Numerical Simulations of the backward facing step for a laminar 2D flow

By

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Contents

List of Figures

1 Introduction

The project is based on the classical benchmark of the backward-facing step for a laminar 2D flow. The computations are performed using ISIS-CFD Navier-Stokes solver which is integrated into FINE/MARINE. For 3 different nested meshes, the influence of Convergence Criteria, influence of discretization scheme, the influence of the relaxation parameter, and the influence of the diagonal dominance are studied. The results are compared with the paper *Gualtieri*2005, Numerical Simulations of Laminar Backward-Facing Step Flow With FEMLAB 3.1.

2 Test case

The complex flow pattern downstream of a backward facing step involves several different flow regions.There are 7 different regions which can be distinguished,they are,

- (I) Initial Boundary Layer
- (II) Separated free shear layer
- (III) Reattachment zone
- (IV) Primary re-circulation or separation region
- (V) Corner eddy
- (VI) Redeveloping boundary layer
- (VII) Second separation region

The following diagram shows the these different regions, The distance L_r known as primary

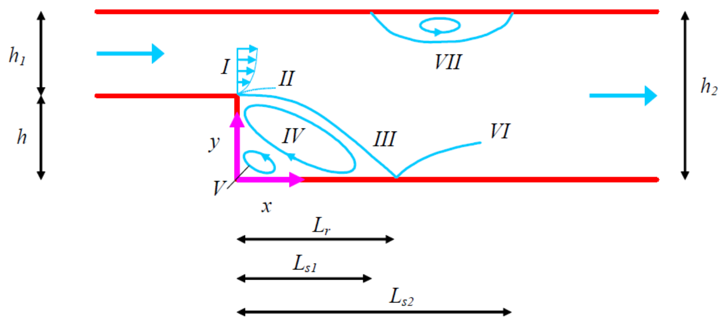


Figure 1: Sketch of flow field in a backward-facing step (*Gualtieri*2005)

reattachment length.At this distance the flow reattaches and the new boundary layer develops.The primary reattachment length L_r depends on the two parameters

- the Reynolds number which is based on the step height.
- the expansion ratio E which is the ratio of the outlet channel height h_2 to the inlet channel height h_1.

We are going to study the laminar flow over a backward-facing step.

3 Analysis of the numerical Configuration

Three different meshes are created by changing the parameter **NY**.The following nested meshes are considered for the study,

- **NY** $= 20$
- **NY** $= 40$
- **NY** $= 60$

4 Influence of the Convergence criteria,Analysis of the discretisation error

For the three different meshes considered, different values of stopping criteria ($conv\_criteria\_gain$) are set. The other parameters are fixed and the convergence criteria correspond to the gain on the momentum residual. The maximum number of iterations is set to 20,000. Based on the considerations, simulations are performed and the results are analyzed.

4.1 Nested mesh size,NY=20

The simulations were ran for the following $conv\_criteria\_gain(CCG)$ values,4,6,8.The following table shows the results obtained. It can be observed that as the stopping criteria are in-

CCG	**CPU time(mins)**	**Iterations**	L_r**(approx.)**
4	0.912	3217	6.360
6	1.196	5795	6.464
8	1.740	8435	6.464

Table 1: Table of results for the NY=20

creased, the number of iterations also increases with respect to it. The corresponding CPU time also increases. The L_r remains the same for the CCG values 6 and 8. The below graph represents the same.The pressure resolution($gain\_PCGSTAB$ and $gain\_BOOMER$) are increased.It was observed that as we increase these values, the CPU time is affected. So we set these values to 15. We define a convergence criterion that has a good compromise between iteration error and

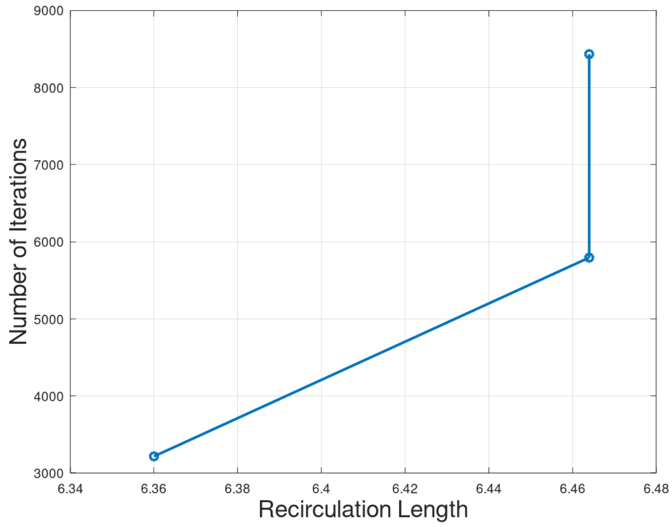
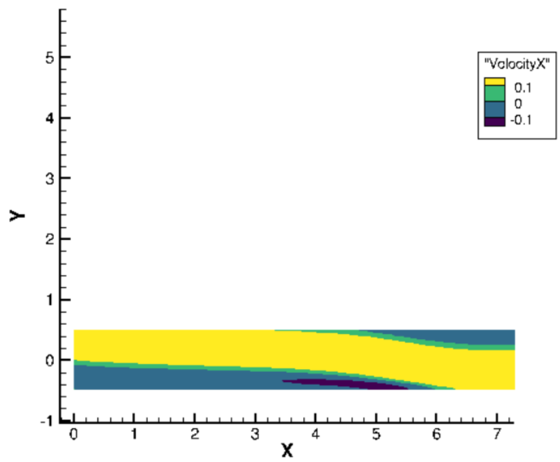
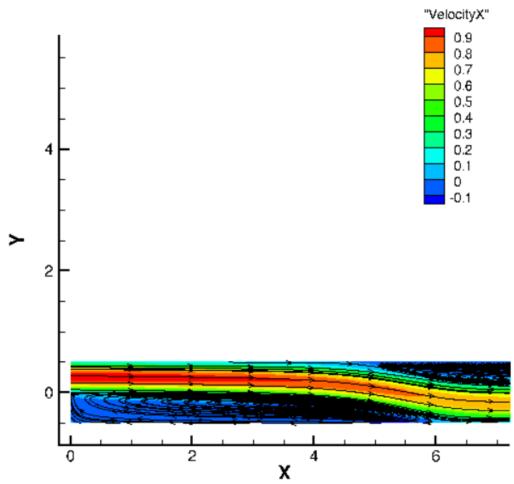


Figure 2: Graph of L_r vs iterations for NY=20

CPU time, which is CCG=6 and Pressure resolution values =15. The following images show the velocity profile and the streamline profile for the considered convergence criteria values.



(a) Velocity Profile



(b) Streamline Profile

Figure 3: Contour plot of Velocity profile and Streamline profile for $NY = 20$

4.2 Nested mesh size,NY=40

Similarly,The simulations were ran for the following $conv\_criteria\_gain(CCG)$ values,4,5,6.The following table shows the results obtained. It can be observed that as the stopping criteria are

CCG	CPU time(mins)	Iterations	L_r(approx.)
4	3.132	6807	7.77
5	4.418	9583	7.805
6	1.740	12573	7.805

Table 2: Table of results for the NY=40

increased, the number of iterations also increases with respect to it. The corresponding CPU time also increases. The L_r remains the same for the CCG values 5 and 6. The below graph represents the same.The pressure resolution($gain\_PCGSTAB$ and $gain\_BOOMER$) are increased.It was observed that as we increase these values, the CPU time is affected. So we set these values to 20. We define a convergence criterion that has a good compromise between iteration error and

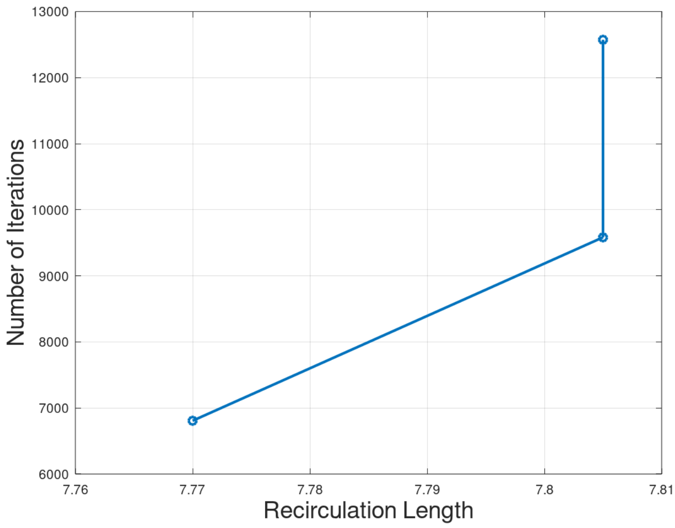
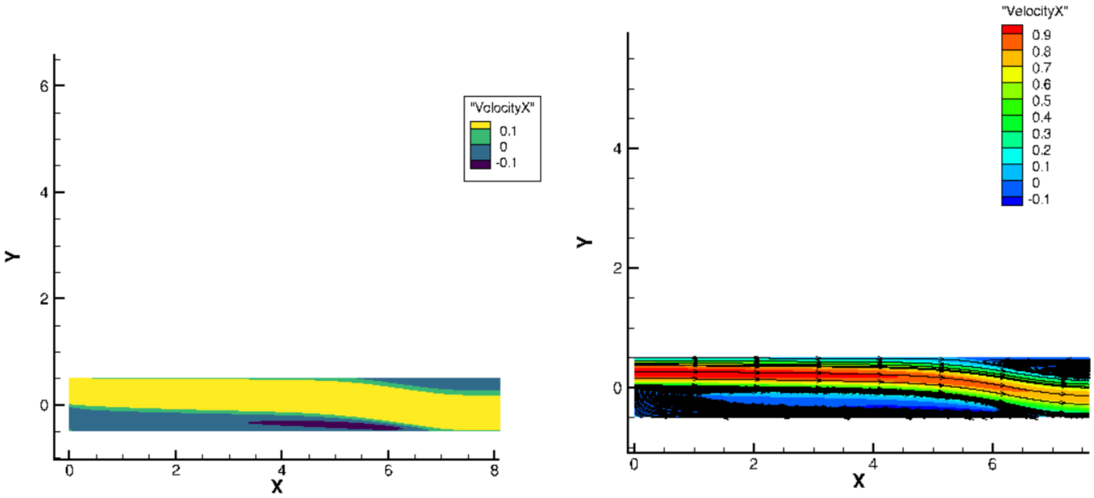


Figure 4: Graph of L_r vs iterations for NY=40

CPU time, which is CCG=5 and Pressure resolution values =20. The following images show the velocity profile and the streamline profile for the considered convergence criteria values.



(a) Velocity Profile

(b) Streamline Profile

Figure 5: Contour plot of Velocity profile and Streamline profile for $NY = 40$

4.3 Nested mesh size,NY=60

Similarly,The simulations were ran for the following $conv\_criteria\_gain(CCG)$ values,2,4,6.The following table shows the results obtained. It can be observed that as the stopping criteria are

CCG	CPU time(mins)	Iterations	L_r(approx.)
2	3.243	3164	6.40
4	13.917	14148	7.95
6	18.639	20000	7.35(not converged)

Table 3: Table of results for the NY=60

increased, the number of iterations also increases with respect to it. The corresponding CPU time also increases. For CCG value 6, the solution does not converge for the maximum number of iteration,20000. The L_r remains in the same range for the CCG values 4 and 6. The below graph represents the same.The pressure resolution(*gain_PCGSTAB* and *gain_BOOMER*) are increased.It was observed that as we increase these values, the CPU time is affected. So we set these values to 25. We define a convergence criterion that has a good compromise between

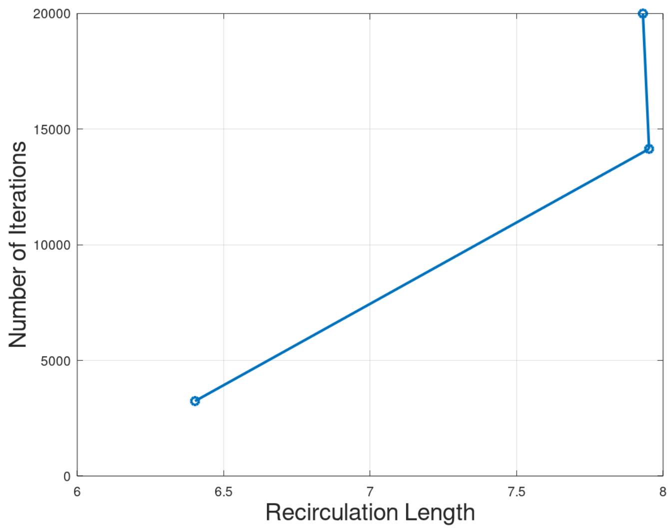
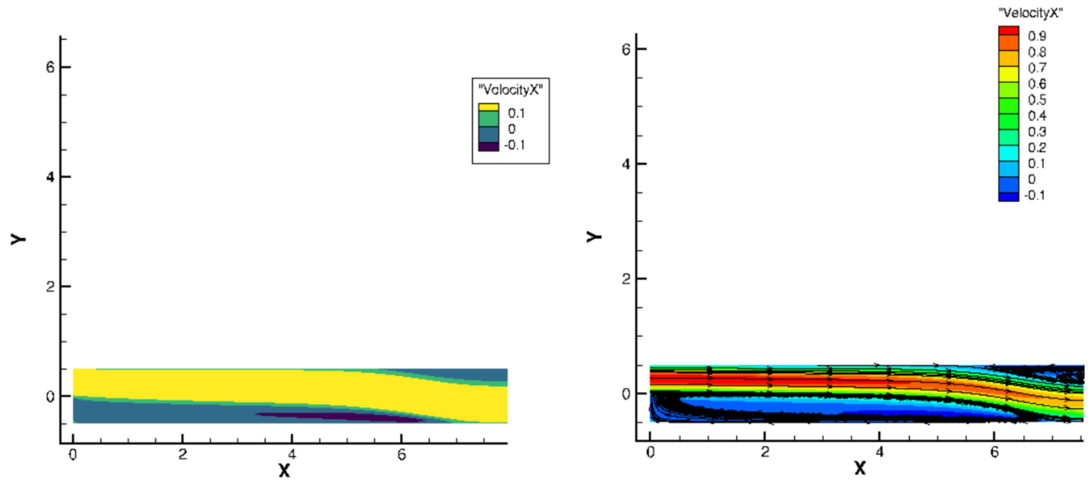


Figure 6: Graph of L_r vs iterations for NY=60

iteration error and CPU time, which is CCG=4 and Pressure resolution values =25. The following images show the velocity profile and the streamline profile for the considered convergence criteria values.



(a) Velocity Profile

(b) Streamline Profile

Figure 7: Contour plot of Velocity profile and Streamline profile for $NY = 60$

4.4 Stopping Criteria analysis

The CCG was set to 4 and 6,the following table shows the observation made for different nested mesh sizes. It can be observed that as the mesh size increases the number of iteration also

CCG	Iterations(NY=20)	Iterations(NY=40)	Iterations(NY=60)
4	3217	6807	14148
6	8435	12573	20000

Table 4: Table of results for a particular CCG value for different nested mesh sizes

increases gradually for the same CCG value. This is because the gain on momentum residual will be the same, so it will take more computational time and also more iterations to reach the convergence. So for finer meshes, if we reduce the CCG value, we can reduce the number of iterations taken to converge. But a compromise should be made between the iteration error and the computational time.

4.5 Discretisation error

To examine the Discretisation, we calculate the $\frac{L_r}{h}$ ratio for the corresponding Reynolds number. We have set the Reynolds number to 840.The h value is 0.5.This ratio is compared with the values from the study presented in $Gualtieri$2005.So,for the Reynolds number 840,the $\frac{L_r}{h}$ ratio is around 13-15.Comparing this value with the obtained values

- For $NY = 20, \frac{L_r}{h} = 12.928$
- For $NY = 40, \frac{L_r}{h} = 15.61$
- For $NY = 60, \frac{L_r}{h} = 15.90$

So,these ratio are approximately in correspondence with the values presented in the study $Gualtieri$2005.

5 Influence of Discretisation Scheme

For the three nested meshes we have considered and convergence criteria which ensure that the iteration error is under control we analyze the influence of the discretization scheme.We are investigating two schemes, the AVLSMART scheme, and the first-order scheme UPWIND scheme. We focus on the recirculation length and the velocity profiles for these schemes.

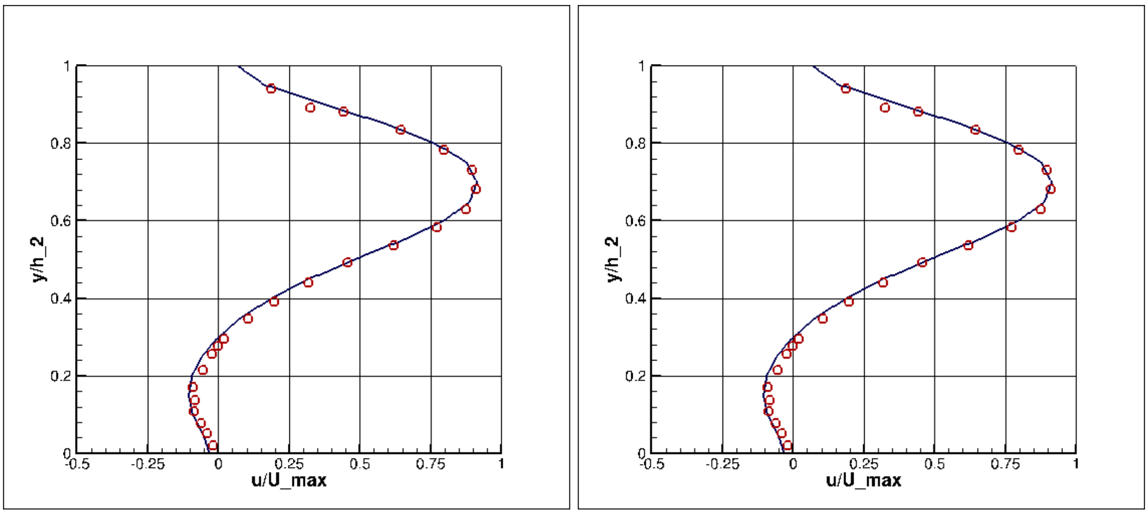
5.1 NY=20

The following L_r values was obtained for AVLSMART and UPWIND scheme. It can be ob-

Scheme	L_r
AVLSMART	6.4647
UPWIND	6.4647

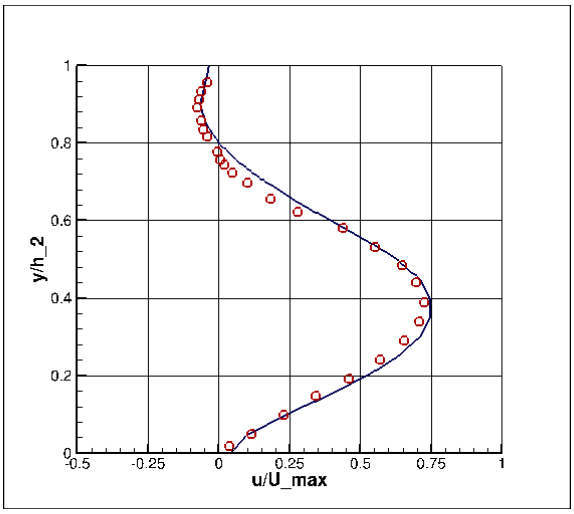
Table 5: Table of L_r values for AVLSMART and UPWIND scheme

served that the L_r values are similar between the schemes. The velocity profiles obtained were compared with the velocity profiles obtained from the study *Gualtieri*2005.The following images represent the comparison between them.

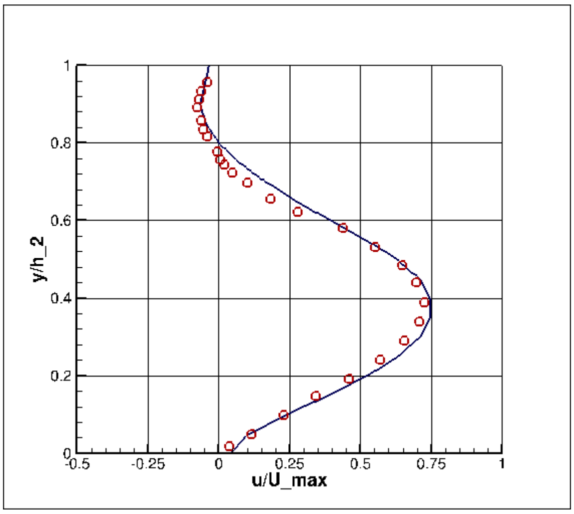


(a) AVLSMART (b) UPWIND

Figure 8: Comparison of velocity profiles for $\frac{x}{h} = 7.04$



(a) AVLSMART



(b) UPWIND

Figure 9: Comparison of velocity profiles for $\frac{x}{h} = 19.04$

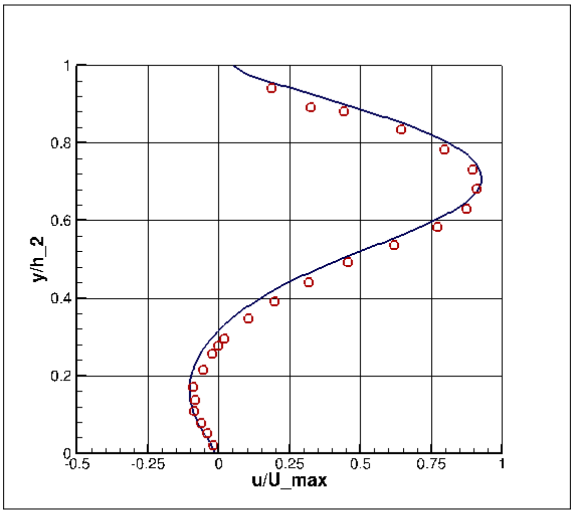
5.2 NY=40

he following L_r values was obtained for AVLSMART and UPWIND scheme. It can be observed

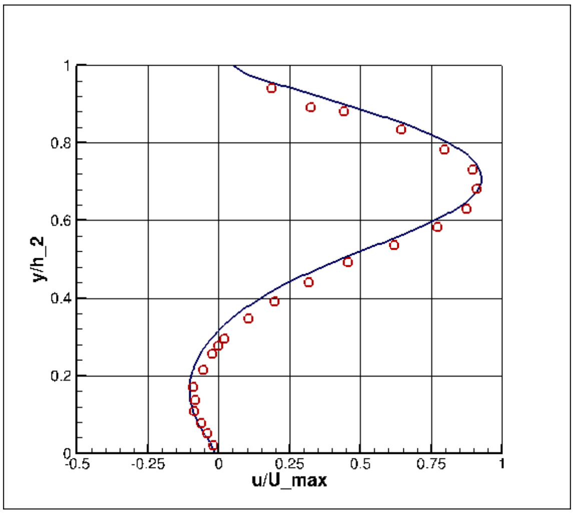
Scheme	L_r
AVLSMART	7.8105
UPWIND	7.79

Table 6: Table of L_r values for AVLSMART and UPWIND scheme

that the L_r values are similar between the schemes. The velocity profiles obtained were compared with the velocity profiles obtained from the study *Gualtieri*2005.The following images represent the comparison between them.

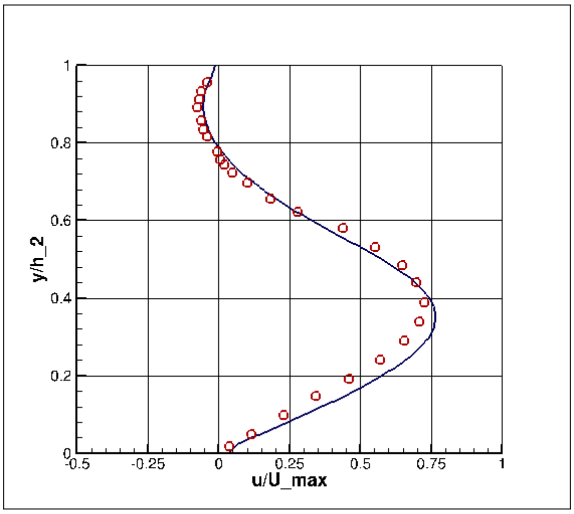


(a) AVLSMART

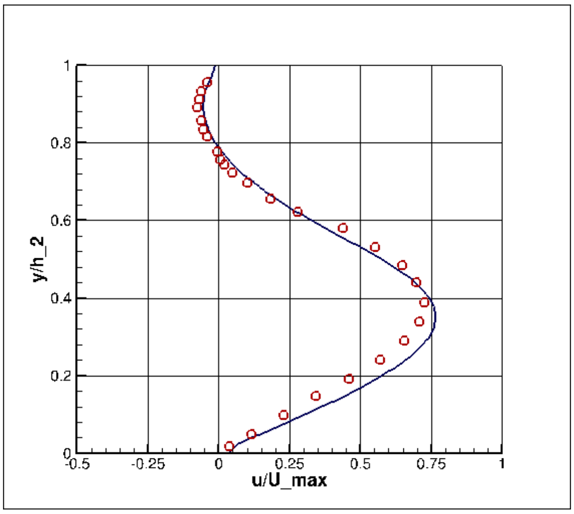


(b) UPWIND

Figure 10: Comparison of velocity profiles for $\frac{x}{h} = 7.04$



(a) AVLSMART



(b) UPWIND

Figure 11: Comparison of velocity profiles for $\frac{x}{h} = 19.04$

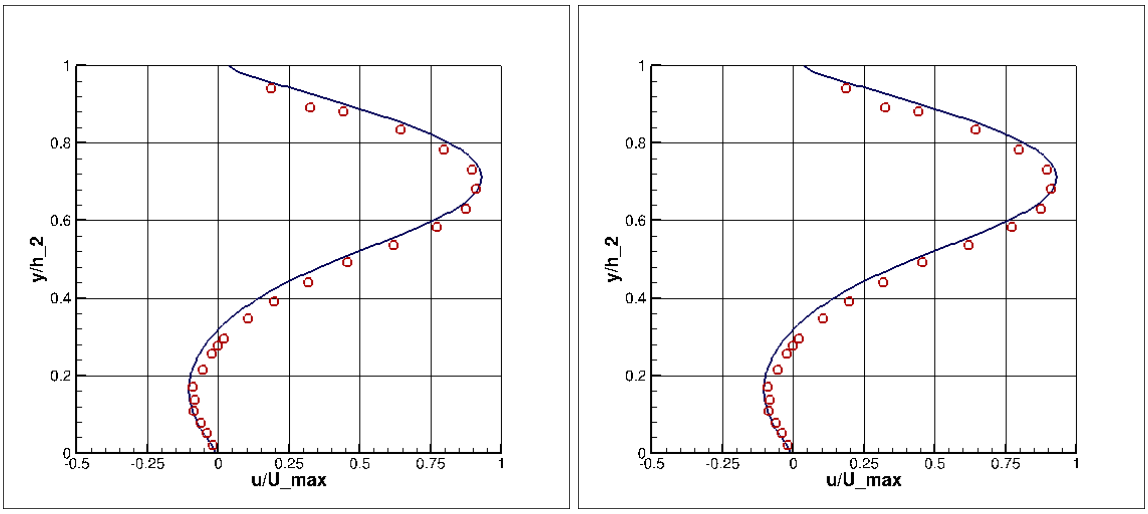
5.3 NY=60

he following L_r values was obtained for AVLSMART and UPWIND scheme.

Scheme	L_r
AVLSMART	7.952
UPWIND	7.952

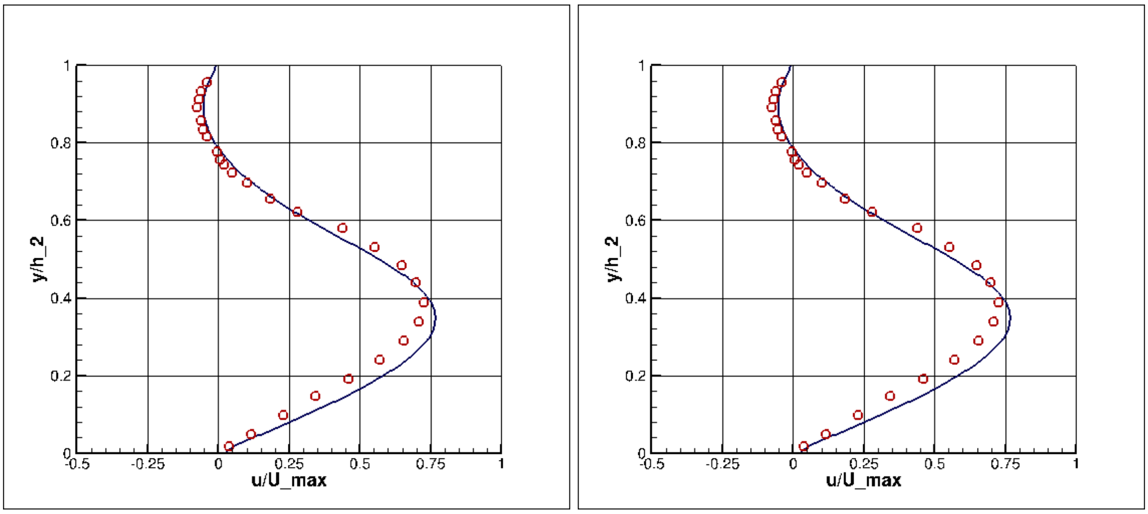
Table 7: Table of L_r values for AVLSMART and UPWIND scheme

It can be observed that the L_r values are similar between the schemes. The velocity profiles obtained were compared with the velocity profiles obtained from the study *Gualtieri*2005.The following images represent the comparison between them.



(a) AVLSMART (b) UPWIND

Figure 12: Comparison of velocity profiles for $\frac{x}{h} = 7.04$



(a) AVLSMART (b) UPWIND

Figure 13: Comparison of velocity profiles for $\frac{x}{h} = 19.04$

6 Influence of the relaxation parameter

To analyze the influence of the relaxation parameter, we are choosing the nested mesh size of $NY = 40$.Three different sets of under-relaxation for both velocity and pressure are considered, simulations are performed based on these values. The following table shows the results obtained from this simulation. It can be observed that as these parameters are increased, the number of

relaxVit	*relaxP*	**CPU time(mins)**	**Iterations**
0.3	0.1	4.499	9583
0.5	0.3	4.649	9583
0.7	0.5	4.703	9583

Table 8: Table of results for different values of relaxation parameters

iterations taken to convergence remains the same. But there is a small change in the CPU time.

7 Influence of the diagonal dominance

To analyze the influence of the diagonal dominance, we are choosing the nested mesh size of $NY = 40$.Three different values of $DiagDomRate$ are considered,30,50,70.Simulations are performed based on these values. The following table shows the results obtained from this simulation. It can be observed that as these parameters are increased, the number of iterations

$DiagDomRate$	**CPU time(mins)**	**Iterations**
30	4.668	9583
50	4.667	9585
70	4.503	9583

Table 9: Table of results for different values of $DiagDomRate$

are same for different values of $DiagDomRate$.But there is are small variations in respect to the CPU time.