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i. Problem Statement:

The backward facing step is a standard test problem in CFD. Given below is the domain

where a uniform flow of air enters from the left with a Reynolds number of 200.

a) Simulate the flow using a transient solver. Find the reattachment length for this phenomenon. Would this length be longer for turbulent flows? Explain your answer.

b) Plot the velocity profile (on a line) along the cross-section at

the reattachment point . Plot the velocity profile before and after the reattachment point.

Explain the profiles obtained.

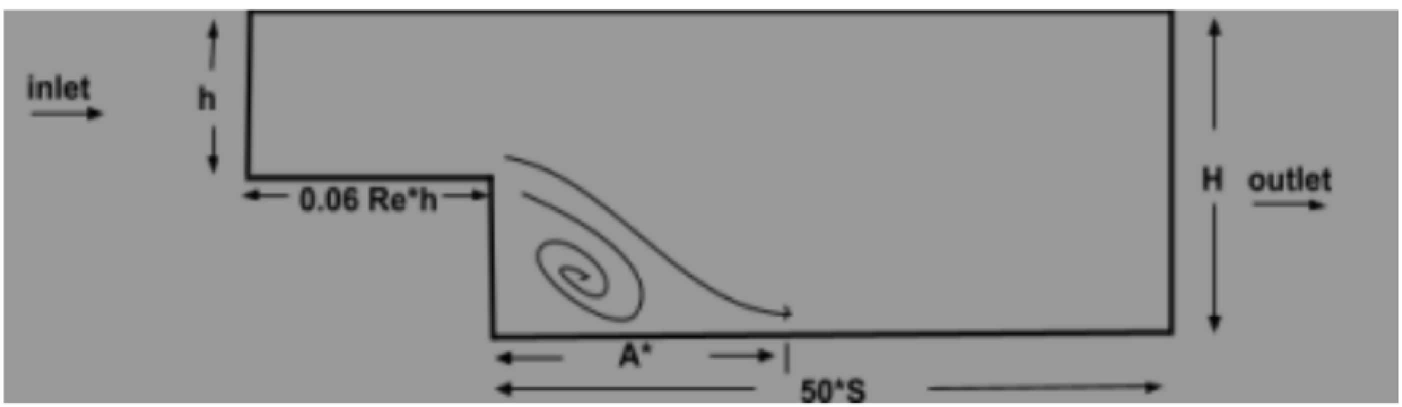


Figure 1: Domain and Geometry

Explain necessary theory, formula, calculations, OpenFOAM data, plots/contours and

conclusion in the report.(Quality of the report is one of the criteria of evaluation)

The two sub-questions are answered

Given data:

H = 30mm

H/h = 2 = Expansion ratio

S = 15 mm

Re = 200

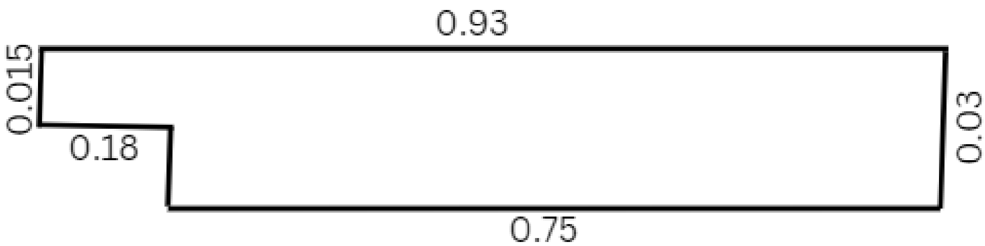
ρ = 1.247 kg/m3

ν = 1.76*10-5m2/s

A* = Reattachment length

ii. Geometry Definition

All dimensions are in meters



Expansion ratio=H/h=2

Step height=0.03/2=0.015m

S*50= 0.015*50=0.75 m

μ=1.76x10^{-5} m^2/s (kinematic viscosity)
ρ=1.274 kg/m^3
Tu_l=0.06*Re*h=0.06*200*0.015=0.18m

Mesh Settings:

blockMesh is used to make the mesh. 2D mesh is made with 0.05 is extrusion in z-direction, The file is included in system/blockMeshDict

Structured- hexahedral mesh has been used. Four patches are defined:

Patch	Type
inlet	patch
outlet	patch
walls	wall
frontAndBack	empty

checkMesh command is used to verify the mesh and evaluate its credibility. checkMesh result is included in checkMesh file.

OpenFOAM version 11 is used for running the simulation and incompressibleFluid solver is used.

The simulation starts at t=0 and converges at t=0.911 with delta T=0.0005. Maximum Courant number is given as 0.5. In Paraview, the converged solution is defined at 577s.

iii. Boundary and Initial Conditions

Re=$\frac{U*l}{\eta}$ where η=1.76*$10^{-5}$$m^2$/s; l=step height=0.015

U=0.234 m/s

Following files are included in /0 folder

- U- (0.234 0 0) at inlet ; noSlip for walls
- p- zeroGradient at inlet and 0 at outlet
- k- 8.2134e-8 m2/s2 fixedValue at inlet
- omega- 0.00159 /s fixedValue at inlet
- nut
- epsilon
- nuTilda

Wall functions are used for walls patch and empty for frontAndBack patch
RAS simulation type is used with k-omega SST model. Explanation is provided in the next topic.

Turbulence Model- k-ω SST model

k-epsilon and k-omega models are generally used for many problems to model turbulence where shear flow along walls is important.
€- measures turbulence dissipation rate: rate at which kinetic energy converts to thermal energy.
ω - measures specific turbulence dissipation rate
Both describe dissipation of turbulent kinetic energy.
However, both models have flaws-
k-epsilon model is not good at predicting adverse pressure gradient and k-omega model is very sensitive to freestream turbulence conditions.
Hence in 1992, later modified in 2006 by Wilcox, k-omega SST model was proposed which combines k-epsilon and k-omega model. This is used to predict behavior near walls and in problems where analysis of flow separation and reattachment is important.

k-ω SST model

It is a two equation model with two variables, k and w to capture turbulence effects. k measures turbulence energy and w measures scale of turbulence. SST model combines k-ϵ, used in the freestream region and k-w near the wall.

Continuity equation:

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_i}(\rho u_i) = 0$$

Momentum equation:

$$\frac{\partial}{\partial t}(\rho u_i) + \frac{\partial}{\partial x_j}(\rho u_i u_j) = -\frac{\partial P}{\partial x_i} + \frac{\partial \tau_{ij}}{\partial x_j}$$

For k:

$$\frac{\partial k}{\partial t} + U_j \frac{\partial k}{\partial x_j} = P_k - \beta^* k\omega + \frac{\partial}{\partial x_j}\left[(\nu + \sigma_k \nu_T)\frac{\partial k}{\partial x_j}\right]$$

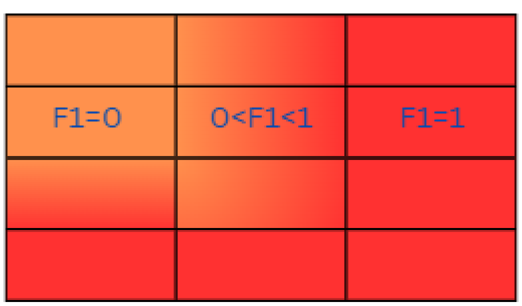
For w:

$$\frac{\partial \omega}{\partial t} + U_j \frac{\partial \omega}{\partial x_j} = \alpha S^2 - \beta\omega^2 + \frac{\partial}{\partial x_j}\left[(\nu + \sigma_\omega \nu_T)\frac{\partial \omega}{\partial x_j}\right] + 2(1 - F_1)\sigma_{\omega 2}\frac{1}{\omega}\frac{\partial k}{\partial x_i}\frac{\partial \omega}{\partial x_i}$$

For kinetic viscosity:

$$\nu_T = \frac{a_1 k}{\max(a_1\omega, SF_2)}$$

In these equations,
Uj is the component of velocity in j-direction
Xj- coordinates in j-direction
σ_k and σ_w are constants
F1 is a constant that represents the blending between ϵ and ω.
F2 is also a blending function and acts as viscosity limiter. It increases with decrease in distance with wall.
α, α_1, β* are empirical constants



F1 is 1 near walls; k-w is applicable
F1 varies between 0 and 1 ; blending function is used
F1 is 0 in freestream region; k-ϵ is applicable

$$k = \frac{3}{2}\,(U\,I)^2$$

I: Turbulent intensity. To simulate laminar flow (very low Re), I=0.1% is used

U=0.234 m/s

$$\omega = \frac{\sqrt{k}}{l}$$

l: turbulence length (=0.18m)

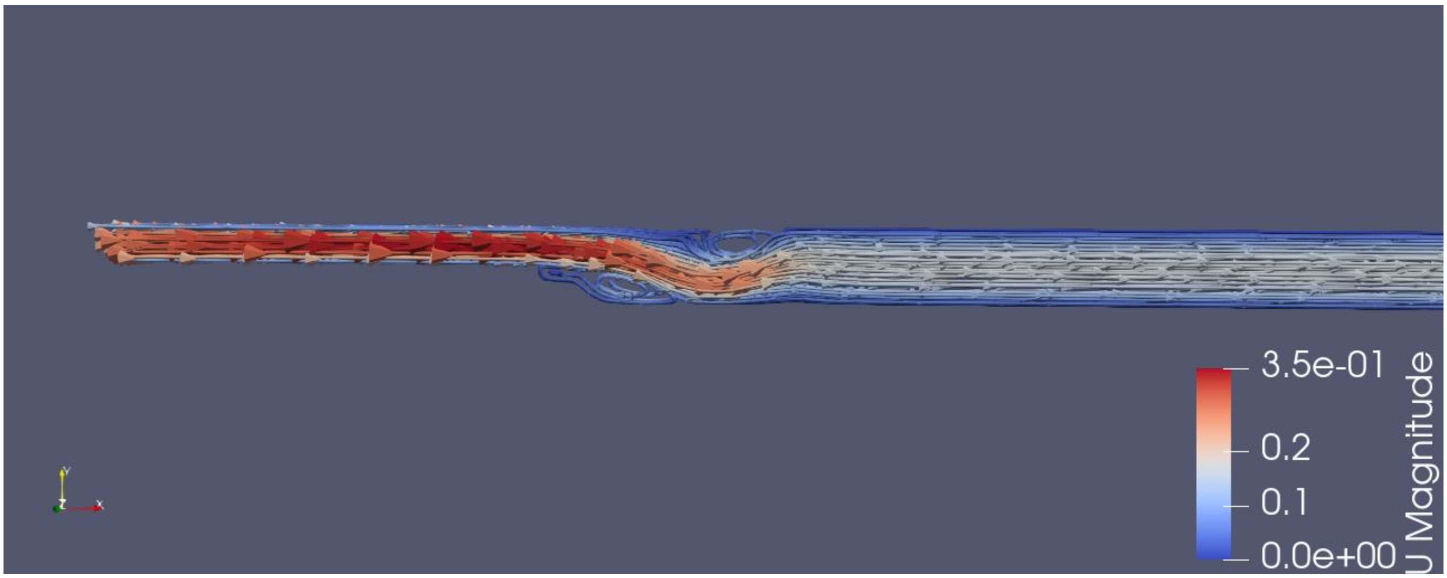
These relations are used to calculate the initial values of parameters k and ω.

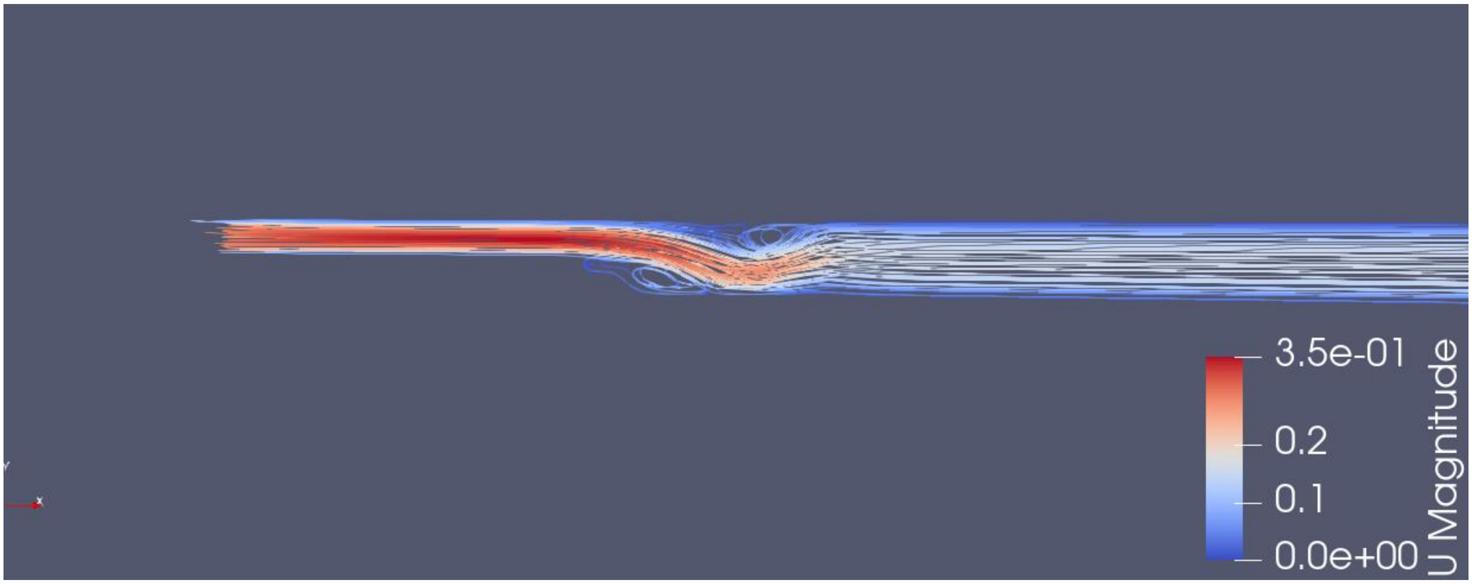
iv. Simulation Results

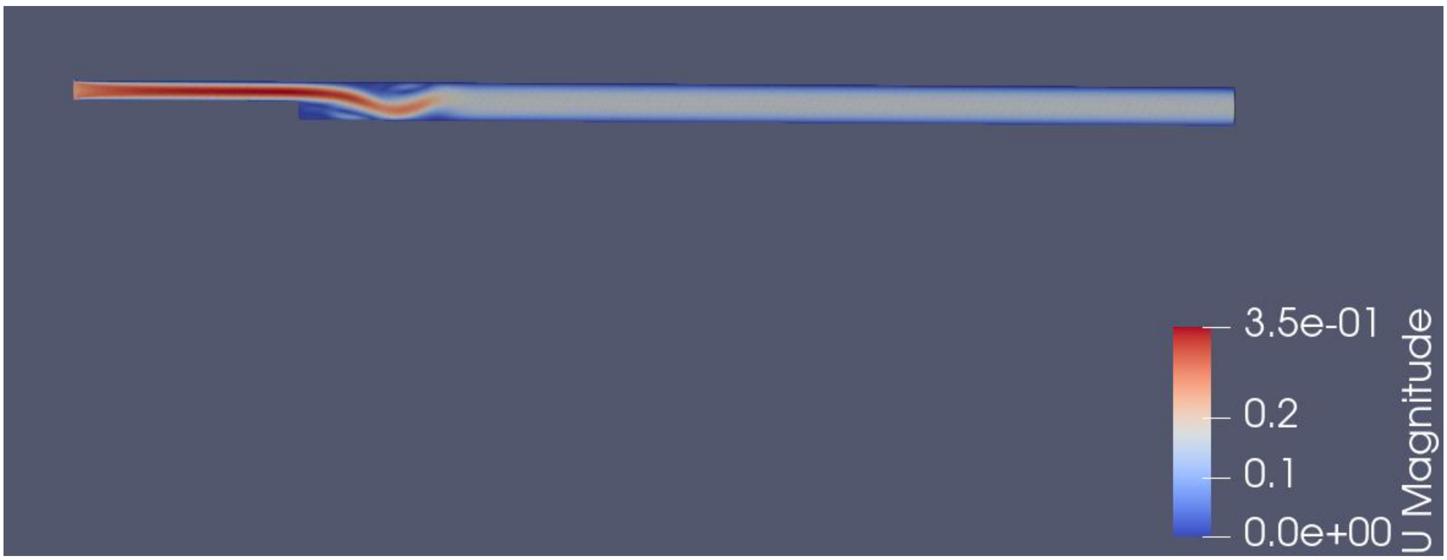
Velocity Magnitude

After converging at t=577:

Velocity contour:




3.5e-01
0.2
0.1
0.0e+00
U Magnitude


3.5e-01
0.2
0.1
0.0e+00
U Magnitude

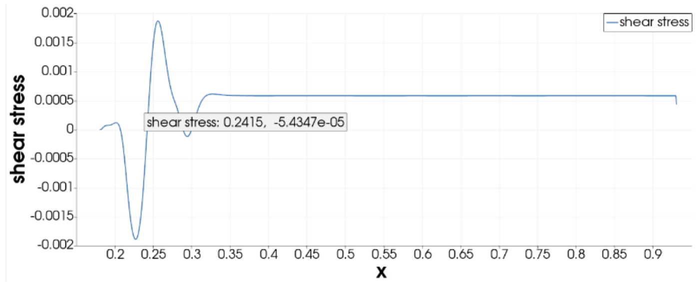
Pressure

At t=222s

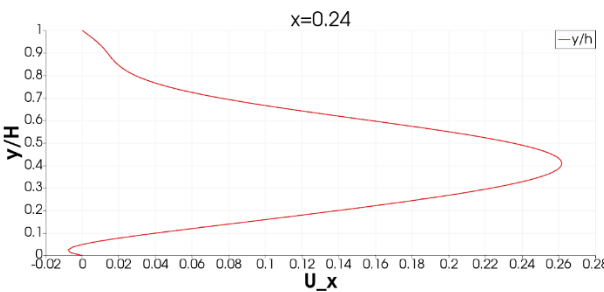
At t= 577s

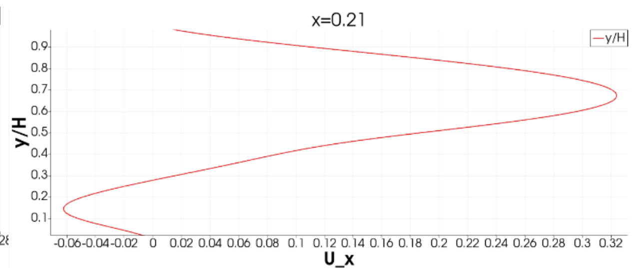
k

Results

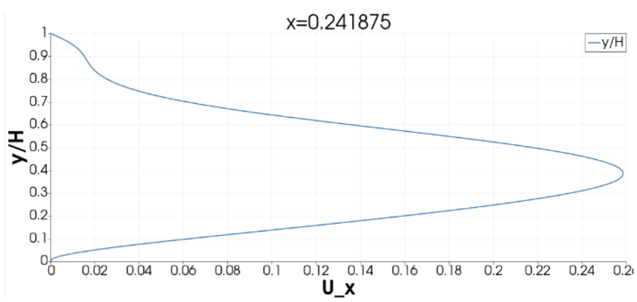


Before reattachment:

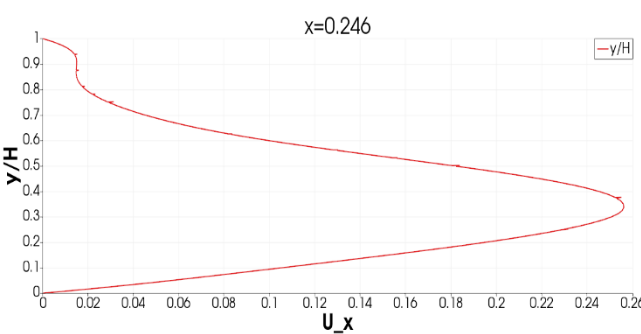


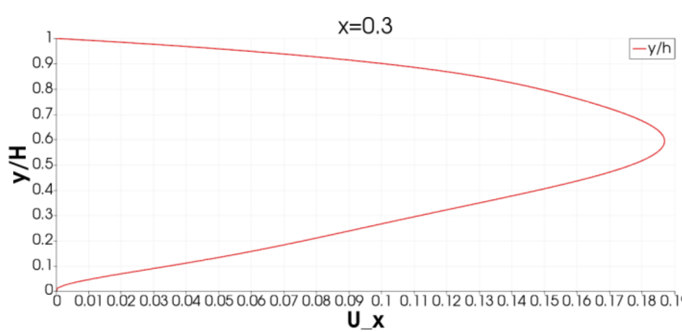


At reattachment:



After reattachment:



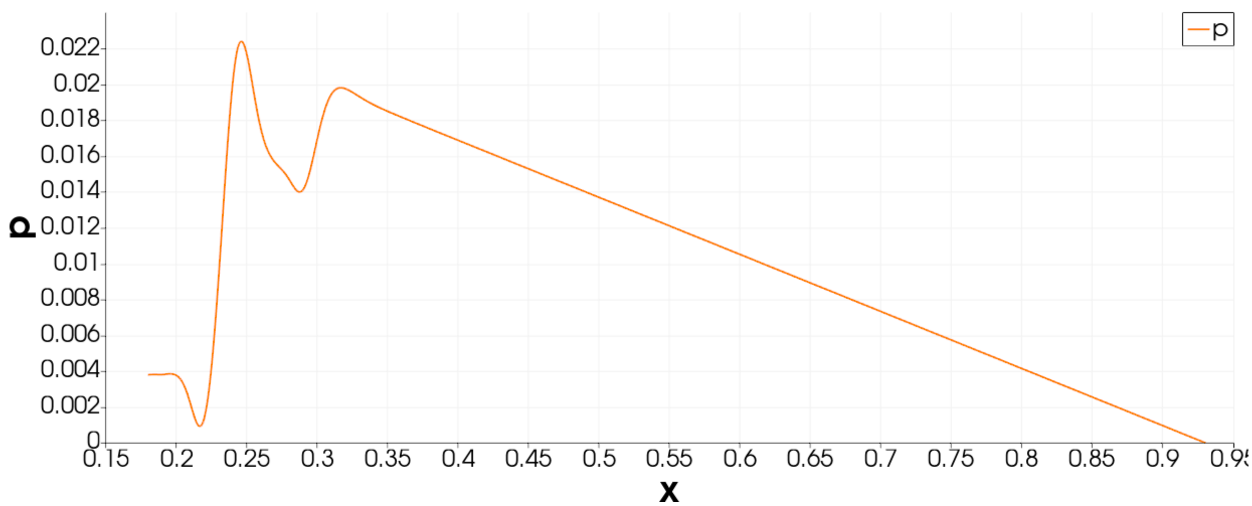


Geometry:

From the velocity profiles we observe that the velocity reverses direction, indicating separation. At x=0.241875, flow re-attaches, with velocity in positive in x direction and no reverse velocity.

(At t=168s)

Here we can observe a drop in pressure due to backward facing step. Drop in pressure causes velocity in x direction to reverse as fluid flows from high pressure to low pressure region. Hence pressure is increasing as we move towards positive x-axis, resulting in adverse pressure gradient.



Here we see adverse pressure gradient represented by increase in pressure between x=0.23 and x=0.25.

Due to adverse pressure gradient due to expansion in geometry, flow separates. Reattachment is the point where flow contacts the base of the channel.

Recirculation is formed as vortexes and depends on step height.

Reattachment length is usually calculated by extracting the point where sign of wall shear stress changes from negative to positive. It is zero at the step. Negative shear stress indicates recirculation region (as flow is reversed at walls and stress is applied at negative x-direction) and positive indicates reattachment.

Wall shear stress is given by:

$\tau=\mu \frac{du}{dy}$ where: μ is kinematic viscosity and $\frac{du}{dy}$ is velocity gradient

From the graph and extracting data from Paraview, we find that reattachment occurs at x=0.241875m .

From the velocity profiles we see that the flow reverses in the negative x direction for x=0.21 and 0.24, indicating separation due to pressure gradient forced by the step At x=0.2418 we observe that flow does not reverse.

v. Effect of turbulent flow

We will look at the effect of turbulence from perspective of Reynold’s number and turbulence intensity.

According to [1] and [2], reattachment length increases with increase in Reynold’s number. High Reynold’s number of range 15000 and 64000 is considered. According to [3], expansion ratio of 20 is taken and has concluded that in laminar region, reattachment length increases with increase in Re. In transition regime, it slightly decreases whereas in fully turbulent regime, it almost remains constant. Reynold’s number represents ratio between inertial force and viscous force. Higher Reynold’s number leads to more energetic flow. The higher momentum associated with such flow can make it harder for the flow to reattach quickly. Certain studies such as [5], show that on further increase in Reynold’s number, reattachment length slightly decreases and later increases again. The relation between Reynold’s number and reattachment length is nonlinear, although general trends show an increase.

According to [4], the reattachment length decreases with increase in freestream turbulence intensity. Higher turbulence intensity leads to development of inner mixing layer. Higher turbulence level can intensify turbulent eddies, leading to more efficient momentum transfer. This helps in reattaching flow sooner potentially decreasing reattachment length.

Reattachment length in turbulent flow depends on various factors, including geometry factors like expansion ratio and depends strongly on step height.

vi. Conclusion:

The step causes sudden expansion ratio resulting in wall shear stress zero and drop in pressure. This results in adverse pressure gradient causing in reverse velocity at the wall and negative wall shear stress. At the reattachment point, there is no velocity in reverse direction and wall shear stress is positive. This point is extracted from OpenFOAM data at x=0.241875 or x/h=4.125. The reattachment length generally increases with increase in Reynold’s number. However, this relation is non-linear. At high Reynold’s number, corresponding to fully developed turbulent flow, the reattachment length decreases slightly and increases again. On increasing turbulence intensity, the reattachment length is found to decrease.

References

[1]Jagannath Rajasekaran, “On the flow characteristics behind a backward-facing step and the design of a new axisymmetric model for their study”, 2011

[2] Ajay Pratap Singh, Akshoy Ranjan Paul , Pritanshu Ranjan, “Investigation of reattachment length for a turbulent flow over a backward facing step for different step angle”, 2011

[3] K Isomoto, S.Honami, “The Effect of Inlet Turbulence Intensity on the Reattachment Process Over a Backward-Facing Step” 1989

[4] Bala Kawa M. Saleem, Andam Mustafa, Dalshad Ahmed Kareem, Mehmet Ishak Yuce, Michał Szydłowski, Nadhir Al-Ansari,” Numerical Analysis of Turbulent Flow over a Backward-facing Step in an Open Channel”, 2023

[5] Joshua Brinkerhoff, N. Moallemi,” Numerical analysis of laminar and transitional flow in a planar sudden expansion”, 2016