



## 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  $10^4$ . 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.

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### 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.

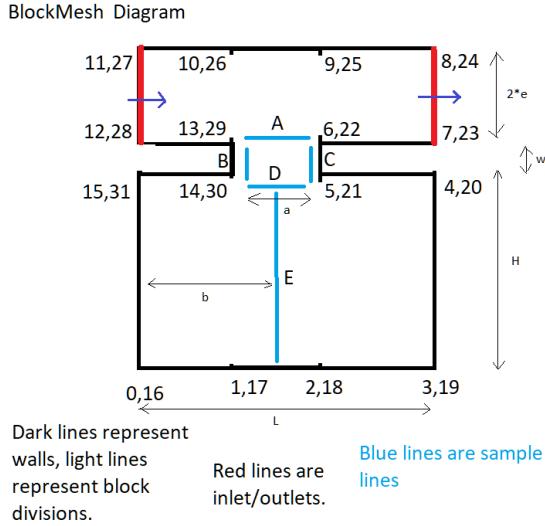
### 2. Implementation

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

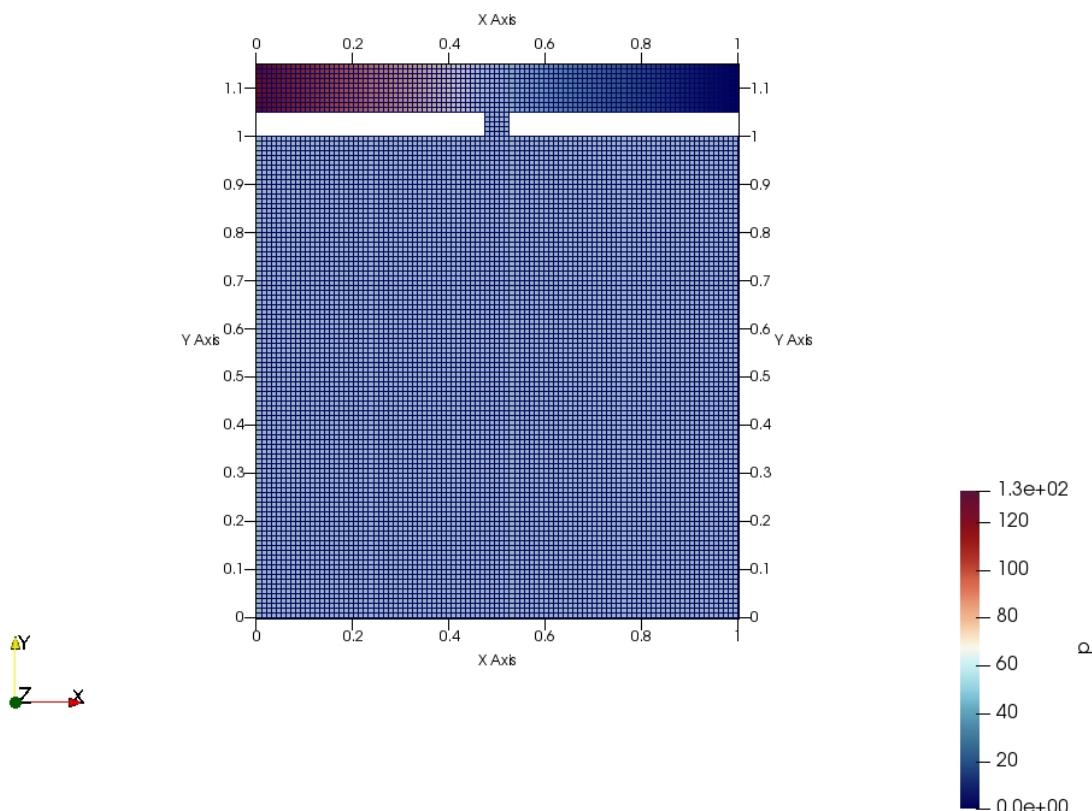
Table 2:

BlockMeshDict and similar files are available at [the repository](#).

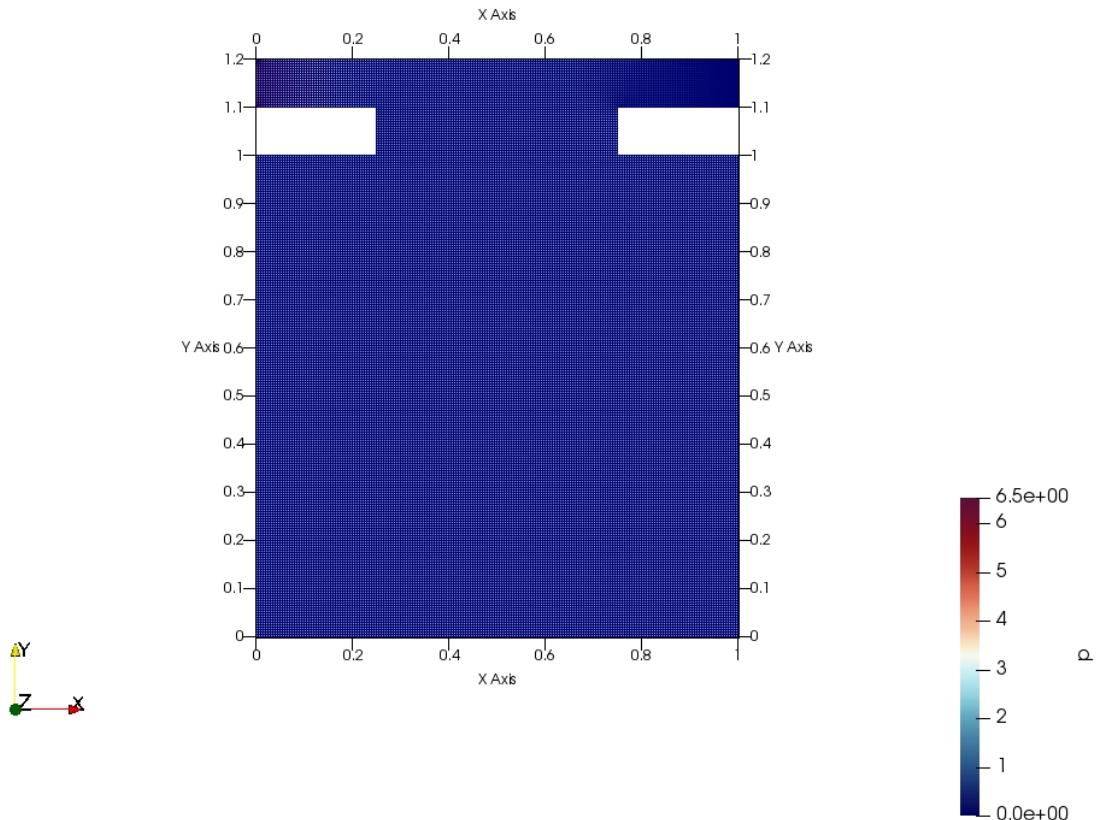
### 3.3. Mesh Images

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 tandem generating lift on top of normal stressors. As roof connections rely primarily on gravity to ensure stability, 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 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  $\frac{p}{\rho U^2}$ .

### 5.4. General Solution Form

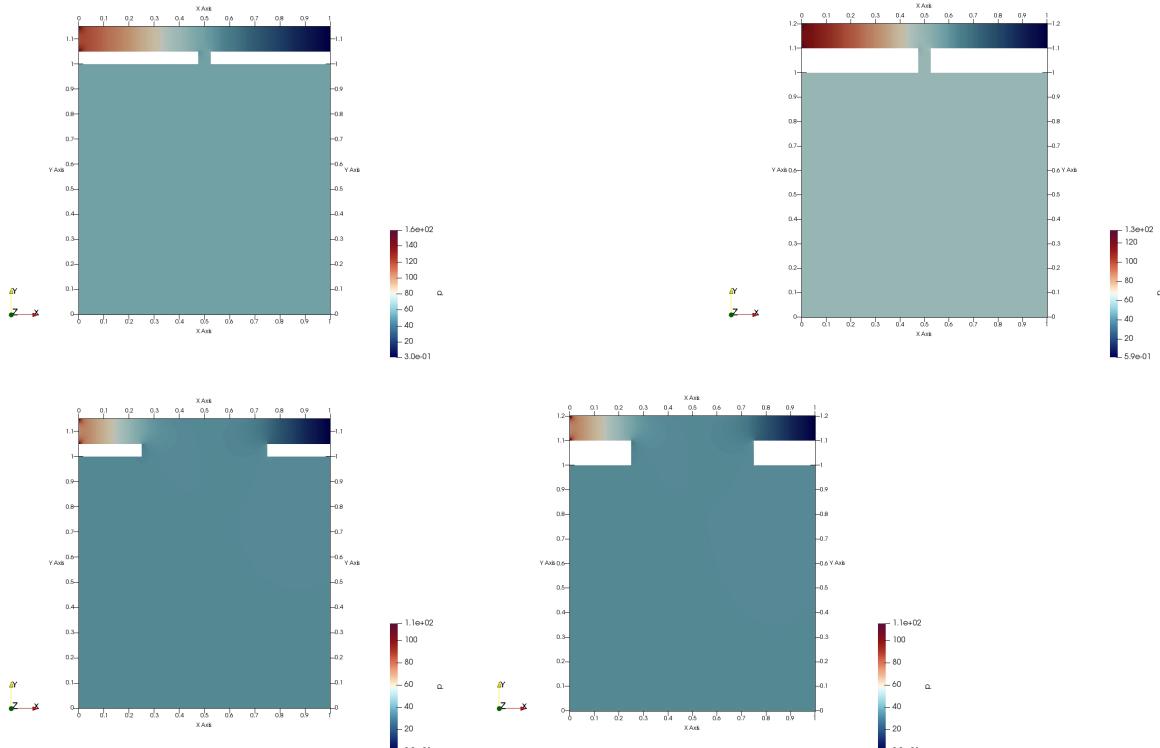
We will now show the pressure, X-velocity, Y-velocity, and streamlines in sets of 4 by varying geometry along the following pattern. Contours are not shown due to their bias toward out-of-cavity portions and the coarse mesh will be omitted for brevity. Convergence studies will be done numerically afterward.

Pattern:

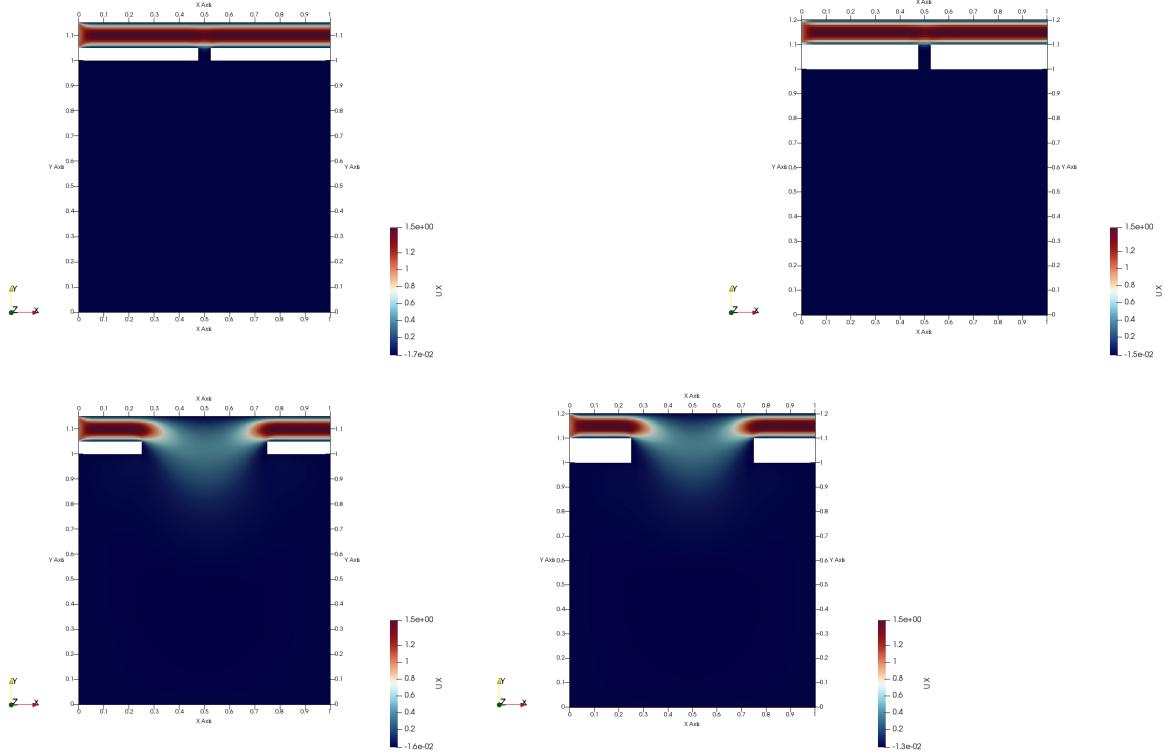
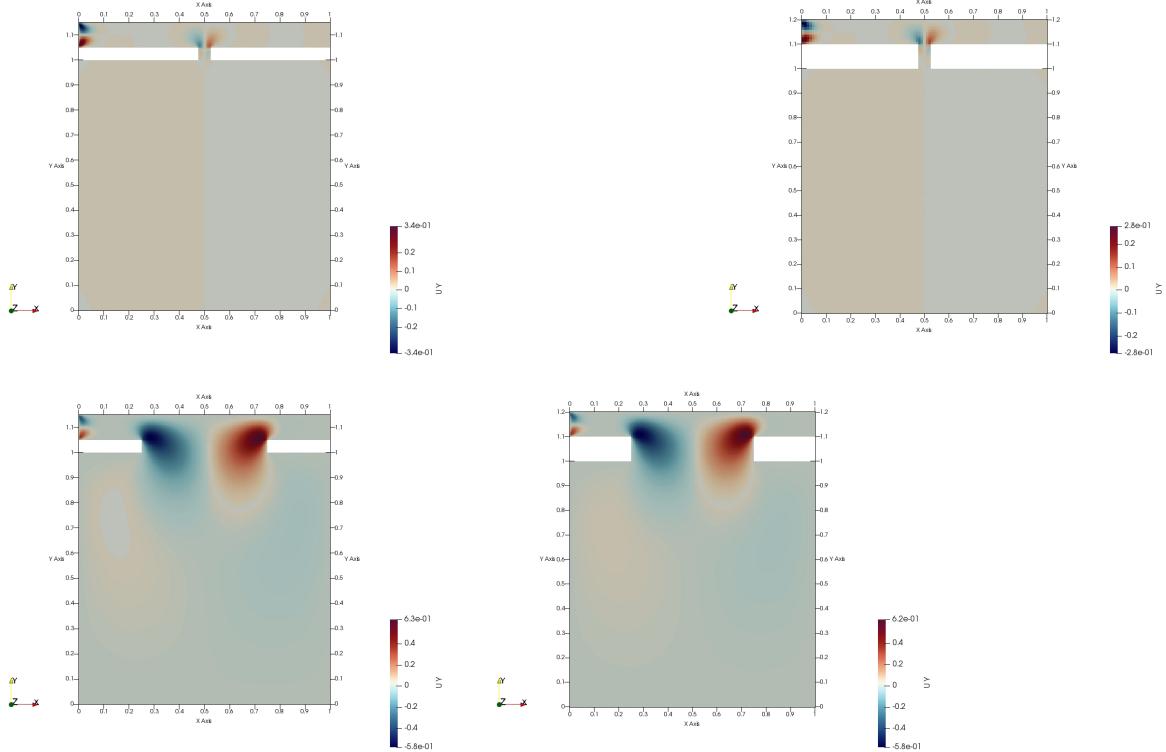
window.size.a	wall.thickness.w
0.05	0.05
0.05	0.10
0.50	0.05
0.50	0.10

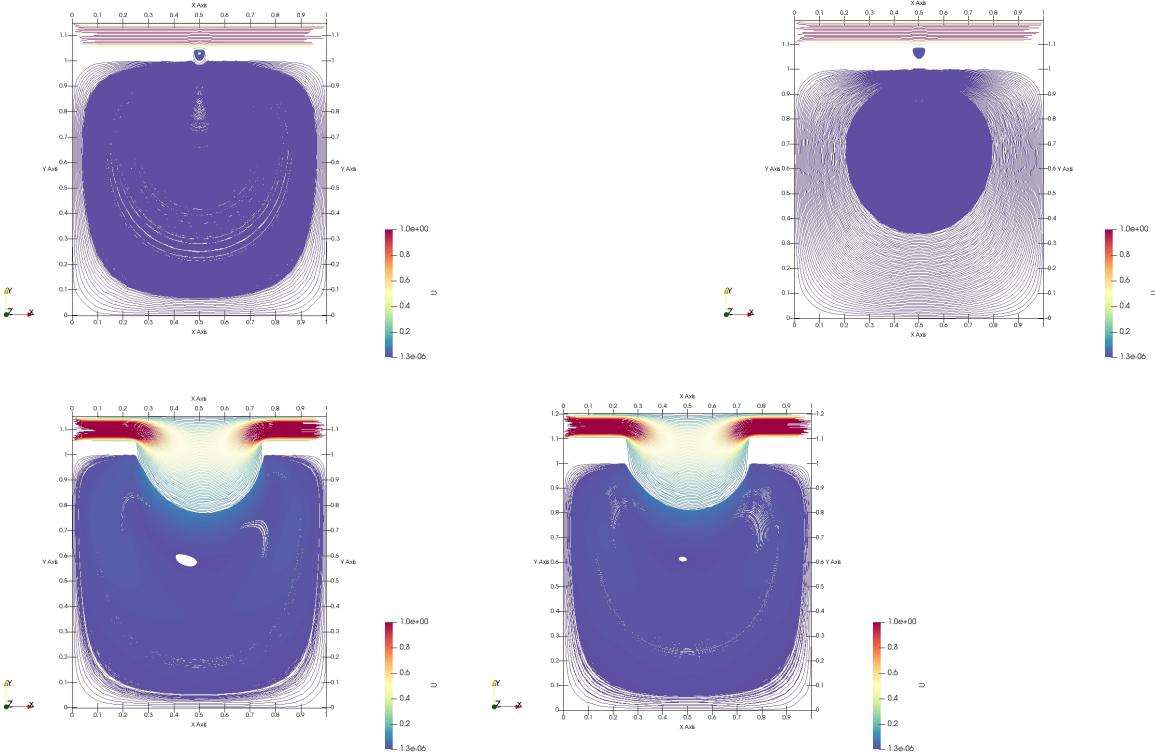
Table 3:

### Re=10, Pressure



### Re=10, X-velocity

**Re=10, Y-velocity****Re=10, Streamlines**



## 5.5. Vortice Positions

- table of vortice positions

## 5.6. Window Wall Solution Profiles

- profiles for Left and Right

## 5.7. Cavity Midline Solution Profile

- midline profiles  
# High Reynolds Number - Part 1

## 5.8. General Solution Form

- show basic solution images here for both Re and make general arguments

## 5.9. Strouhal Number and Vortex Shedding

- FFT plots
- STFT plots
- table of values for Strouhal

## 5.10. Volumetric Flow Rate and Mixing

- plots
- generic argument / example for UAV and

## 5.11. Window Wall Strain Rate

**T = 1.47 (unsteady startup)**

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

**Maximum Strain Rate over Time**

## **6. High Reynolds Number - Part 2**

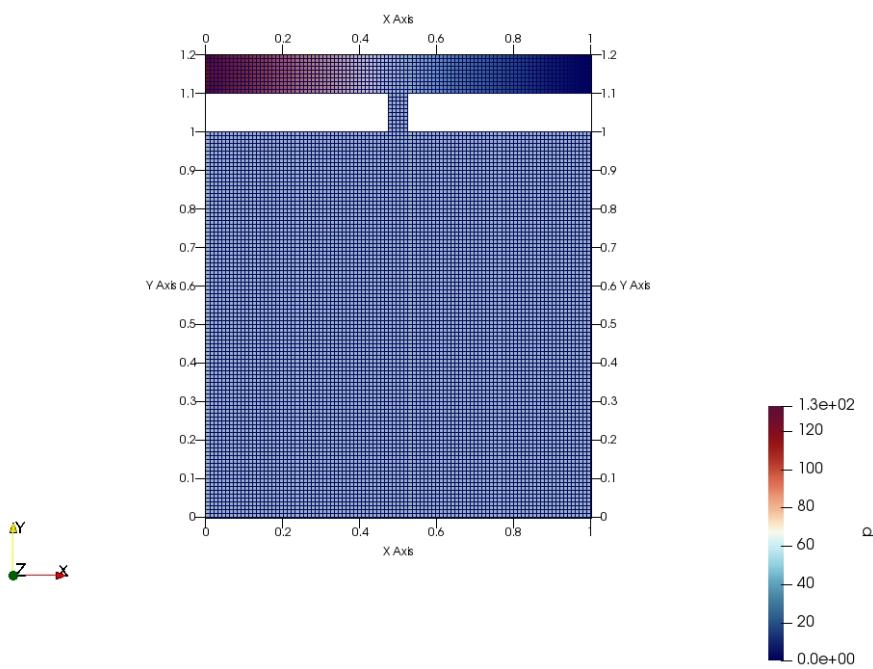
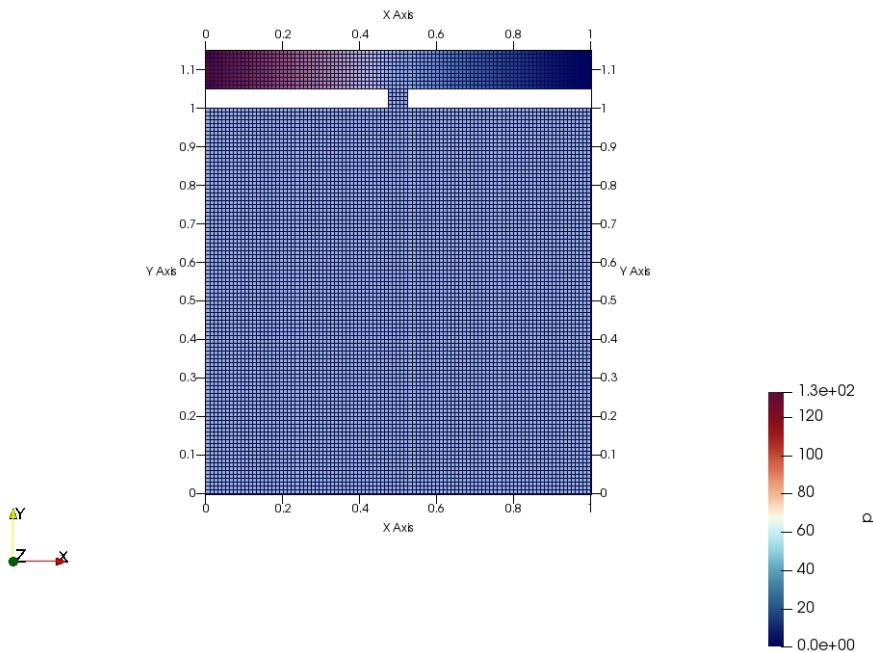
## **7. Conclusions**

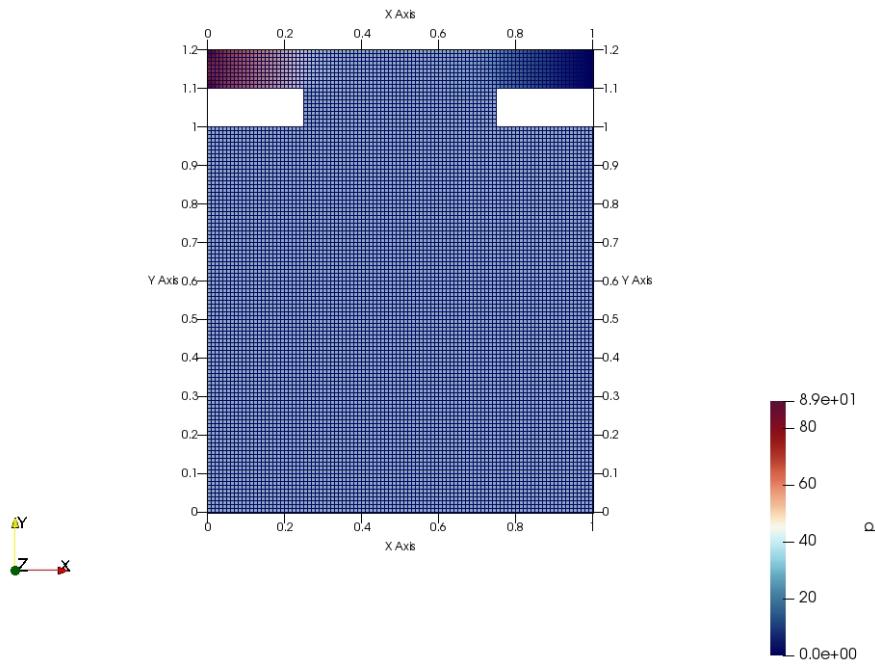
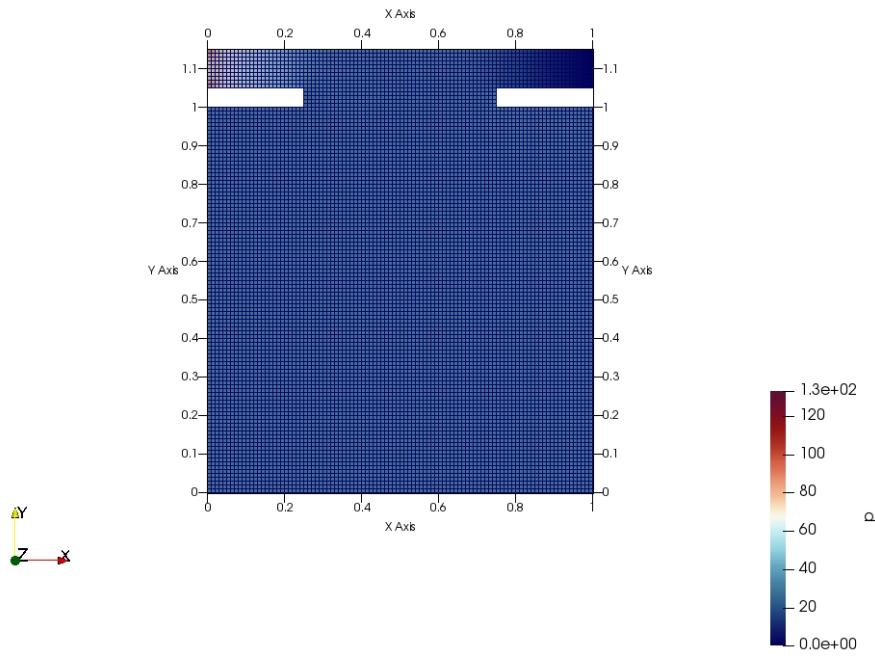
## **8. References**

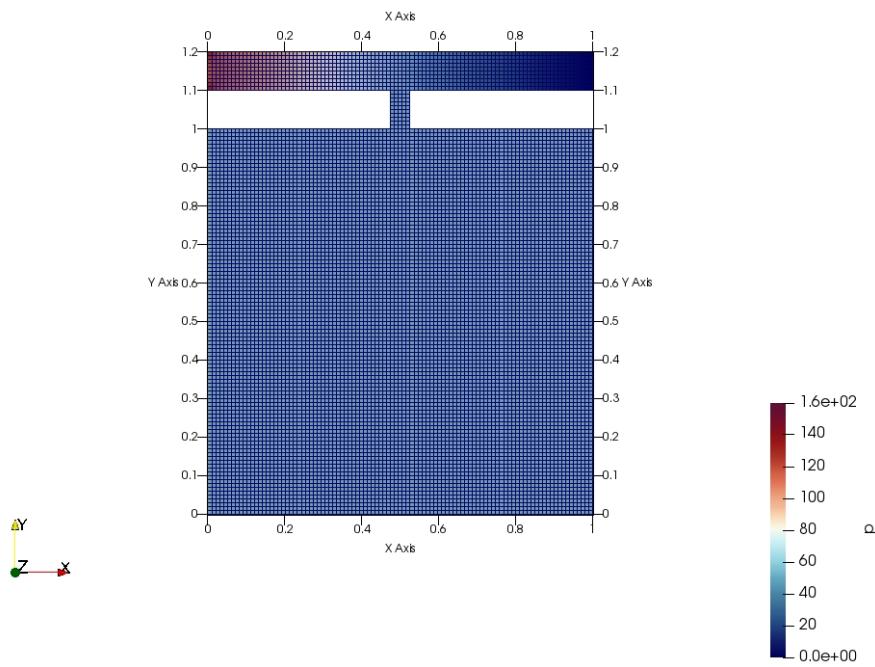
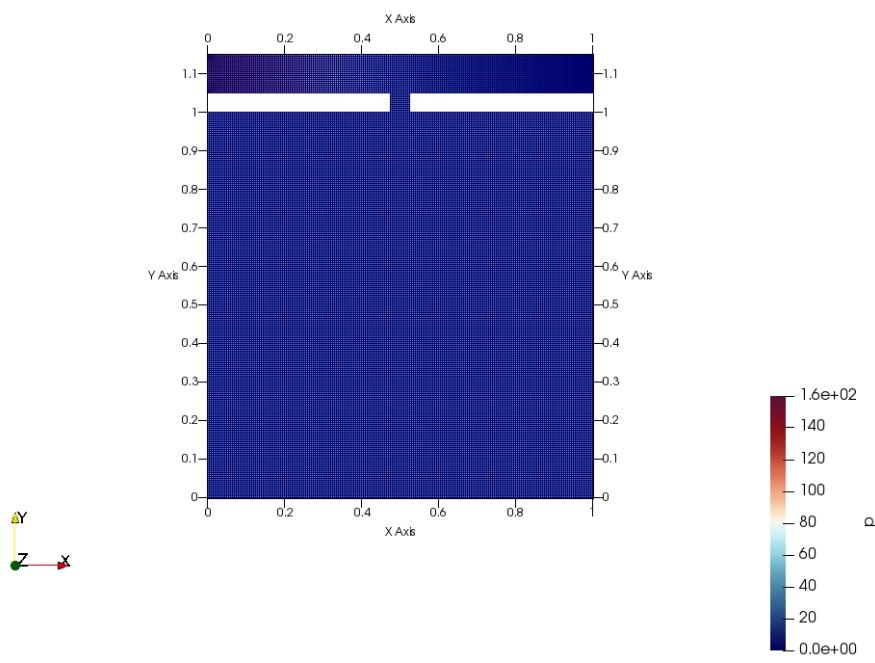
## **9. Appendix**

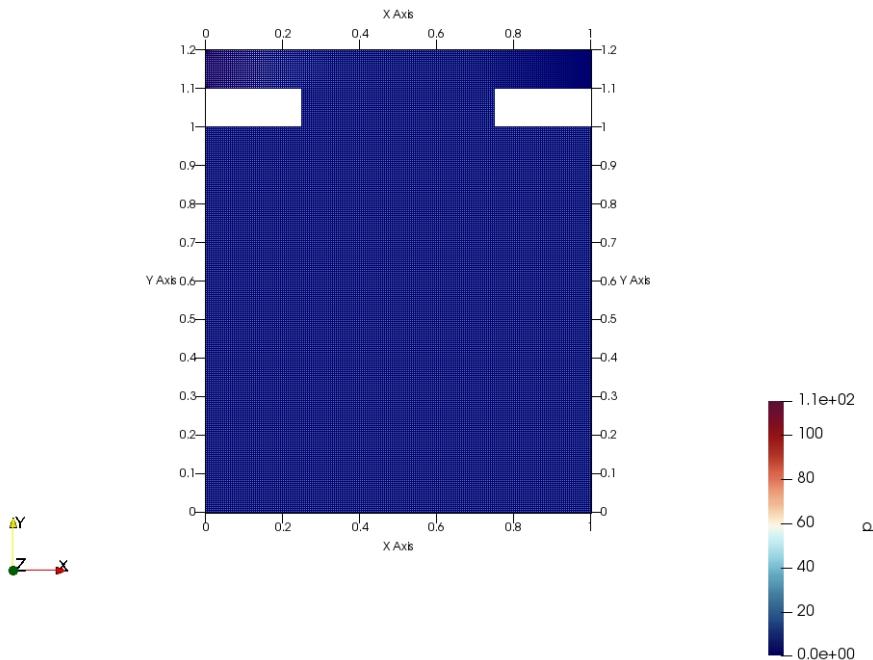
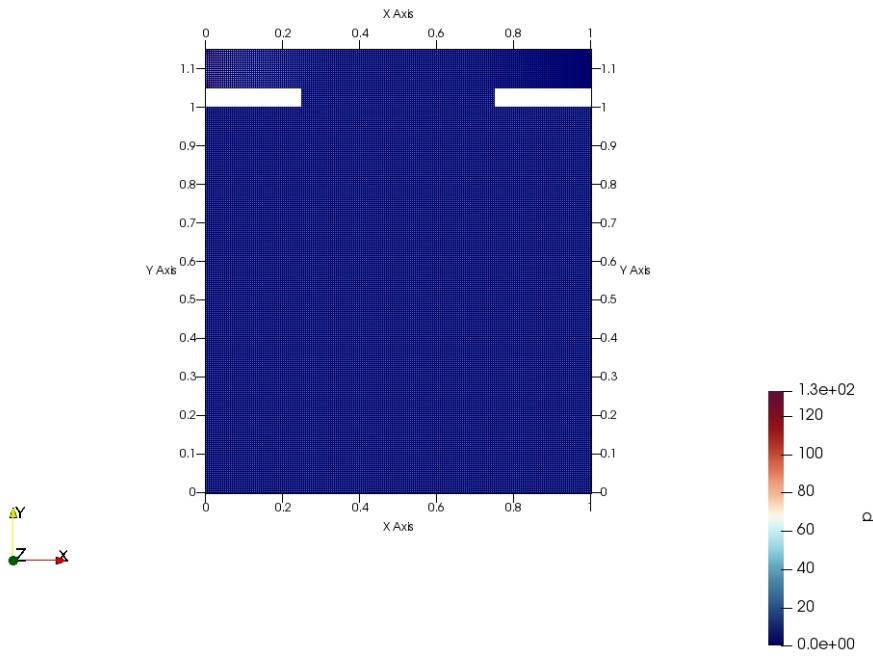
### **9.12. Mesh Images**

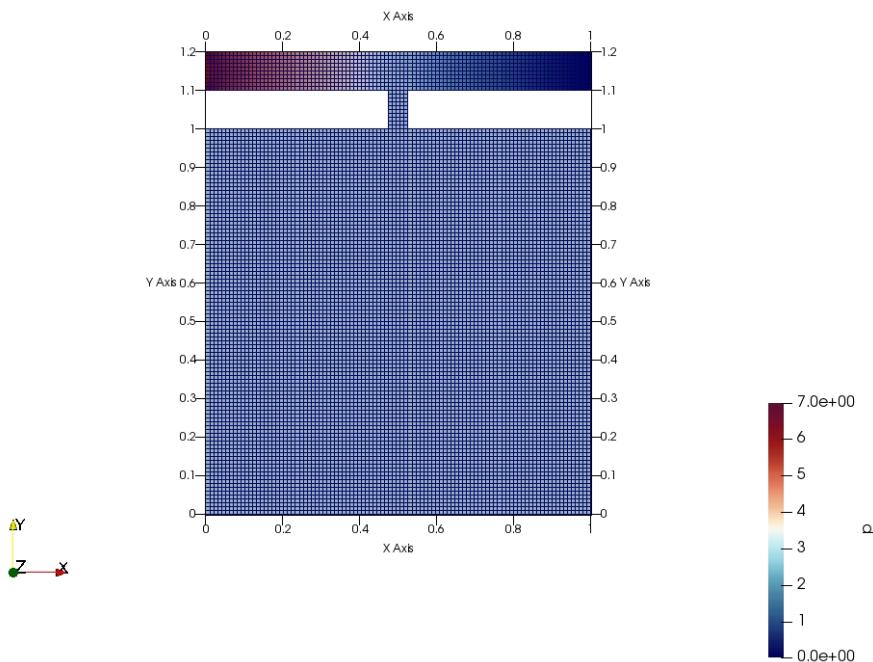
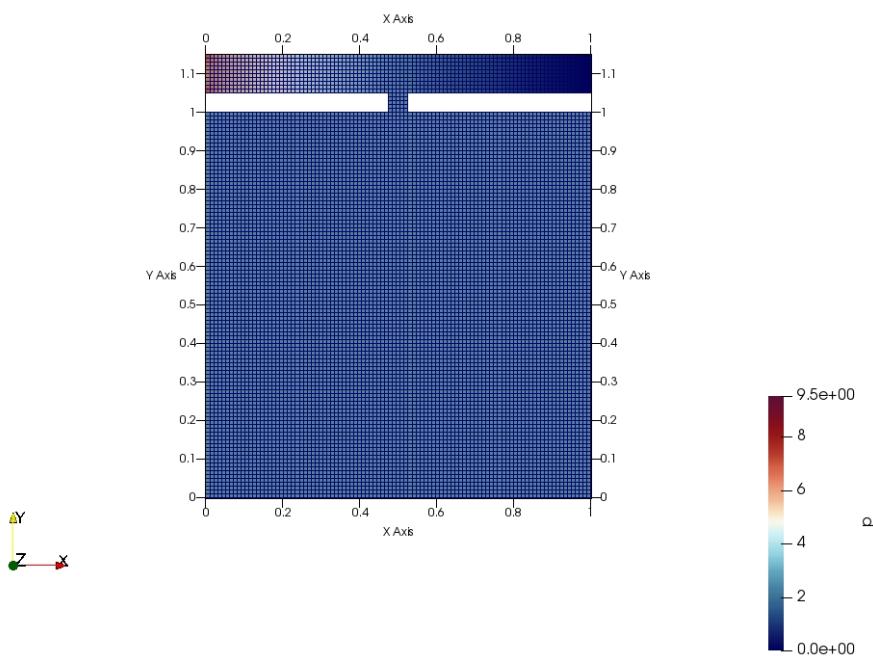
**Mesh Images for the Low Reynolds simulations (same order)**

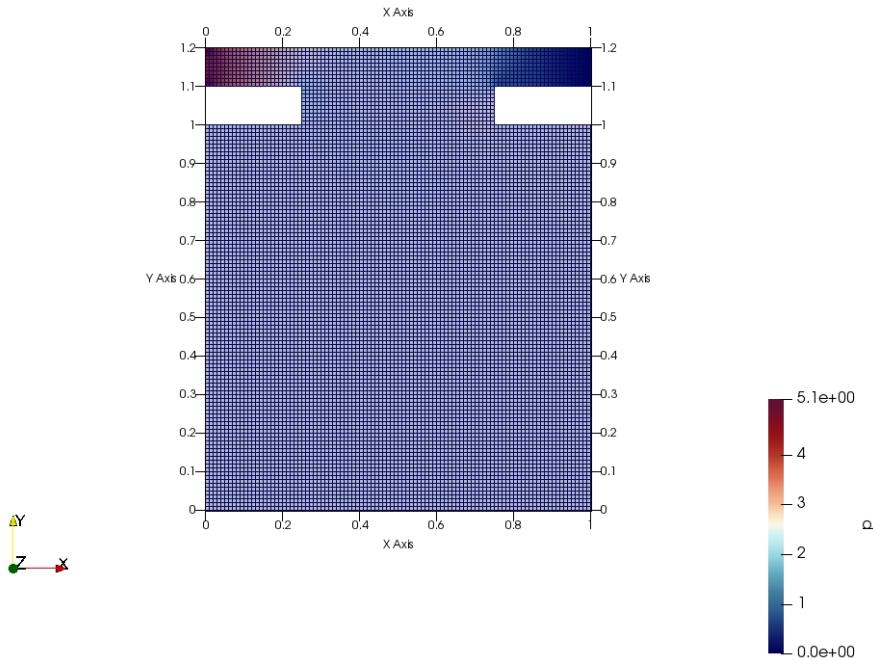
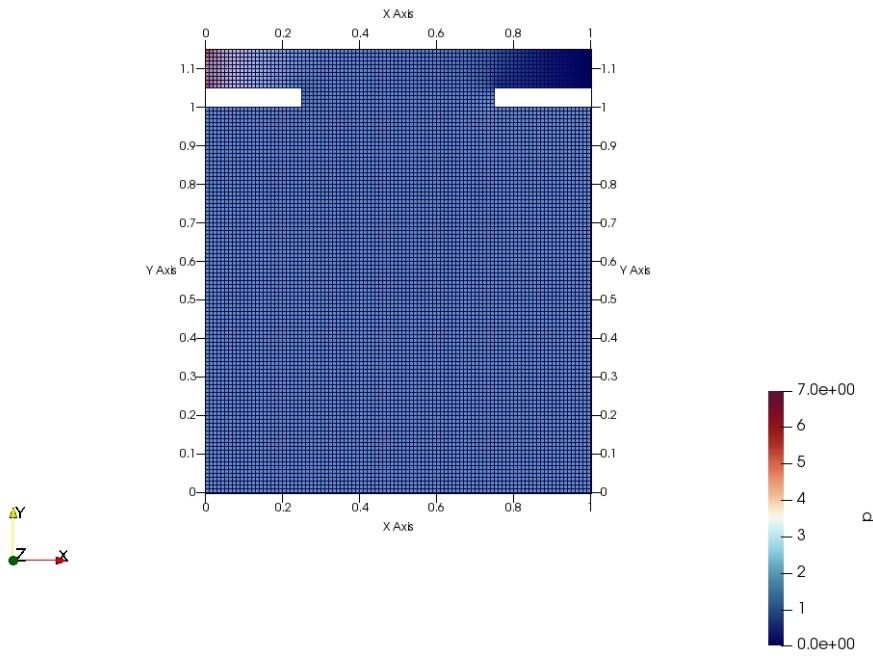


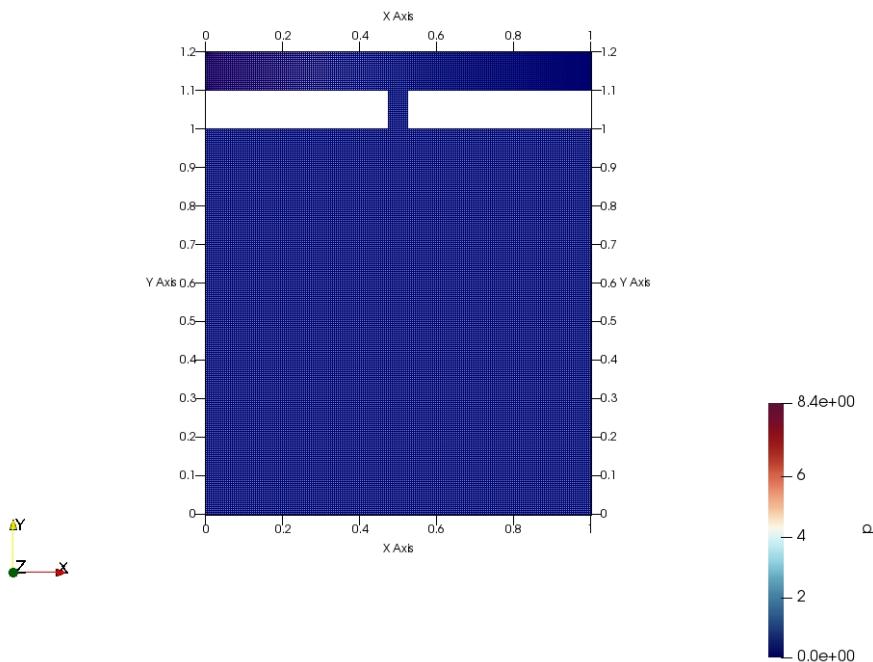
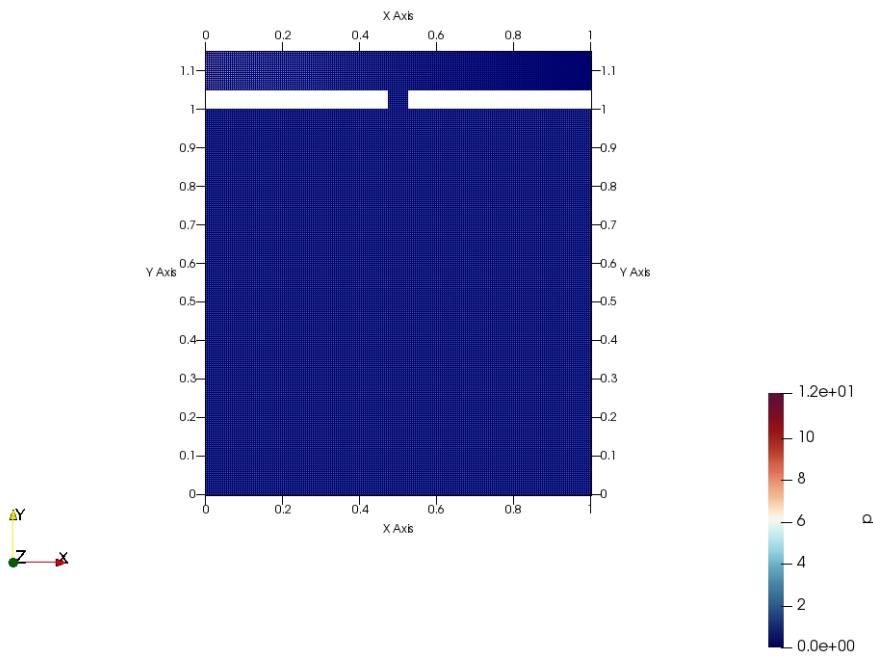


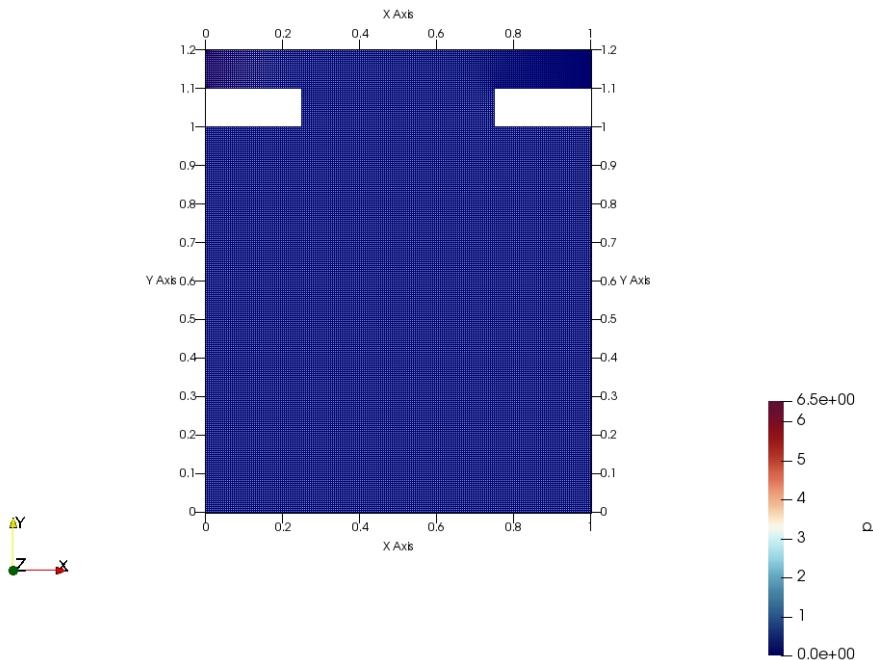
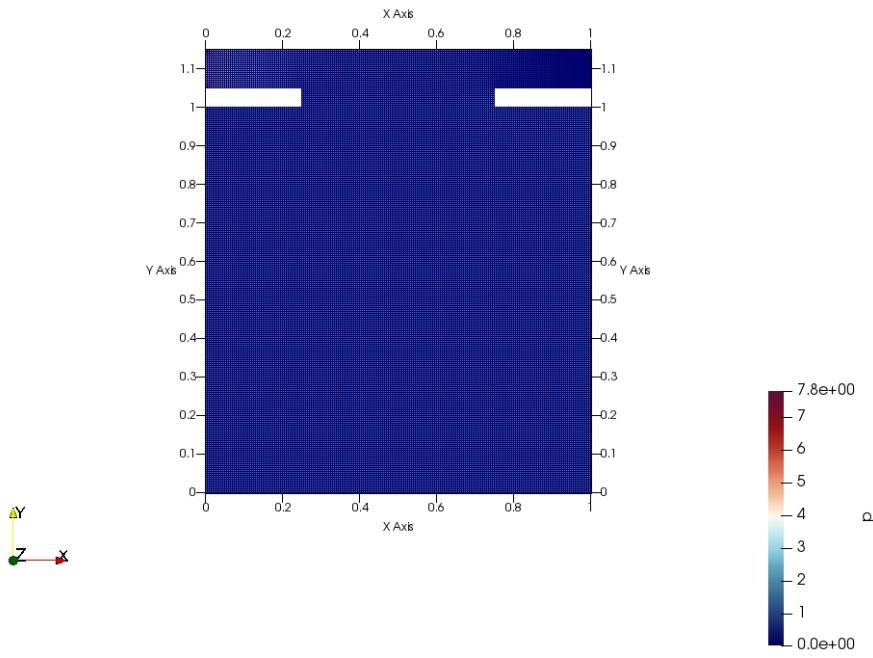




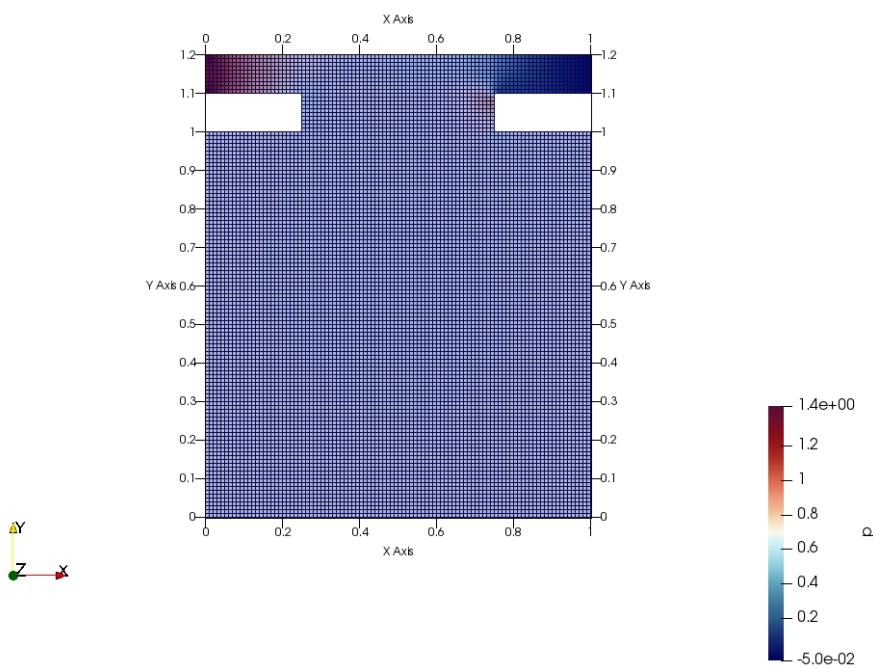
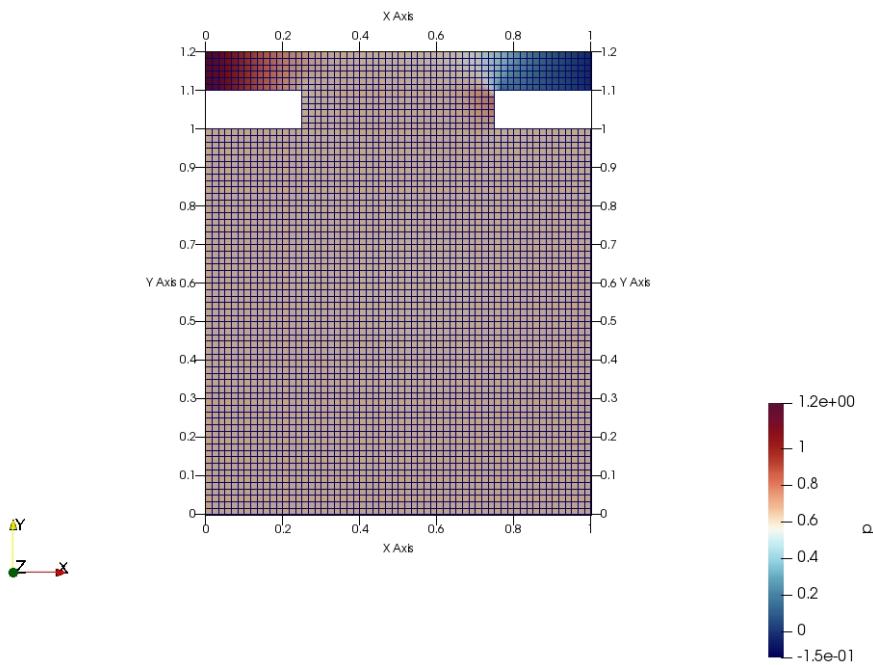


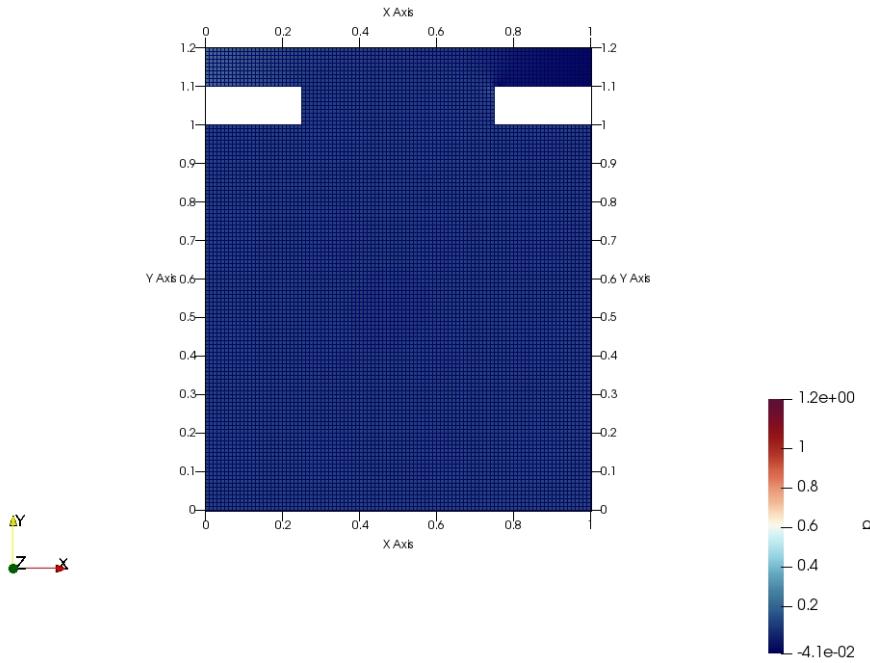
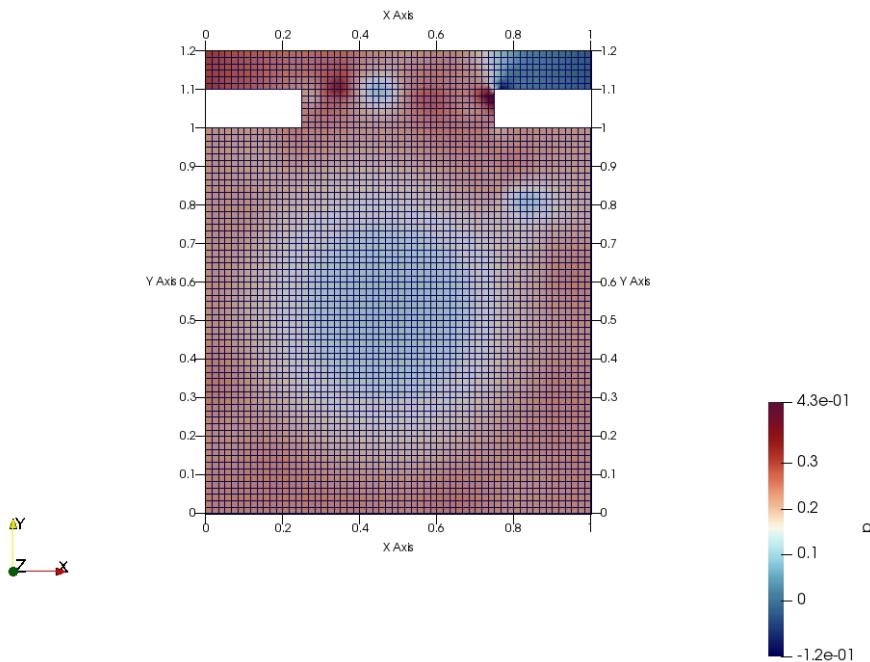






**Mesh Images for the High Reynolds simulations (same order)**





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## 10. Acknowledgements

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