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A Flow-Driven Cavity as an Air Cycling Model for Window Flow

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Abstract

A lid-driven cavity is flow-driven to describe stress on and circulation inside buildings and small insect-to-UAV-size aircraft due to open windows or sidewall punctures. The transition between steady & unsteady flow is also roughly bounded, by investigating the Reynolds number at 4 values between 10 to 10ˆ4. A sparse simulation of low-speed and much higher-speed incompressible flows is undertaken, estimating feature shapes at the minimum computational cost.

Keywords: computational fluid dynamics, CFD, incompressible, Paraview, R, Python, coe347, spring 2022, window, building, tornado, high, reynolds, unsteady, steady, stress, strain, rate, mixing, volumetric, flow.

1. Motivation

For severe storms, it is widely known that puncture damage is the primary cause of failure for most buildings and aircraft. Once a puncture has been created, the resultant pressure differential can cause fast inflow and damage to the interior. We seek to study this inflow, and stresses near the opening walls, which can cause structural issues leading to collapse of one or more walls.

Most relevant studies use incredibly large amounts of computational power, due to the large scale of the problem (Reynolds numbers for tornadoes and hurricanes can easily start in the millions). We seek to show the applicability of lower Reynolds simulations to higher Reynolds situations, since the general large-scale flow structure remains the same.

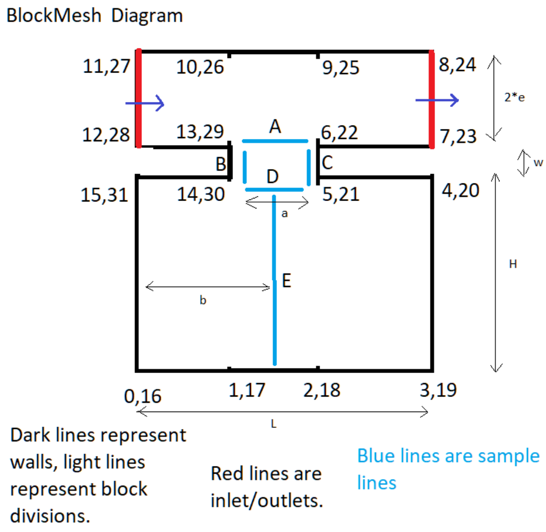
2. Implementation

We implement all simulation with OpenFoam, analysis with Paraview and Python3, and documentation code in R Xie, Dervieux, and Riederer (2020).

3. Mesh Assembly

We assemble a 2D mesh template as below, with the following parameters, all lengths nondimensionalized in terms of dimension L:

mutable: wall thickness w, window width a,
immutable: window location $b = 0.5$, cavity height $H = 1$, cavity width $L = 1$, and free-stream width $2e = 0.1$.



Two sets of simulations are performed, one for the low Reynolds (Re) numbers of 10 and 200, which will be shown to be steady, and another for $Re = 1000, 10000$.

Each mesh also has a corresponding refinement, which is described by the $meshFactor$ parameter, representing the refinement in each dimension.

Full lists are available below.

3.1. Meshes for the Low Reynolds simulations

meshfactor	Reynolds	a	w
5	10	0.05	0.05
5	10	0.05	0.10
5	10	0.50	0.05
5	10	0.50	0.10
10	10	0.05	0.05
10	10	0.05	0.10
10	10	0.50	0.05
10	10	0.50	0.10
5	200	0.05	0.05
5	200	0.05	0.10
5	200	0.50	0.05
5	200	0.50	0.10
10	200	0.05	0.05
10	200	0.05	0.10
10	200	0.50	0.05
10	200	0.50	0.10

Table 1:

3.2. Meshes for the High Reynolds simulations

meshfactor	Reynolds	a	w
3	1000	0.5	0.1
5	1000	0.5	0.1
3	10000	0.5	0.1
5	10000	0.5	0.1

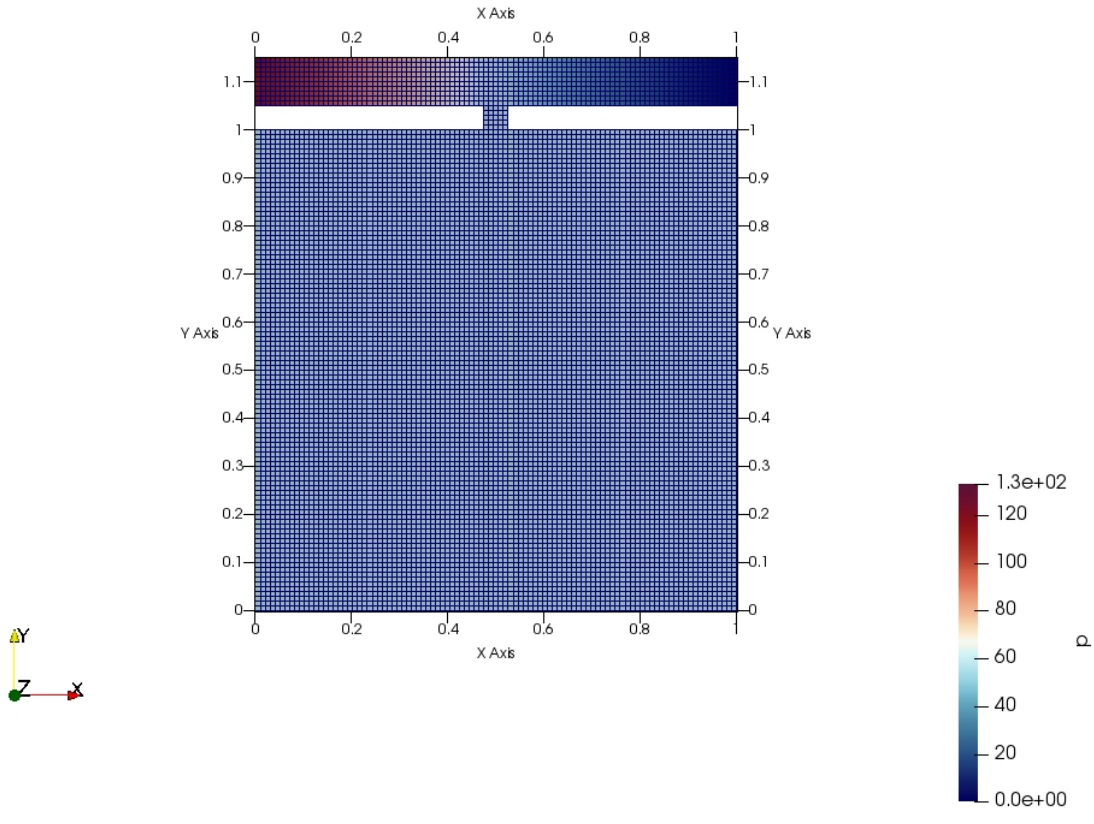
Table 2:

BlockMeshDict and similar files are available at the repository.

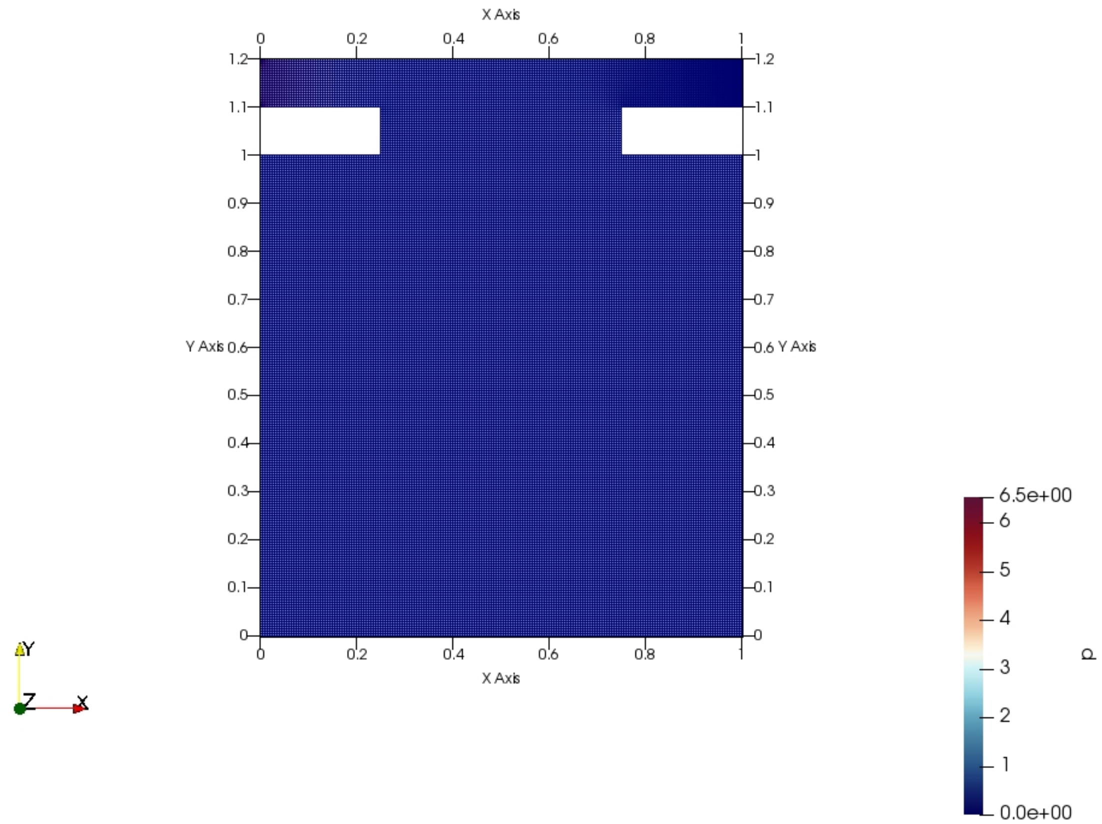
3.3. Mesh Images

A couple mesh samples are shown here; see the appendix for all images.

meshFactor, Re, windowWidth, wallThickness=5, 10, 0.05, 0.05:



meshFactor, Re, windowWidth, wallThickness=10, 200, 0.5, 0.1:



Now that the mesh resolutions can be seen as adequate, we will move to results.

4. Literature Review

Wind speeds may be categorized as dangerous once reaching the threshold of 50mph. Winds of this caliber may occur during storms and tornados, and can be catastrophic to infrastructure.(2019; Hadhazy 2011; Tessner 2021)

Structurally, windows are weak in comparison to the surrounding structure and therefore are generally the first to break when confronted with strong winds. The missing window then creates a cavity with a pressure differential to the outside wind that may encourage further destruction. The fragility of windows is why many coastal buildings near hurricane hotspots have shutters, and in the event of a storm, those without shutters often cover their windows with materials such as plywood to protect against the oncoming winds.(2019; Hadhazy 2011; Tessner 2021)

The average home is designed to withstand winds of 90mph for around 3 seconds, which is far from sufficient to withstand even a moderate class of tornado. Especially when including forces working in tadem generating lift on top of normal stressors. As roof connections rely primarily on gravity to ensure stabiity, any opposing force to gravity need only overcome the weight force of the roof to remove it from the structure entirely.(2019; Hadhazy 2011; Tessner 2021)

Due to the propensity of air to create vortices when exposed to nonzero velocity and pressure differential, the way air may travel through the structure could pose an additional destructor on top of the exterior conditions. It has been proven advantageous for homes in storm-prone areas to install shutters, so prevention of inducing cavity-like flow on a structure is of import.(2019; Hadhazy 2011; Tessner 2021)

5. Low Reynolds Number

Note all values are nondimensionalized - all lengths are in terms of L, the cavity length, all speeds in terms of U, the initial flow speed, and all times in terms of $\frac{L}{U}$.

The pressure is in terms of $\frac{p}{\rho U^2}$.

5.4. General Solution Form

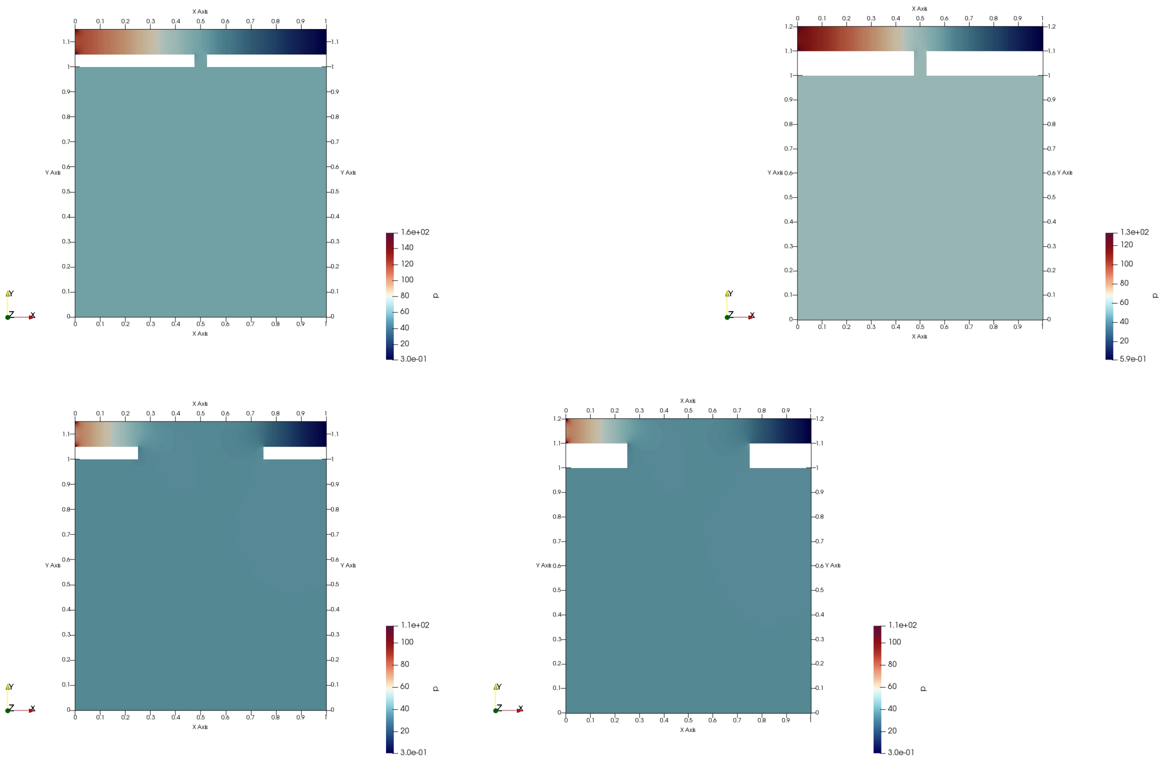
We will now show the pressure, X-velocity, Y-velocity, and streamlines in sets of 4 by varying geometry along the following pattern. Contours are not shown due to their bias toward out-of-cavity portions and the coarse mesh will be omitted for brevity. Convergence studies will be done numerically afterward.

Pattern:

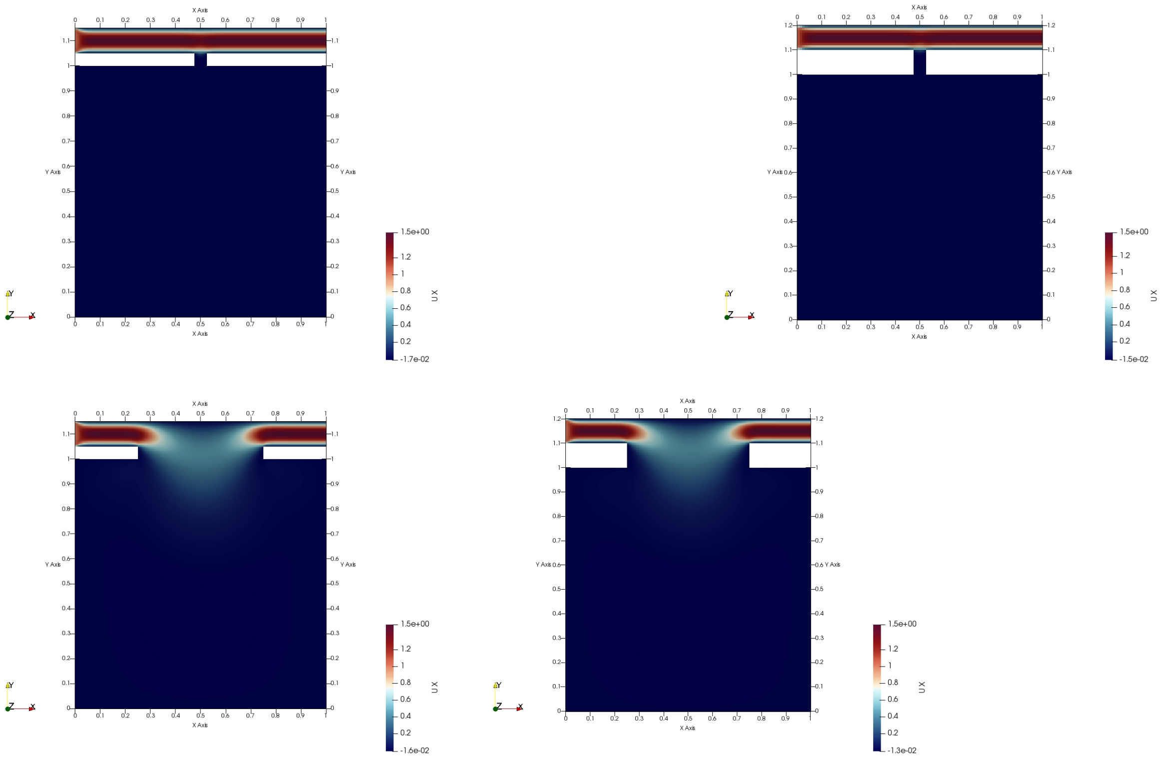
window.size.a	**wall.thickness.w**
0.05	0.05
0.05	0.10
0.50	0.05
0.50	0.10

Table 3:

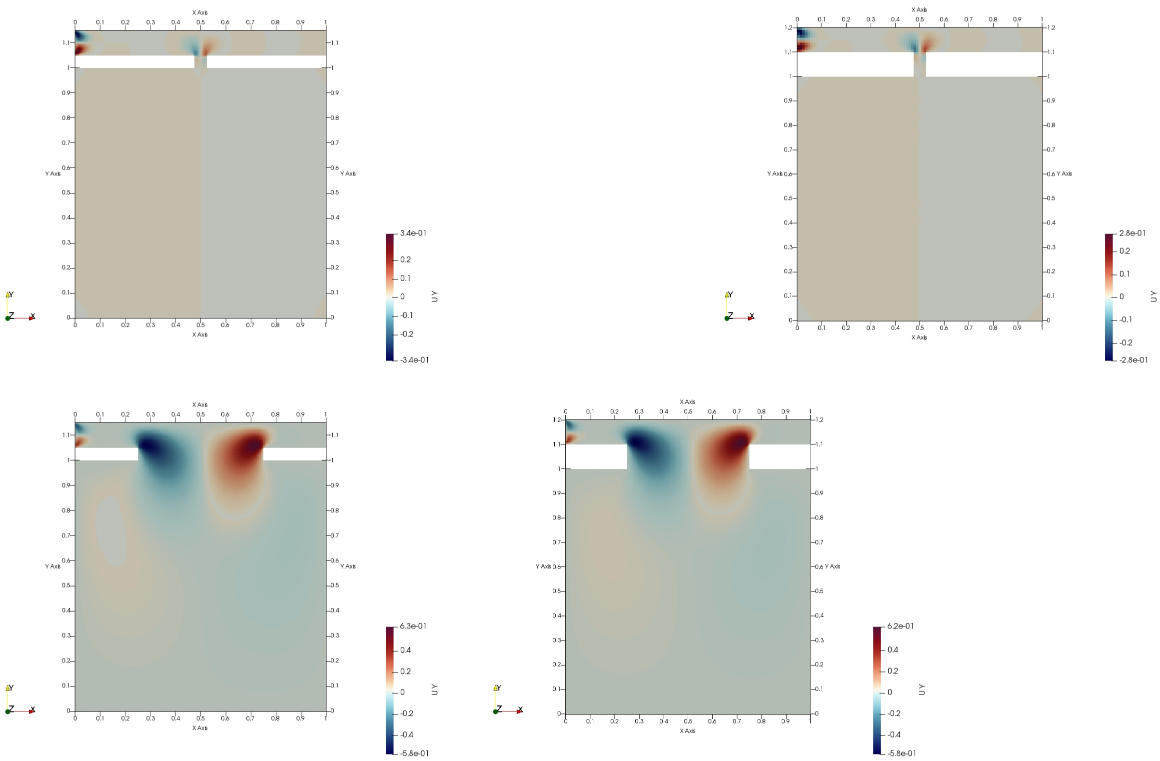
Re=10, Pressure



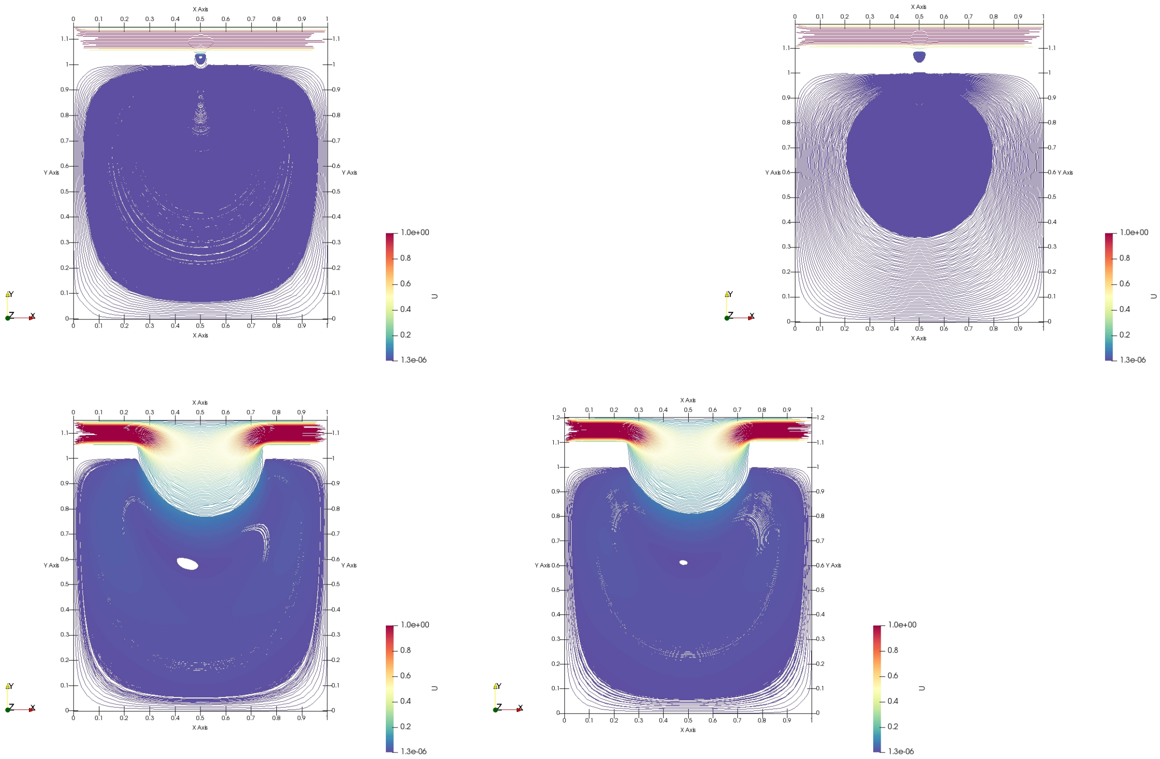
Re=10, X-velocity



Re=10, Y-velocity



Re=10, Streamlines



5.5. Vortice Positions

Convergence can easily be seen by looking at the centralized vortex position for both meshes, by differing geometry.

meshfactor	Reynolds	window.a.	wall.w.	Vortex.Center.Location.along.Y
5	10	0.05	0.05	0.8350
10	10	0.05	0.05	0.8525
5	10	0.05	0.10	0.9650
10	10	0.05	0.10	0.9650
5	10	0.50	0.05	0.5650
10	10	0.50	0.05	0.5725
5	10	0.50	0.10	0.6050
10	10	0.50	0.10	0.6075
5	50	0.05	0.05	0.8350
10	50	0.05	0.05	0.8525
5	50	0.05	0.10	0.9650
10	50	0.05	0.10	0.6075
5	50	0.50	0.05	0.6550
10	50	0.50	0.05	0.6625
5	50	0.50	0.10	0.6850
10	50	0.50	0.10	0.6875
5	200	0.05	0.05	0.8550
10	200	0.05	0.05	0.8675
5	200	0.05	0.10	0.9750
10	200	0.05	0.10	0.6875
5	200	0.50	0.05	0.7650
10	200	0.50	0.05	0.7725
5	200	0.50	0.10	0.8250
10	200	0.50	0.10	0.8325

Table 4:

5.6. Window Wall Solution Profiles

- profiles for Left and Right

5.7. Cavity Midline Solution Profile

- midline profiles

6. High Reynolds Number Part 1

Note again all values are nondimensionalized - all lengths are in terms of L, the cavity length, all speeds in terms of U, the initial flow speed, and all times in terms of $\frac{L}{U}$.

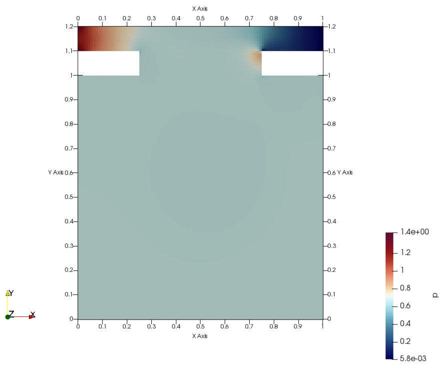
The pressure is in terms of $\frac{p}{\rho U^2}$.

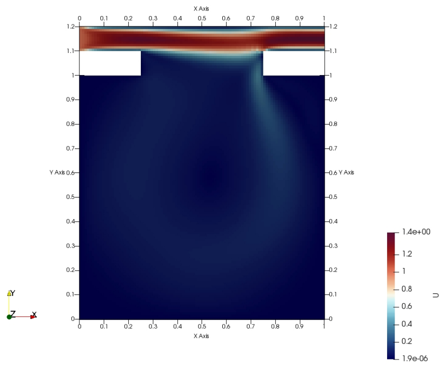
6.8. General Solution Form

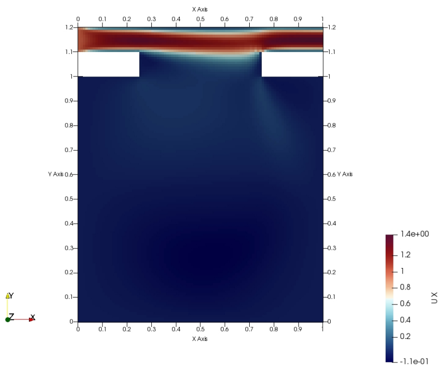
Given the results from the Low Reynolds simulations, we will now consider only a window width of 0.5 and a wall thickness of 0.1. Images only for the refined mesh will be shown, for brevity.

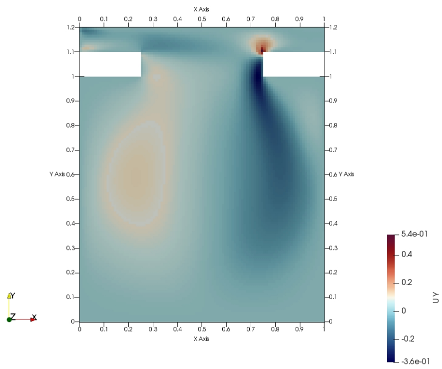
Plots will be shown in the following order: P, U, UX, UY, P-contour, U-contour, UX-contour, UY-contour, Streamlines for T=60.

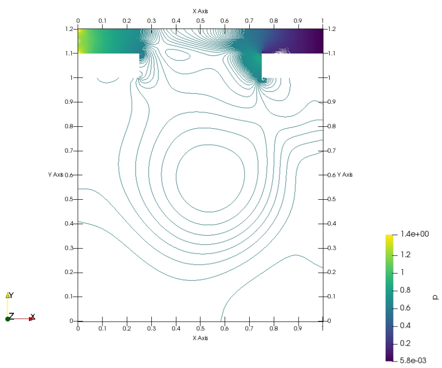
Re=1000

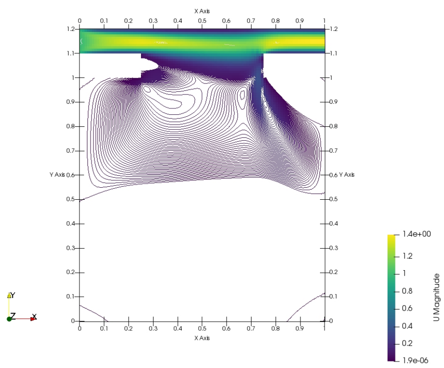


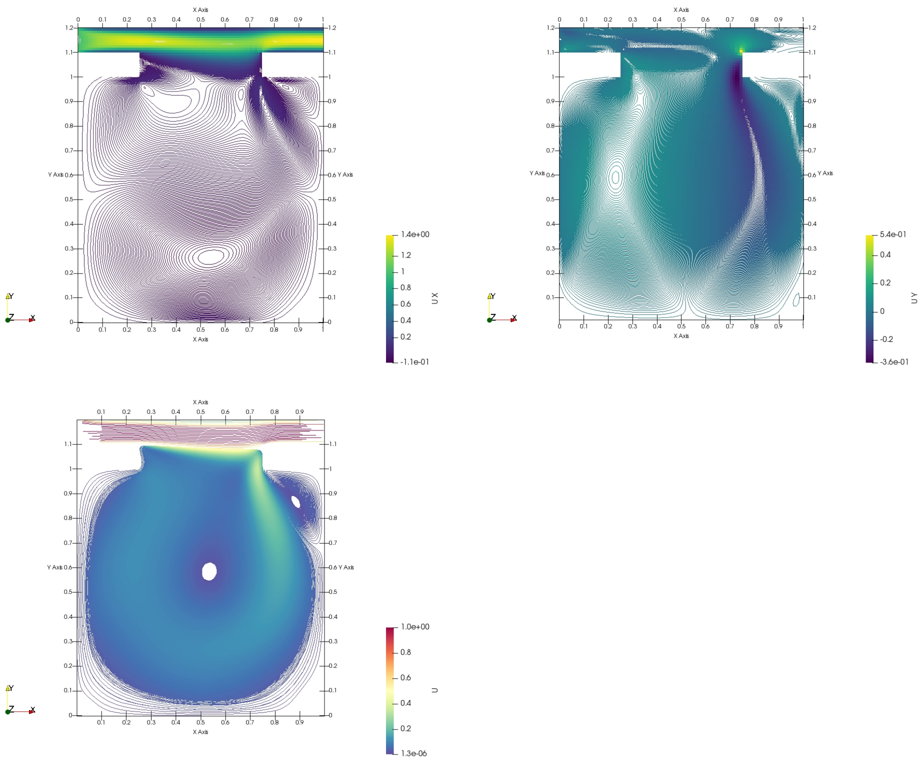




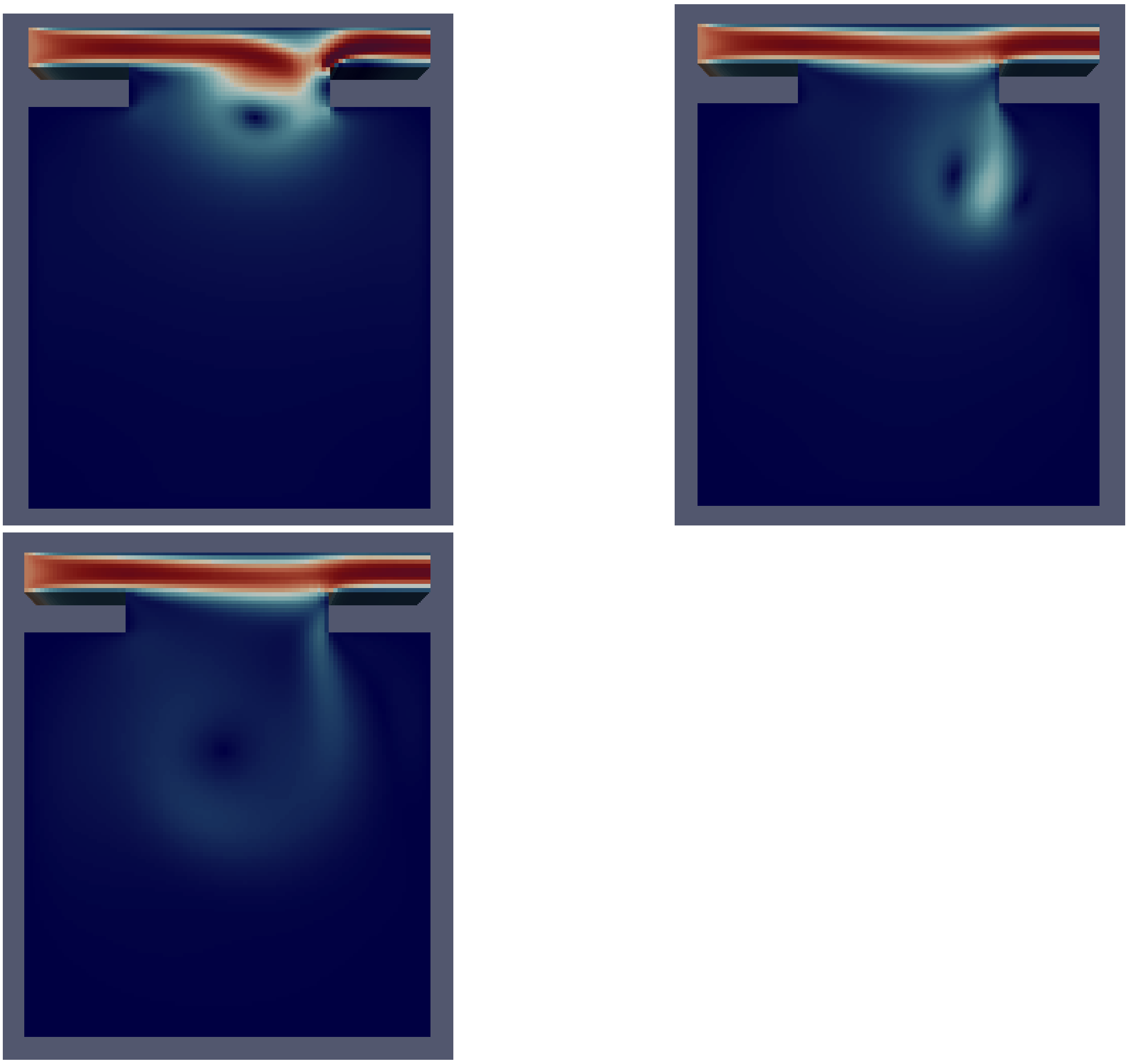




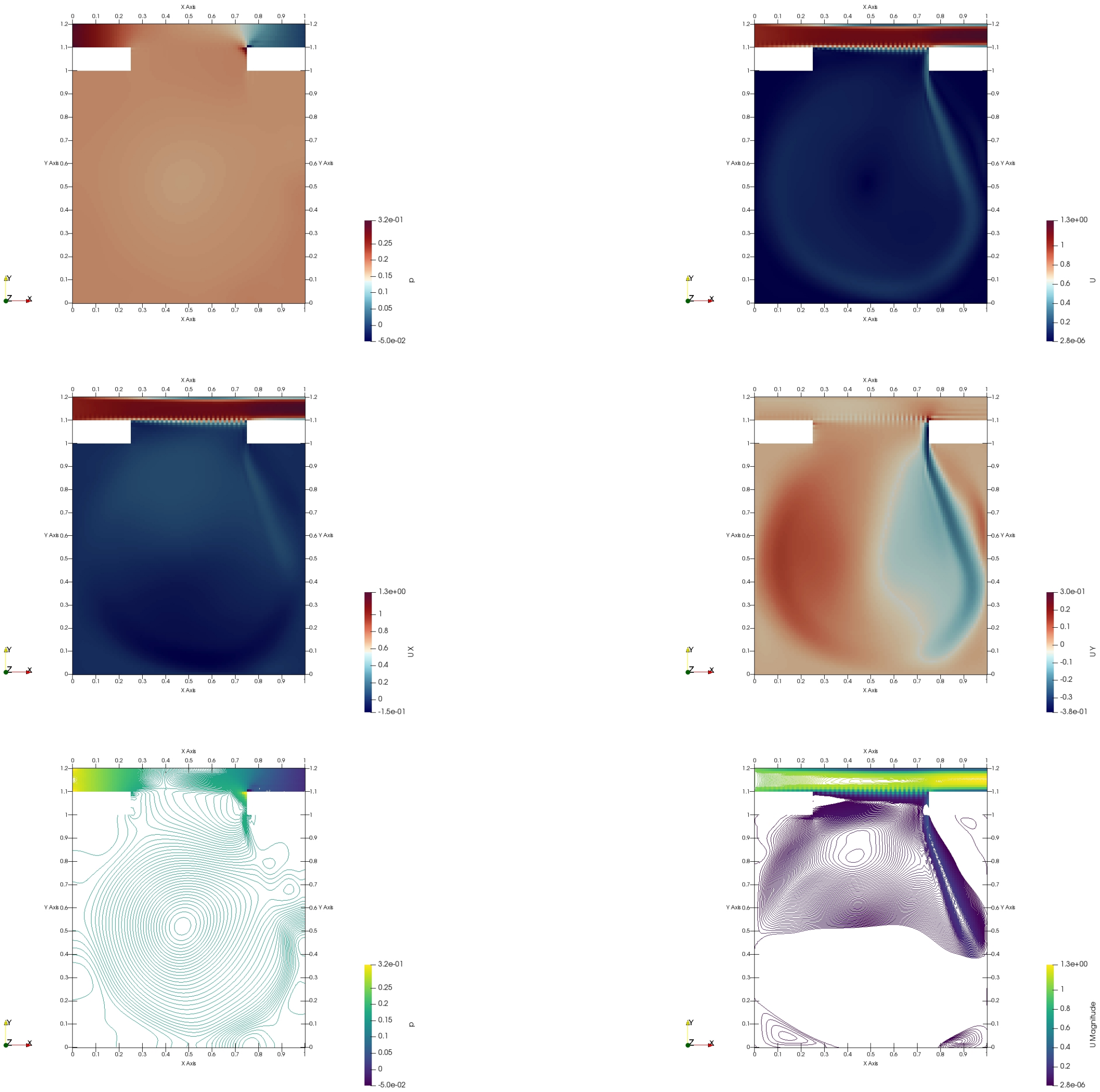


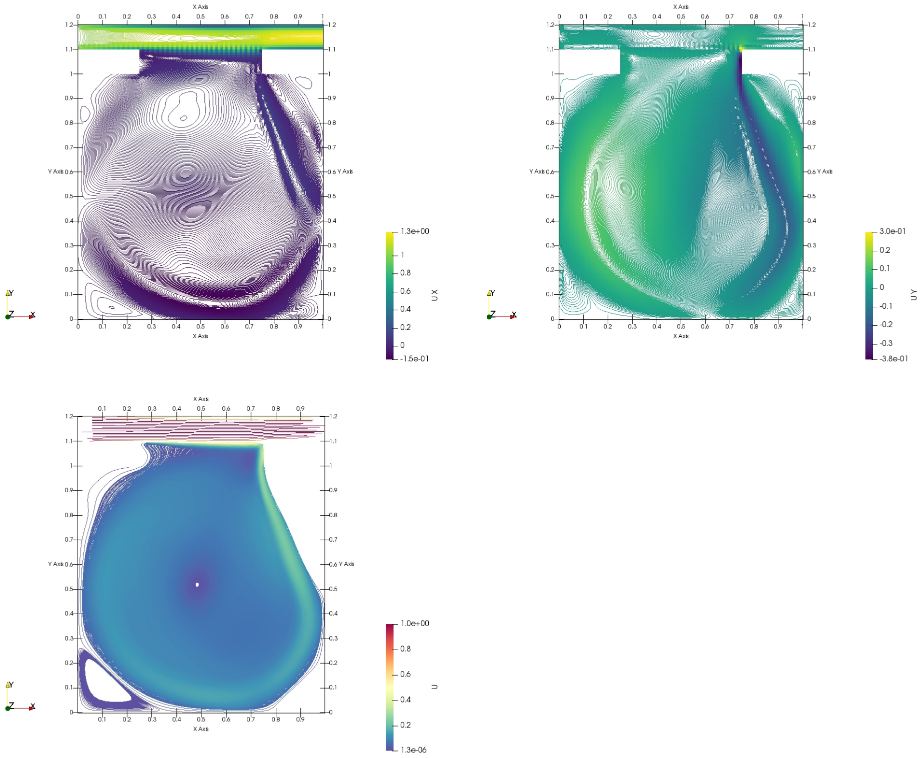


Re=1000, U at T=1,2,6

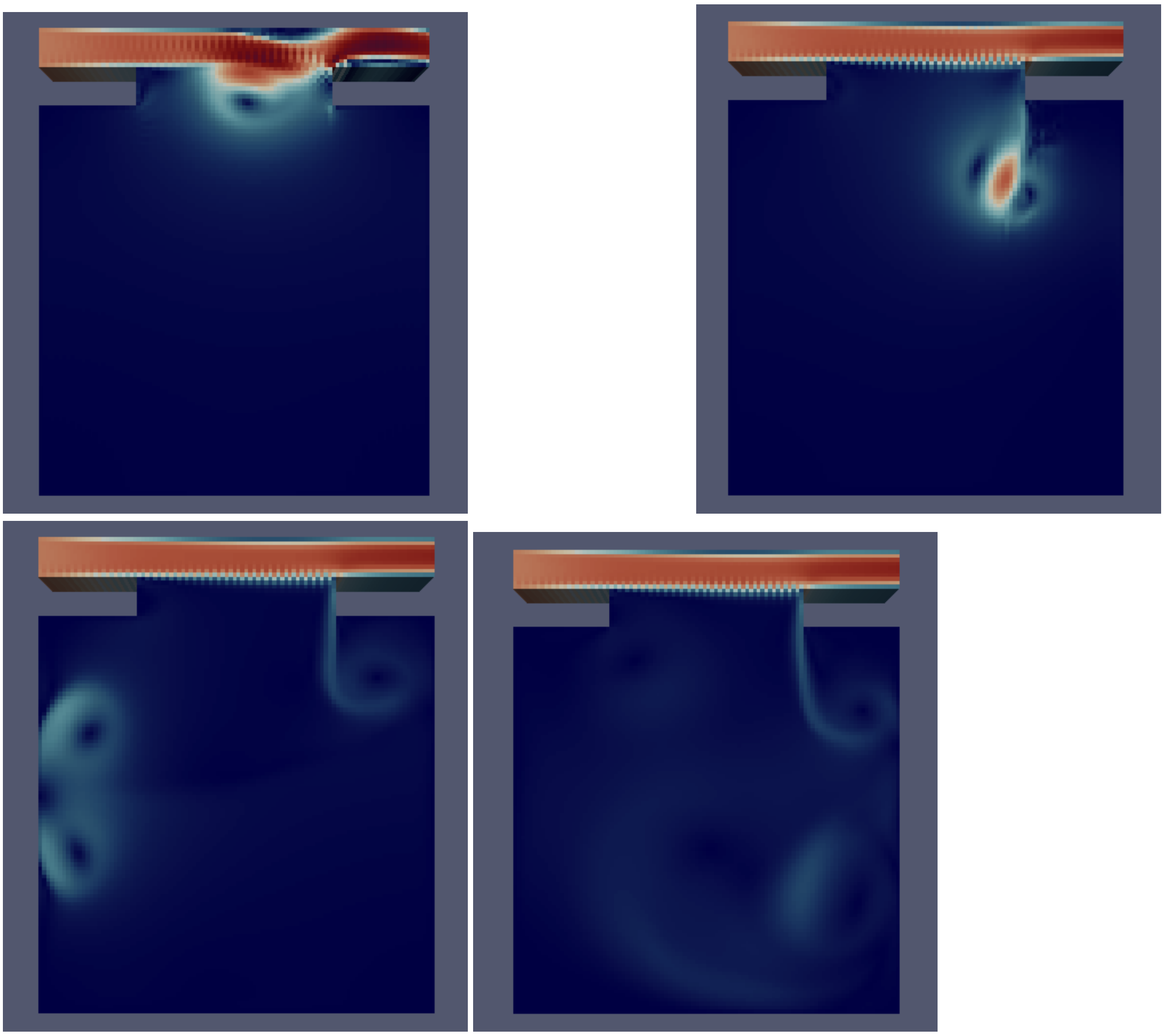


Re=10000


X Axis
Y Axis
p
U
U X
U Y
U Magnitude



Re=10000, U at T=1,2,6,30



6.9. Vortice Positions

Convergence can again easily be seen by looking at the centralized vortex position for both meshes, by differing geometry.

meshfactor	Reynolds	window.a.	wall.w.	Vortex.Center.Location.along.Y
3	1000	0.5	1	0.691667
5	1000	50.0	1	0.705000
3	10000	0.5	1	0.641667
5	10000	50.0	1	0.595000

Table 5:

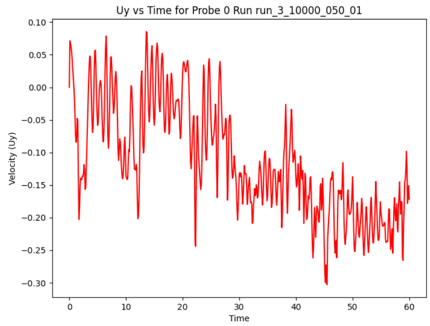
6.10. Strouhal Number and Vortex Shedding

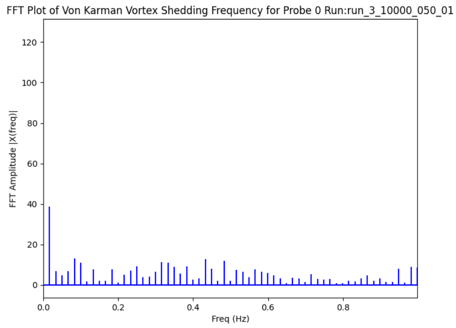
We will now look at the frequency of the vortex shedding that occurs at the right window wall. In non-dimensional form (in terms of L/U), this is the Strouhal number.
Two probes are placed 0.025 to the left and right of the right vertical wall, 0.05 below the lower edge. We will denote the left probe as probe 0, and the right probe as probe 1.
Coarse meshes will be shown along with their refinements.

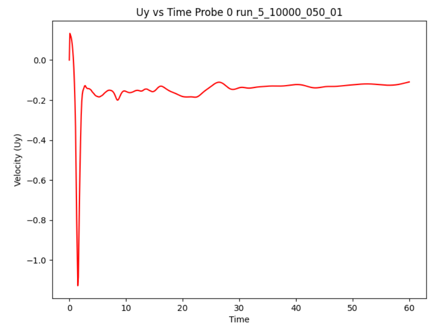
Fast Fourier Transform (over all time)

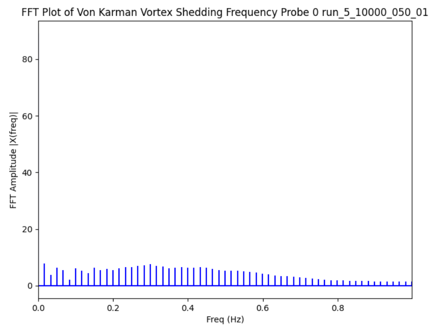
From the images shown earlier, clearly there is no vortex shedding for the Re=1000 case, and it seems to stabilize quickly, so one might assume that the flow is steady.
Below we have only treated the Re=10000 case, since the Re=1000 case does not produce useful filtered output (which might seem to corroborate the above.

Re=10000, Probe 0

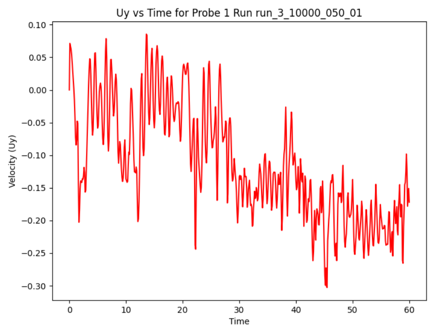


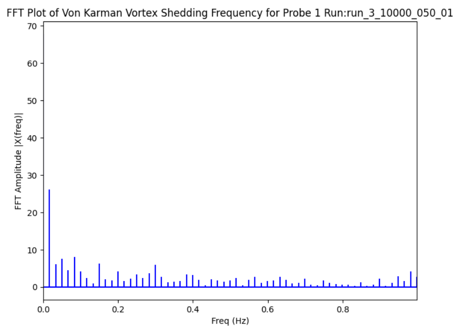


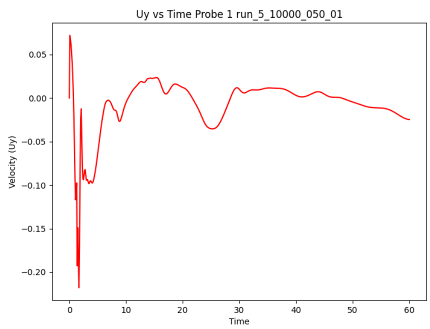


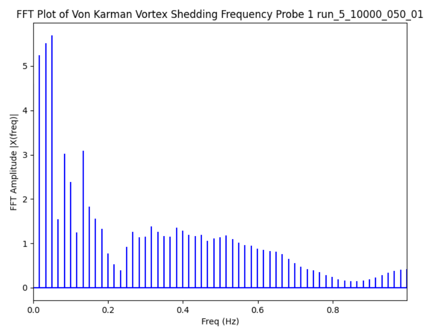


Re=10000, Probe 1





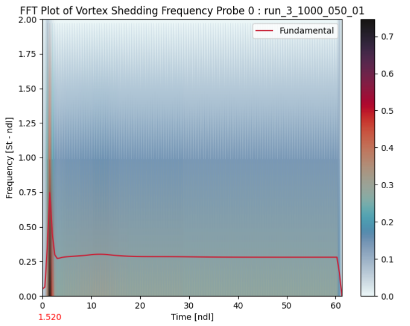


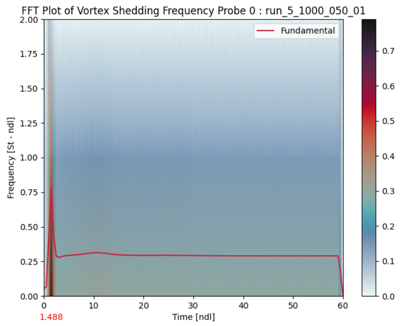


Note that the meshFactor of 3 fails to capture solution behavior (see the added oscillation).

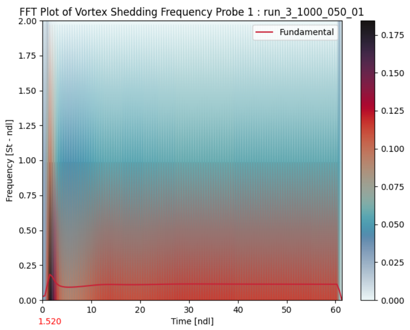
Short Time Fourier Transform (spectrogram to see time evolution)

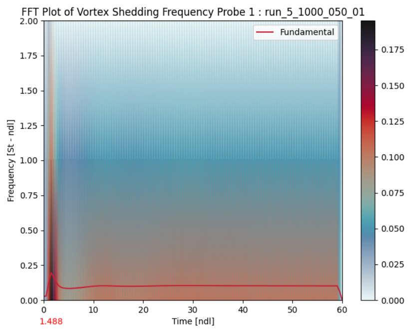
Re=1000, Probe 0





Re=1000, Probe 1



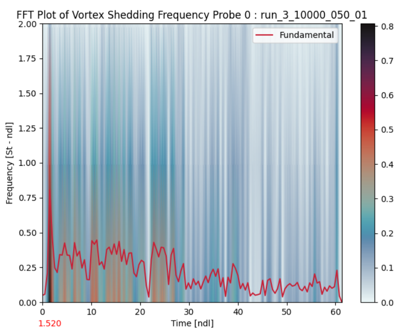


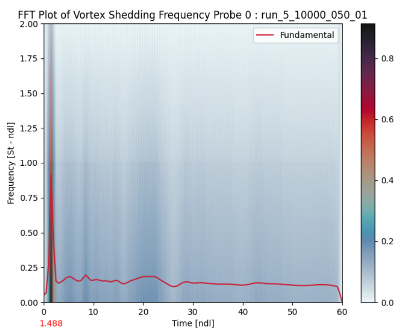
Interestingly, the Re=1000 plot is not at 0 Strouhal number! So we can clearly see that the large-scale flow does not have any steady-state oscillation (which is what the previous FFT plots show), but the small-scales are unsteady, with a typical Strouhal number near 0.2, as seen in the later table.

This is confirmed by the following:

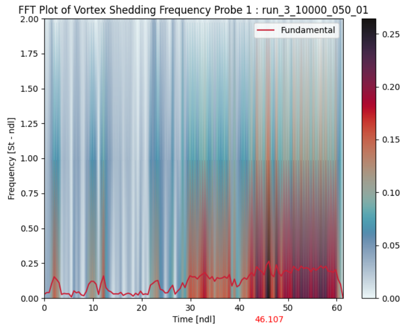
```
For spheres in uniform flow in the Reynolds number range of 8×10^2 < Re < 2×10^5 there co-exist two value
```

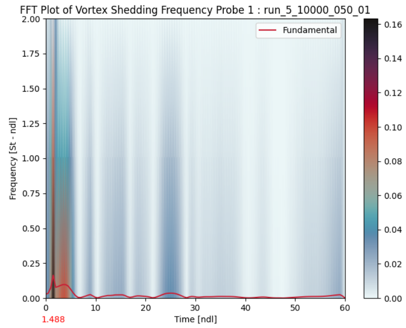
Re=10000, Probe 0





Re=10000, Probe 1





Continuing the former analysis, we see that the large scale instabilites are independent (since we get another Strouhal number for Re=10000 near 0.2 later in the flow). On the other hand, the small-scale instabilities are more prominent here, in the form of disturbances to the transform. We do not capture the other Strouhal number due to placement of the probes; we are interested in the large scale flow, so the other Strouhal number is not relavant for this paper.

Equilibrium Large-Scale Strouhal Values

Note that transient Strouhal numbers exist for Re=1000, and there are also small-scale Strouhal numbers for Re=1000, but those are neither relevant nor easily retrievable for this study.

meshfactor	Reynolds	ProbeNumber	Strouhal
3	10000	0	0.116472
3	10000	1	0.166389
5	10000	0	0.316139
5	10000	1	0.149750

Table 6:

Note the stark difference between left and right frequencies - the higher one may be the second Strouhal number mentioned in the previously cited articles.

7. High Reynolds Number - Part 2

7.11. Volumetric Flow Rate and Mixing

- plots
- generic argument / example for UAV and ..

7.12. Window Wall Solution Profiles

- profiles for Left and Right

T = 1.47 (unsteady startup)

T = 60 (steady-state for large-scales of flow)

Maximum Strain Rate over Time

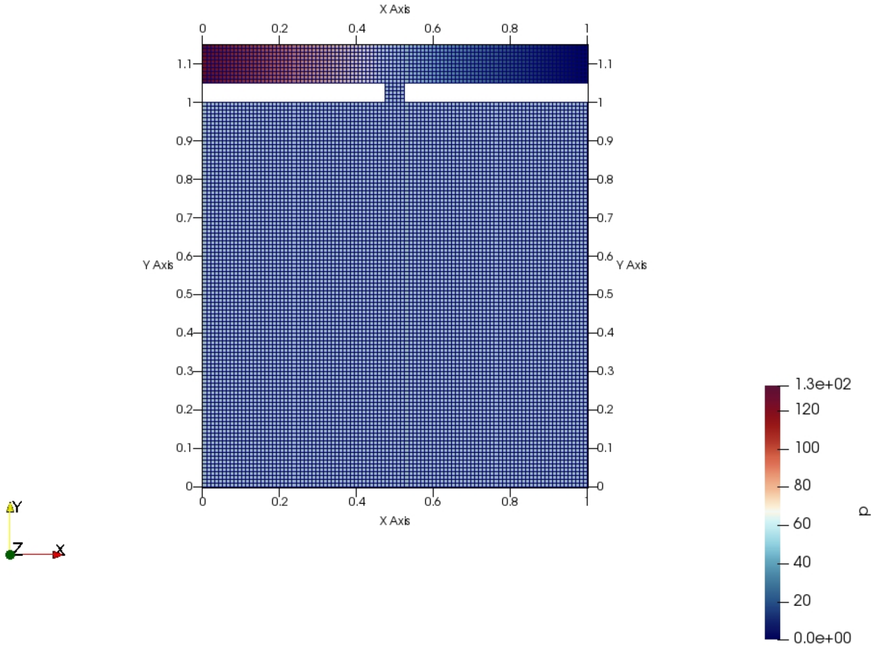
7.13. Cavity Midline Solution Profile

- midline profiles
  # Conclusions
  # References {.unnumbered}

8. Appendix

8.14. Mesh Images

Mesh Images for the Low Reynolds simulations (same order)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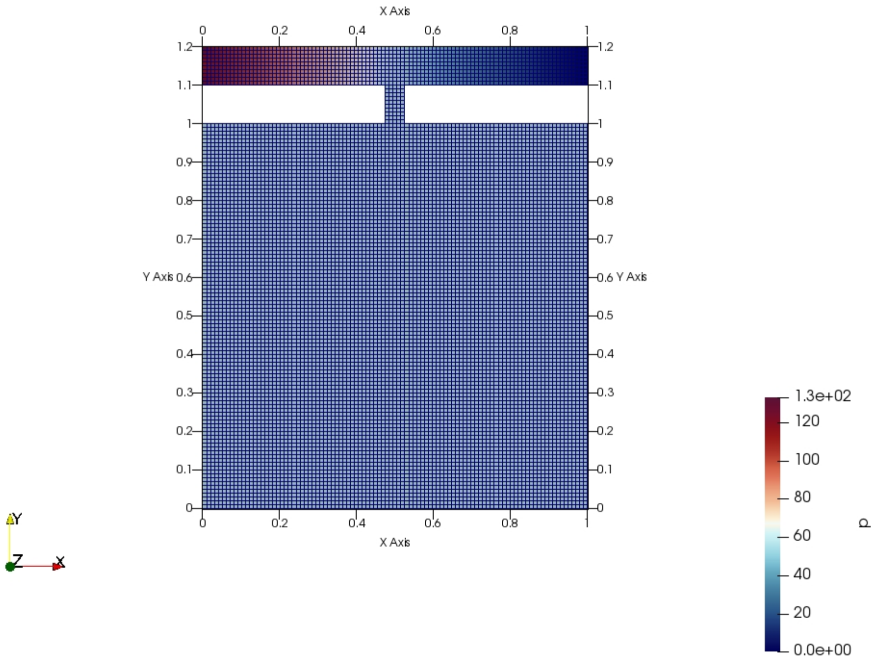
0.2
0.4
0.6
0.8
1
1.1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
Y Axis
1.3e+02
120
100
80
60
40
20
0.0e+00
p
Y
Z
X


X Axis
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0.4
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1.2
1.1
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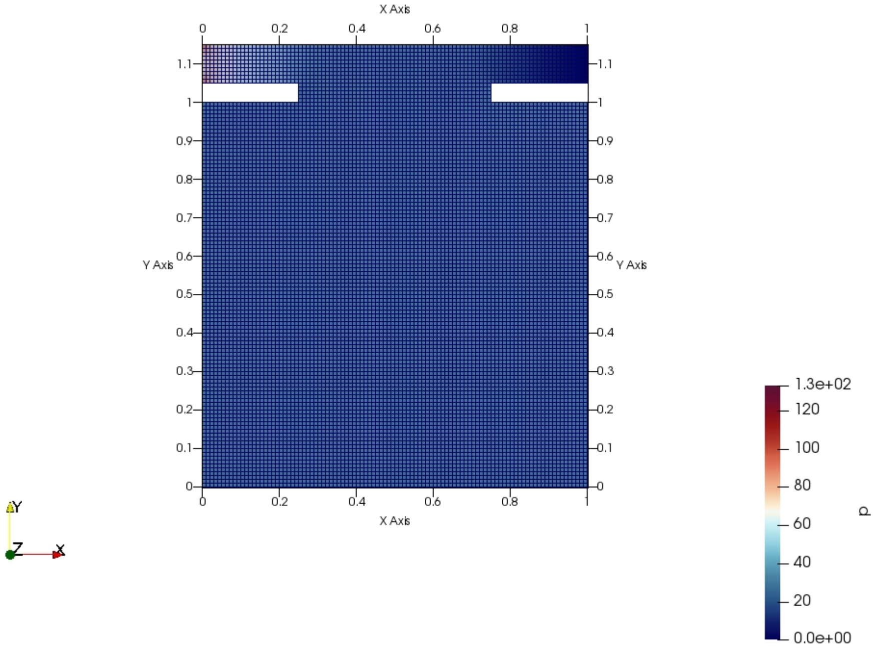
0.7
0.6
0.5
0.4
0.3
0.2
0.1
Y Axis
1.3e+02
120
100
80
60
40
20
0.0e+00
p
Y
Z
X


X Axis
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0.2
0.4
0.6
0.8
1
1.1
0.9
0.7
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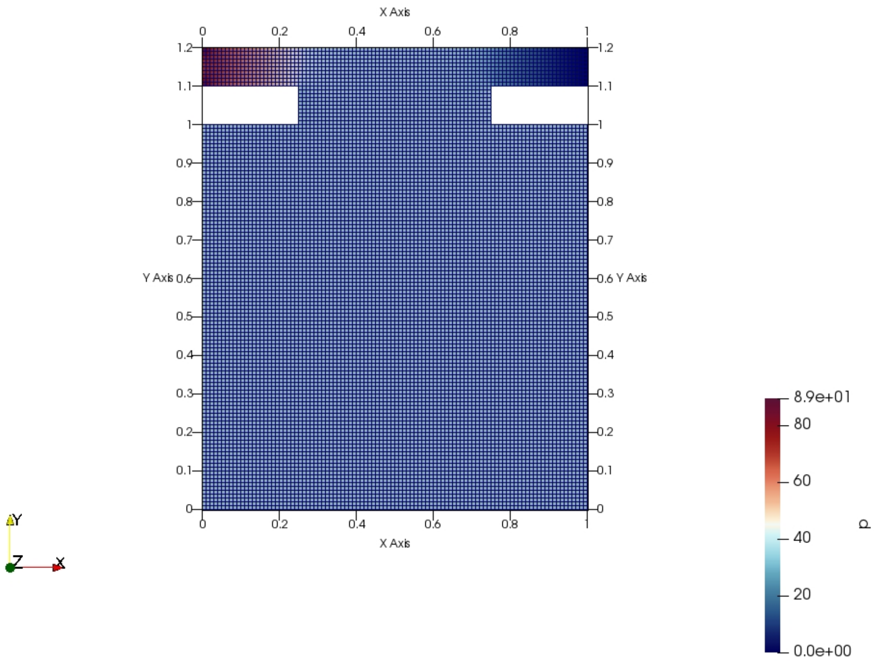
Y Axis
1.3e+02
120
100
80
60
40
20
0.0e+00
p


X Axis
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0.2
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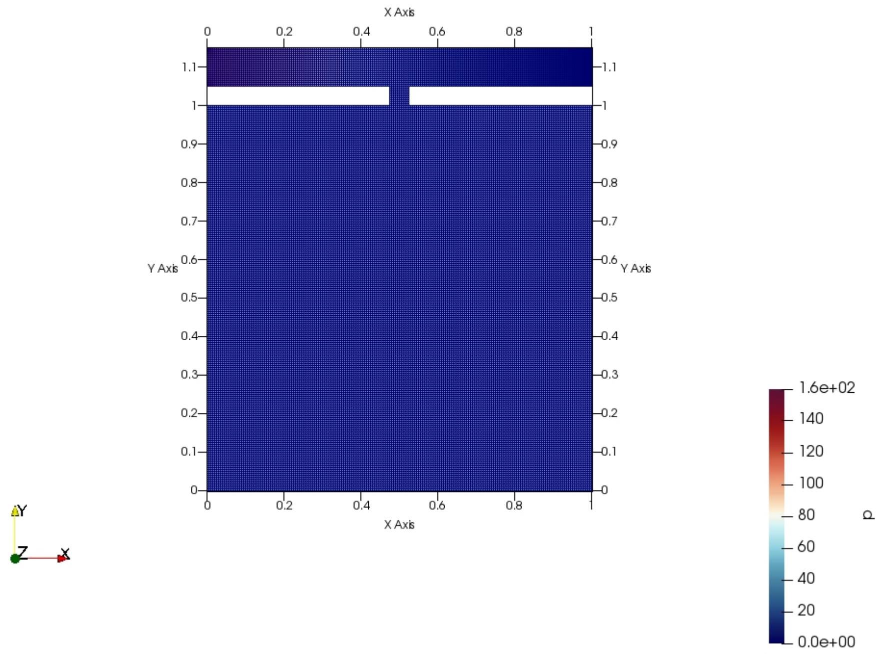
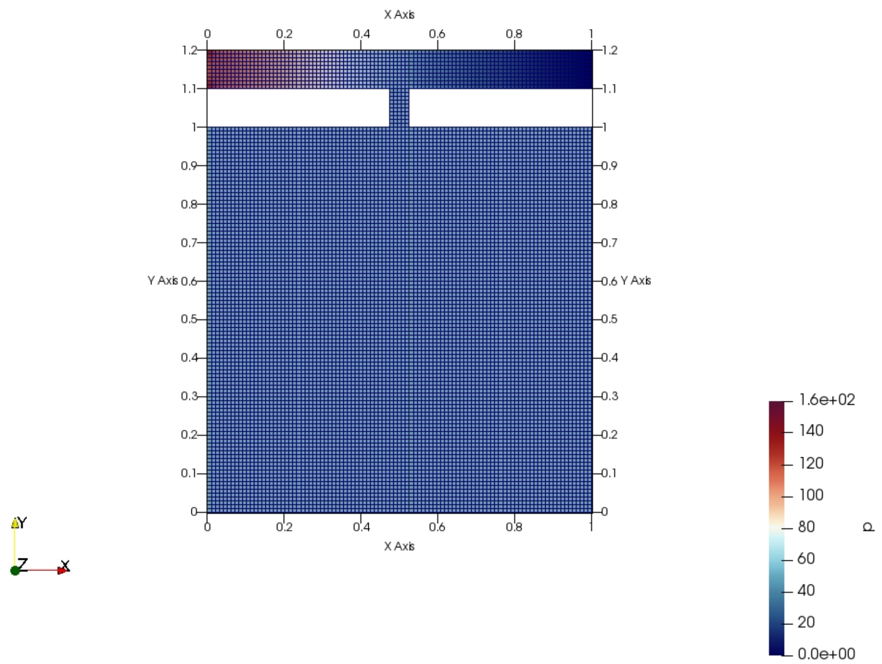
0.6
0.8
1
1.2
1.1
0.9
0.7
0.5
0.3
0.1
Y Axis
8.9e+01
80
60
40
20
0.0e+00
p


X Axis
0
0.2
0.4
0.6
0.8
1
1.1
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
Y Axis
X Axis
Y
Z
X
1.6e+02
140
120
100
80
60
40
20
0.0e+00
p


X Axis
0
0.2
0.4
0.6
0.8
1
1.2
1.1
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
Y Axis
X Axis
Y
Z
X
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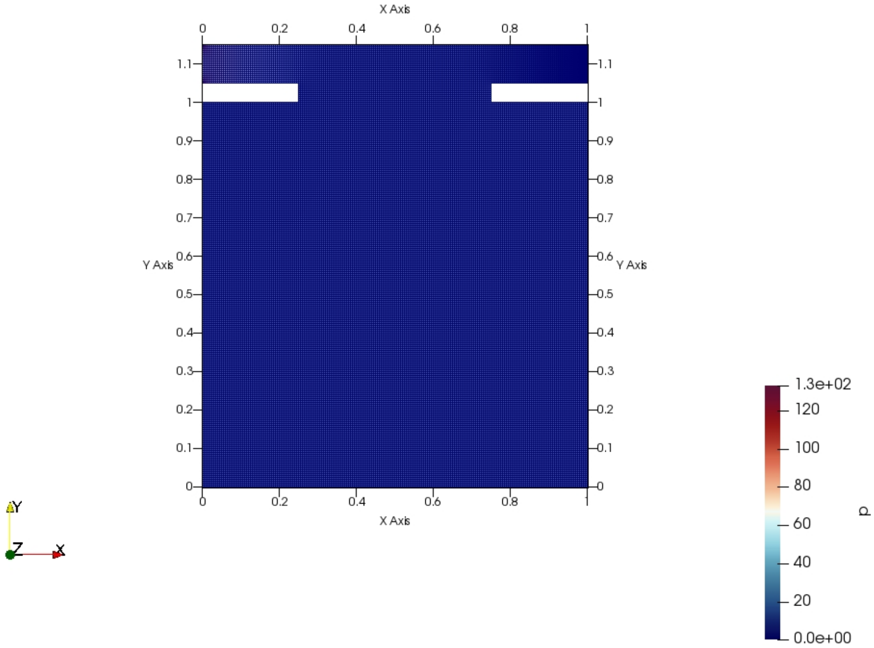
120
100
80
60
40
20
0.0e+00
p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0.3
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Y
Z
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80
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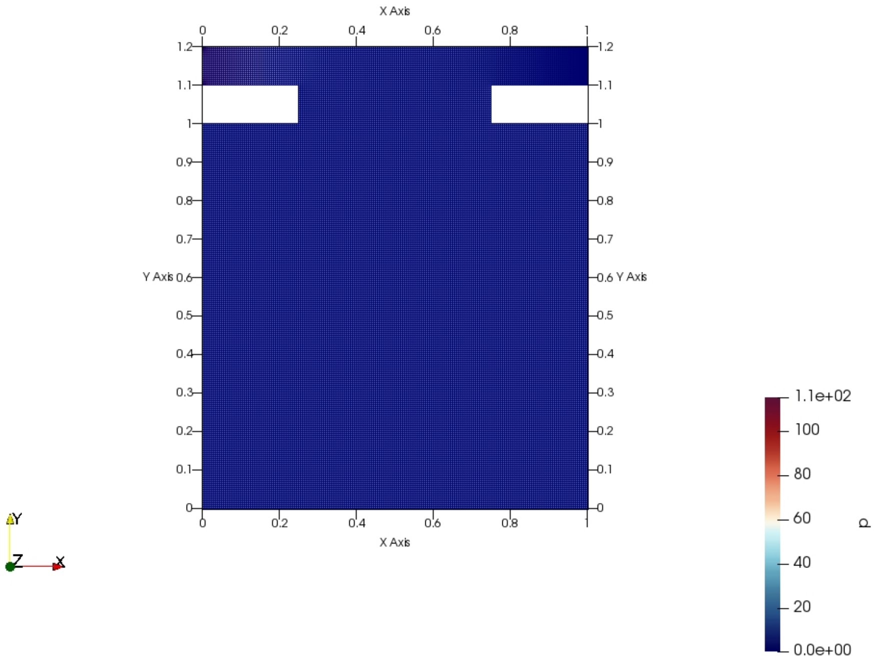
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0.4
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Y Axis
Y
Z
X
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80
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40
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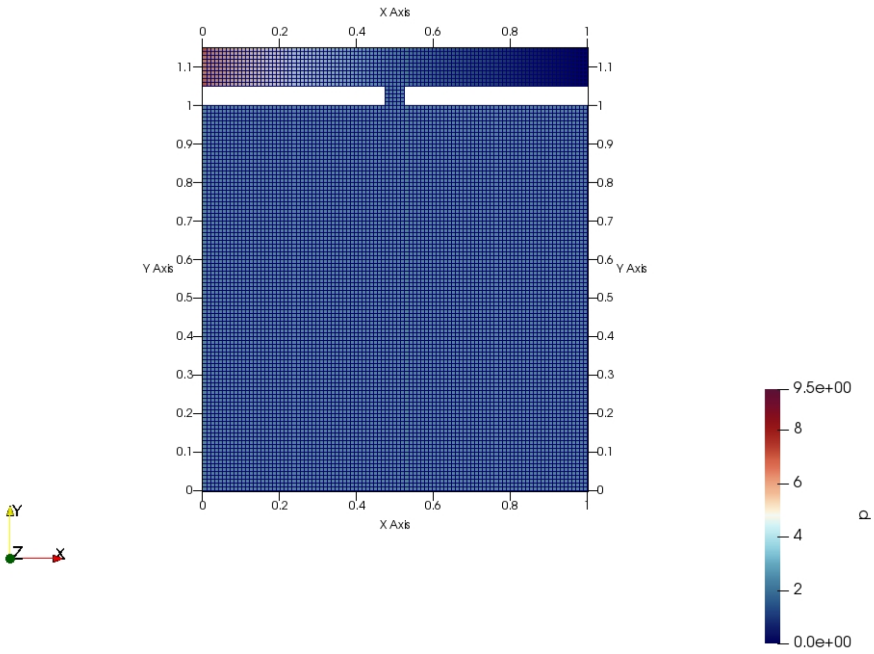
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0.2
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Y Axis
Y Axis
X Axis
Y
Z
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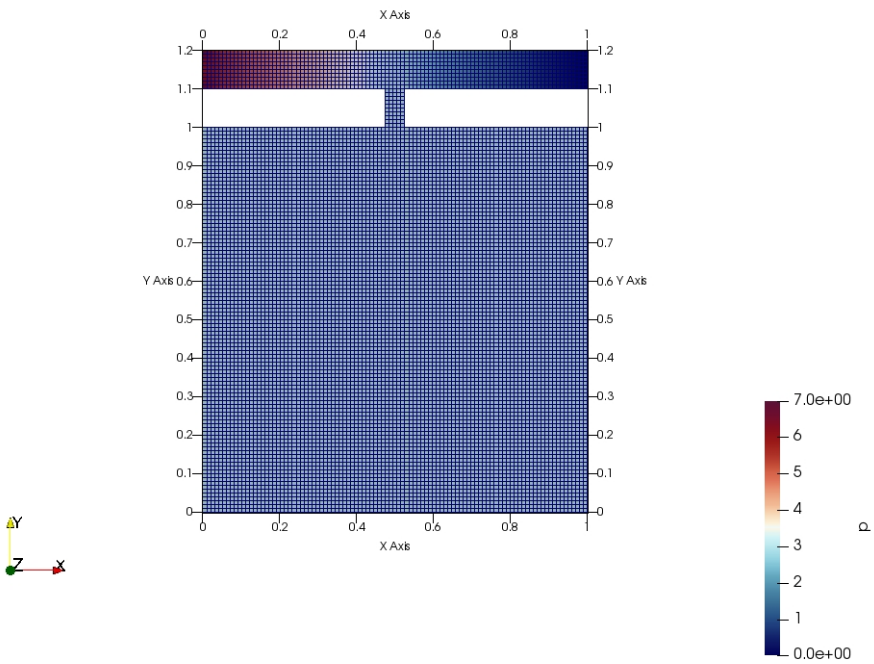
4
2
0.0e+00
p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0.3
0.2
0.1
0
Y Axis
Y Axis
X Axis
Y
Z
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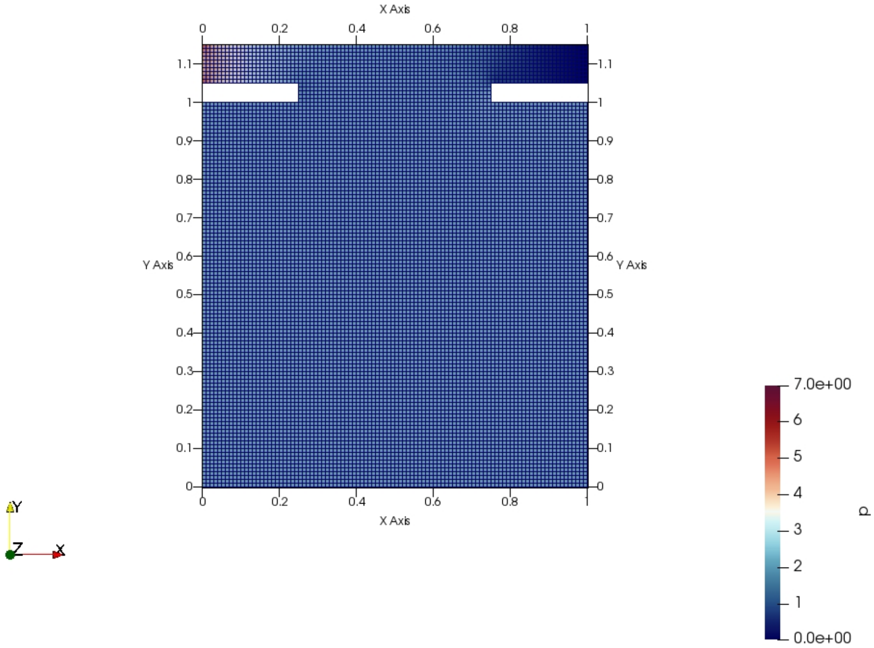
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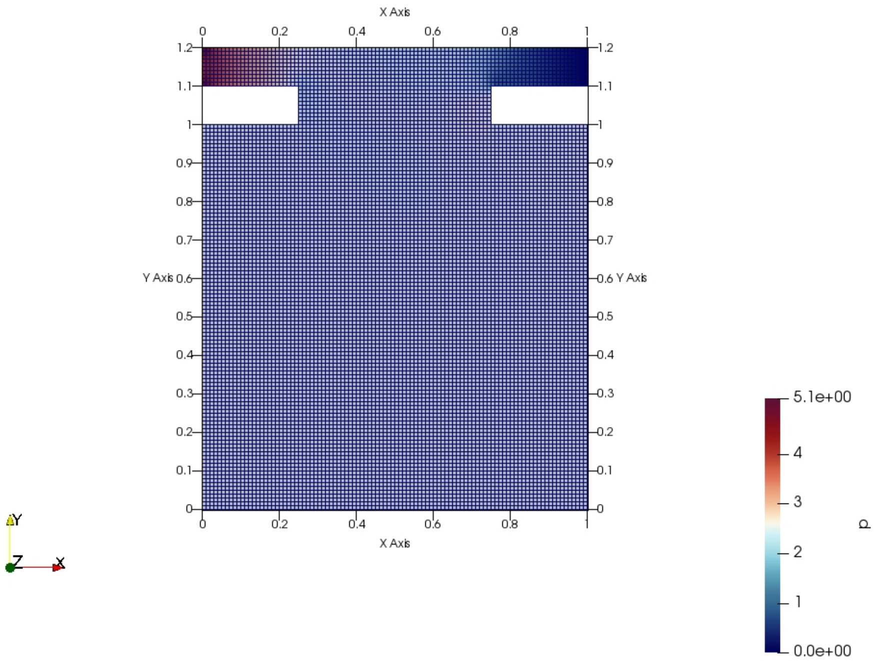
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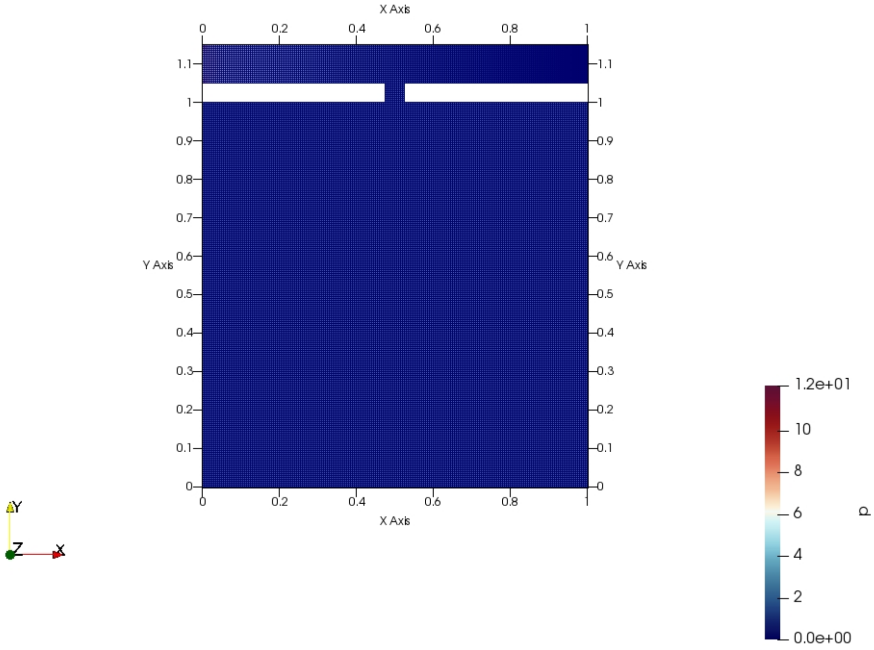
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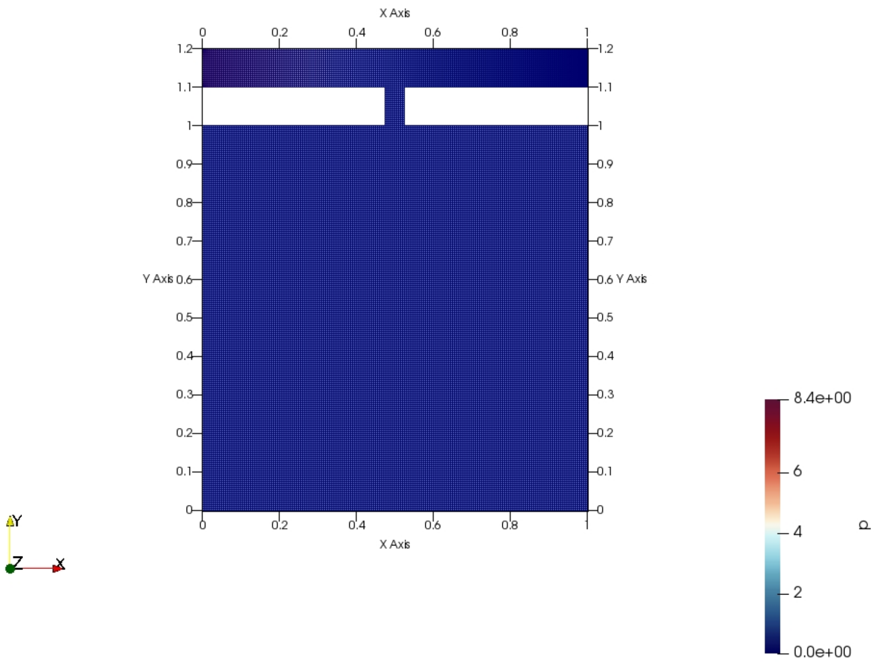
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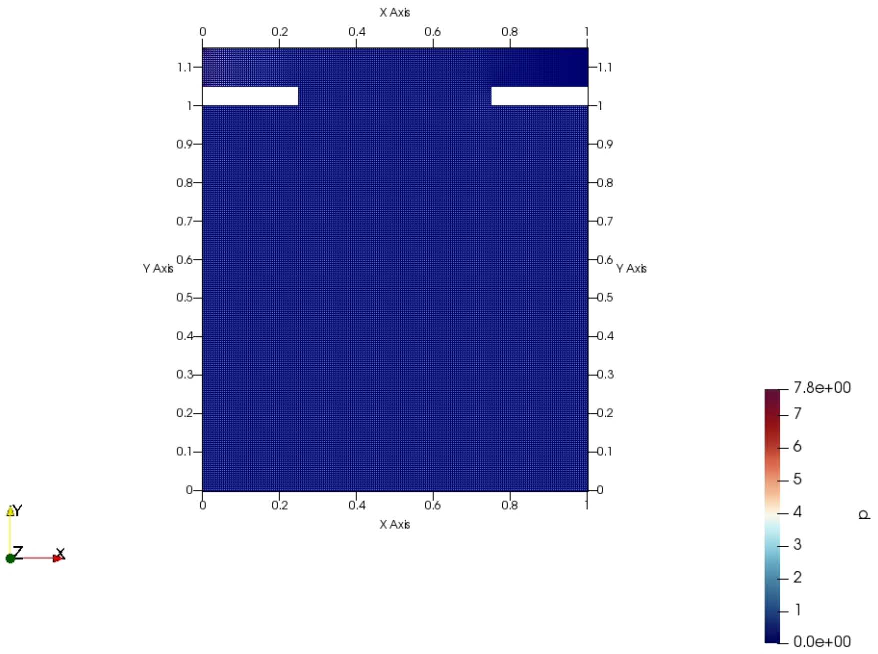
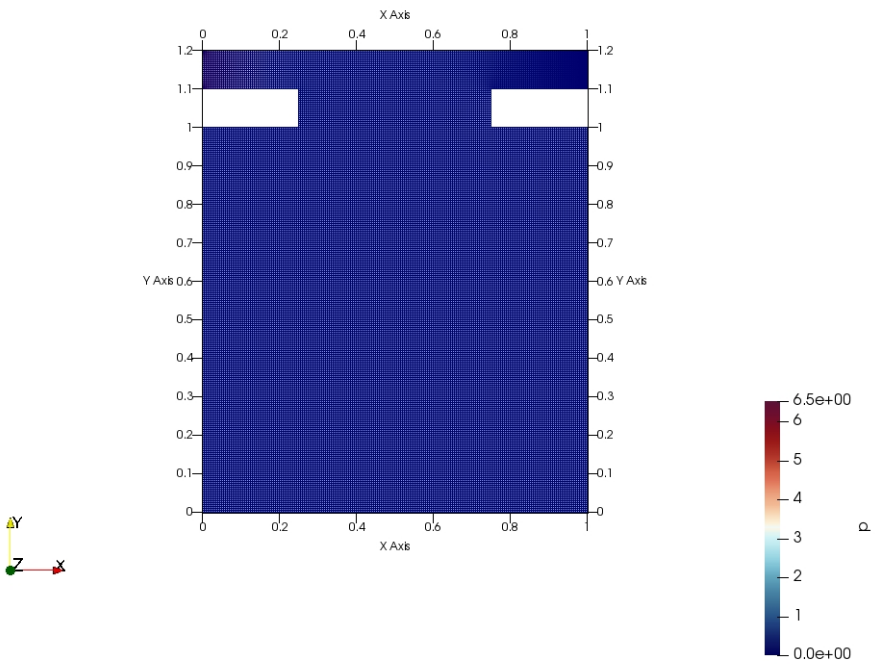
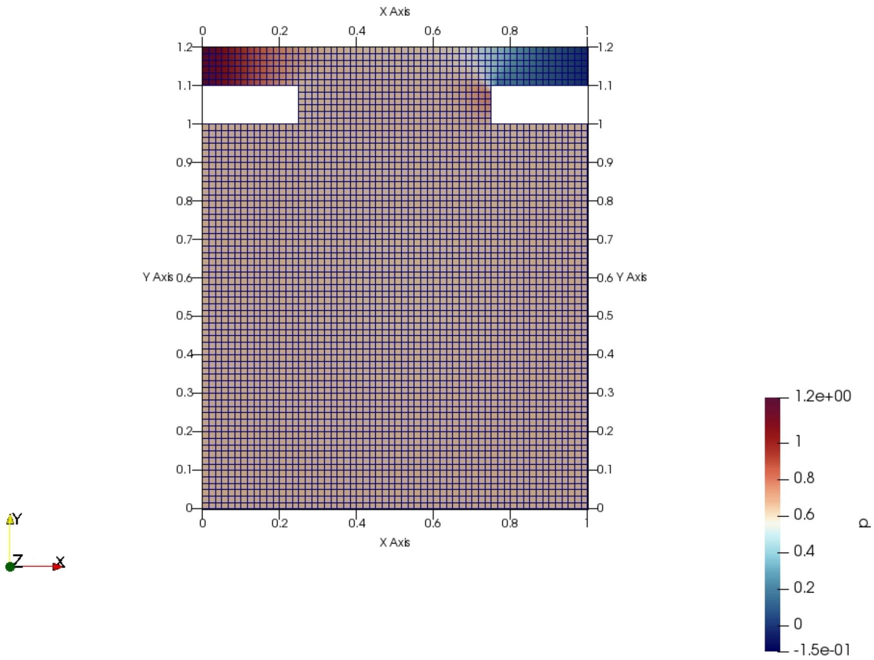




Mesh Images for the High Reynolds simulations (same order)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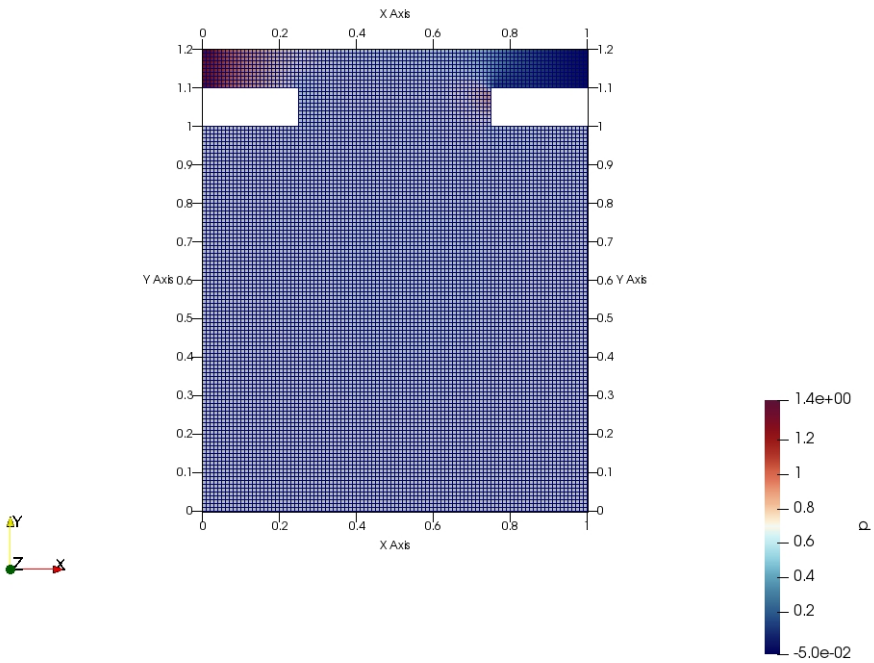
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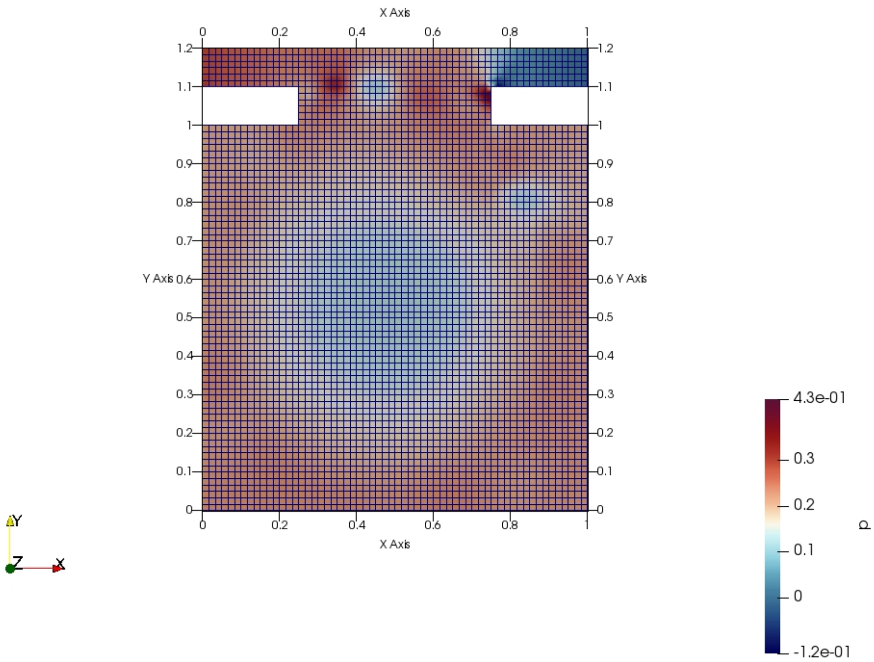

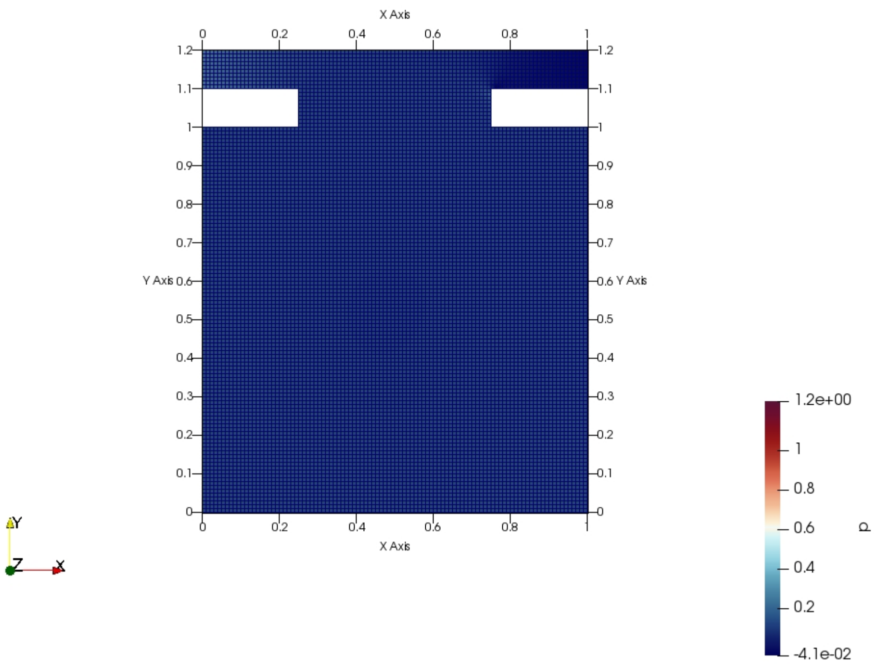

(2019, May). *Super Inspection Pros*. Retrieved from https://superinspectionpros.local:57400/blog/how-high-does-wind-speed-need-to-be-to-damage-a-home/

Allaire J, Xie Y, McPherson J, Luraschi J, Ushey K, Atkins A, Wickham H, Cheng J, Chang W, Iannone R (2021). *Rmarkdown: Dynamic Documents for r*. Retrieved from https://CRAN.R-project.org/package=rmarkdown

Bengtsson H (2021). *R.utils: Various Programming Utilities*. Retrieved from https://github.com/HenrikBengtsson/R.utils

Hadhazy A (2011, May). "How a Tornado Can Destroy a House." *Popular Mechanics*. Retrieved from https://www.popularmechanics.com/outdoors/survival/stories/gone-in-four-seconds-how-a-tornado-destroys-a-house

Tessner T (2021, August). "What Are Hurricane Shutters? An Introduction to Hurricane Shutters." *Eurex Shutters*. Retrieved from https://eurexshutters.com/what-are-hurricane-shutters/

Urbanek S (2021). *Jpeg: Read and Write JPEG Images*. Retrieved from http://www.rforge.net/jpeg/

Xie Y (2013). "animation: An R Package for Creating Animations and Demonstrating Statistical Methods." *Journal of Statistical Software*, **53**(1), 1–27. Retrieved from https://doi.org/10.18637/jss.v053.i01

Xie Y (2014). "Knitr: A Comprehensive Tool for Reproducible Research in R." In *Implementing reproducible computational research*, eds. V Stodden, F Leisch, and RD Peng,. Chapman; Hall/CRC. Retrieved from http://www.crcpress.com/product/isbn/9781466561595

Xie Y (2015). *Dynamic Documents with R and Knitr* 2nd ed. Chapman; Hall/CRC, Boca Raton, Florida. Retrieved from https://yihui.org/knitr/

Xie Y (2021a). *Animation: A Gallery of Animations in Statistics and Utilities to Create Animations*. Retrieved from https://yihui.org/animation/

Xie Y (2021b). *Knitr: A General-Purpose Package for Dynamic Report Generation in r*. Retrieved from https://yihui.org/knitr/

Xie Y, Allaire JJ, Grolemund G (2018). *R Markdown: The Definitive Guide*. Chapman; Hall/CRC, Boca Raton, Florida. Retrieved from https://bookdown.org/yihui/rmarkdown

Xie Y, Dervieux C, Riederer E (2020). *R Markdown Cookbook*. Chapman; Hall/CRC, Boca Raton, Florida. Retrieved from https://bookdown.org/yihui/rmarkdown-cookbook

9. Acknowledgements

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