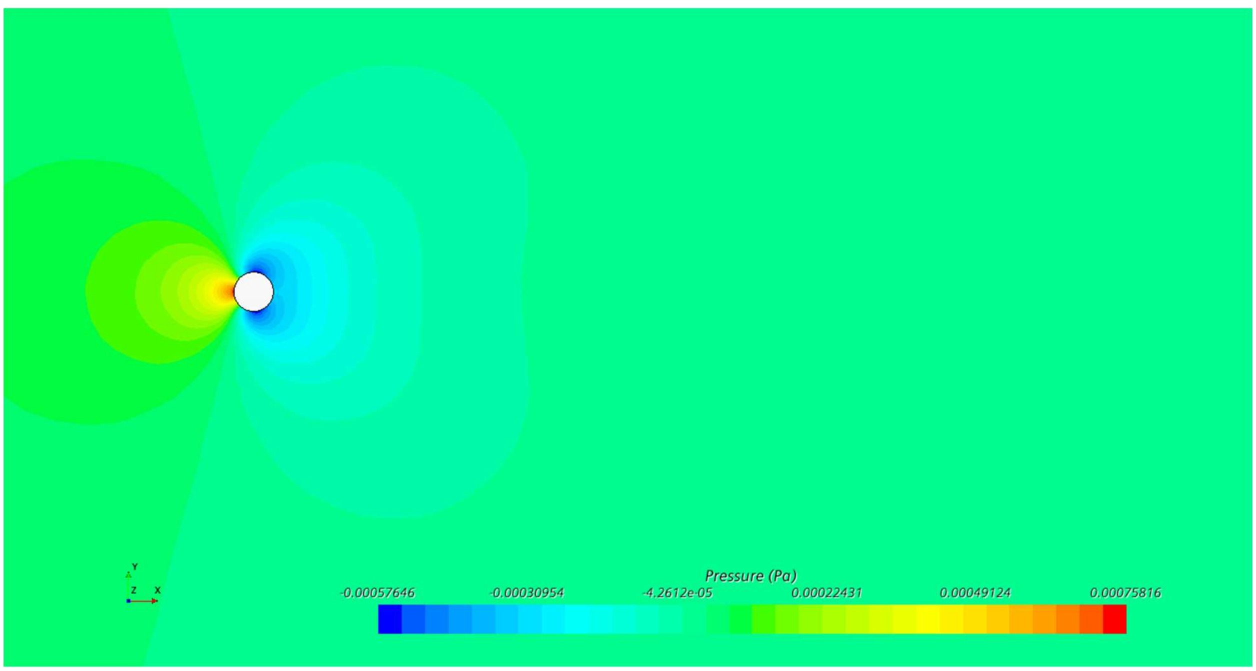
0.014423
0.021635
0.028846
0.036058
Y
Z
X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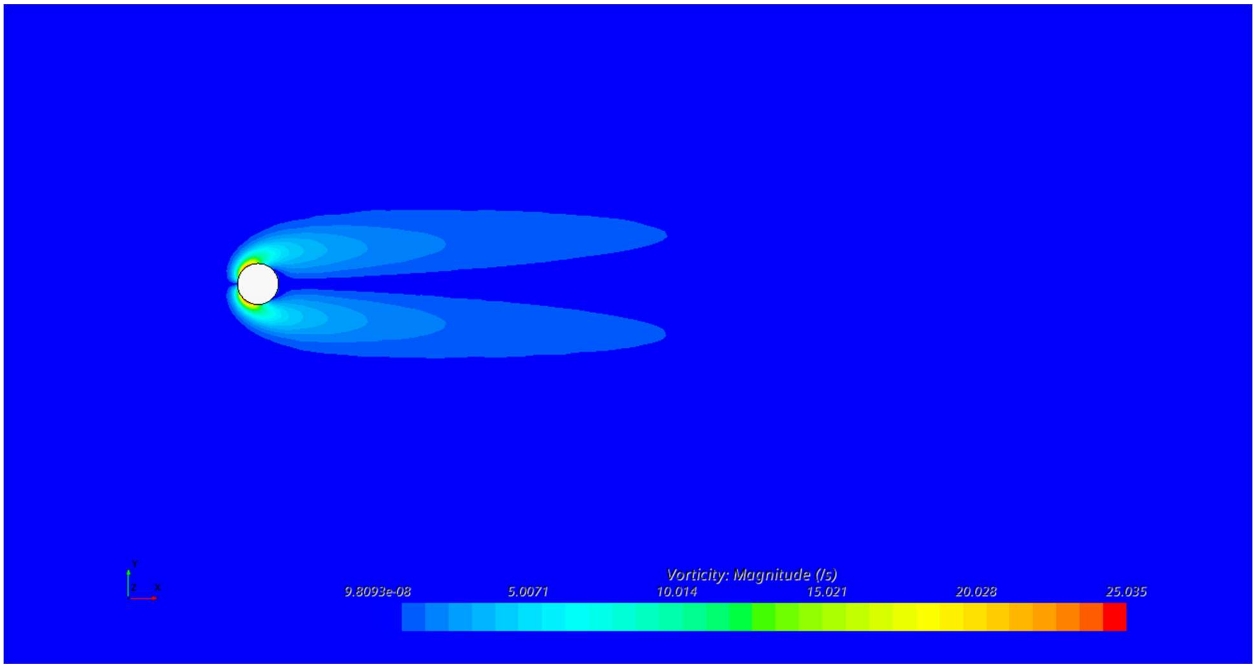
Y
Z
X


Vorticity: Magnitude (/s)
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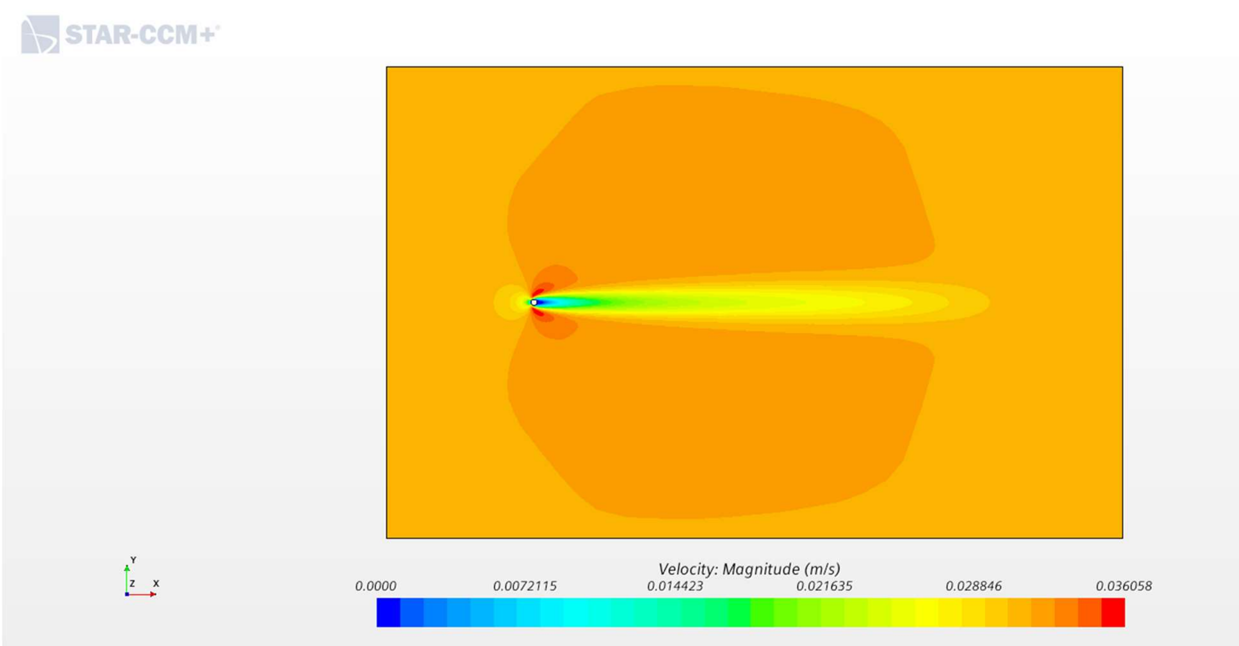
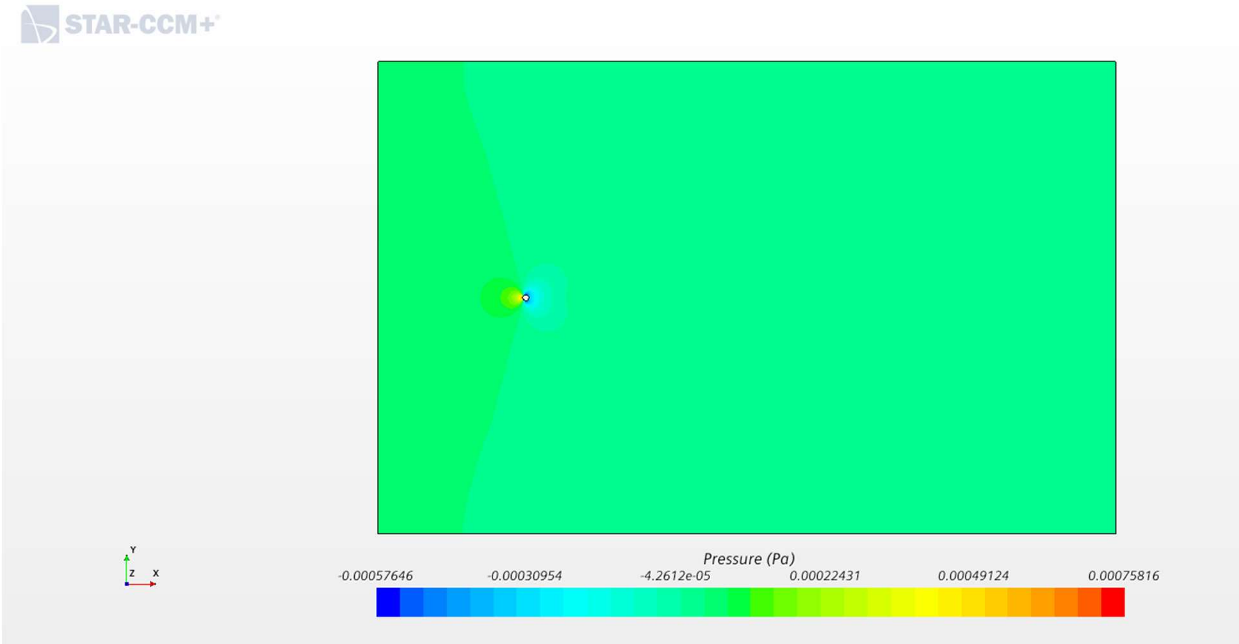
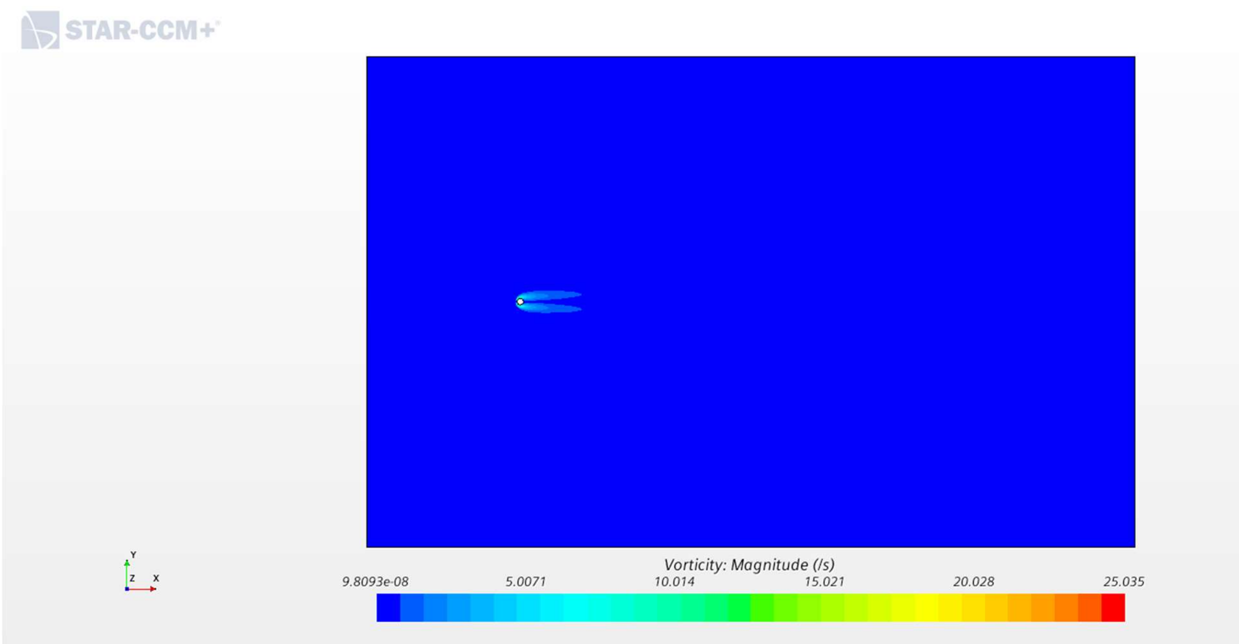
5.0071
10.014
15.021
20.028
25.035


STAR-CCM+
Velocity: Magnitude (m/s)
0.0000
0.0072115
0.014423
0.021635
0.028846
0.036058





Julia Code

```
#=
CFDPrepandProcessing.jl
March 20th, 2024
Jacob Child
Pseudocode:
```

```
Prep - Use the given Reynolds number and diameter to solve for velocity etc. Any
other prep needed for the simulations.
Processing - import the data from the simulation and plot it.
=#

using Plots, DelimitedFiles, LaTeXStrings

# Helpful functions
function RichardsonExtrap(valsf)
    Pf = log((valsf[3] - valsf[2])/ (valsf[4] - valsf[3])) / log(2)
    QFinal = valsf[4] + (valsf[3] - valsf[4]) / (1 - 2^(round(Pf,digits=2)))
    println("The order of the simulation is $(round(Pf,digits=2)).")
    println("The Grid Converged value is $(QFinal).")
    return Pf, QFinal
end

#Prep
Re = 20
D = .01
rho = 1.18415 #kg/m^3
mu = 1.85508 * 10 ^-5 #Pa*s
V = Re * mu / (rho * D)

#Prism Layer Height
H = 1.72*D/sqrt(Re) #from Blasius for a laminar flat plate
yplus = 1 #yplus value for the first cell
cf = 1.328/sqrt(Re) #skin friction coefficient (Blasius)
h = yplus*D/Re *sqrt(2/cf) #height of the first cell
r = 1.15 #growth rate of the cells
n = log(r, (H/h*(r-1)+1)) #number of cells for the prism layer

#Convergence Studies
#Time Step
Δts = [.8, .4, .2, .1, .05]
ConvgCdsdts = [2.0476560281, 2.047129, 2.047079, 2.04701124, 2.046985984]
P, Q = RichardsonExtrap(ConvgCdsdts[2:end])
dtConvgPlot = plot(Δts, ConvgCdsdts, title = "Convergence Study for Time Step",
xlabel = "Time Step", ylabel = "Cd", xflip = true, markers = true, legend
=:topright, label = "Cd")
hline!([Q], label = "Richardson Extrapolation Value")
dtPercentDiff = @. abs((ConvgCdsdts - Q) / Q) * 100
#Base Size Mesh Study
BS = [.08, .04, 0.02, .01, .005, .0025]
ConvgCdsBS = [2.06418185, 2.0525381, 2.0484387, 2.0447162, 2.044842, 2.050734]
BSavg = sum(ConvgCdsBS) / length(ConvgCdsBS)
```

```julia
BSPercentDiff = @. abs((ConvgCdsBS - ConvgCdsBS[end]) / ConvgCdsBS[end]) * 100
BSavgPercentDiff = @. abs((ConvgCdsBS - BSavg) / BSavg) * 100
BSPlot = plot(BS, ConvgCdsBS, title = "Convergence Study for Base Size Mesh",
xlabel = "Base Size", ylabel = "Cd", xflip = true, markers = true, legend
=:topright, label = "Cd")
#time study on the right computer


#close up study was .01m mesh, dt = 0.005sec, for 2 seconds

#main study was .01m mesh, dt = 0.02sec, for 30 seconds

#Import Data from Simulation, run the first time run only

VeloDataFiles = readdir("VeloData")
VortDataFiles = readdir("VortData")
VeloDict = Dict()
VortDict = Dict()
for i in 1:length(VeloDataFiles)
    VeloData, _ = readdlm("VeloData/$(VeloDataFiles[i])", ',', header = true)
    x = VeloData[:,2]
    y = VeloData[:,1]
    name = split(VeloDataFiles[i], ".")[1]
    VeloDict[VeloDataFiles[i]] = (x, y)
end
for i in 1:length(VortDataFiles)
    VortData, _ = readdlm("VortData/$(VortDataFiles[i])", ',', header = true)
    x = VortData[:,2]
    y = VortData[:,1]
    name = split(VortDataFiles[i], ".")[1]
    VortDict[VortDataFiles[i]] = (x, y)
end
SteadyStateCd, _ = readdlm("SteadyStateCd256sec.csv", ',', header = true)
SSCd = SteadyStateCd[:,2]
SSCdTime = SteadyStateCd[:,1]
UnsteadyCd, _ = readdlm("CloseUpCd2sec.csv", ',', header = true)
usCd = UnsteadyCd[:,2]
usCdTime = UnsteadyCd[:,1]


#Plot Palooza
SteadyStateCdPlot = plot(SSCdTime, SSCd, title = "Coefficient of Drag vs Time",
xlabel = "Time (s)", ylabel = L"C_d" , label = L"C_d", ylim= (1.7,2.8) )
UnsteadyCdPlot = plot(usCdTime, usCd, title = "Coefficient of Drag vs Time",
xlabel = "Time (s)", ylabel = L"C_d" , label = L"C_d")
```

```
CombinedCdPlot = plot(usCdTime, usCd, title = "Coefficient of Drag vs Time",
xlabel = "Time (Log Scale, sec)", ylabel = L"C_d" , label = "$(L"C_d") , Δt =
0.005 (s)")
plot!(SSCdTime, SSCd, label = "$(L"C_d") , Δt = 0.4 (s)", ylim = (1.9, 3),
xscale=:log10)

# Extract the time value from the key
get_timeVelo(key) = parse(Float64, replace(key, r"Velo|\.csv" => "")) / 10
get_timeVort(key) = parse(Float64, replace(key, r"Vort|\.csv" => "")) / 10

# Sort the dictionaries by the time value
sortedVeloDict = sort(VeloDict, by = key -> get_timeVelo(key))
sortedVortDict = sort(VortDict, by = key -> get_timeVort(key))

# Velocity Profiles Plot
colors = cgrad(:magma)
num_lines = length(sortedVeloDict)
VeloPlot = plot()
for (i, (key, value)) in enumerate(sortedVeloDict)
    time = get_timeVelo(key)
    label = "$(time) sec"
    color = get(colors, (i-.75) / num_lines)
    plot!(value[2], value[1], label = label, ylabel = "Velocity (m/s)", xlabel =
"Distance From Cylinder (m)", title = "Velocity Profiles One Diameter From
Cylinder", xlim = (-.2,.2), linecolor = color, lw = 2)
end

# Vorticity Profiles Plot
num_lines = length(sortedVortDict)
VortPlot = plot()
for (i, (key, value)) in enumerate(sortedVortDict)
    time = get_timeVort(key)
    label = "$(time) sec"
    color = get(colors, (i-.75) / num_lines)
    plot!(value[2], value[1], label = label, ylabel = "Vorticity (1/s)", xlabel =
"Distance From Cylinder (m)", title = "Vorticity Profiles One Diameter From
Cylinder", xlim = (-.1, .1), linecolor = color, lw = 2)
end
```