REPORT 1: BACKWARD-FACING STEP WITH A DOWNSTREAM BUMP

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1. INTRODUCTION

The purpose of this report is to provide a CFD analysis of a variant of the backward facing step geometry. The main focus being how the CFD produced flow-fields are affected by different residual tolerances. Four different residual tolerances will be investigated: 0.1, 0.01, 0.001 and 0.0001.

The residuals are the only variable that is altered in the investigation and all other variables such as the geometry, boundary conditions, fluid properties, mesh design and solution methods are consistent prior to each simulation.

2. GEOMETRY AND BOUNDARY CONDITIONS

2.1 Geometry

In figure 1, the layout of the solution domain is illustrated. Lengths, X_1 and X_2 were purposely extended in length. X_1 was extended to allow for the flow to fully develop (boundary layer formation) in the inlet channel. X_2 was extended to ensure that the reattachment point, if present, was captured and was not outside of the solution domain.

Table 1: Dimensions of solution domain

Parameter	Length (mm)
X_1	300
X_2	600
X_3	136
X_B	60
h	40
H_B	20
H	53

2.2 Boundary Conditions

All walls are stationary and non-slip. This is to simulate real walls which have boundary layer development. There is only one inlet and one outlet. The inlet velocity was calculated using the Reynolds equation (1) and substituting the fluid properties and solution domain data provided.

$$R_e = \frac{\rho U_\infty H}{\mu} \qquad (1)$$

$$24500 = \frac{1.225 * (U_\infty) * 0.053}{(1.7894e-05)}$$

$$U_\infty = 6.752453\ m/s$$

2.3 Turbulence Models

Initially a K-epsilon (k-ε) turbulence model was used but the wall thickness required to get a y+ value within the desired 30-300 range was undesirable. The wall thickness was large and required the adjacent cells to be increased in size to avoid poor cell quality due to skewness. This however, lead to a low cell resolution where the flow gradients were expected to be large. To resolve this issue, the K-Omega SST model was applied. K-Omega allows for a finer grid resolution on boundary walls and allowed for a fine, high-resolution mesh to be used. The SST variant of the K-Omega model "combines the advantages" [1] of both k-ε and K-ω turbulence models. It uses the k-ε model in the freestream and K-ω in the boundary layer and has blending function to bridge the two models [1].

2.4 Solution Methods

For structured hexahedral meshes, Green-Gauss Cell Based method is optimal and applied. All

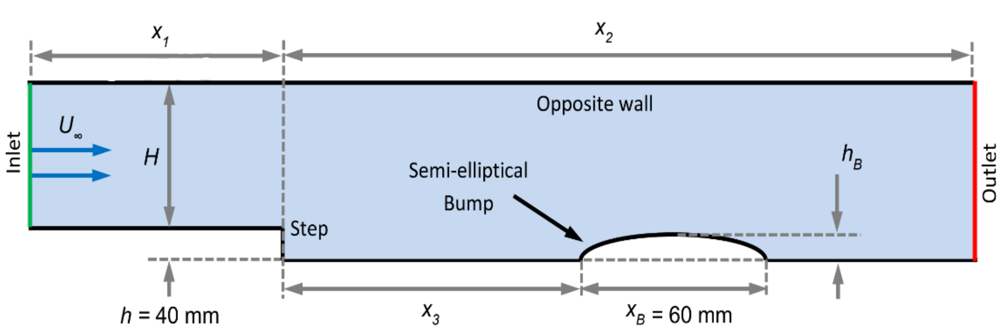


Figure 1: Backward-facing step with elliptical bump layout (not to scale)

spatial discretization terms were set to second order upwind for greater accuracy.

3. MESH DESIGN

A hexahedral mesh was selected as the geometry is mostly cartesian in nature. Applying this type of mesh and utilising specific face sizing and inflation layers, it was possible to refine the mesh where the highest flow gradients are expected.

The highest gradients are expected just after and below the step as seen from previous backward facing step simulations. As such, the cells in the lower region were refined to a size of 5e-4m. This is a reduced sizing from the general element size of 2e-3m. In addition to this, an inflation layer, parallel to chamber walls, starting from the top of the step and extending to the outlet was also added to help capture the flow field.

To ensure that the flow gradients close to the boundary walls and ellipse are captured correctly using a K-Omega (K-ω) turbulence model, an inflation layer on all the walls and ellipse was necessary. The first layer thickness was chosen iteratively until a y+ value approximately equalled the desired value of 1. The first wall thickness is 1.4e-4m and yielded a y value of 1.15. The number of maximum layers for the inflation layer was increased until the skewness of cells was minimised. The optimal number of layers was found to be 7. Figure 2 illustrates the mesh and the density of cells in the lower, aft region of the step.

The mesh was adjusted to reduce skewness, not just generally but also to make sure the most skewed cells were not in the areas of interest and where skewness increased from meshing the curved ellipse wall that it was within acceptable limits (below 0.9). this was done qualitatively by visually inspecting the skewness colour map of the mesh (figure 3) and quantitatively using the built-in mesh metric bar graph in Ansys (figure 4).

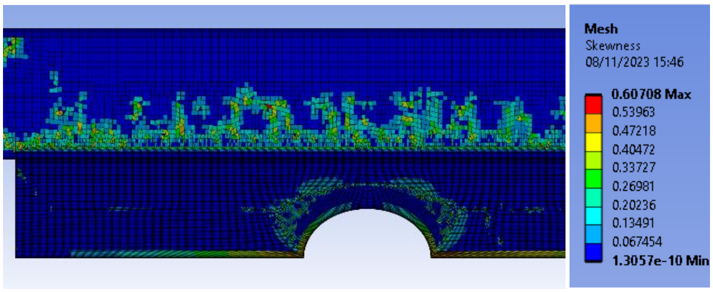


Figure 3: Skewness colour map

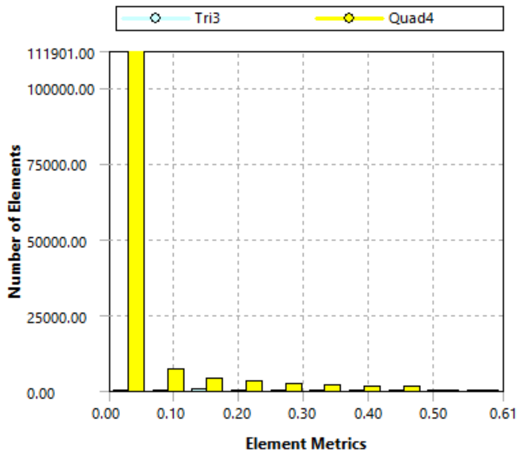


Figure 4: Mesh skewness metric bar chart

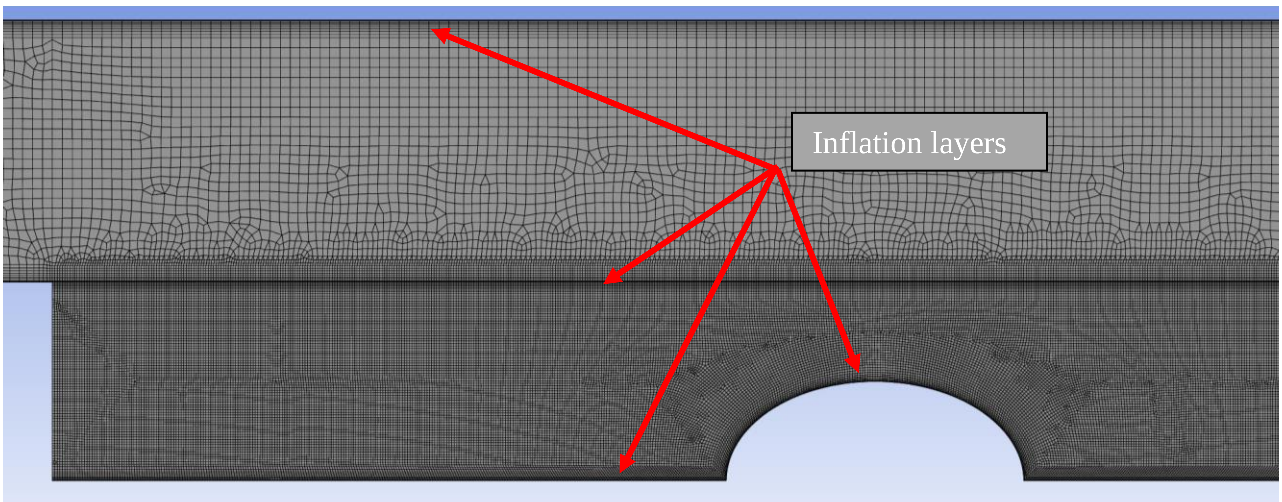


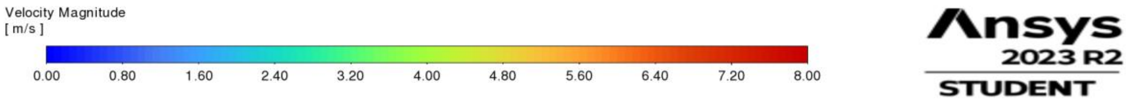
Figure 2: Mesh of target area

4. RESULTS AND ANALYSIS

4.1 Results/Analysis

4.1.1 Vector Magnitude Plot

Figure 5.1: Residual 0.1



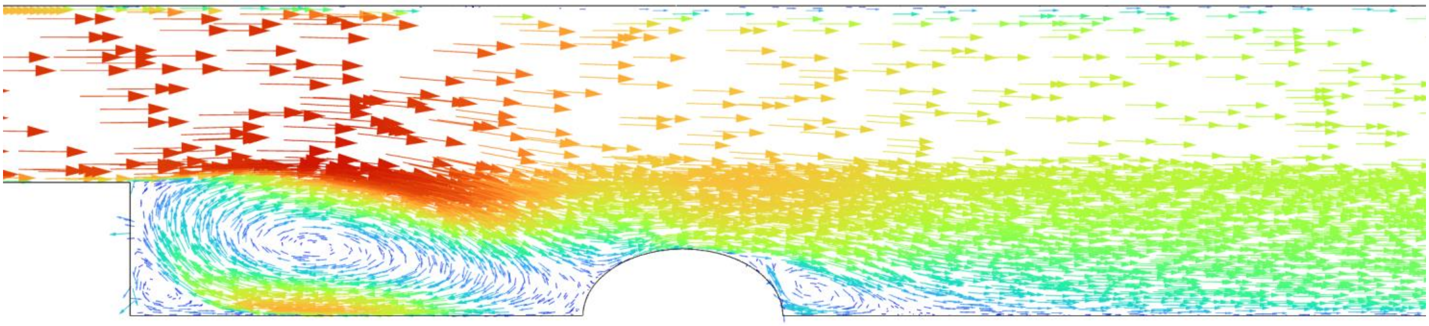


Figure 5.2: Residual 0.01

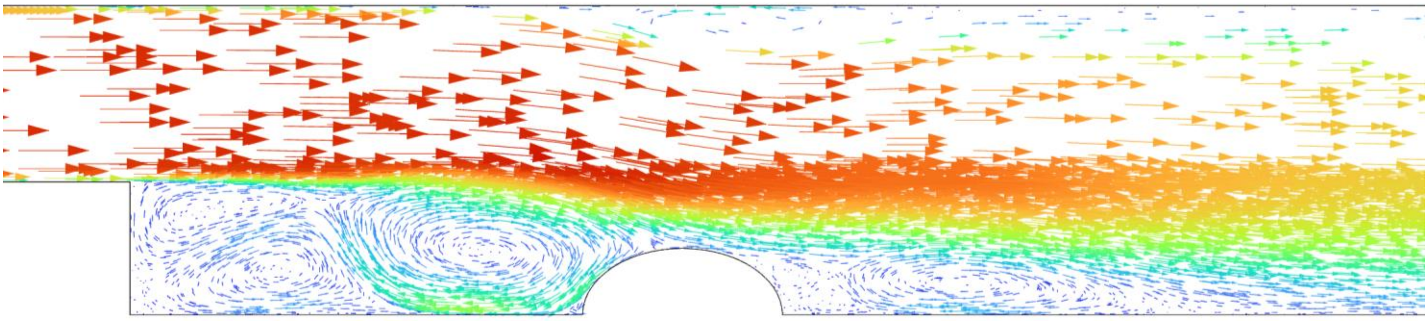


Figure 5.3: Residual 0.001

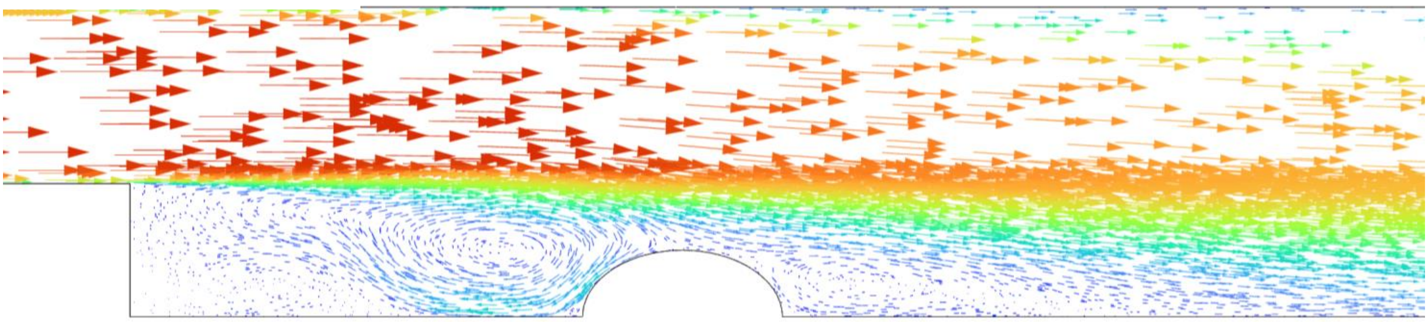
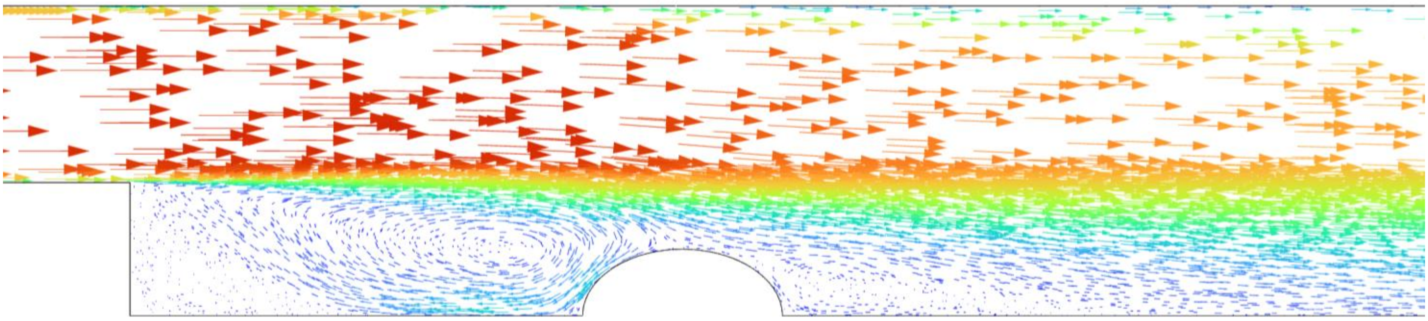
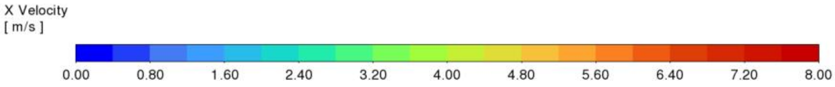


Figure 5.4: Residual 0.0001



4.1.2 X-Velocity plots showing only positive values.

Figure 6.1: Residual 0.1



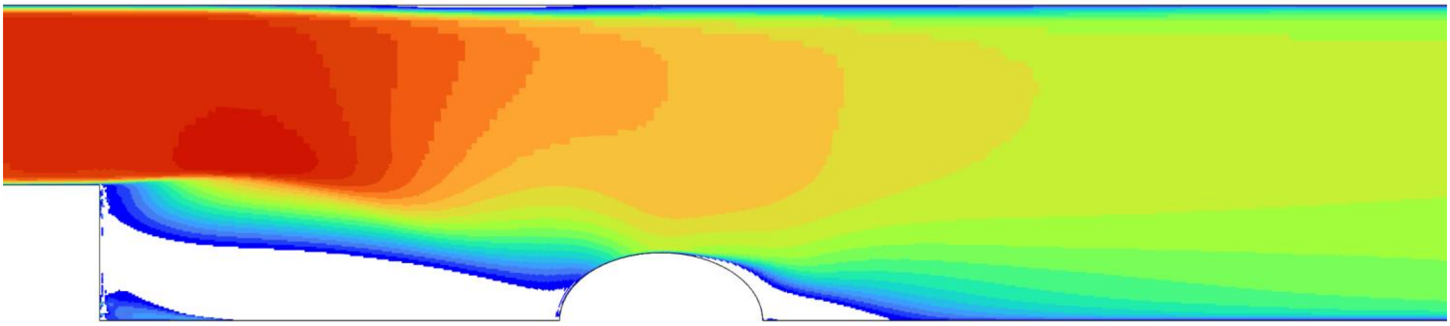


Figure 6.2: Residual 0.01

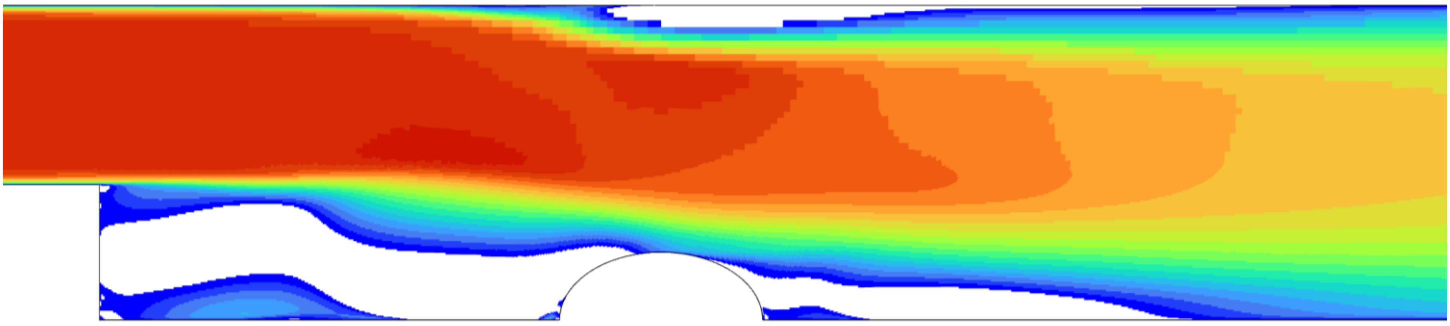


Figure 6.3: Residual 0.001

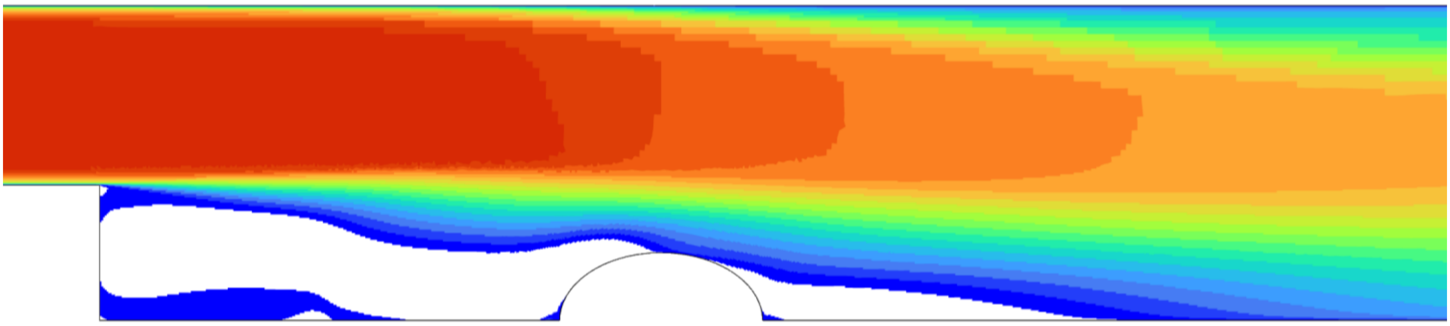
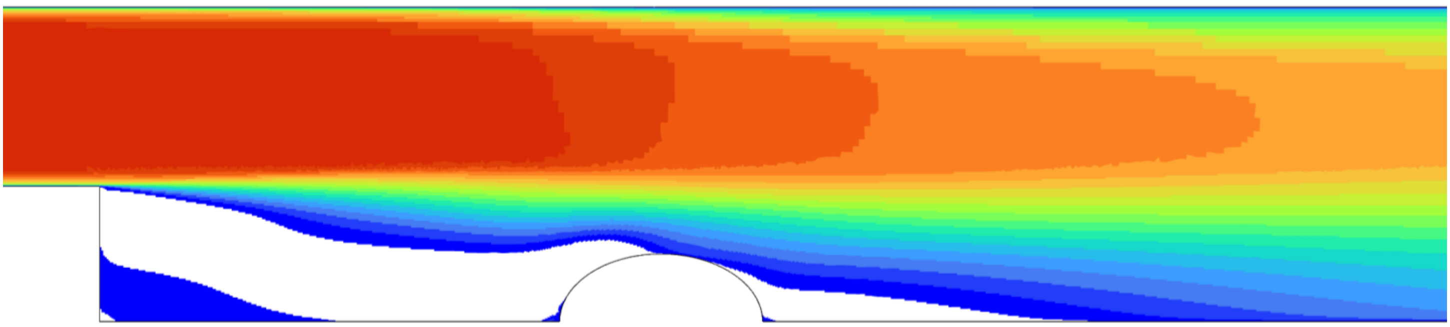


Figure 6.4: Residual 0.0001



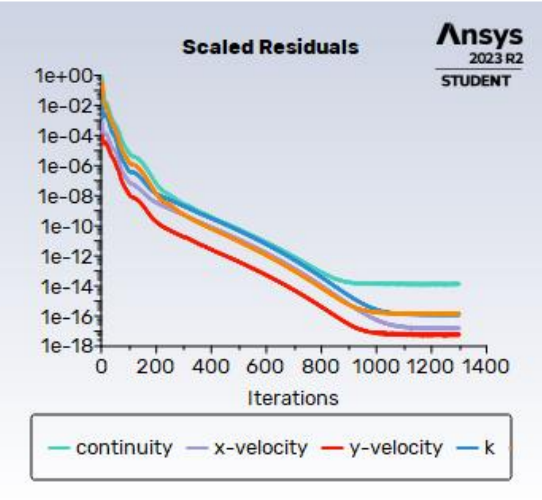
4.1.3 Tabulated results

Table 2: Tabulated results of the four simulations

Residual	0.1	0.01	0.001	0.0001	Units
Velocity magnitude minimum	0.001982	0.000408	4.38E-05	5.19E-06	m/s
Velocity magnitude maximum	7.529049	7.481229	7.118342	7.137501	m/s
X-velocity minimum	-5.436128	-3.727354	-2.325777	-2.19949	m/s
X-velocity maximum	7.525603	7.458963	7.118307	7.136654	m/s
Y-velocity minimum	-1.795925	-2.247669	-1.614224	-1.57622	m/s
Y-velocity maximum	2.767147	1.793817	0.8000863	0.522697	m/s
Turbulent Kinetic Energy (k) sum	8955.96	44177.35	71501.07	85011.31	m^2/s^2
Turbulent Kinetic Energy (k) max	0.872728	1.861809	2.076312	2.085975	m^2/s^2
Mass imbalance sum	0.00547328	0.0004161	1.18E-05	-1.01E-05	kg/s
Mass imbalance max	0.00041617	4.95E-05	1.30E-06	2.97E-08	kg/s
Sum of Dynamic Pressure on ellipse wall	36.03956	22.72211	13.00993	12.68038	Pa
Reattachment length (L/step height)	5.809318	8.17025375	7.67777275	7.500942	Dimensionless

4.1.4 Scaled residuals

Figure 7: Scaled residuals



4.1.5 Analysis of results

Figures **5.1 – 5.4** illustrate the fluid flow and regions of recirculation. Comparing the four plots we can establish a that figures **5.3** and **5.4** are vastly different from figures **5.1** and **5.2**. This is likely because residuals 0.1 and 0.01 did not have tolerances strict enough to allow for the solution converge. In figure **5.2** there are 5 recirculation regions and one of them is surprisingly on the ceiling of the domain. This is highly unexpected and most probably not a valid solution. Figures **5.3** and **5.4** are very similar likely because both solutions have converged or, are close to being converged.

Figures 6 are used to help identify the reattachment point. Figure **6.1** seems to undershoot the reattachment point and figure **6.2** overshoots the reattachment point. When looking at figures **6.1 - 6.2** a similar trend occurs to that of figures **5.1 - 5.2**. Residuals 0.1 and 0.01 seem to be drastically variable and residuals 0.001 and 0.0001 seem to be tending towards a common result.

The reattachment point is tabulated in Table 2. It can be seen that the reattachment length is stable and likely close to 7.5-7.6 (L/step height). the reattachment length for residuals 0.1 and 0.01 is far too volatile to assume that these are valid solutions.

This trend is synonymous with most of the other tabulated results. The general trend is that residuals 0.1 and 0.01 vary greatly and that residuals 0.001 and 0.0001 are close in value indicating a converging solution. Figure 7 shows the residuals are converging roughly around 1e-16 after 1000 iterations.

4.2 Summary of Observed Flow Features

1. Boundary layers on the walls of the inlet chamber showing that the free-stream is fully developed.
2. Flow separation at the step
3. Recirculation region upstream of the ellipse
4. Shear layers in the free stream due to velocity gradients
5. Flow reattachment at around 7.5 times the step height along the boundary floor from where the flow separates at the step.

5. REFERENCES

1. *K-Omega Turbulence Models | Global Settings | SimScale*. (2023, June 20). SimScale. Available at: https://www.simscale.com/docs/simulation-setup/global-settings/k-omega-sst/#:~:text=The%20k-epsilon%20model%20tends,models%20using%20a%20blending%20function.

6. ENLARGED FIGURES (FOR EASE OF VIEWING)

Figure 3: Skewness colour map