Numerical Fluid Mechanics II
Summer Semester 2016

Deliverable Task 2 : Laminar Backward-Facing Step

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1. Introduction

Backward-Facing step is a benchmark of CFD (Computational Fluid Dynamics). The objective of this task is to simulate flow over a backward facing step at Re = 34700 in simple 2D simulation and extending into 3D simulation using SimpleFoam solver.

2. Boundary conditions

Calculation of inlet velocity (U_b),

Given:

Reynolds number (R_e) = 34700
Step height (h) = 0.0127 m
Density of the fluid (ρ) = 1.14 kg/m^3
Dynamic viscosity (μ) = 1.8354 . 10e-5 kg/ms

By definition,

$$R_e = U_b h \rho / \mu$$

$$U_b = R_e . \mu / h . \rho$$

$$U_b = 34700 \, x \, 1.8354 \, x \, 10^{-5} / 0.0127 \, x \, 1.14$$

$$U_b = 43.9897638 \, m/s$$

Calculation of kinetic energy (k) and turbulent dissipation rate (ϵ) for RANS model,

Given:

Turbulent intensity (I) = 5%
Turbulent length scale (l) = 10 % of inlet length

$$l = 10 \, x \, 0.1016/100$$

$$l = 0.01016 m$$

As we know,

$$k = 3.(UI)^2/2$$

$$k = 3.(43.9897638 \, x \, 0.05)^2/2$$

$$k = 7.25660 \, m^2/s^2$$

and,

$$\epsilon = C_\mu . (k)^{3/2}/l$$

$$\epsilon = 0.09 \, x \, 7.2566^{3/2}/0.01016$$

$$\epsilon = 173.1603 m^2/s^3$$

Velocity boundary conditions :

Wall – No slip boundary condition
Output – Neumann boundary condition

$k-\epsilon$ *boundary conditions:*

Wall functions are used for boundary conditions.

3. Two-dimensional Simulation

- ***Convergence study:***

2D simulations are performed with above values and various mesh sizes as tabulated below,

Mesh size (channel 1)	Mesh size (channel 2)	Mesh size (channel 3)	Wall shear stress kg/ms^2	Viscous length . 10e-5 (m)	Lr / h
30 x 75 x 1	150 x 75 x 1	150 x 15 x 1	1.4893	1.408	3.3760
40 x 100 x 1	200 x 100 x 1	200 x 20 x 1	1.59475	1.4803	4.0085
50 x 125 x 1	300 x 125 x 1	300 x 25 x 1	1.36327	1.472	4.2303
60 x 150 x 1	400 x 150 x 1	400 x 30 x 1	1.12789	1.6186	4.4102
70 x 175 x 1	500 x 175 x 1	500 x 35 x 1	0.93807	1.7748	4.4201

Table 1. Viscous length (m) for various mesh sizes (2D)

As we can see from above table, viscous length and (Lr/h) ratio are not varying so much between higher mesh sizes. So we are fixing the following mesh sizes as,

Channel 1 : 60 x 150 x 1 , Channel 2 : 400 x 150 x 1, Channel 3 : 400 x 30 x 1

- ***Viscous length as a function of x:***

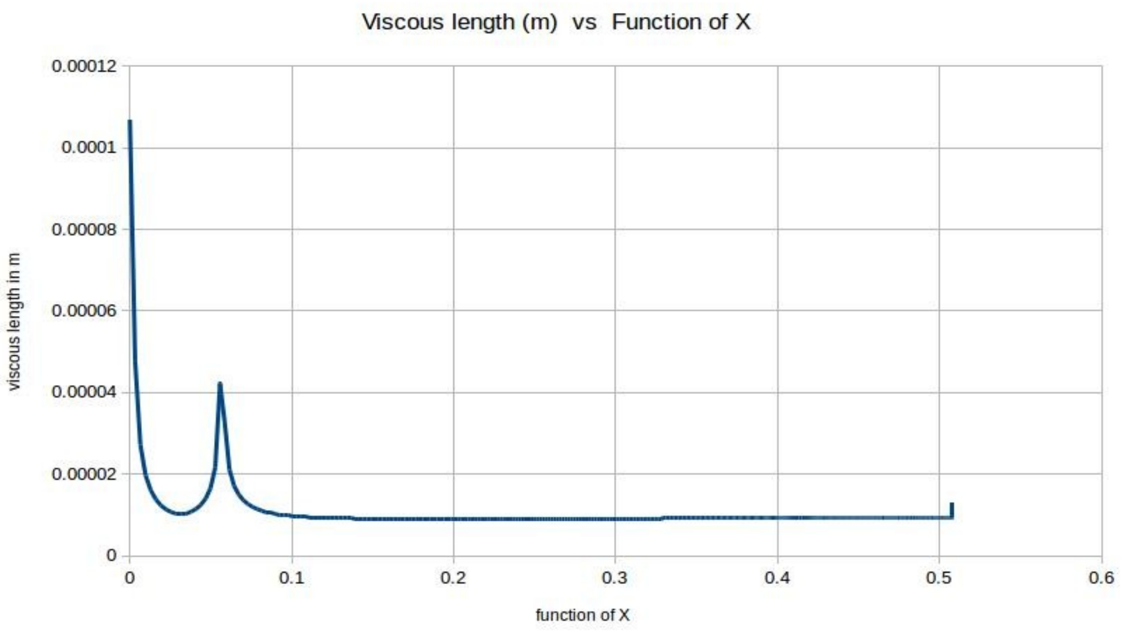

Figure 1. Plot between viscous length (m) along X direction

The below figure shows that viscous length as a function of “x” in 2D. It depicts that, the viscous length reaches maximum when fluid enters recirculation zone and reaches minimum in between and again rises to second maximum when recirculation ends.

- ***Velocity, turbulent kinetic energy and pressure distribution:***

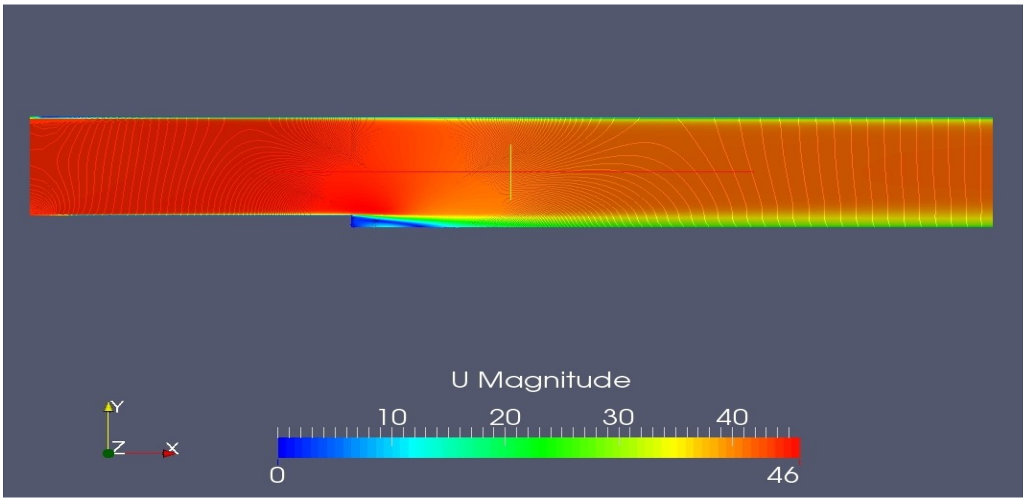

Figure 2. Velocity distribution in 2D

The above figure shows a velocity distribution in 2D. The velocity reaches maximum value at the inlet and getting reduced throughout the channel. In the recirculation zone, the velocity reaches its minimum value and sometimes “zero”.

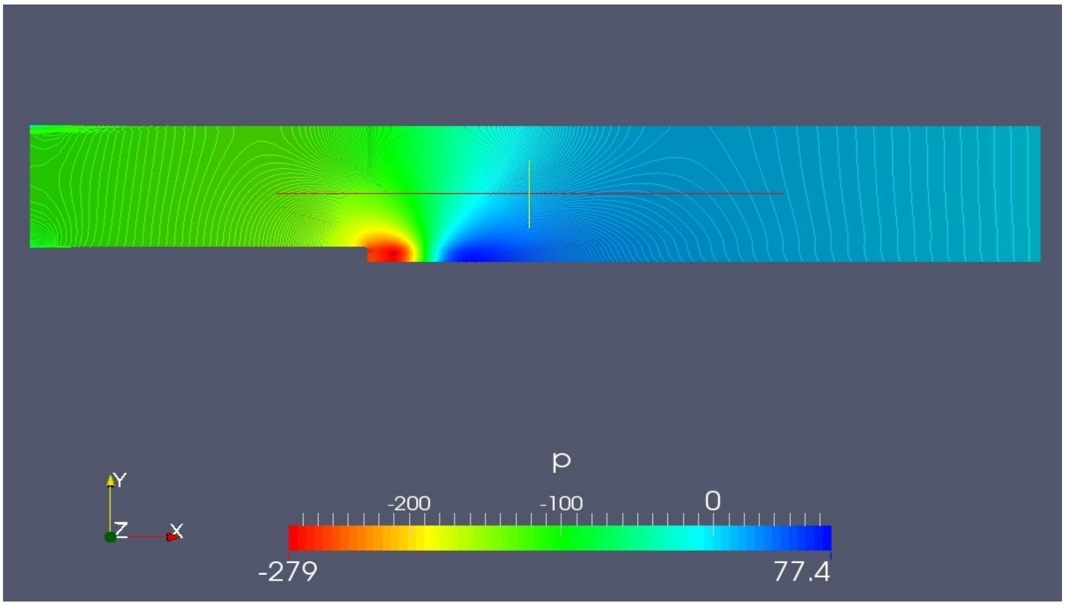

Figure 3. Pressure distribution in 2D

The above figure shows a pressure distribution in 2D. Pressure reaches negative when the fluid enters into recirculation zone where velocity is almost “zero” and reaches maximum after recirculation zone.

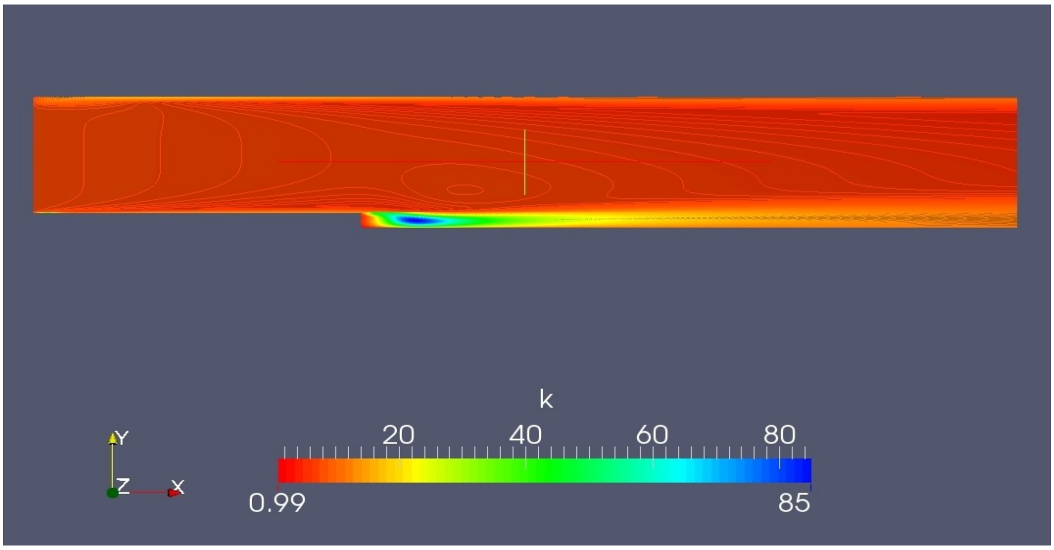

Figure 4. kinetic energy distribution in 2D

4. Three-dimensional Simulation

- *Convergence study:*

  The above simulations are extended to 3D domain with various mesh sizes as follows,

Mesh size (channel 1)	Mesh size (channel 2)	Mesh size (channel 3)	Wall shear stress kg/ms^2	Viscous length . 10e-5 (m)
30 x 75 x 10	150 x 75 x 10	150 x 15 x 10	1.31066	1.5015
40 x 100 x 10	200 x 100 x 10	200 x 20 x 10	1.00172	1.7175
50 x 125 x 10	300 x 125 x 10	300 x 25 x 10	0.587631	2.2424
60 x 150 x 10	400 x 150 x 10	400 x 30 x 10	0.315308	3.0613
70 x 175 x 10	500 x 175 x 10	500 x 35 x 10	0.128803	4.7897

Table 2. Viscous length (m) for various mesh sizes (3D)

As we can see from above table, viscous length is not varying so much between higher mesh sizes. So we are fixing the following mesh sizes as,

Channel 1 : 60 x 150 x 10 , Channel 2 : 400 x 150 x 10, Channel 3 : 400 x 30 x 10

- ***Viscous length as a function of x:***

The below figure shows that viscous length as a function of “x” in 2D. It depicts that, the viscous length reaches maximum when fluid enters recirculation zone and reaches minimum in between and again rises to second maximum when recirculation ends.

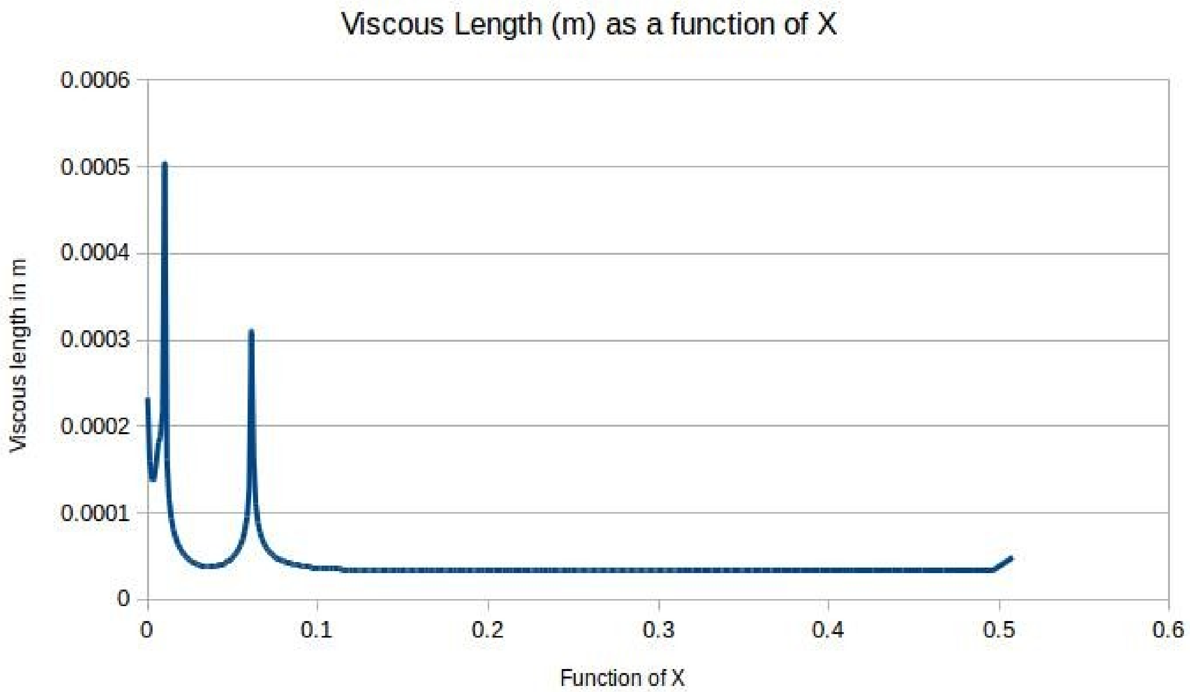

Figure 5. Viscous length as a function of “x” in 3D

- ***Reattachment length (Lr):***

Mesh size (channel 1)	Mesh size (channel 2)	Mesh size (channel 3)	Lr (m)	Lr / h
30 x 75 x 10	150 x 75 x 10	150 x 15 x 10	0.05248340	4.132551
40 x 100 x 10	200 x 100 x 10	200 x 20 x 10	0.05783331	4.553804
50 x 125 x 10	300 x 125 x 10	300 x 25 x 10	0.0626533	4.933333
60 x 150 x 10	400 x 150 x 10	400 x 30 x 10	0.0643589	5.067635
70 x 175 x 10	500 x 175 x 10	500 x 35 x 10	0.0666459	5.247715

Table 3. Reattachment length (m) for various mesh

From the above table, the value of (Lr/h) is 5.067635 which is 19% less than the experimental value, which is acceptable error in $k-\epsilon$ model.

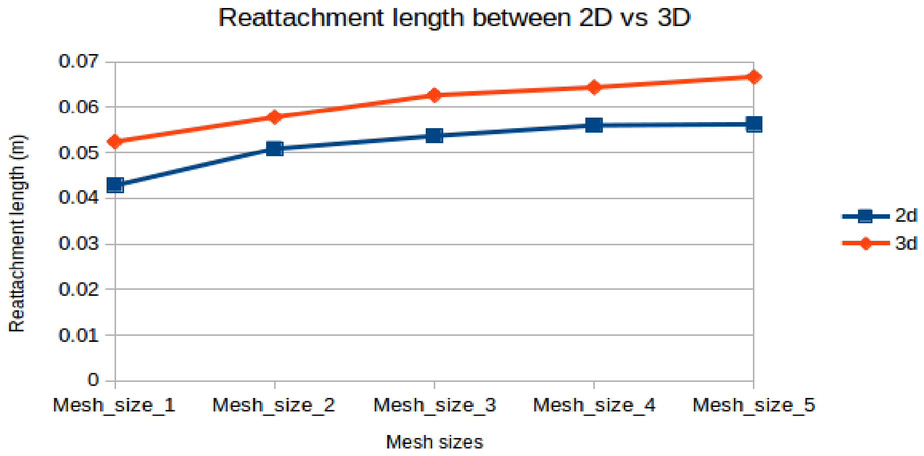

Figure 6. Comparison between 2D vs 3D reattachment length(m)

The 2D simulation deviates only by a factor of 12% of 3D simulations as we can see in the above graph, the behavior of the reattachment length haven't changed much.

- ***Velocity, turbulent kinetic energy and pressure distribution:***

The below figure shows a velocity distribution in 3D. The velocity reached maximum value at the inlet and getting reduced throughout the channel. In the recirculation zone, the velocity reached its minimum value and sometimes “zero”.

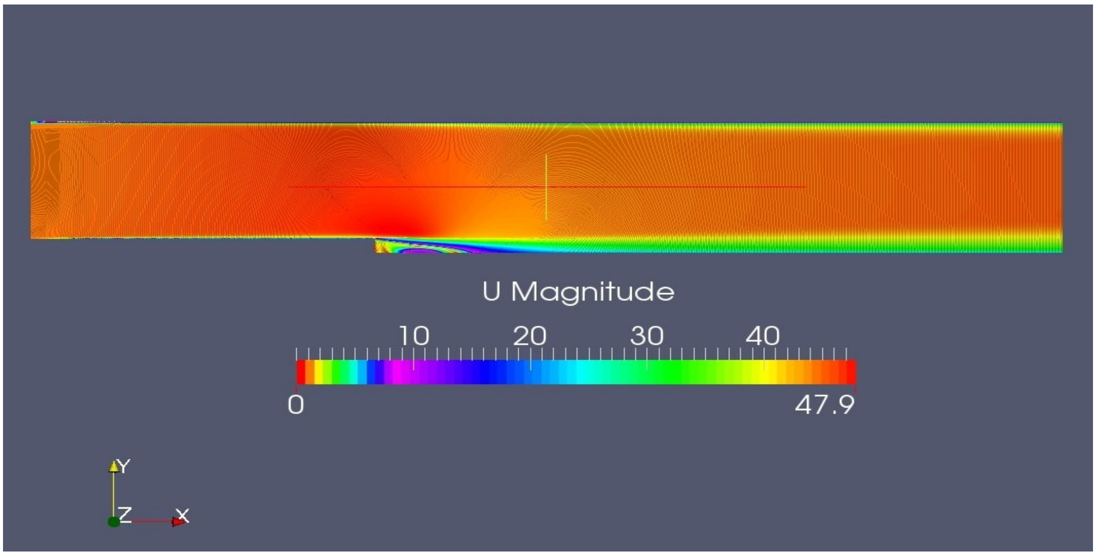

Figure 7. Velocity distribution in 3D

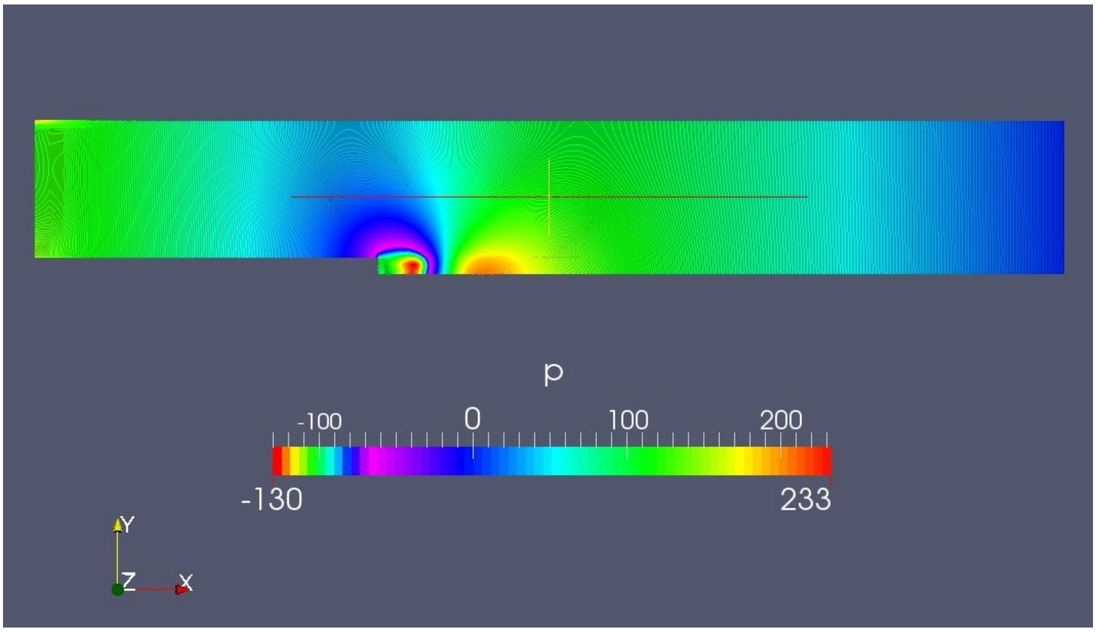

Figure 8. Pressure distribution in 3D

The above figure shows a pressure distribution in 3D. Pressure reaches negative when the fluid enters into recirculation zone and reaches maximum after recirculation zone.

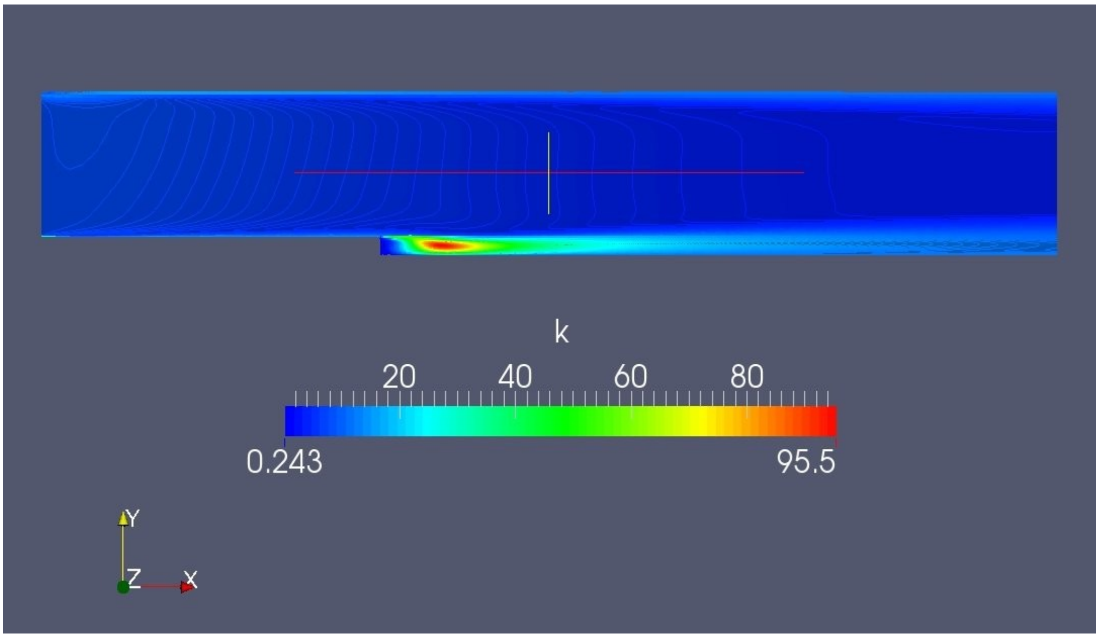

Figure 9. Kinetic energy distribution in 3D

- ***Friction and pressure coefficients:***

The below figure shows that the comparison between the experimental and simulated friction co-efficient c_f . Both curves traveled in the similar path, but the simulated results are not in the experimental results range, which means more mesh sizes give better result.

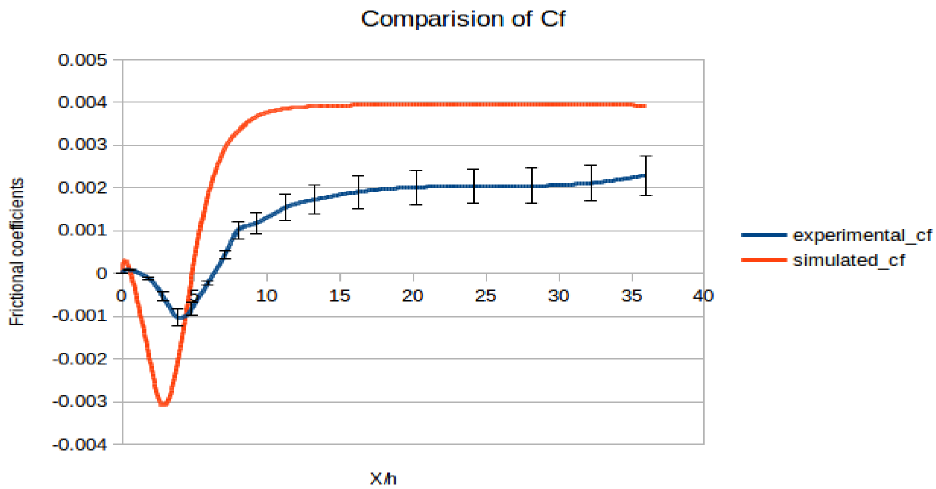

Figure 9. Comparison of C_f

The below figure shows a comparison between the experimental results and simulated results of pressure coefficient C_p . The two curves follow a similar pattern, but simulated results are not in the experimental results range, which means more mesh sizes give better result.

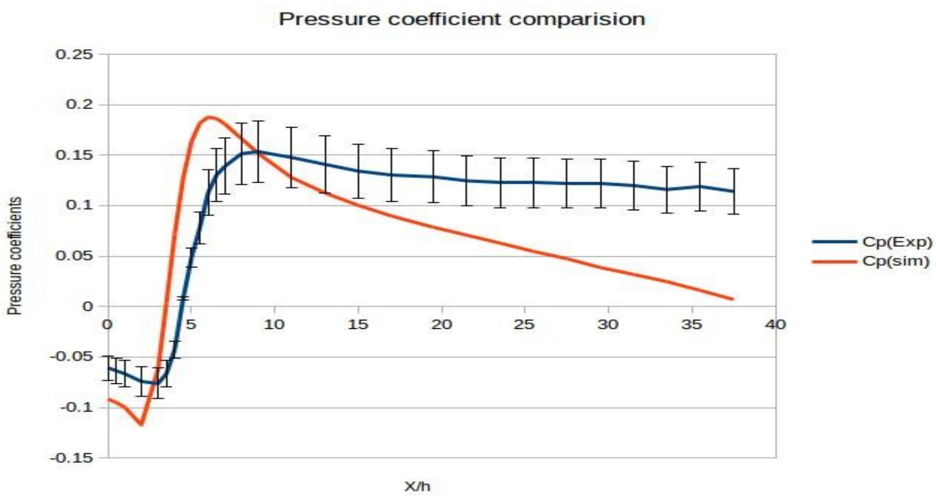

Figure 10. Comparison of C_p

5. Conclusion

In this task we have modeled and simulated the turbulent backward facing step using the $k-\epsilon$ model.

After studying the mesh independences, we decided to use the mesh of *Channel 1 : 60 x 150 x 10 , Channel 2 : 400 x 150 x 10, Channel 3 : 400 x 30 x 10* based on the viscous length (δ_v) at the bottom wall after the step and the reattachment length.

The mesh was then extended into 3D and similar studies were conducted. The simulated values of C_f and C_p were compared to the experimental values. It was also observed that the X/h in 3D was much more closer to the experimental data that was given than the X/h that was found in the 2D.