Introduction to CFD

(Computational Fluid Dynamics)

Assignment # 3

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a) Qualitative Flow Description

The flow across a square cylinder may be expected to have similar basic features as that over a circular cylinder. After all, a circle is a geometry with infinite vertices and a square is a finite polygon; with four sides and vertices, each. However the total frontal area for a square can be said to be larger than a circle of the same characteristic lengths. Thus implying that the pressure drag would be more than that for a circular geometry.

One can expect stagnation points at the centre of the fore and aft of the cylinder; at the sides that are perpendicular to the flow. Whereas, at the sides parallel to the flow, there would be a symmetric pressure distribution, thus causing no net lift force for low Reynolds numbers and steady state simulations.

Since the no-slip boundary condition exists at the periphery, the viscous/shear effects here would contribute in the total drag force, that is expected at all Reynolds numbers (which is also composed of the pressure drag force); decreasing in magnitude as the Reynolds number increases.

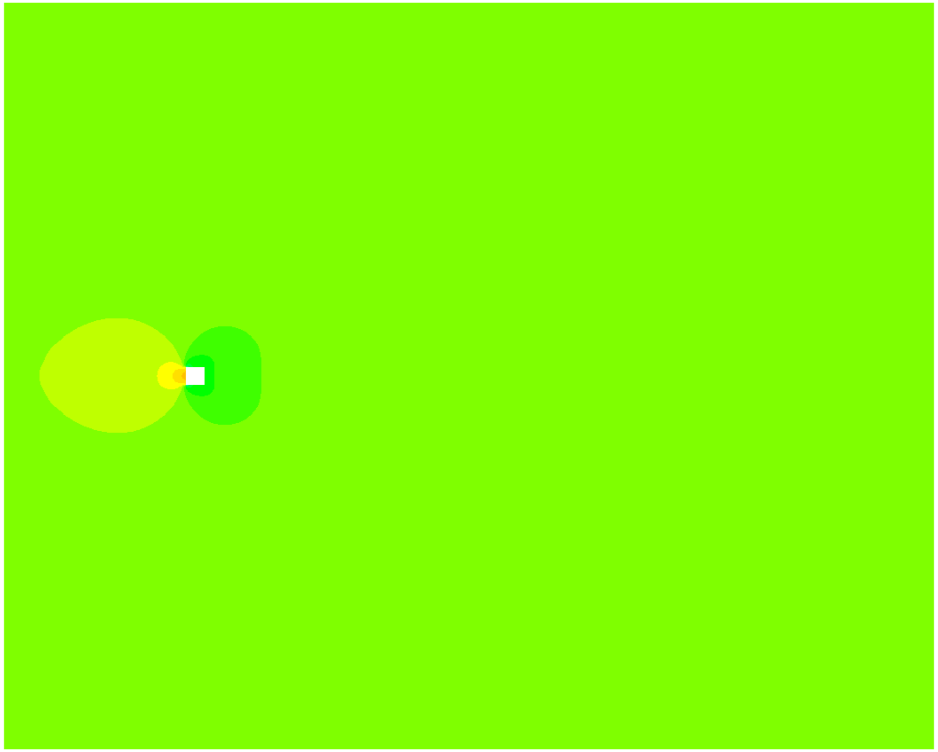
However the pressure drag would increase for higher Reynolds number due to dominance of inertial effects of the fluid to the viscous effects.

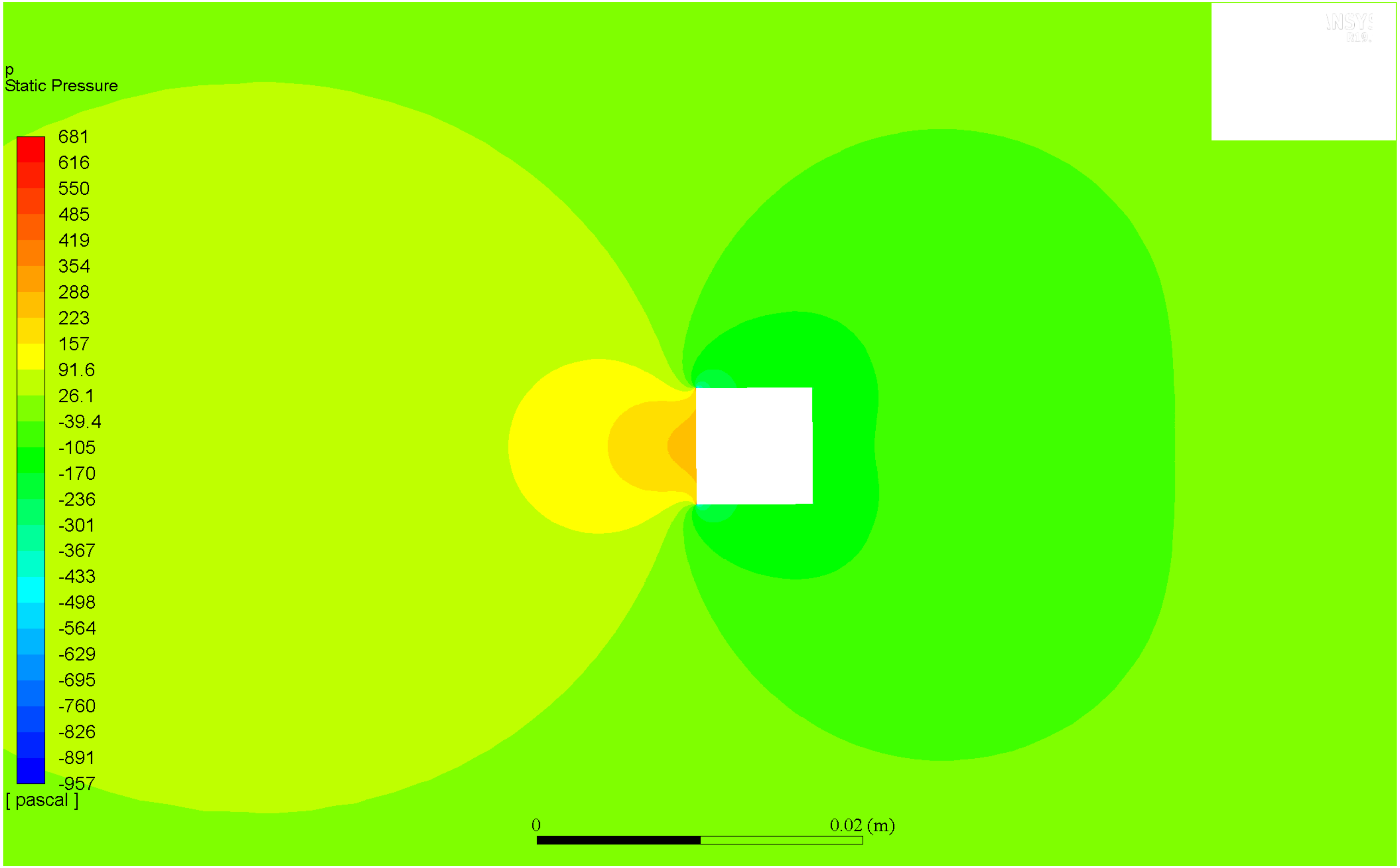
One would also expect to see a wake region, downstream, as well a flow separation at the terminal ends of the *parallel-to-flow* faces.

c) Simulation Results

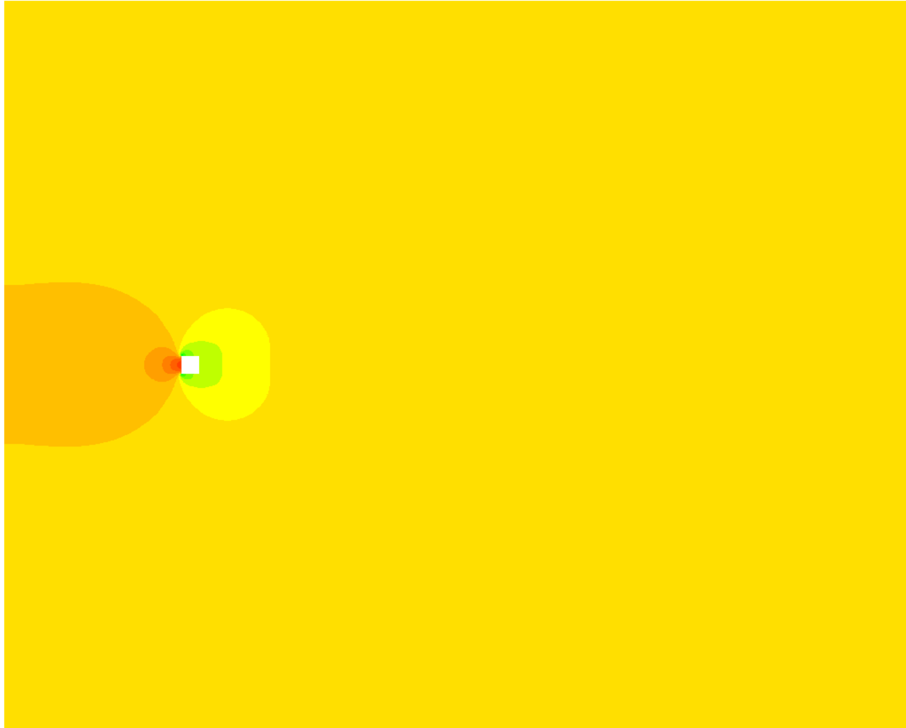
Pressure Contour Plots

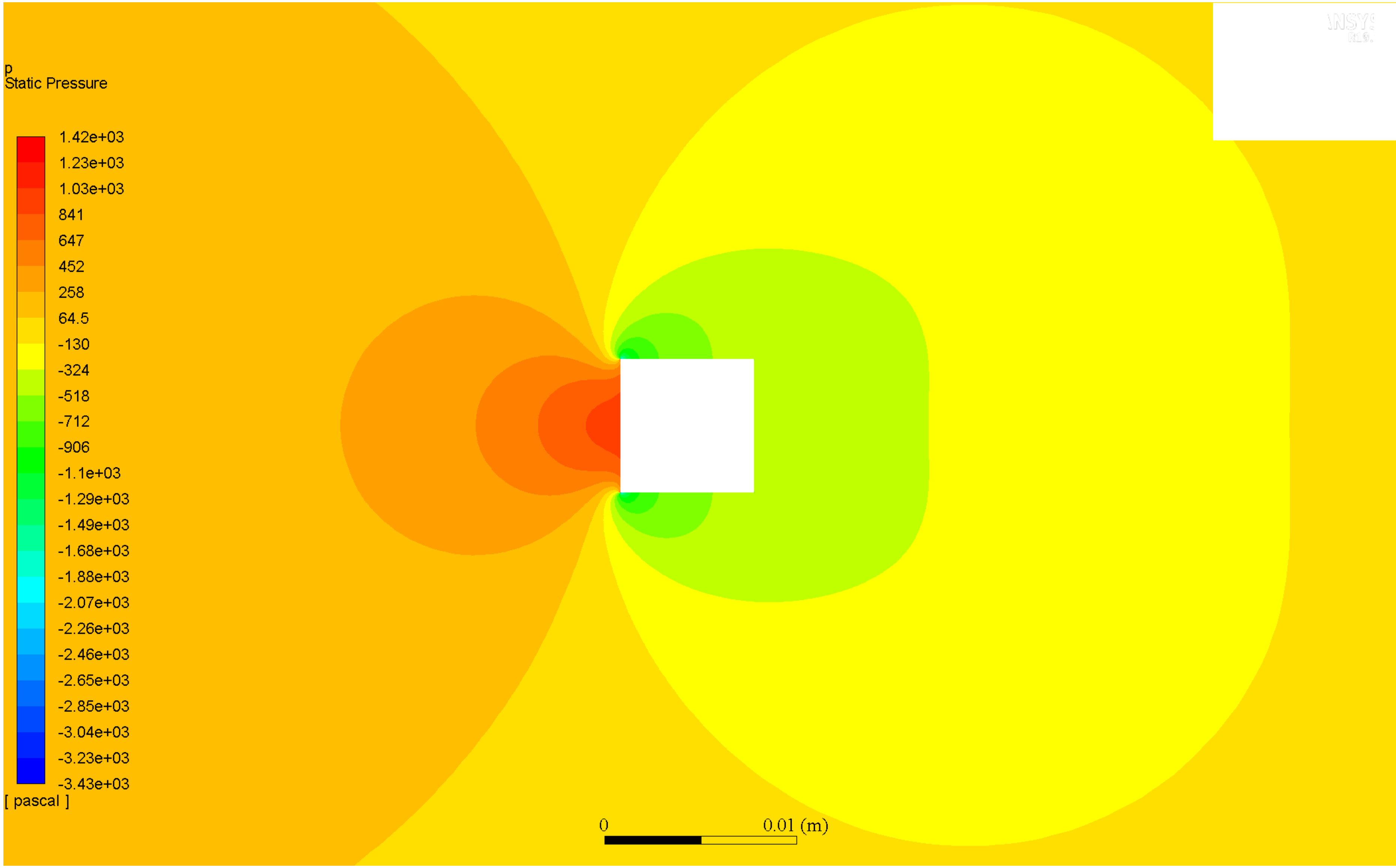
Re = 20



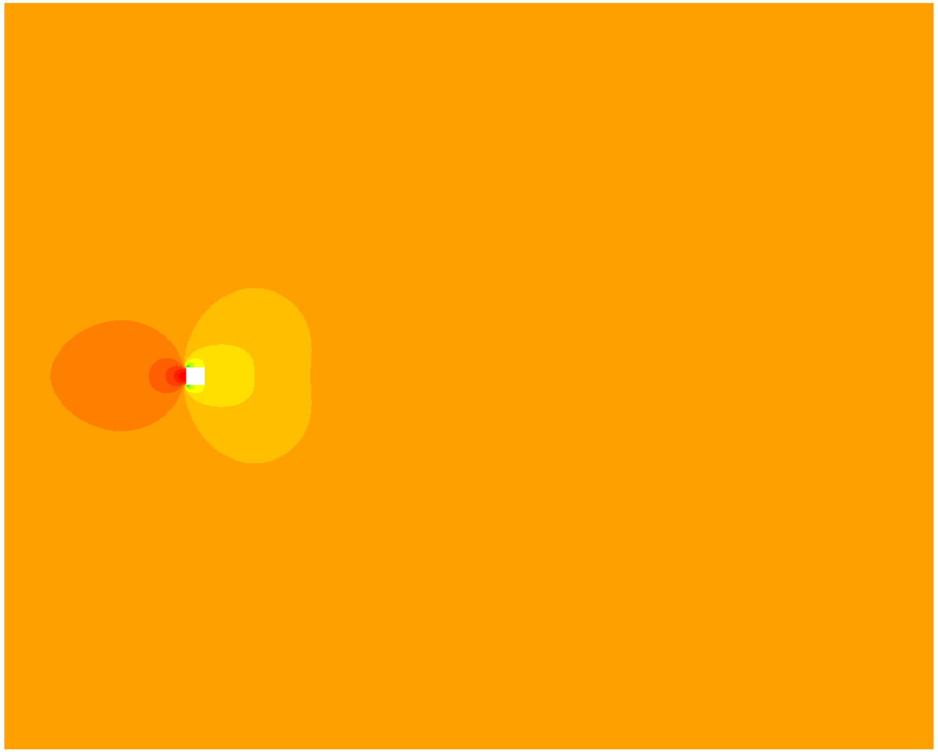

p
Static Pressure
681
616
550
485
419
354
288
223
157
91.6
26.1
-39.4
-105
-170
-236
-301
-367
-433
-498
-564
-629
-695
-760
-826
-891
-957
[pascal]
0
0.02 (m)

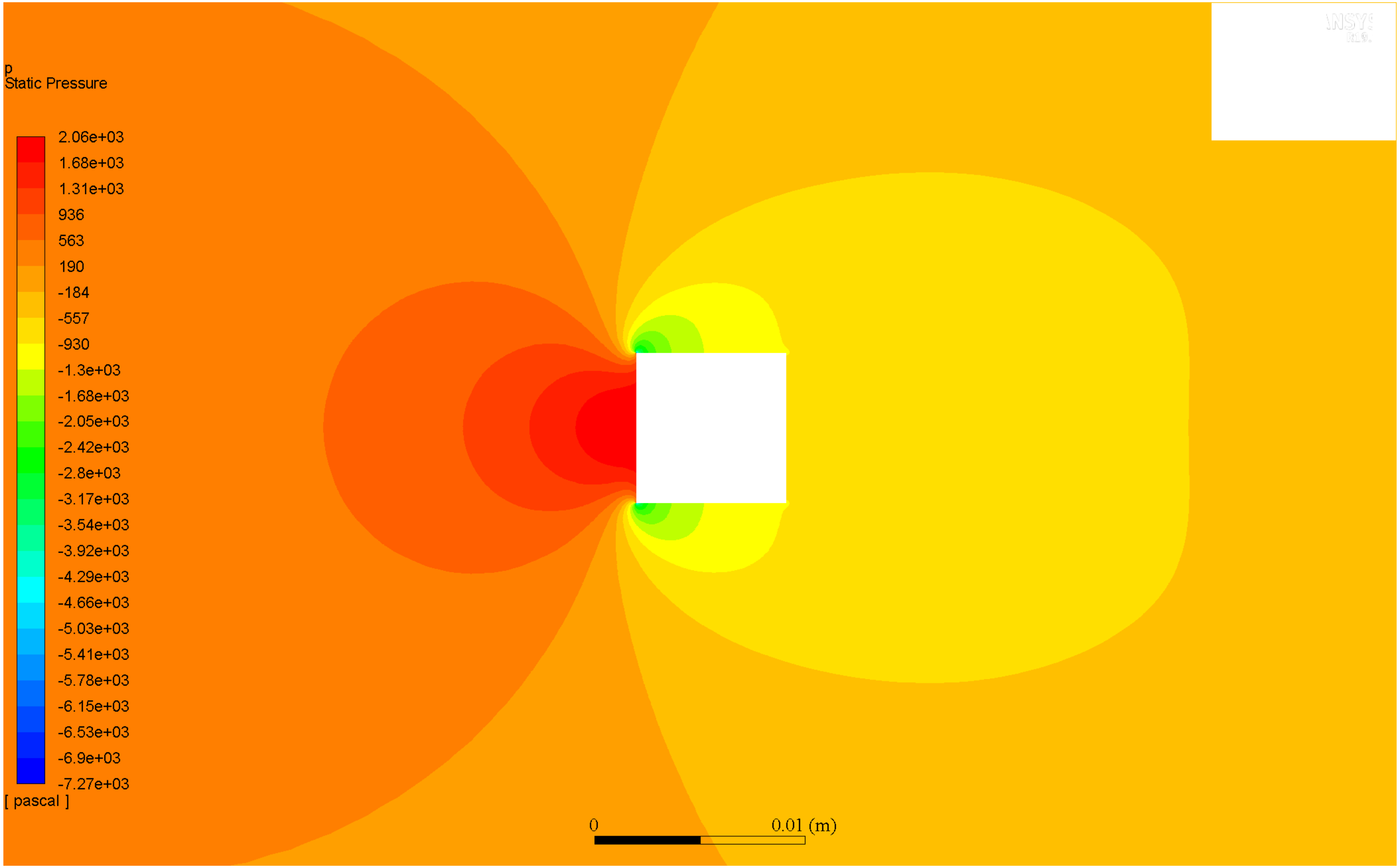
Re = 40



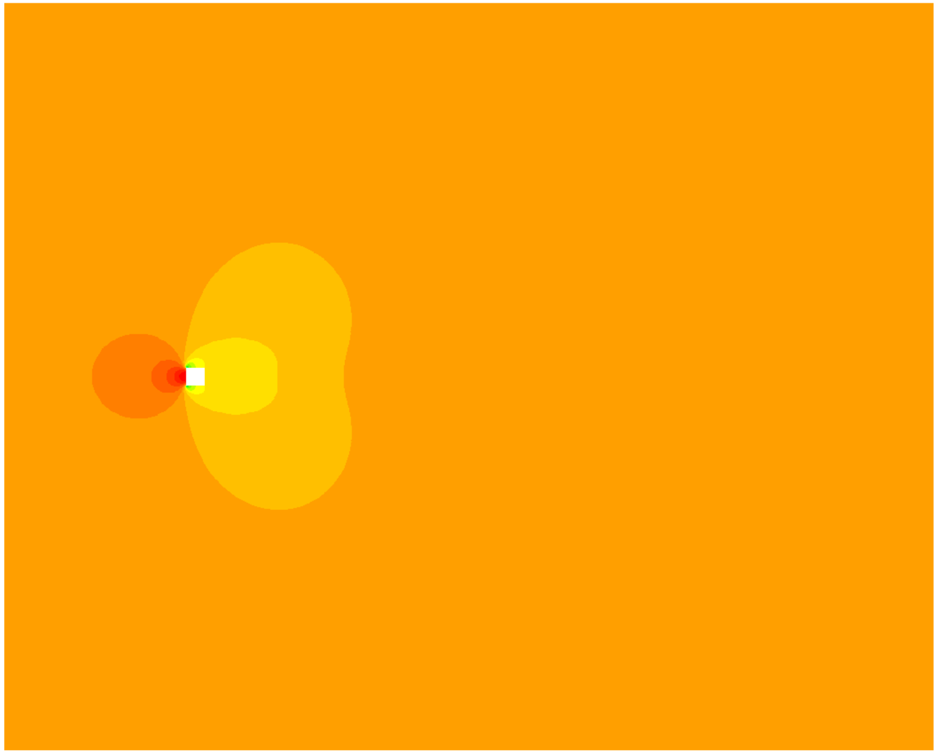

p
Static Pressure
1.42e+03
1.23e+03
1.03e+03
841
647
452
258
64.5
-130
-324
-518
-712
-906
-1.1e+03
-1.29e+03
-1.49e+03
-1.68e+03
-1.88e+03
-2.07e+03
-2.26e+03
-2.46e+03
-2.65e+03
-2.85e+03
-3.04e+03
-3.23e+03
-3.43e+03
[pascal]
0
0.01 (m)

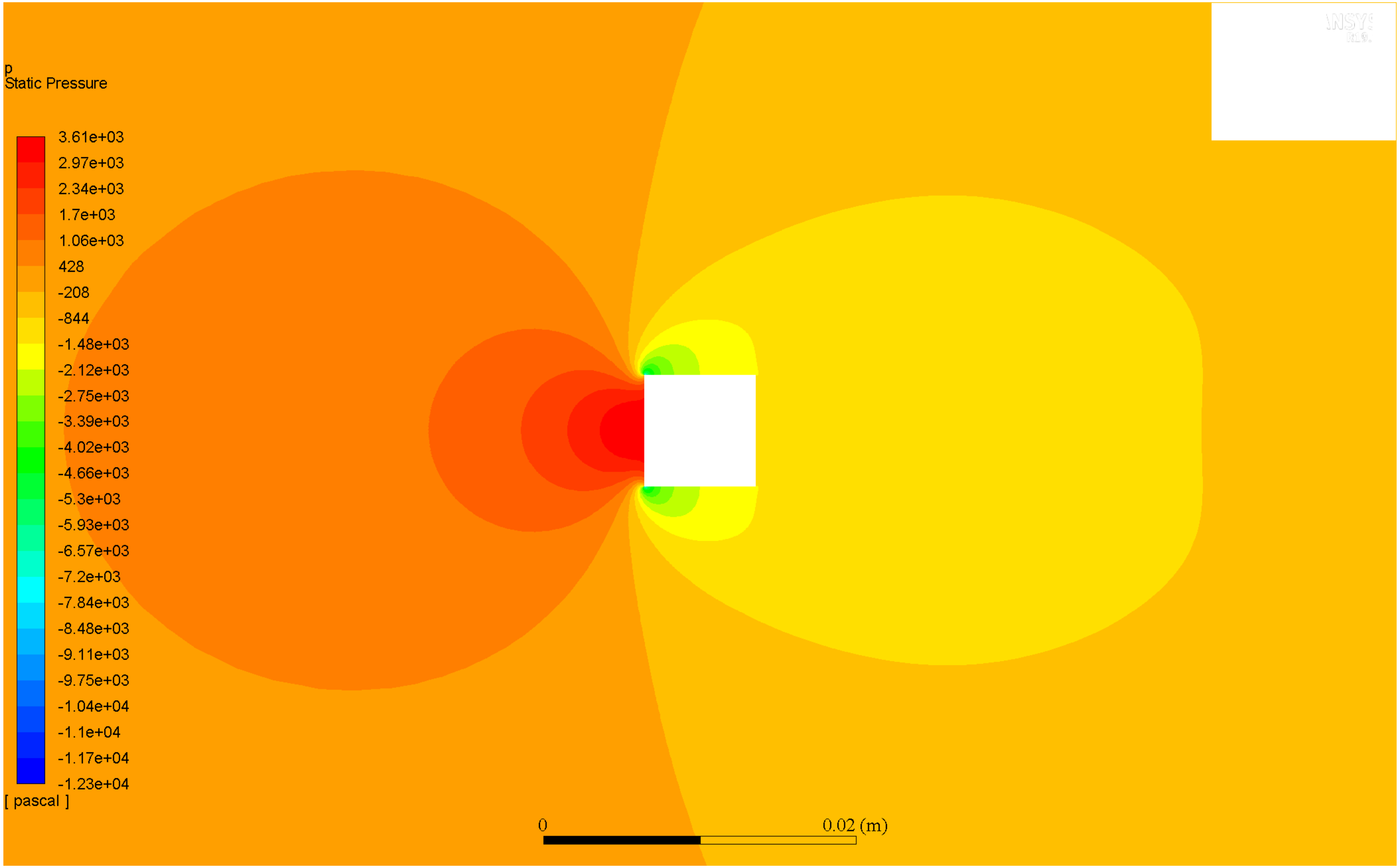
Re = 60



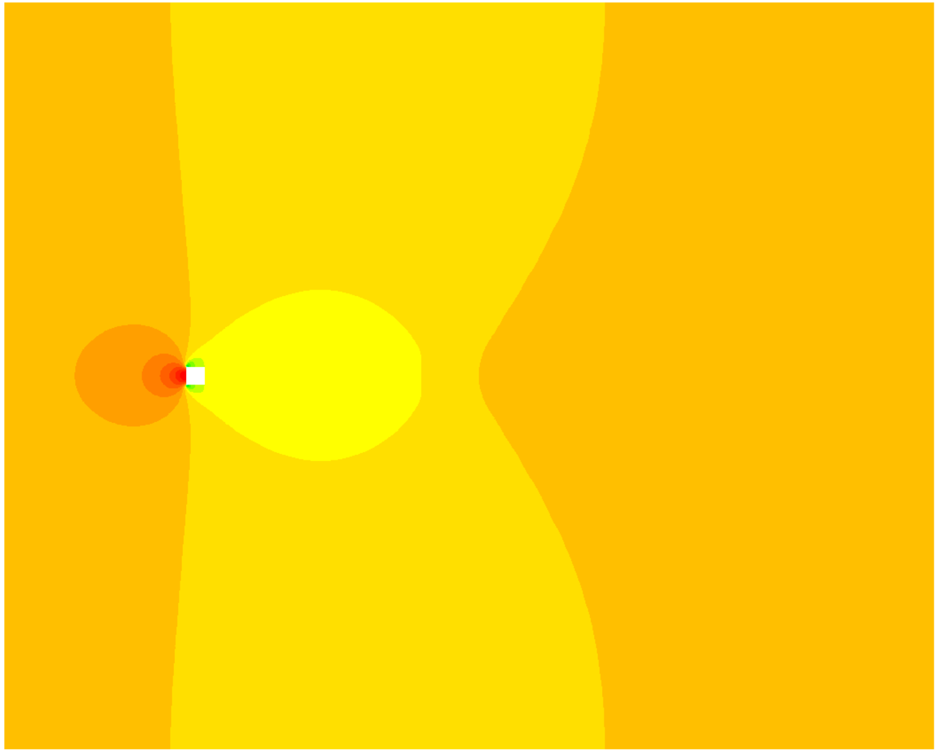

p
Static Pressure
2.06e+03
1.68e+03
1.31e+03
936
563
190
-184
-557
-930
-1.3e+03
-1.68e+03
-2.05e+03
-2.42e+03
-2.8e+03
-3.17e+03
-3.54e+03
-3.92e+03
-4.29e+03
-4.66e+03
-5.03e+03
-5.41e+03
-5.78e+03
-6.15e+03
-6.53e+03
-6.9e+03
-7.27e+03
[pascal]
0
0.01 (m)

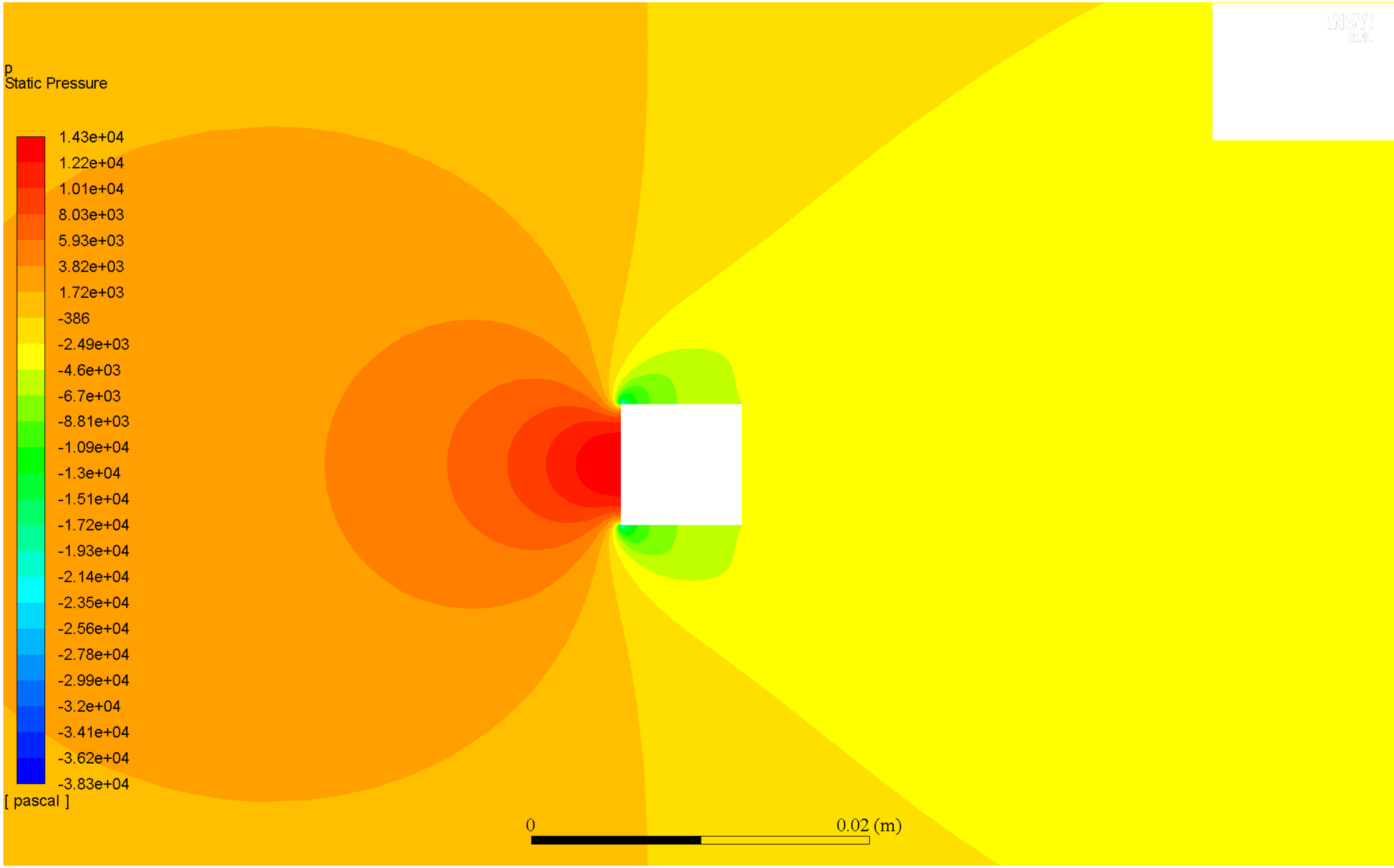
Re = 80




p
Static Pressure
3.61e+03
2.97e+03
2.34e+03
1.7e+03
1.06e+03
428
-208
-844
-1.48e+03
-2.12e+03
-2.75e+03
-3.39e+03
-4.02e+03
-4.66e+03
-5.3e+03
-5.93e+03
-6.57e+03
-7.2e+03
-7.84e+03
-8.48e+03
-9.11e+03
-9.75e+03
-1.04e+04
-1.1e+04
-1.17e+04
-1.23e+04
[pascal]
0
0.02 (m)

Re = 160




p
Static Pressure
1.43e+04
1.22e+04
1.01e+04
8.03e+03
5.93e+03
3.82e+03
1.72e+03
-386
-2.49e+03
-4.6e+03
-6.7e+03
-8.81e+03
-1.09e+04
-1.3e+04
-1.51e+04
-1.72e+04
-1.93e+04
-2.14e+04
-2.35e+04
-2.56e+04
-2.78e+04
-2.99e+04
-3.2e+04
-3.41e+04
-3.62e+04
-3.83e+04
[pascal]
0
0.02 (m)

Comparison & Discussion

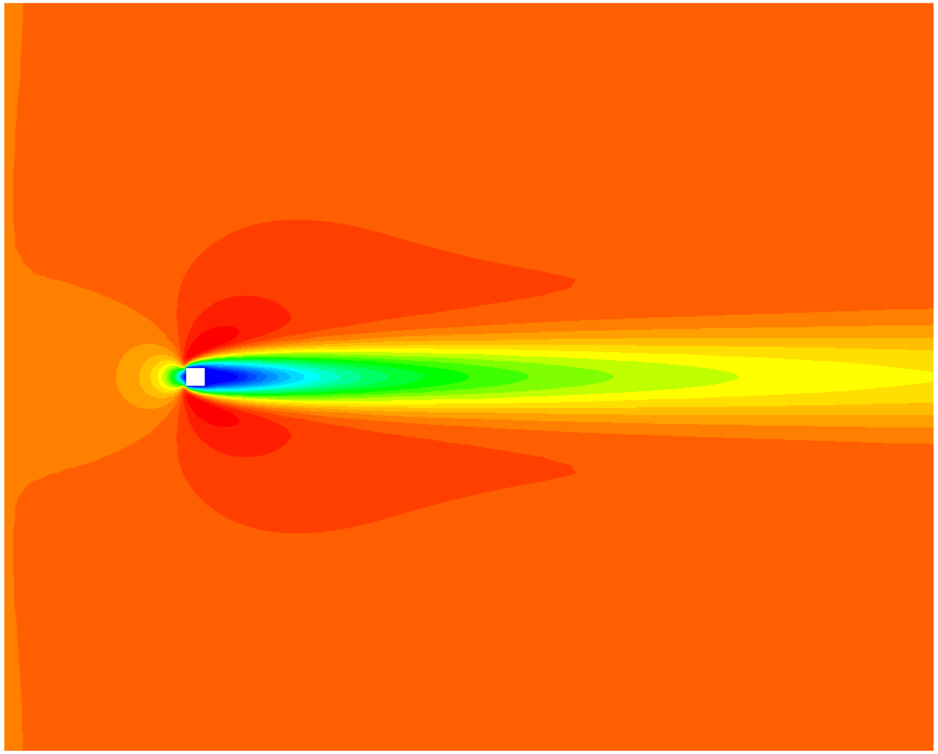
At all Re, the cylinder has positive static pressure in its fore and negative static pressure in its aft region. For increasing Re, the simulations indicate significant increase in the pressure gradient, that is, the magnitudes at the fore and aft of the cylinder, and hence there variation in the vicinity of the cylinder for static pressure become larger.

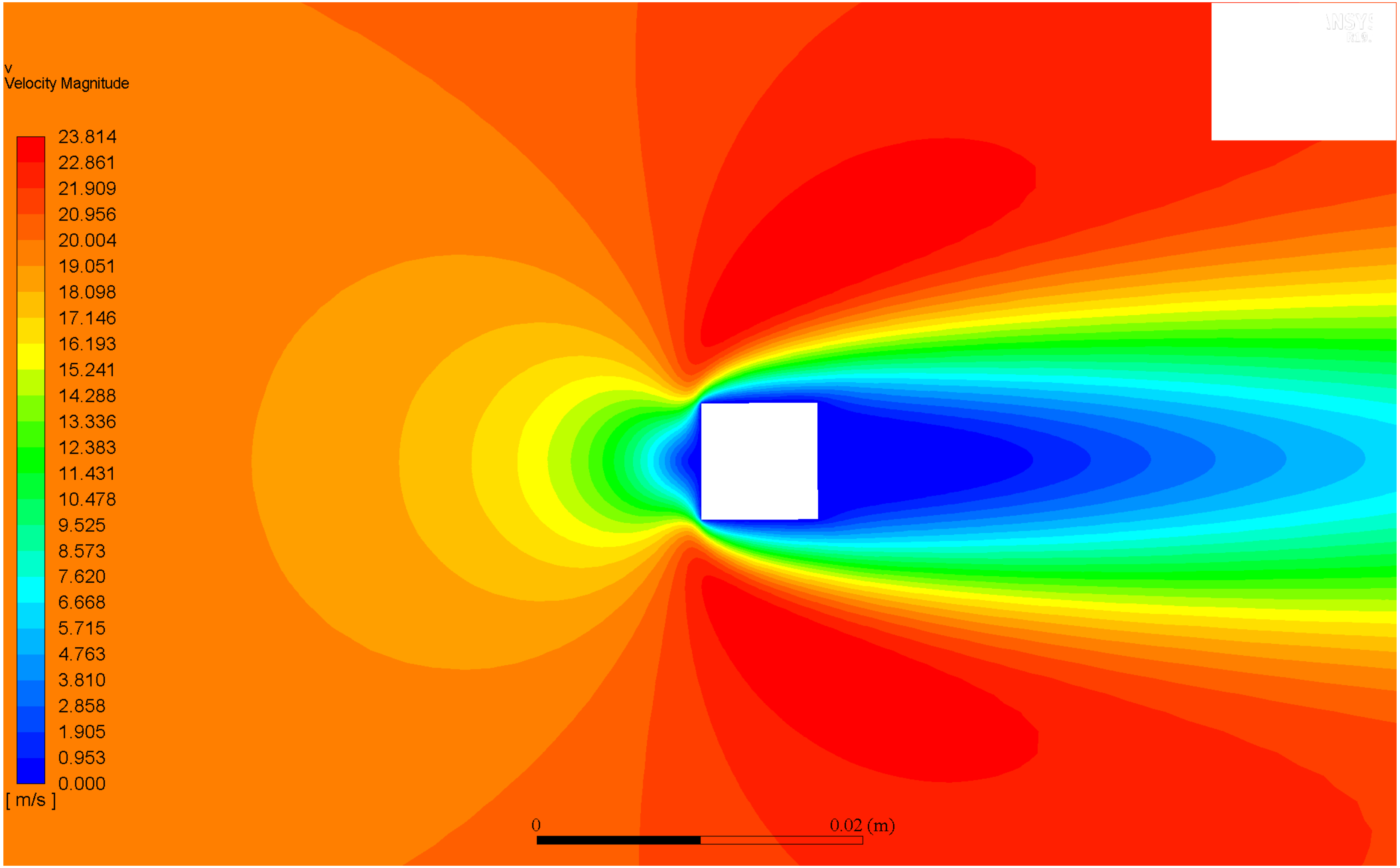
Further, as expected, the pressure contours are symmetric about the x axis.

The region of influence of these increasing pressure gradients also become larger for increasing Re, indicating there may be an onset of instabilities to trigger vortex shedding, hence presenting a need to try transient simulations.

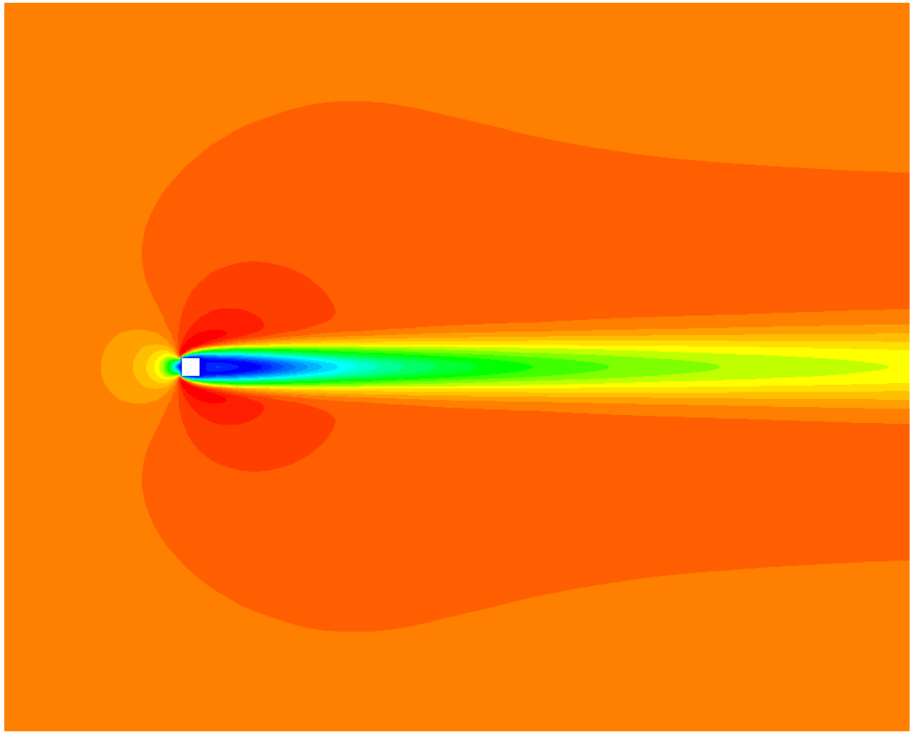
Velocity Contour Plots

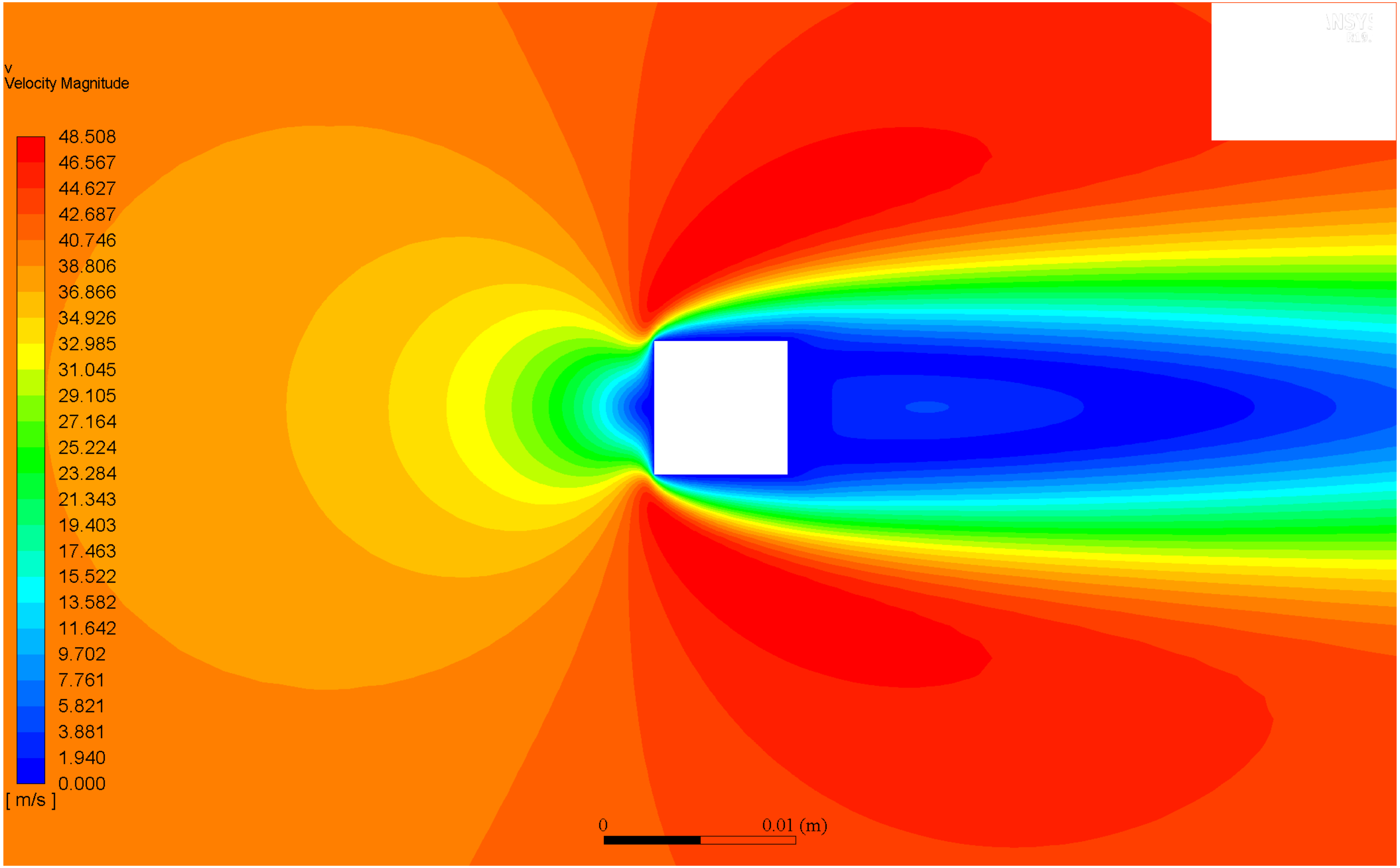
Re = 20



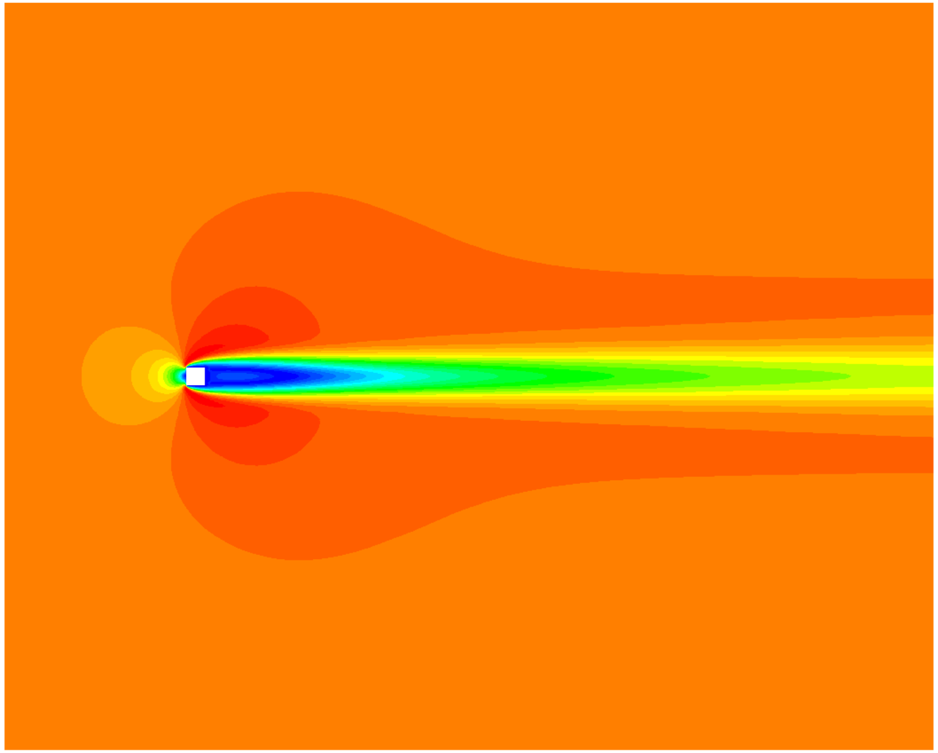

v
Velocity Magnitude
23.814
22.861
21.909
20.956
20.004
19.051
18.098
17.146
16.193
15.241
14.288
13.336
12.383
11.431
10.478
9.525
8.573
7.620
6.668
5.715
4.763
3.810
2.858
1.905
0.953
0.000
[m/s]
0
0.02 (m)

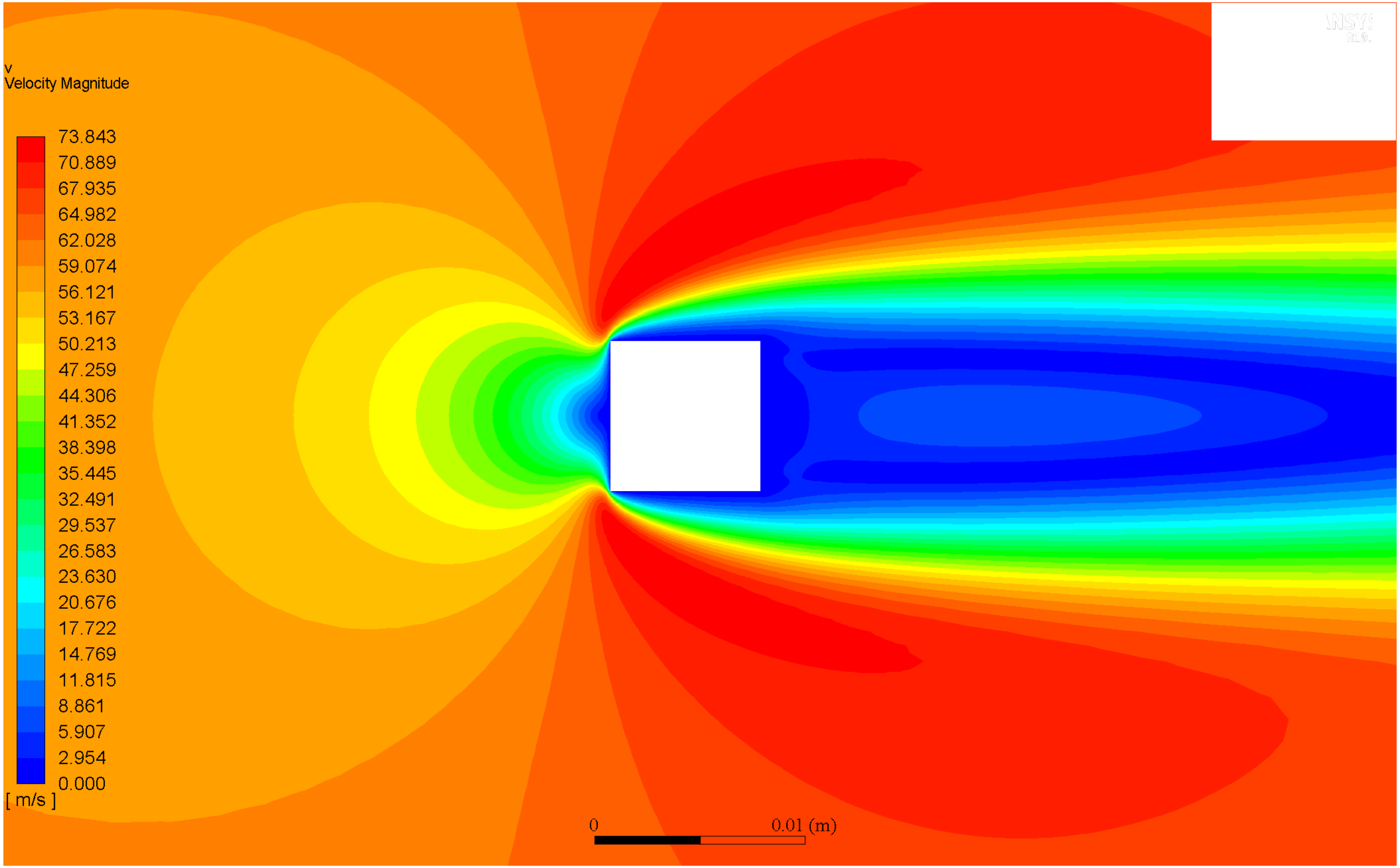
Re = 40



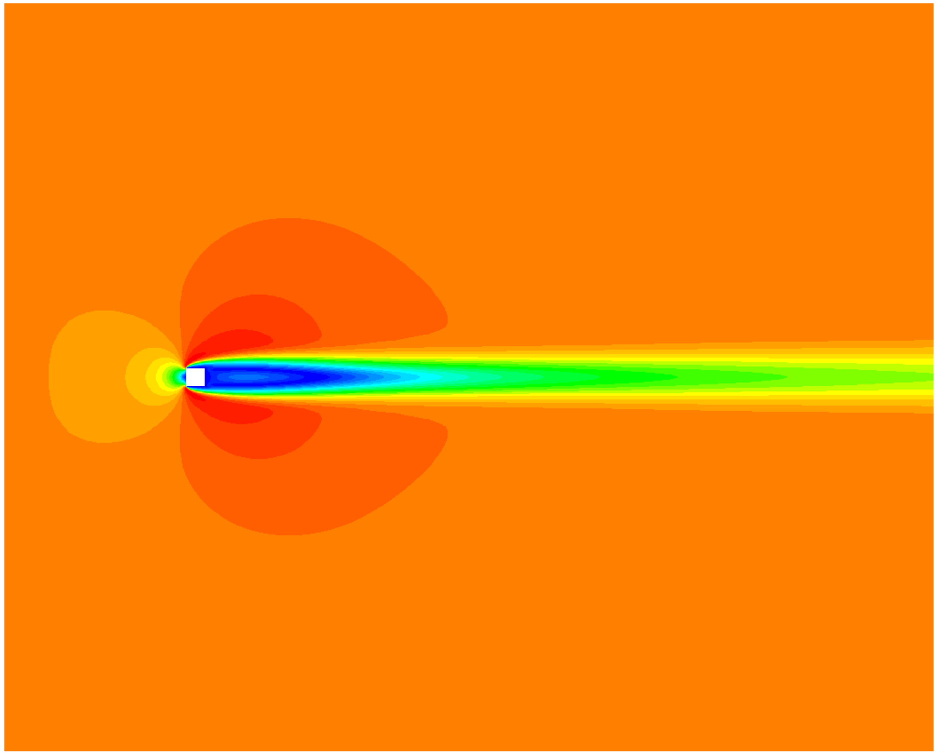

v
Velocity Magnitude
48.508
46.567
44.627
42.687
40.746
38.806
36.866
34.926
32.985
31.045
29.105
27.164
25.224
23.284
21.343
19.403
17.463
15.522
13.582
11.642
9.702
7.761
5.821
3.881
1.940
0.000
[m/s]
0
0.01 (m)

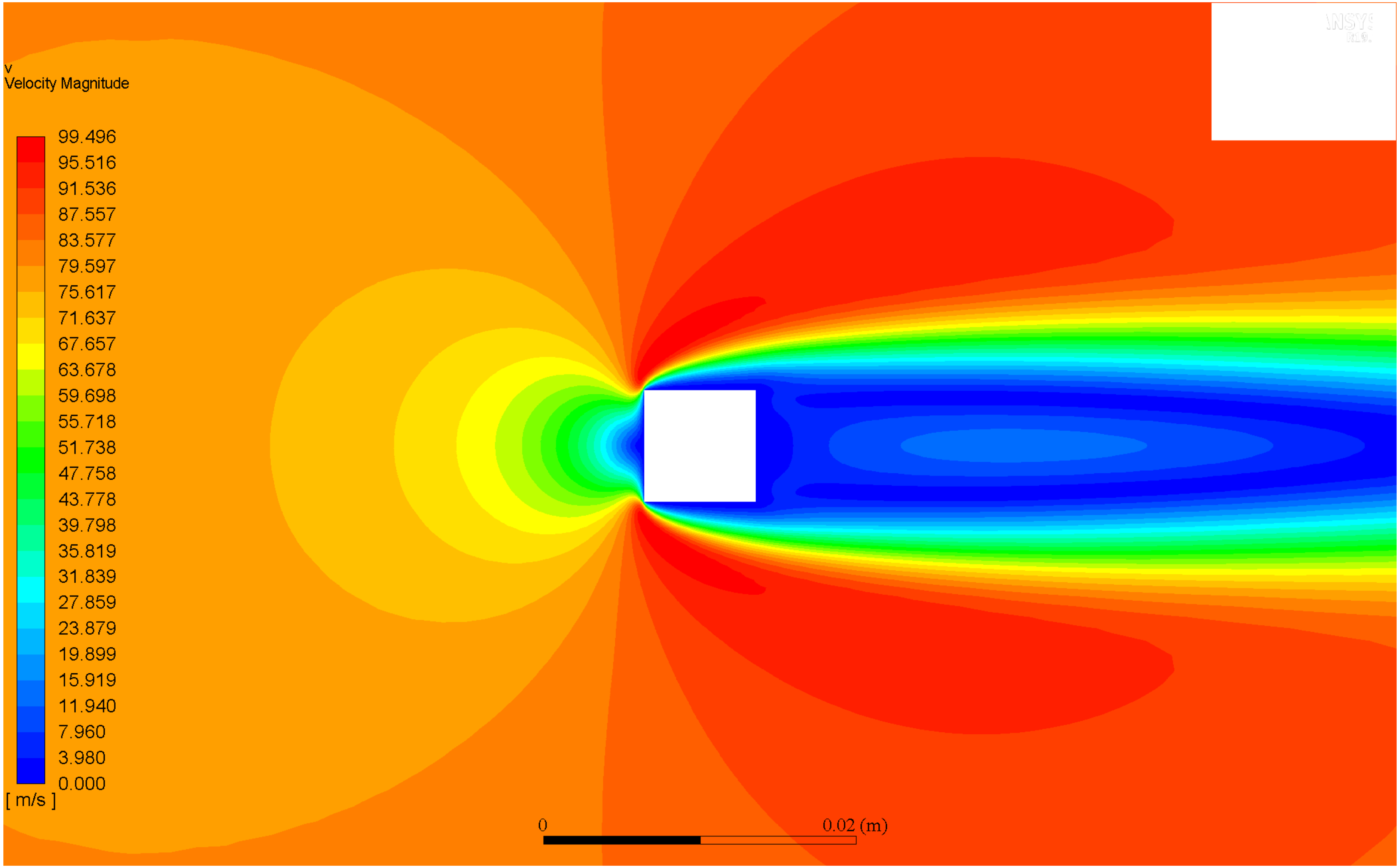
Re = 60



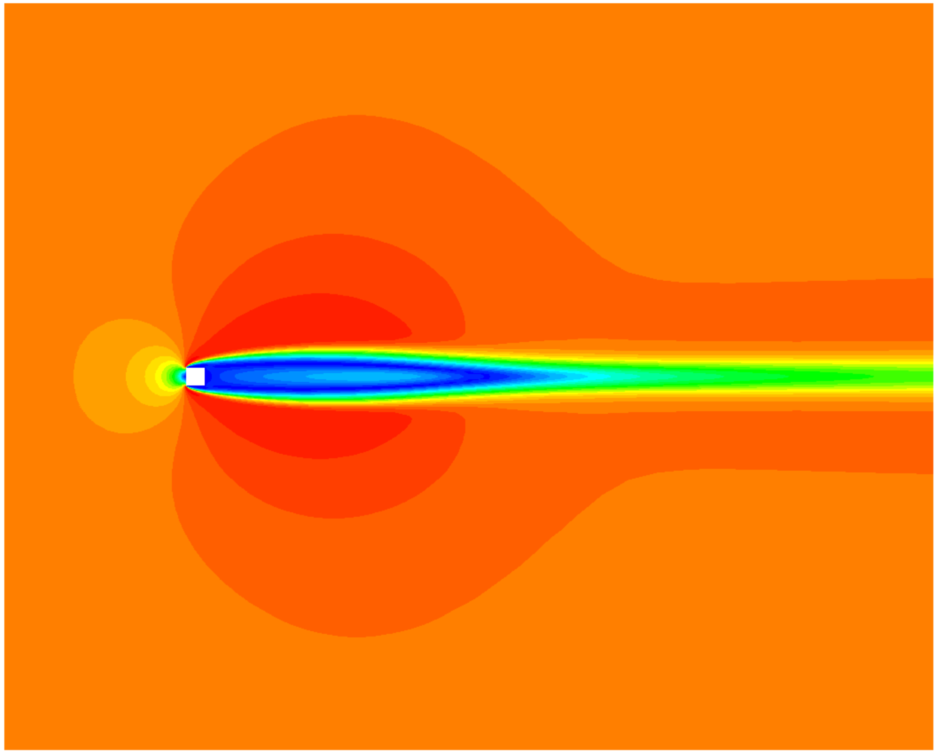

v
Velocity Magnitude
73.843
70.889
67.935
64.982
62.028
59.074
56.121
53.167
50.213
47.259
44.306
41.352
38.398
35.445
32.491
29.537
26.583
23.630
20.676
17.722
14.769
11.815
8.861
5.907
2.954
0.000
[m/s]
0
0.01 (m)

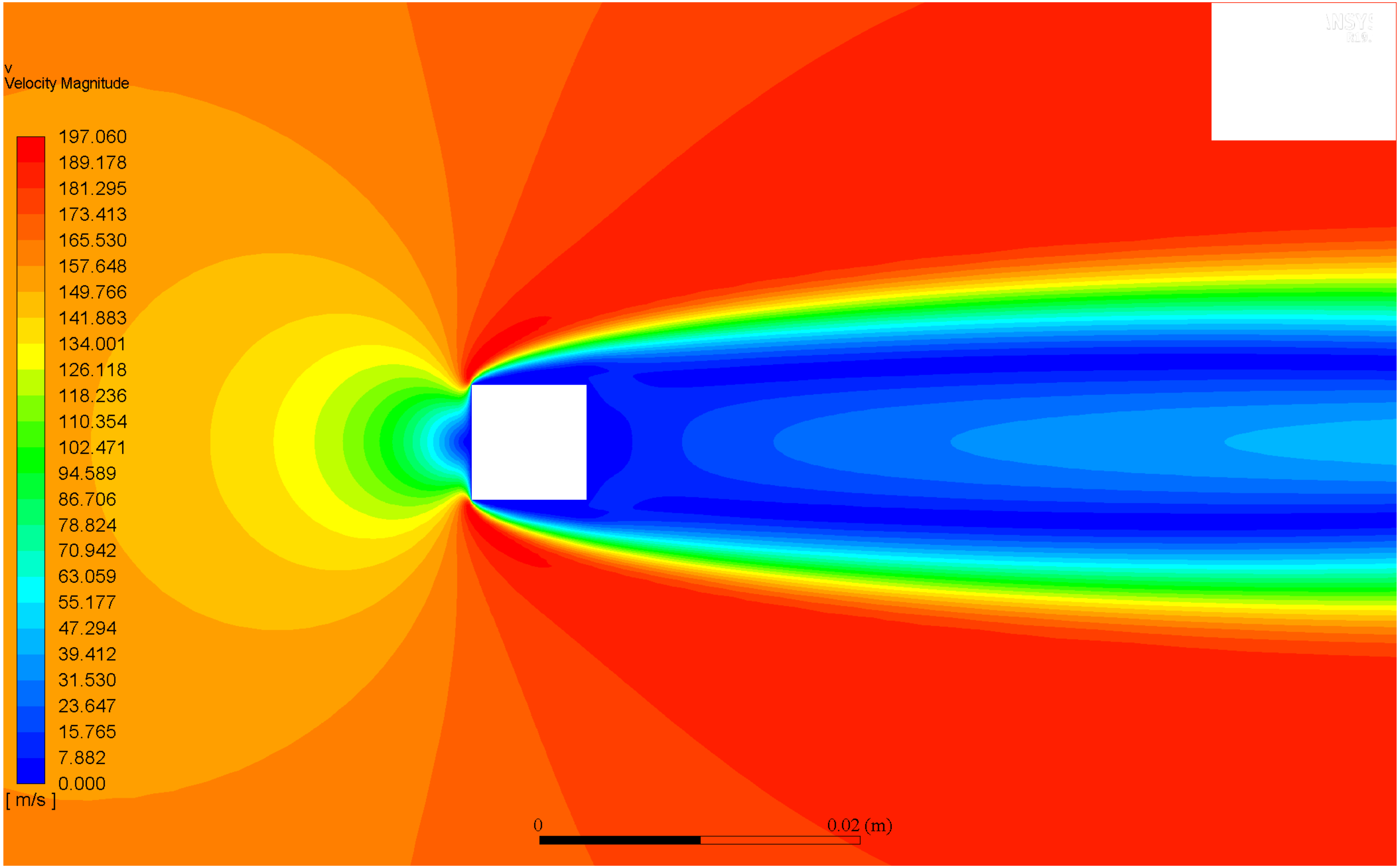
Re = 80




V
Velocity Magnitude
99.496
95.516
91.536
87.557
83.577
79.597
75.617
71.637
67.657
63.678
59.698
55.718
51.738
47.758
43.778
39.798
35.819
31.839
27.859
23.879
19.899
15.919
11.940
7.960
3.980
0.000
[m/s]
0
0.02 (m)

Re = 160




v
Velocity Magnitude
197.060
189.178
181.295
173.413
165.530
157.648
149.766
141.883
134.001
126.118
118.236
110.354
102.471
94.589
86.706
78.824
70.942
63.059
55.177
47.294
39.412
31.530
23.647
15.765
7.882
0.000
[m/s]
0
0.02 (m)

Comparison & Discussion

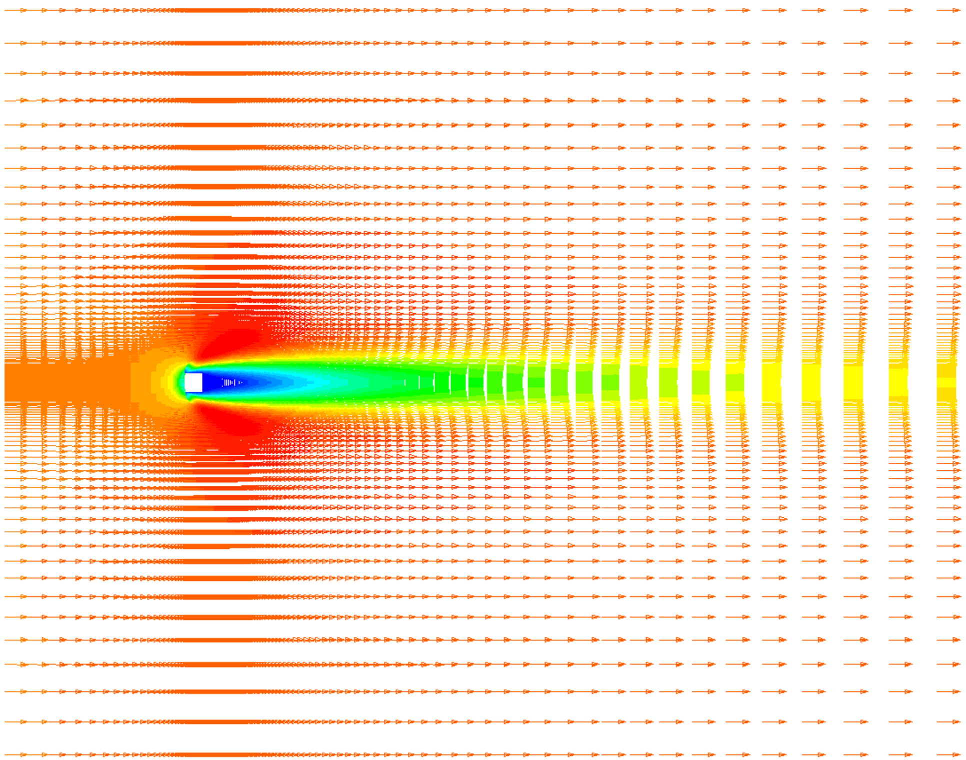
At all Re, the cylinder has stagnation points (zero velocity regions) in its immediate vicinity (fore and aft regions). The flow is seen to separate (that is separation regions form) after the flow crosses the fore vertices of the cylinder for all Re, as well as wake regions downstream, which are seen to become longer as Re increases.

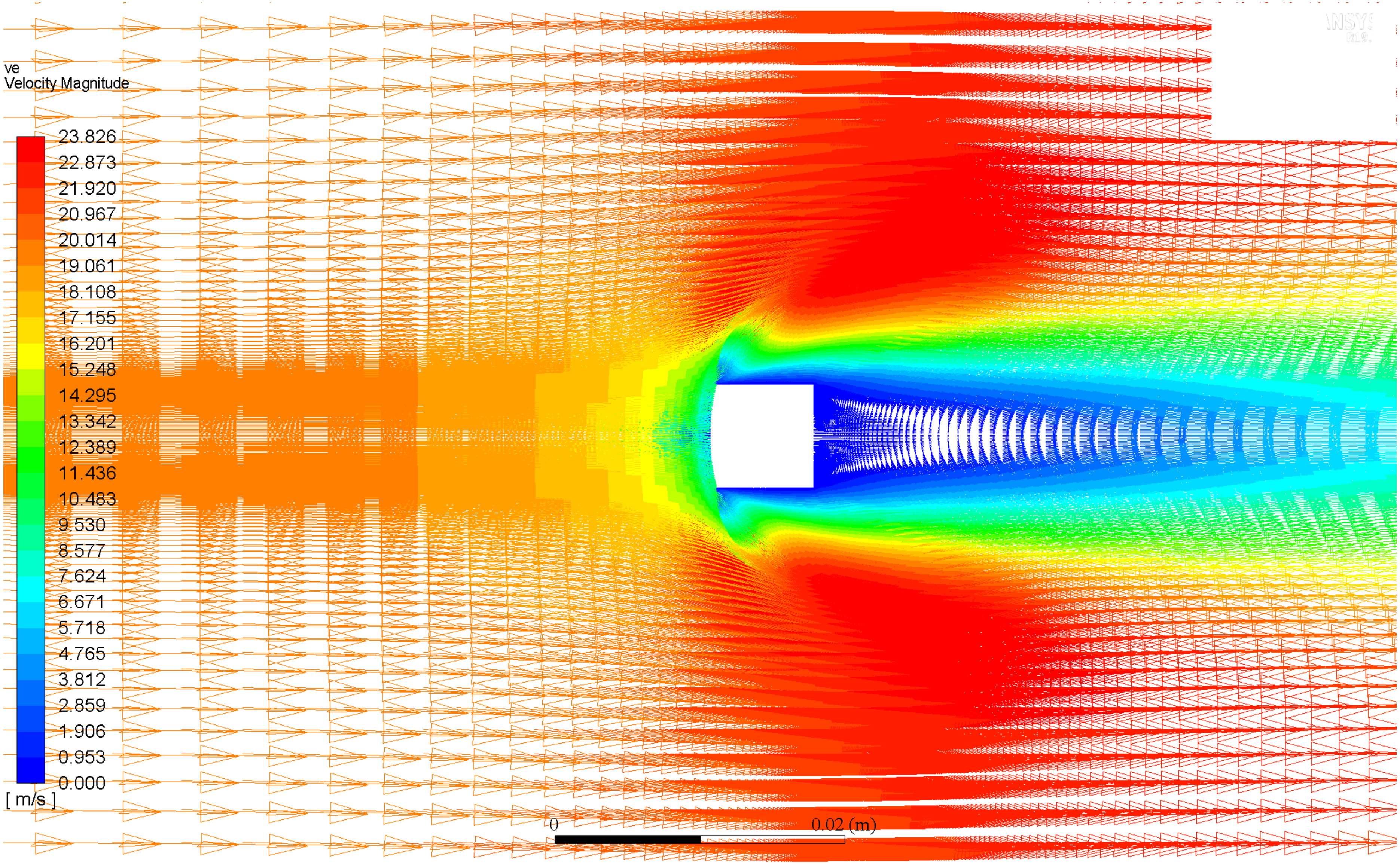
For increasing Re, the simulations indicate significant increase in the velocity gradients, that is, $\frac{\mathrm{d}U}{\mathrm{d}y}$, hence vertically shorter and axially longer boundary layers; indicating the variation in the vicinity of the cylinder become larger.

Velocity Vector Plots

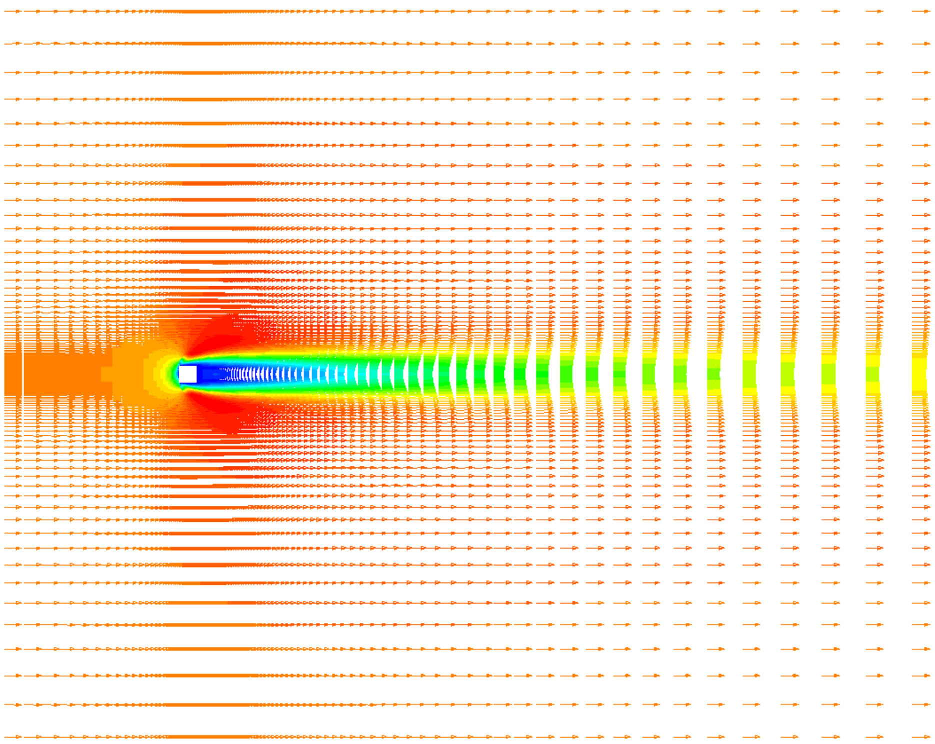
Note: All vectors have been scaled by a factor of 100, with no skip.

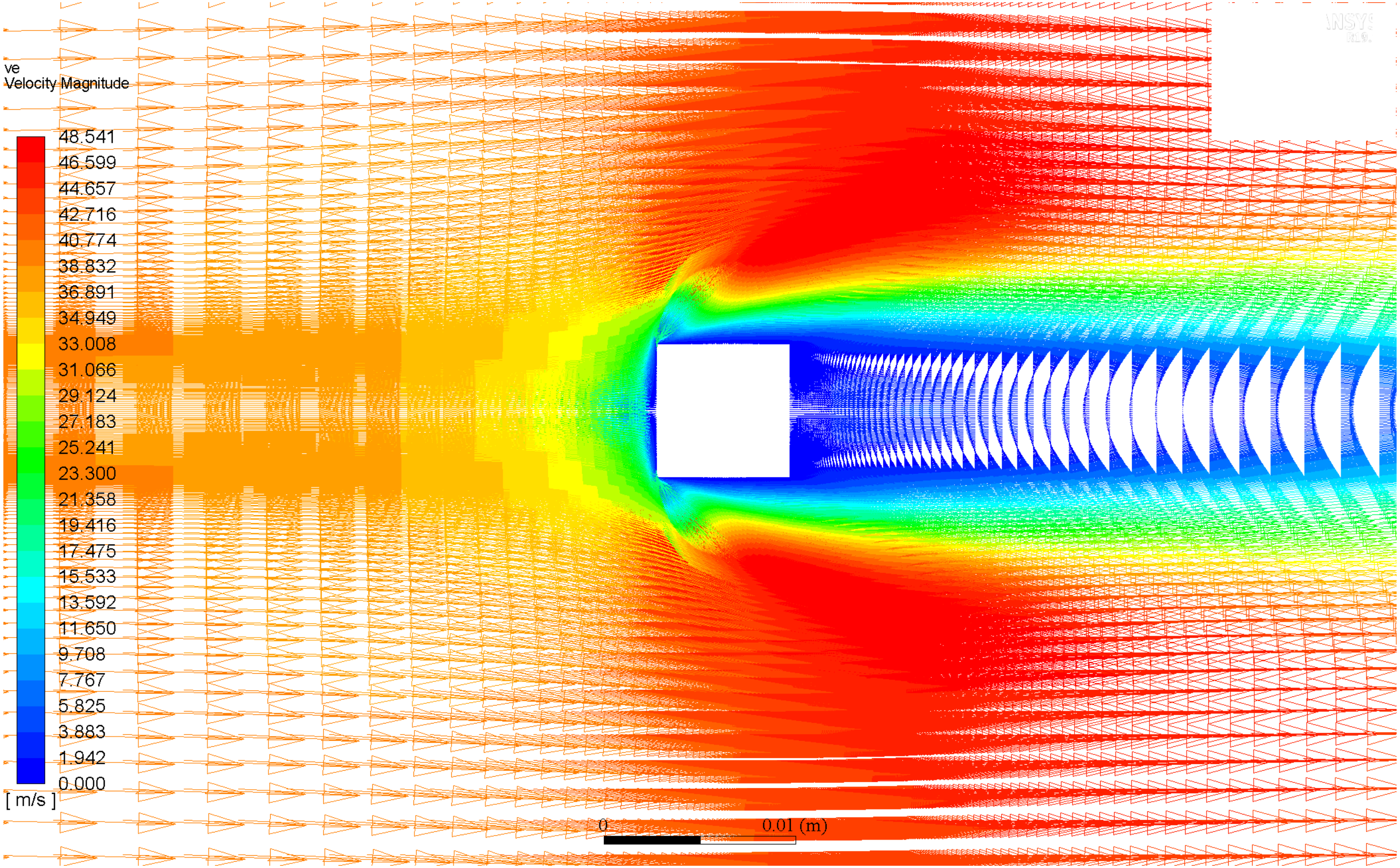
Re = 20



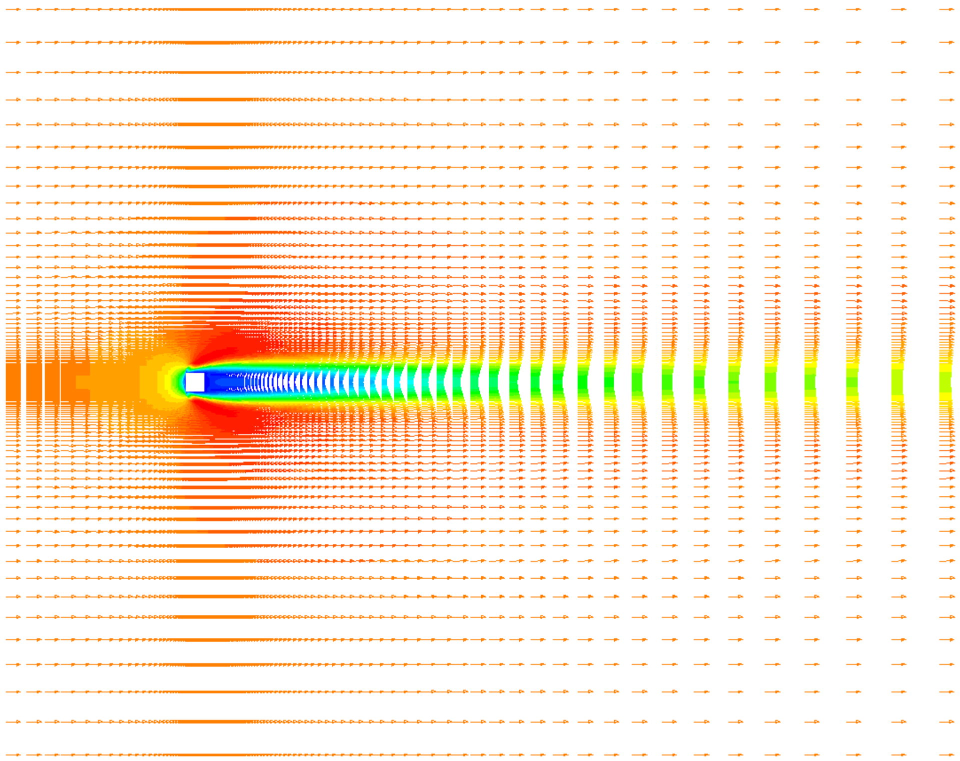

ve
Velocity Magnitude
23.826
22.873
21.920
20.967
20.014
19.061
18.108
17.155
16.201
15.248
14.295
13.342
12.389
11.436
10.483
9.530
8.577
7.624
6.671
5.718
4.765
3.812
2.859
1.906
0.953
0.000
[m/s]
0
0.02 (m)

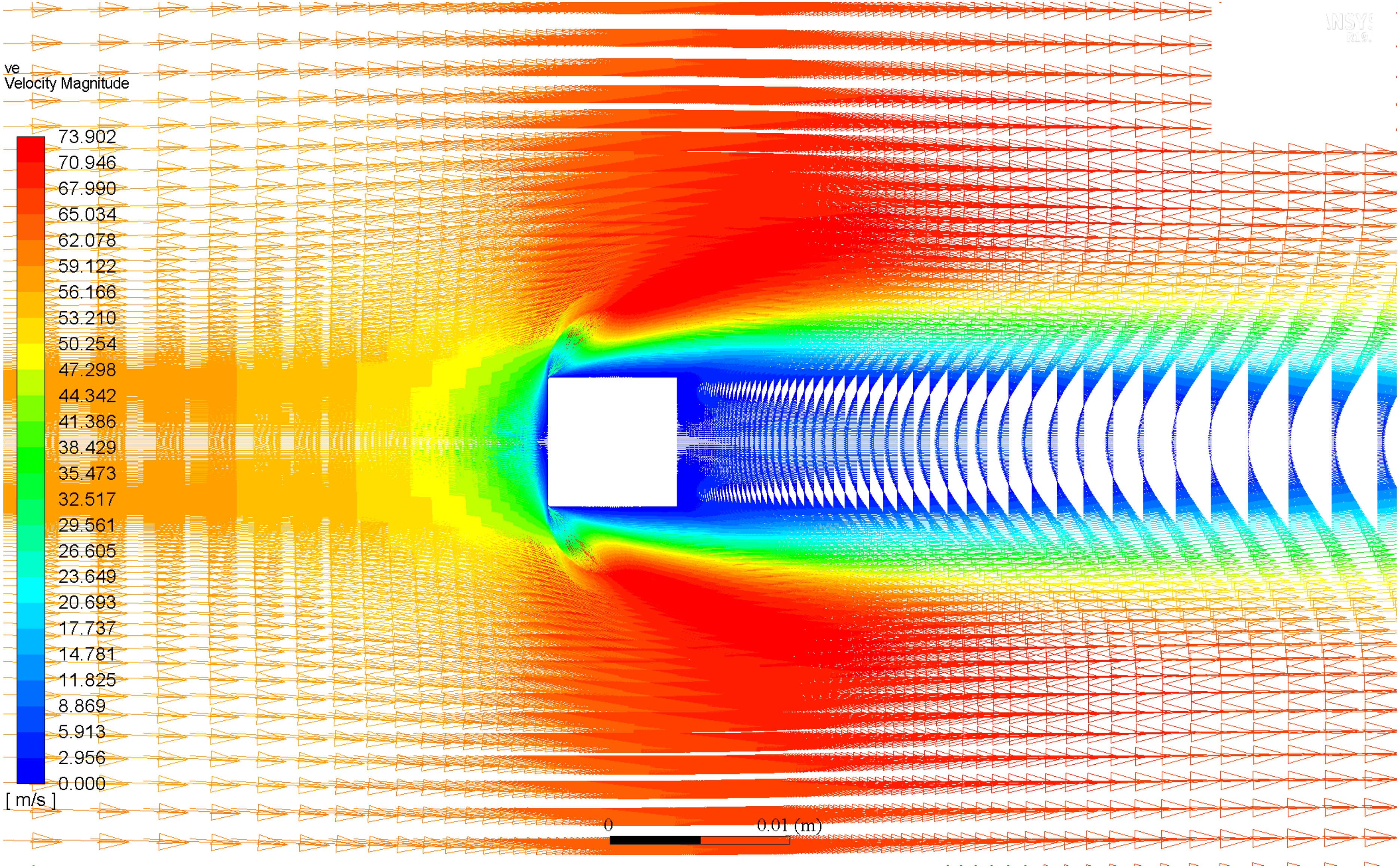
Re = 40



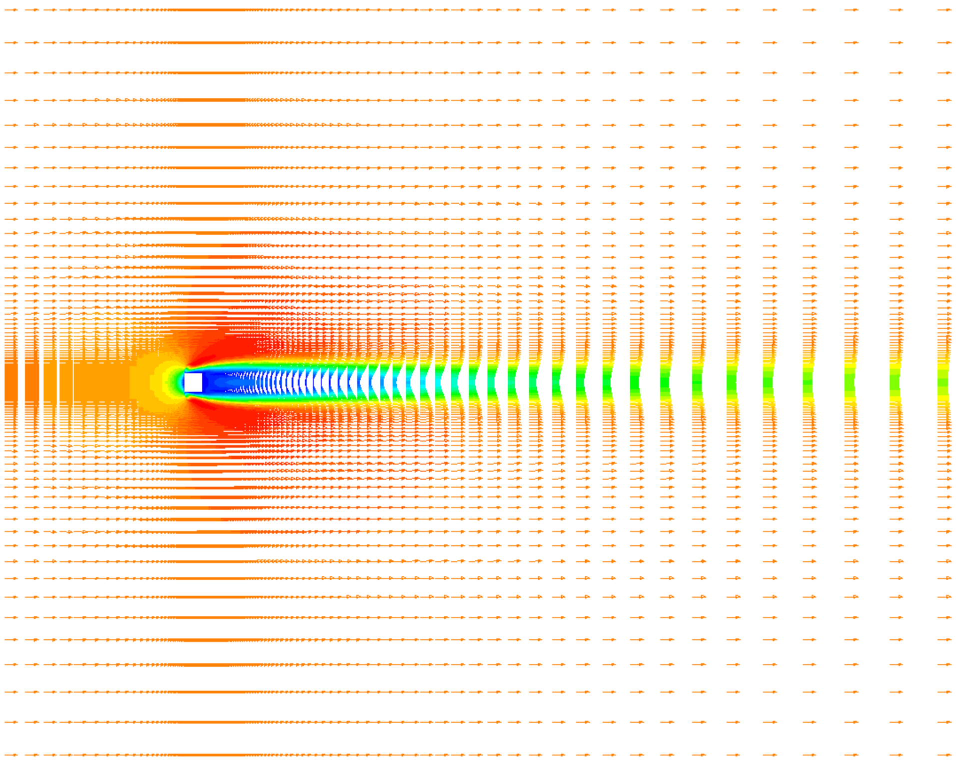

ve
Velocity Magnitude
48.541
46.599
44.657
42.716
40.774
38.832
36.891
34.949
33.008
31.066
29.124
27.183
25.241
23.300
21.358
19.416
17.475
15.533
13.592
11.650
9.708
7.767
5.825
3.883
1.942
0.000
[m/s]
0
0.01 (m)

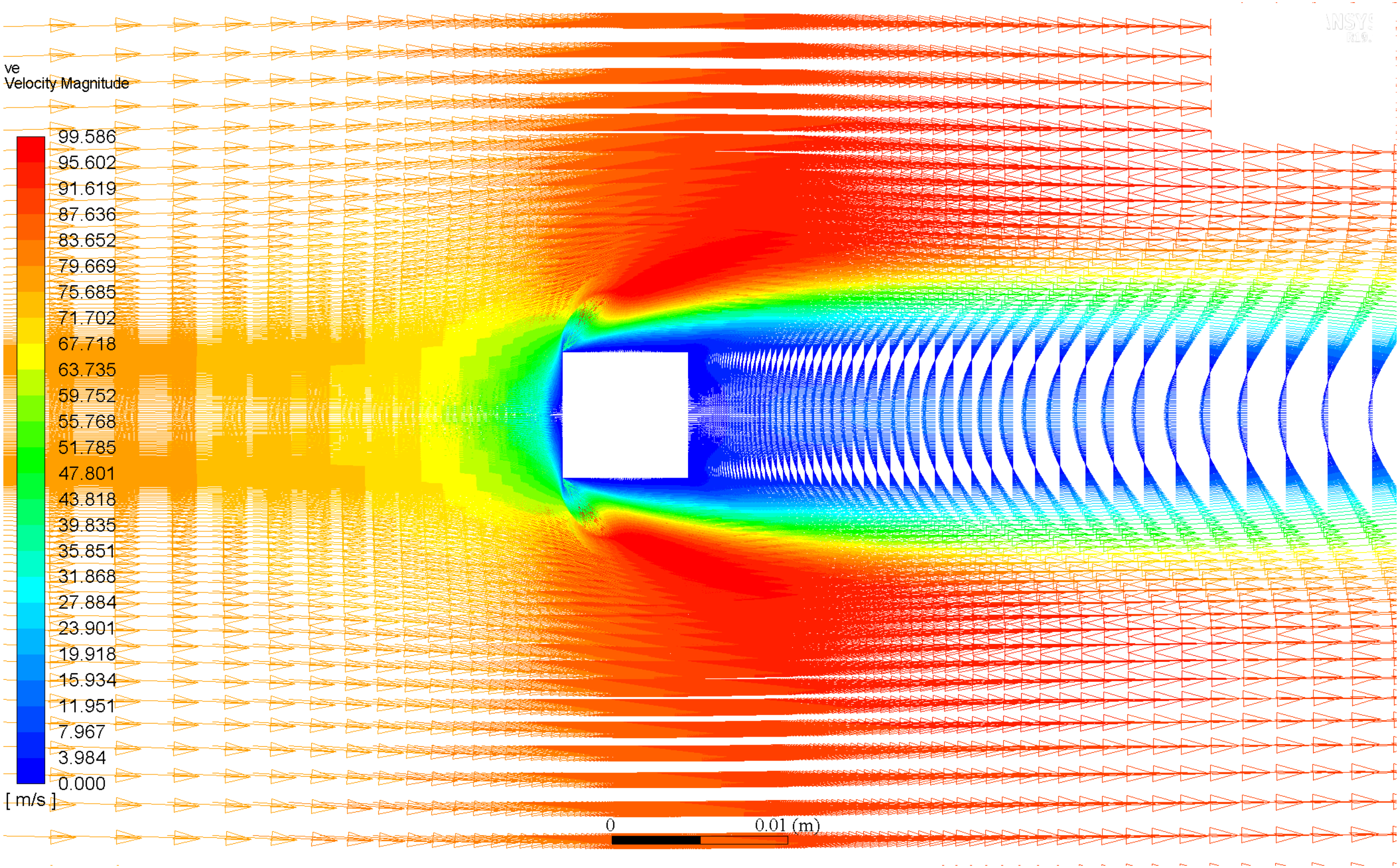
Re = 60



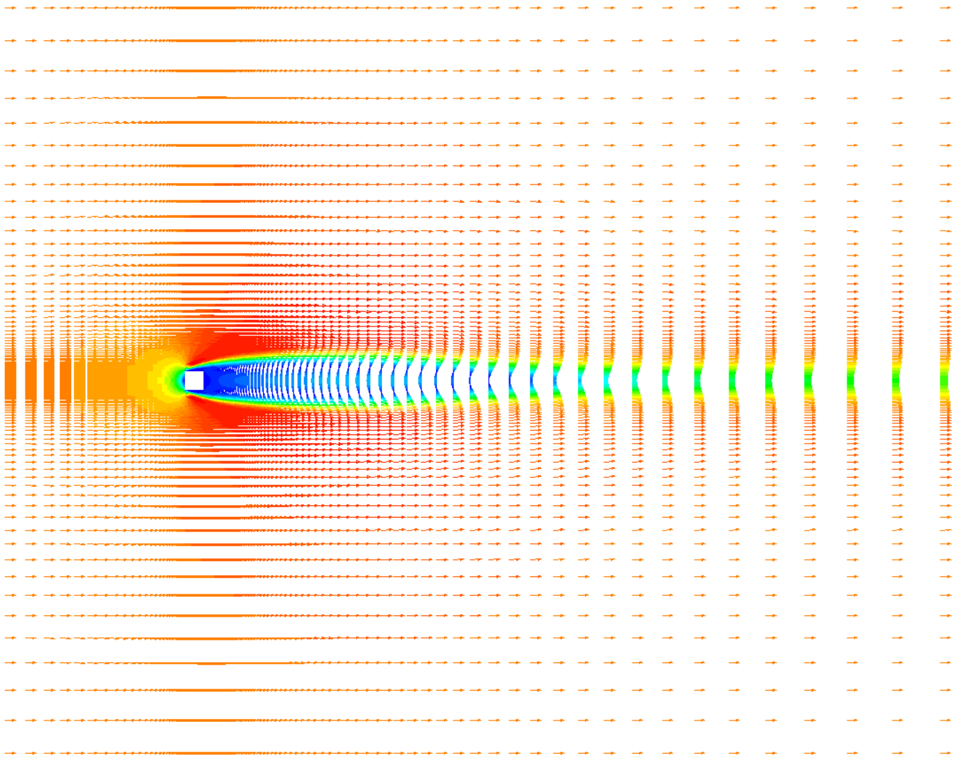

ve
Velocity Magnitude
73.902
70.946
67.990
65.034
62.078
59.122
56.166
53.210
50.254
47.298
44.342
41.386
38.429
35.473
32.517
29.561
26.605
23.649
20.693
17.737
14.781
11.825
8.869
5.913
2.956
0.000
[m/s]
0
0.01 (m)

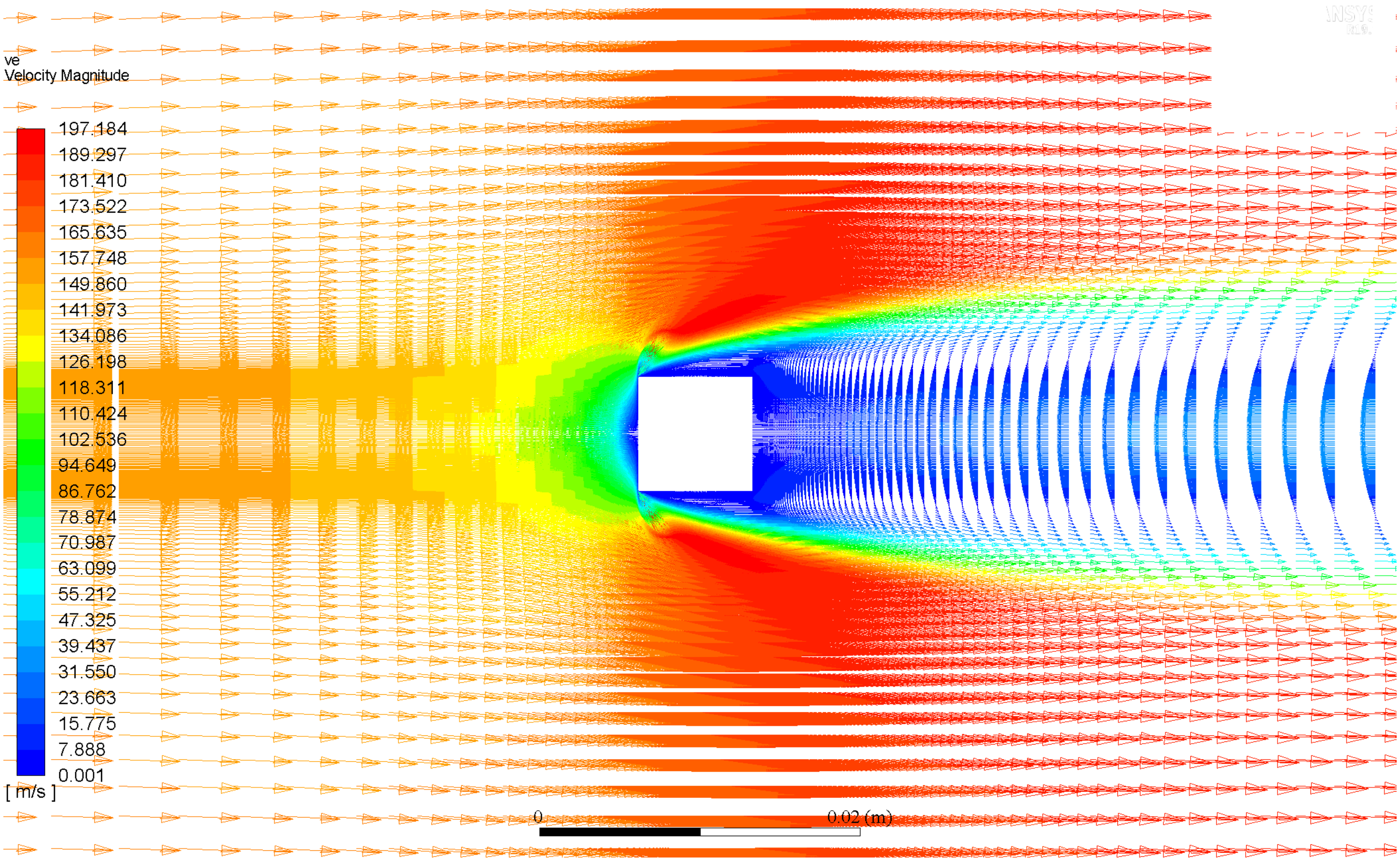
Re = 80




ve
Velocity Magnitude
99.586
95.602
91.619
87.636
83.652
79.669
75.685
71.702
67.718
63.735
59.752
55.768
51.785
47.801
43.818
39.835
35.851
31.868
27.884
23.901
19.918
15.934
11.951
7.967
3.984
0.000
[m/s]
0
0.01 (m)

Re = 160




ve
Velocity Magnitude
197.184
189.297
181.410
173.522
165.635
157.748
149.860
141.973
134.086
126.198
118.311
110.424
102.536
94.649
86.762
78.874
70.987
63.099
55.212
47.325
39.437
31.550
23.663
15.775
7.888
0.001
[m/s]
0
0.02 (m)

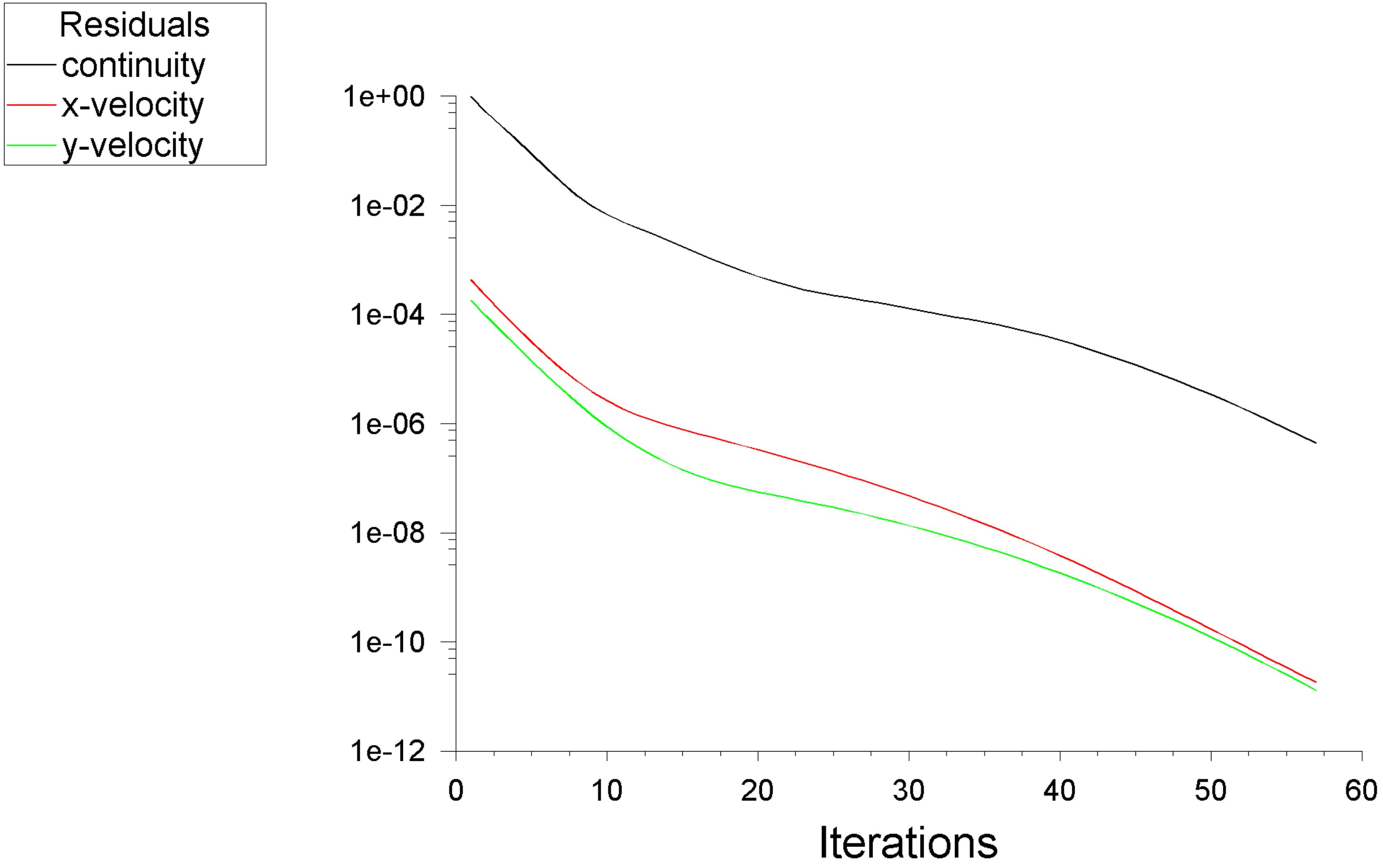
Comparison & Discussion

The general features discussed before can also be inferred from these vectors. However additional insight is provided in the direction of the velocity vectors.

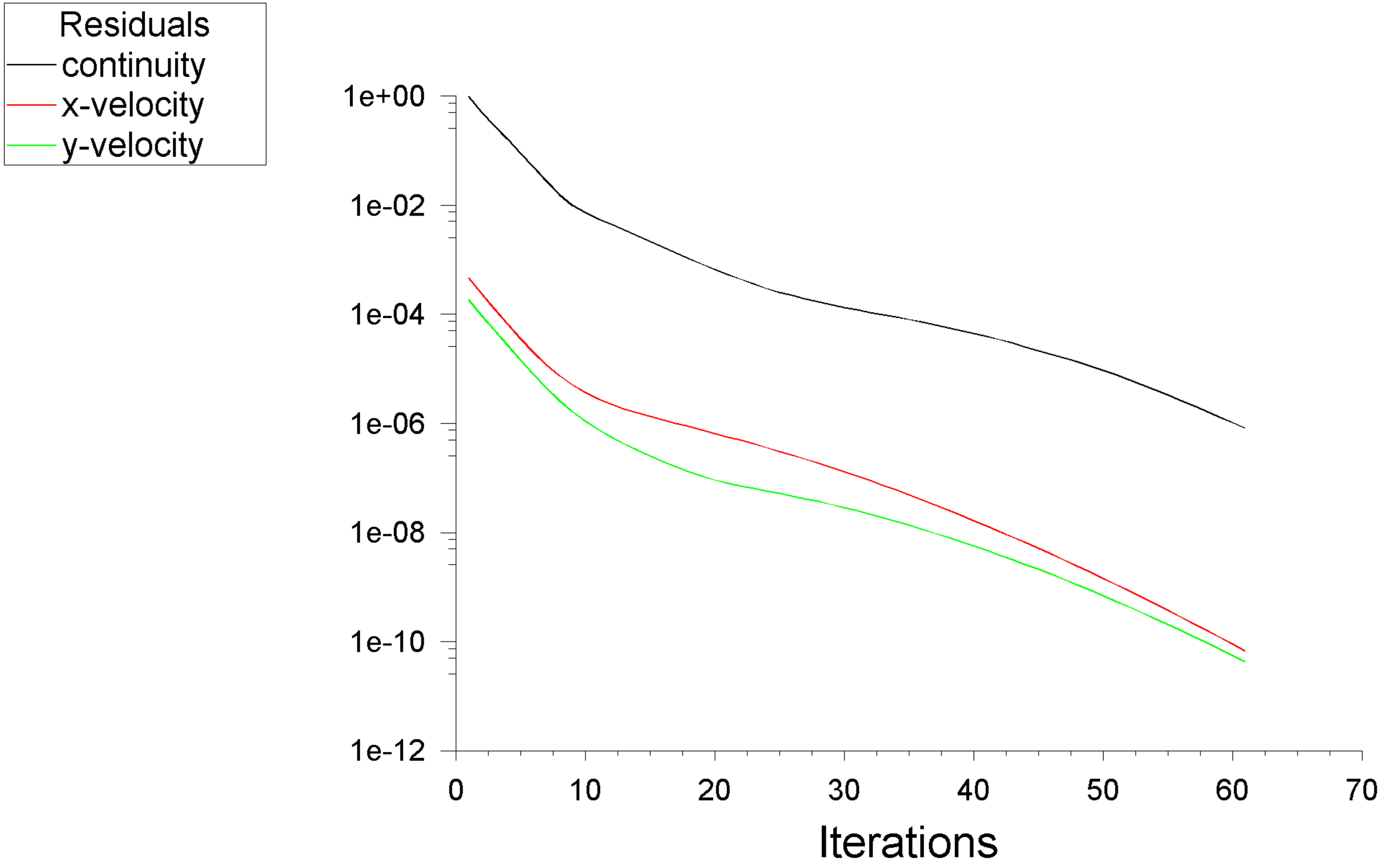
Negative velocity vectors can be seen in the centre of the wake region for all Re, the vicinity of the aft region of the cylinder, which gradually diminish and then are in the direction of flow as one looks away from the region of influence.

Residuals Plots

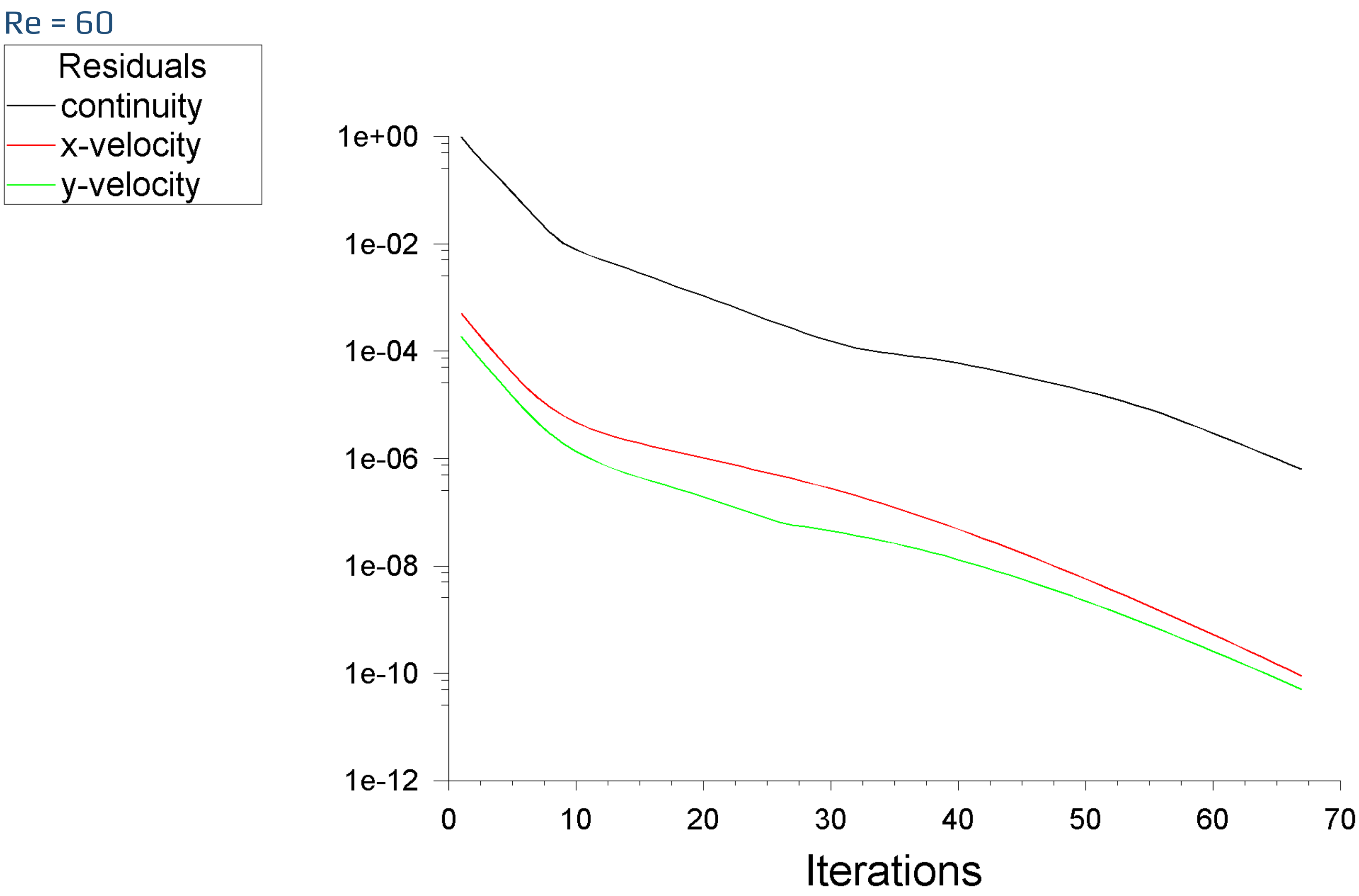
Re = 20



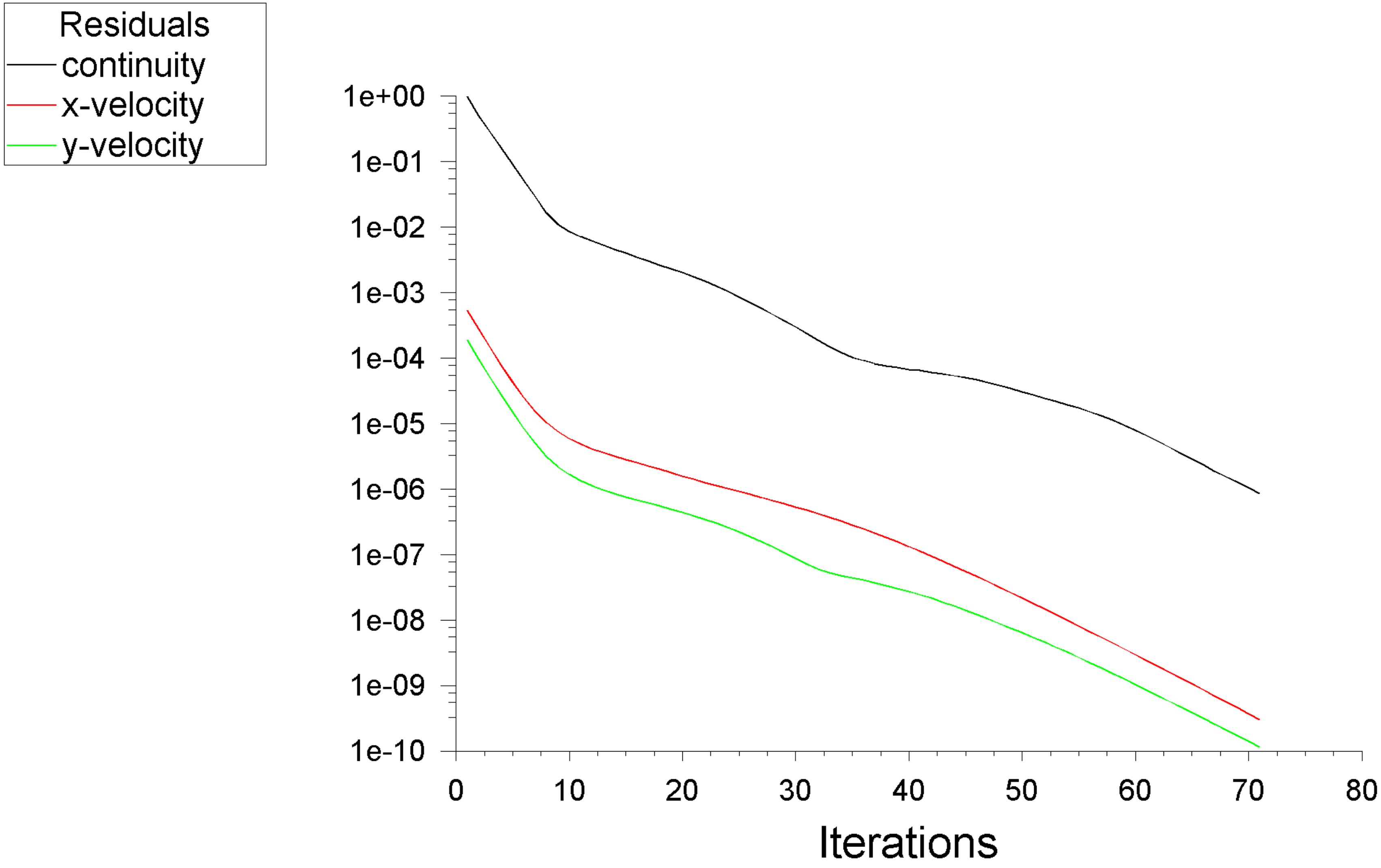
Re = 40



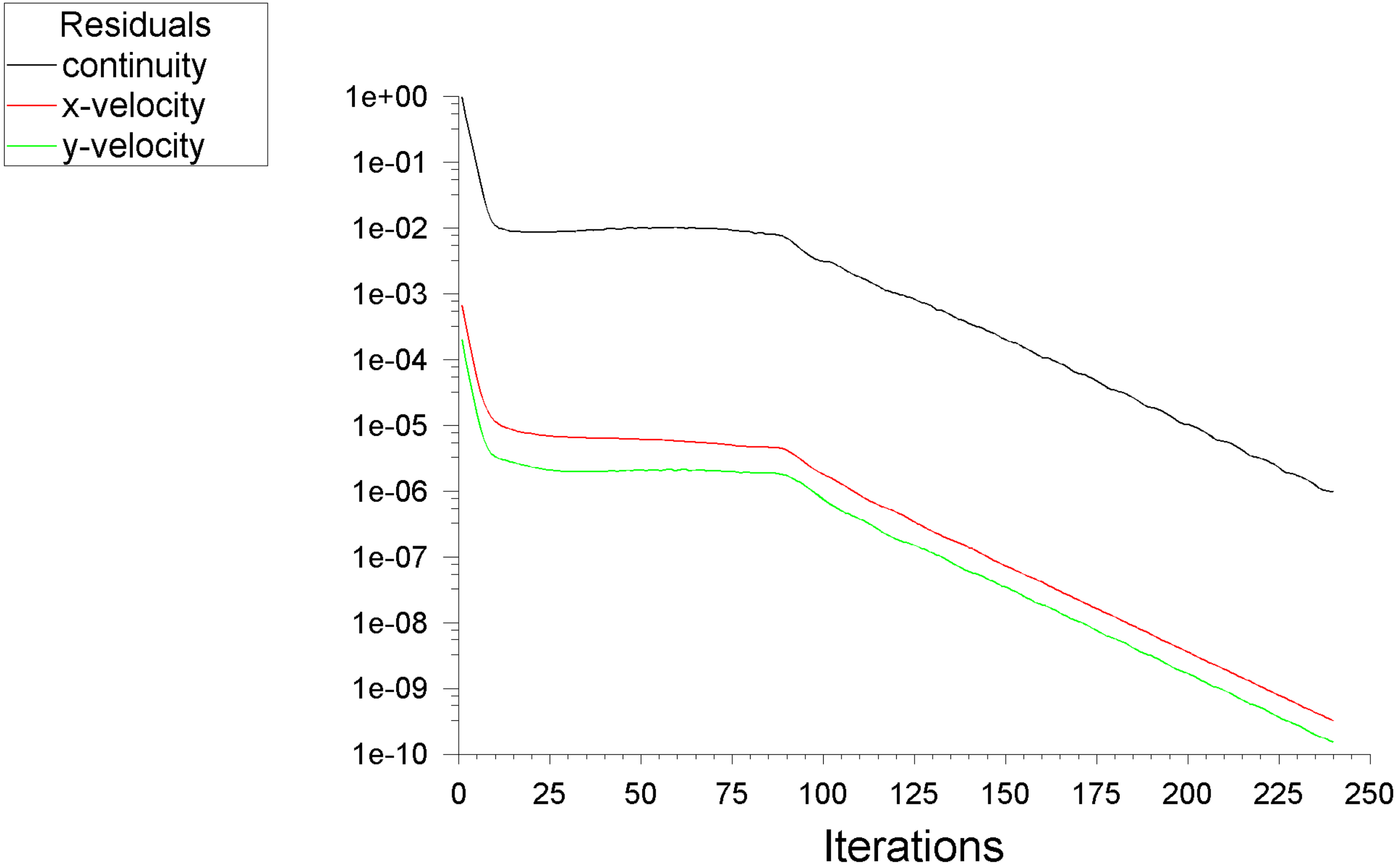
Residuals
continuity
x-velocity
y-velocity
1e+00
1e-02
1e-04
1e-06
1e-08
1e-10
1e-12
0
10
20
30
40
50
60
70
Iterations


Re = 60
Residuals
continuity
x-velocity
y-velocity
1e+00
1e-02
1e-04
1e-06
1e-08
1e-10
1e-12
0
10
20
30
40
50
60
70
Iterations

Re = 80


Residuals
continuity
x-velocity
y-velocity
1e+00
1e-01
1e-02
1e-03
1e-04
1e-05
1e-06
1e-07
1e-08
1e-09
1e-10
0
10
20
30
40
50
60
70
80
Iterations

Re = 160



Residuals
continuity
x-velocity
y-velocity
1e+00
1e-01
1e-02
1e-03
1e-04
1e-05
1e-06
1e-07
1e-08
1e-09
1e-10
0
25
50
75
100
125
150
175
200
225
250
Iterations

Comparison & Discussion

The residuals plots indicate that the simulations take longer CPU time (more iterations) as Re increases. Although the velocity equations converge quickly, the momentum equation largely influences the number of iterations to achieve convergence at the set criterion.

$\mathrm{Re} = 160$ was the most computationally intensive, with a trend of nearly constant residuals from the 10^{th} to 95^{th} iteration, and then heading towards convergence once again (this behaviour was odd from the other simulations).

Coefficients of Drag and Lift

$\mathbf{Re}$	$\mathbf{20}$	$\mathbf{40}$	$\mathbf{60}$	$\mathbf{80}$	$\mathbf{160}$
$\boldsymbol{C_D}$	$\mathbf{2.3386758}$	$\mathbf{1.7437681}$	$\mathbf{1.4949276}$	$\mathbf{1.3539067}$	$\mathbf{1.14102}$
$\boldsymbol{C_L}(\times \mathbf{10^{-8}})$	$\mathbf{-0.43853206}$	$\mathbf{-1.6998364}$	$\mathbf{-1.8761805}$	$\mathbf{-1.7203142}$	$\mathbf{0.3328824}$

Comparison & Discussion

The Coefficient of Lift, C_L is essentially zero, as expected and mentioned in a).

The Coefficient of Drag, C_D, tends to decrease with larger Reynolds Numbers. Looking at the definition of C_D

$$C_D = \frac{F_D}{\frac{1}{2}\rho U^2 AL}$$

The implication that comes to mind is that the drag force, F_D is decreasing and the term accounting for fluid momentum (inertial force) is increasing, to lower C_D.

Since the frontal area, A and the out-of-plane length, L, of the cylinder are essentially constant, as well as the fluid being nearly incompressible (fluid density, ρ, is thus essentially constant), the implication is that the increase in the incoming flow velocity, U is determinant for the value of C_D.

Further U also has a directly proportional relationship with Re, since

$$\mathrm{Re} = \frac{\rho U D}{\mu}$$

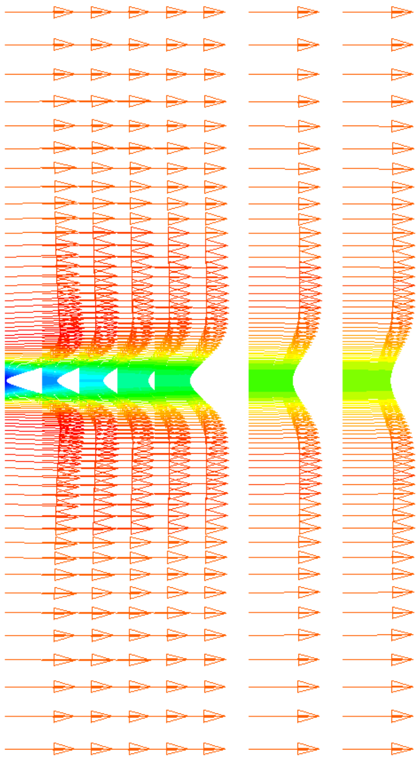
So, it is no surprise that C_D is decreasing with increasing Re. But the results at higher Re are still questionable due to transient phenomena, such as Vortex Shedding, occurring in reality (since these results are from a Pseudo Transient initialization, steady state simulation CFD).

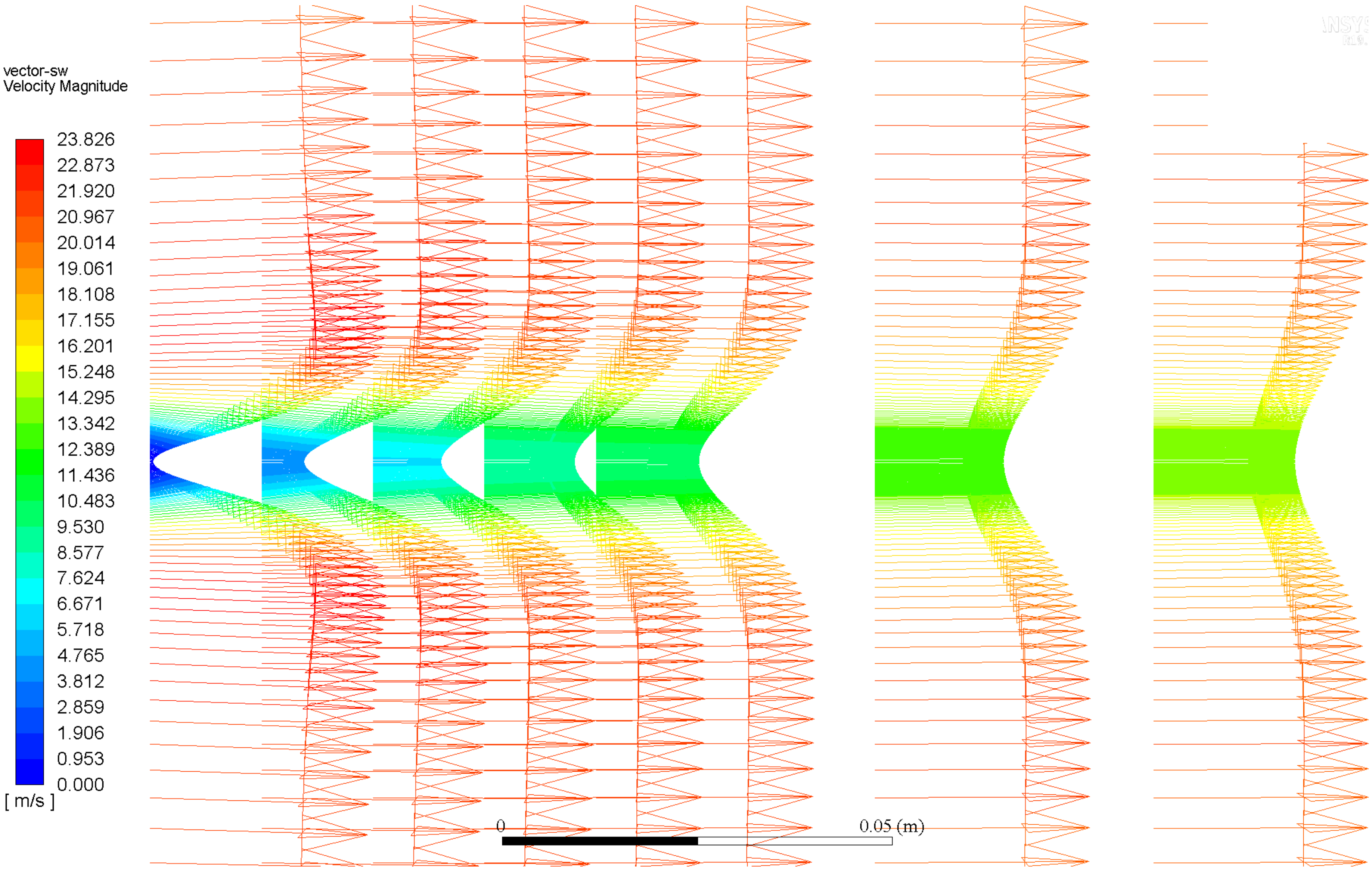
d) Velocity Profiles at defined Stream wise Positions*

*$\boldsymbol{x = 2D, 4D, 6D, 8D, 10D, 15D, 20D}$ for $\boldsymbol{D = 0.01\ \mathrm{m}}$

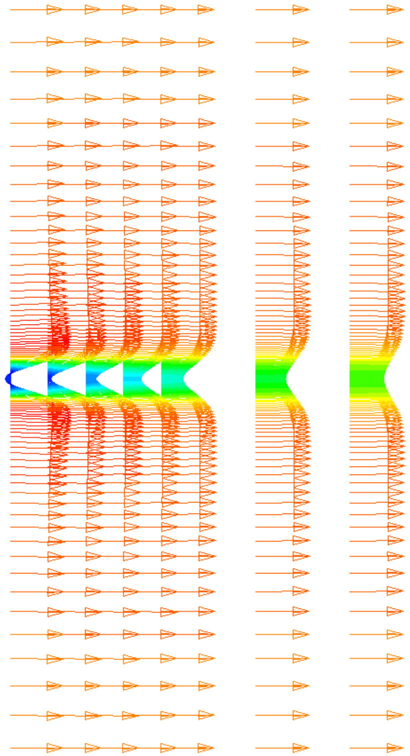
Note: All vectors have been scaled by a factor of 300, with no skip.

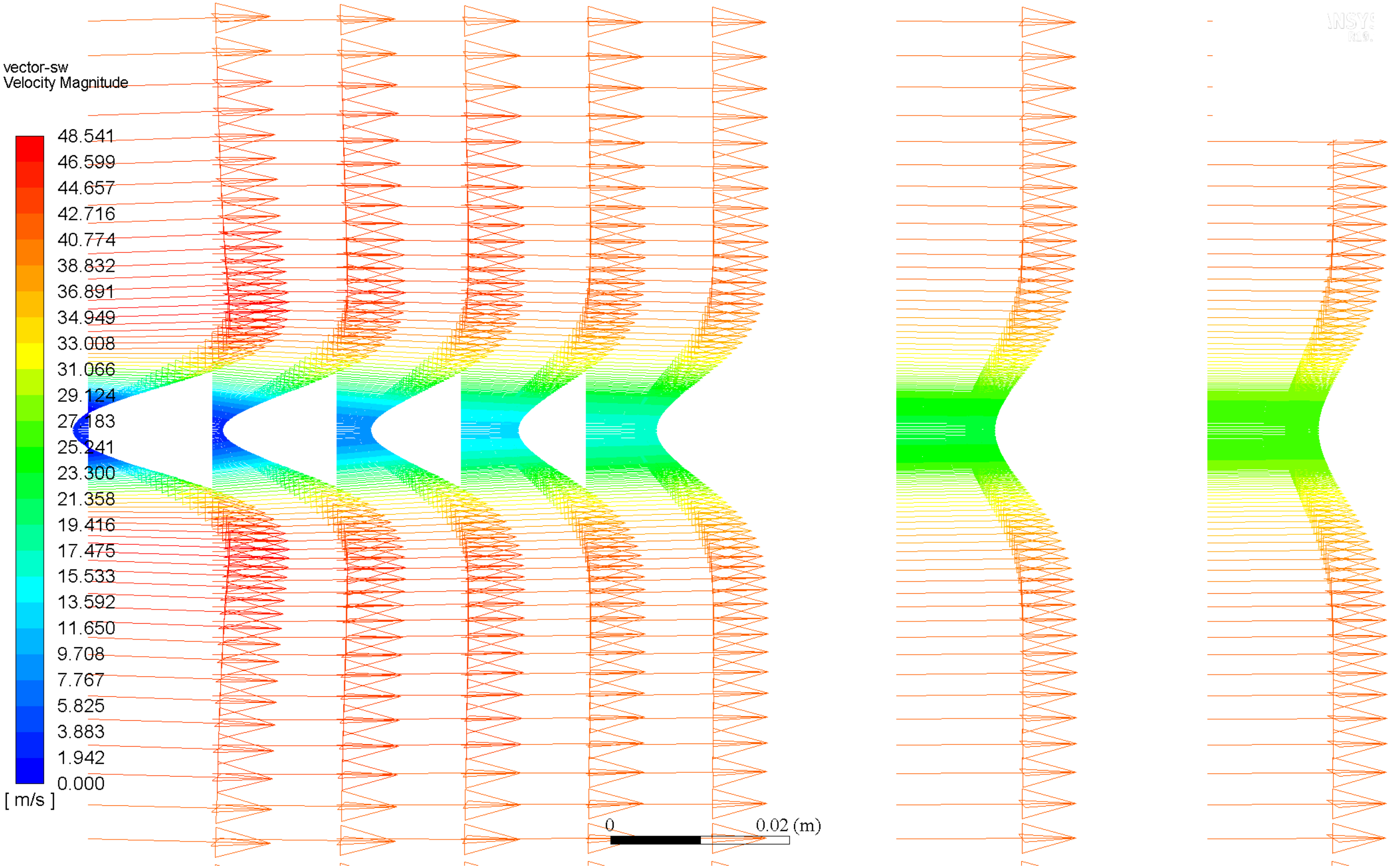
Re = 20



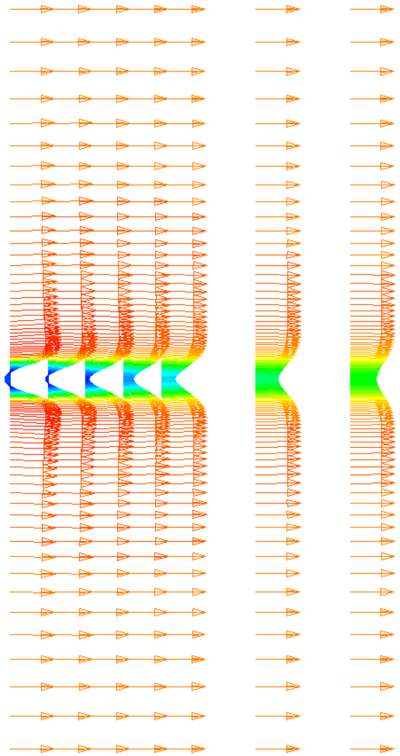

vector-sw
Velocity Magnitude
23.826
22.873
21.920
20.967
20.014
19.061
18.108
17.155
16.201
15.248
14.295
13.342
12.389
11.436
10.483
9.530
8.577
7.624
6.671
5.718
4.765
3.812
2.859
1.906
0.953
0.000
[m/s]
0
0.05 (m)

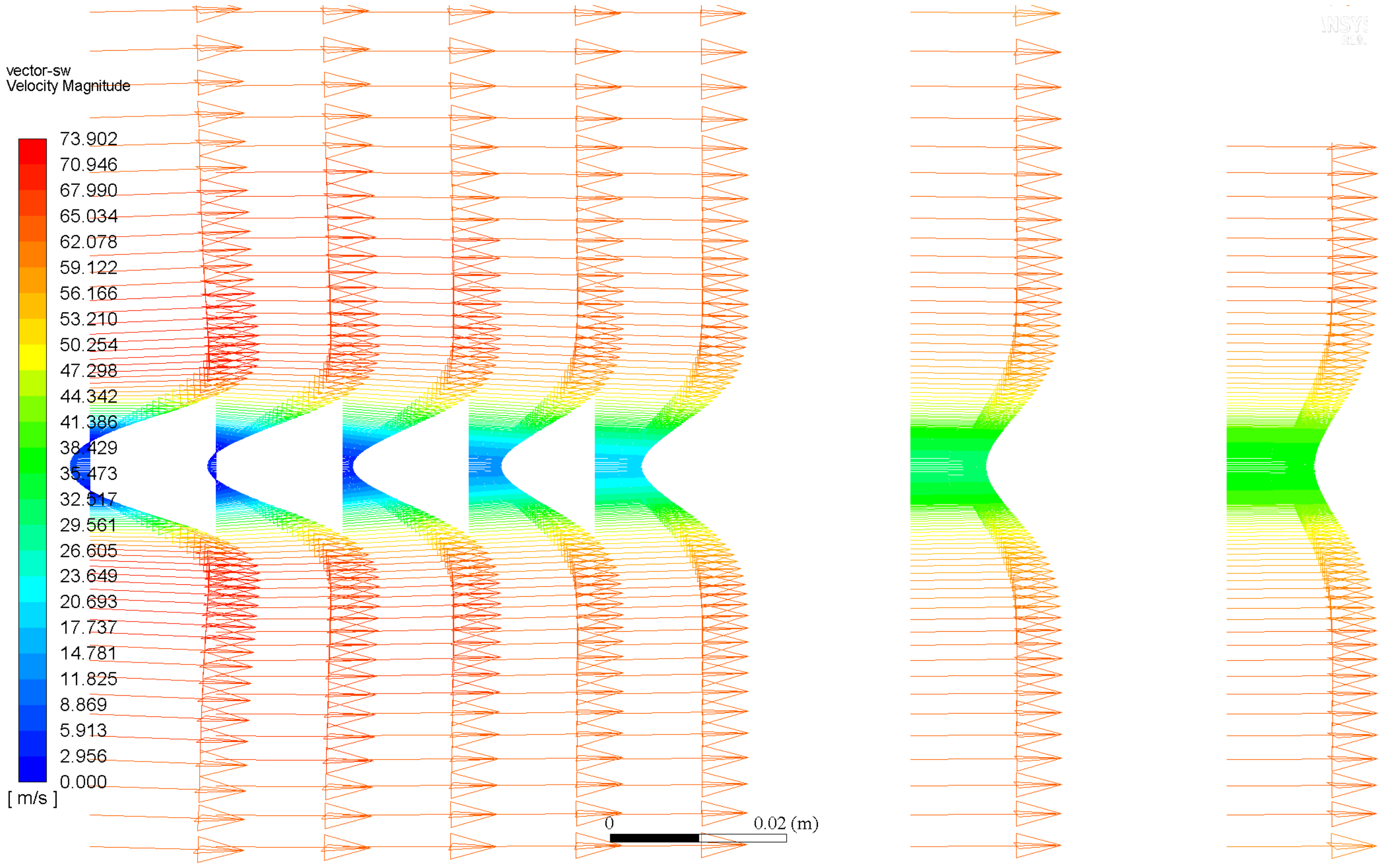
Re = 40



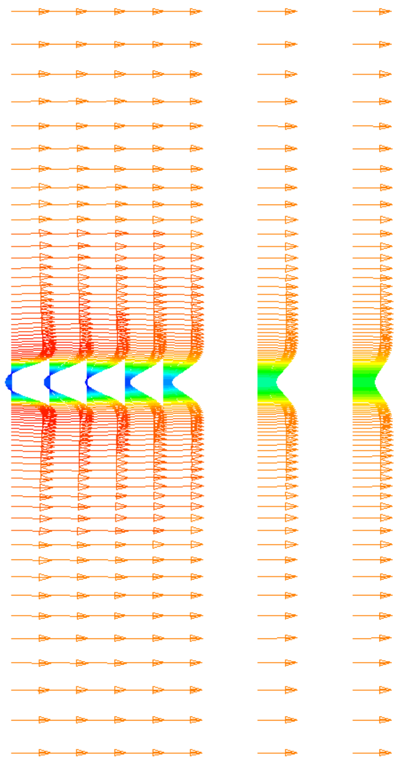

vector-sw
Velocity Magnitude
48.541
46.599
44.657
42.716
40.774
38.832
36.891
34.949
33.008
31.066
29.124
27.183
25.241
23.300
21.358
19.416
17.475
15.533
13.592
11.650
9.708
7.767
5.825
3.883
1.942
0.000
[m/s]
0
0.02 (m)

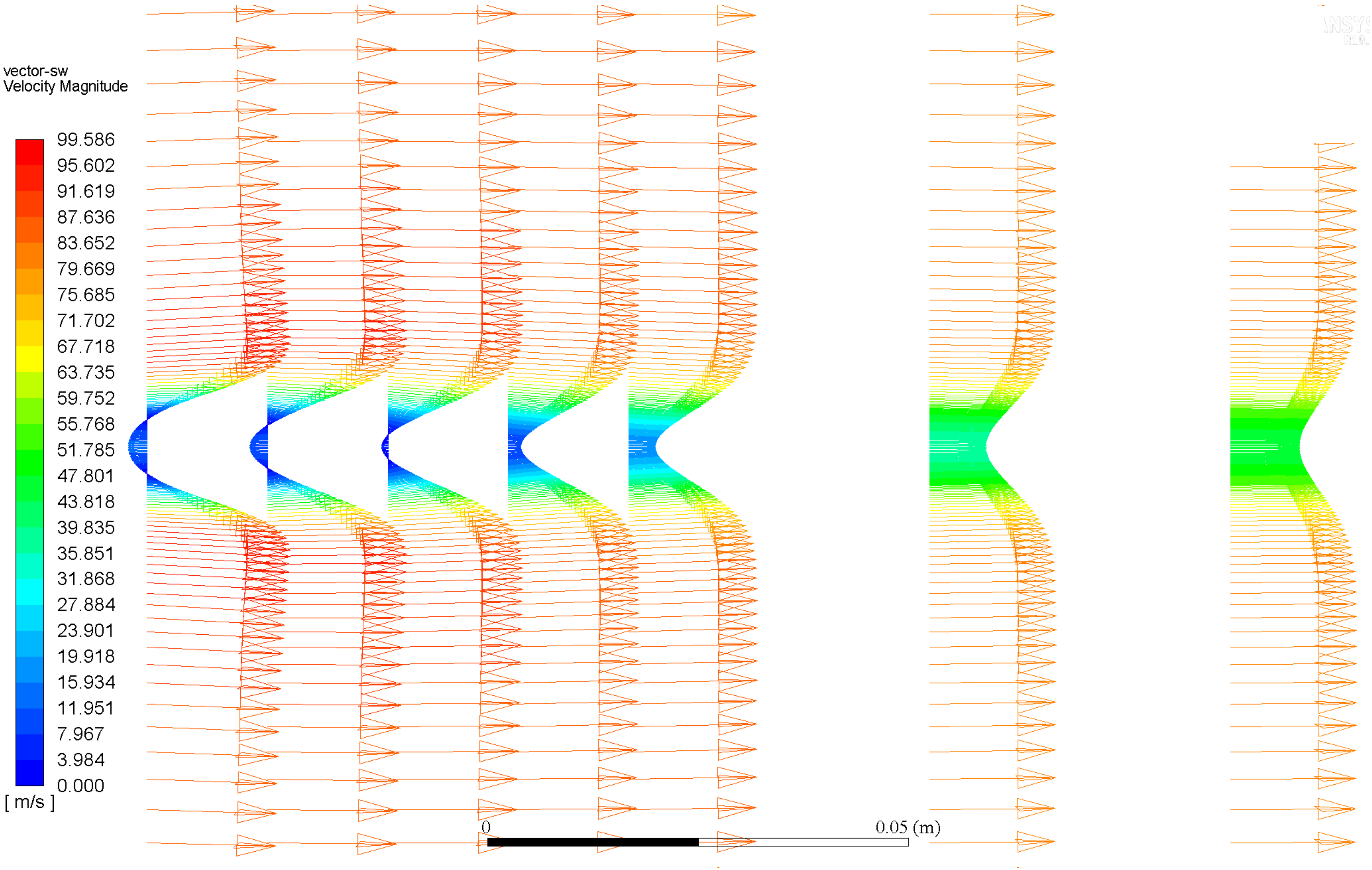
Re = 60



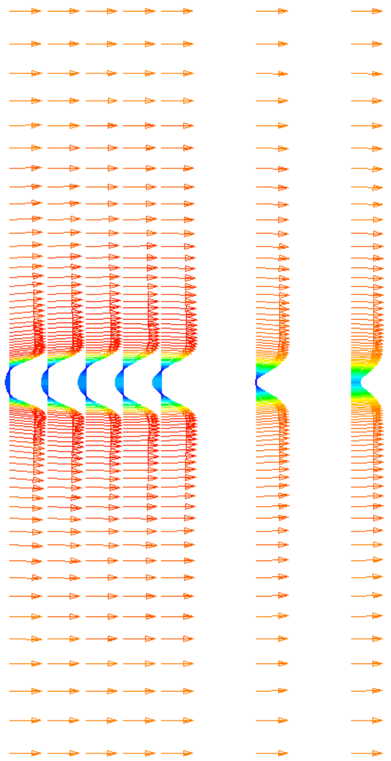

vector-sw
Velocity Magnitude
73.902
70.946
67.990
65.034
62.078
59.122
56.166
53.210
50.254
47.298
44.342
41.386
38.429
35.473
32.517
29.561
26.605
23.649
20.693
17.737
14.781
11.825
8.869
5.913
2.956
0.000
[m/s]
0
0.02 (m)

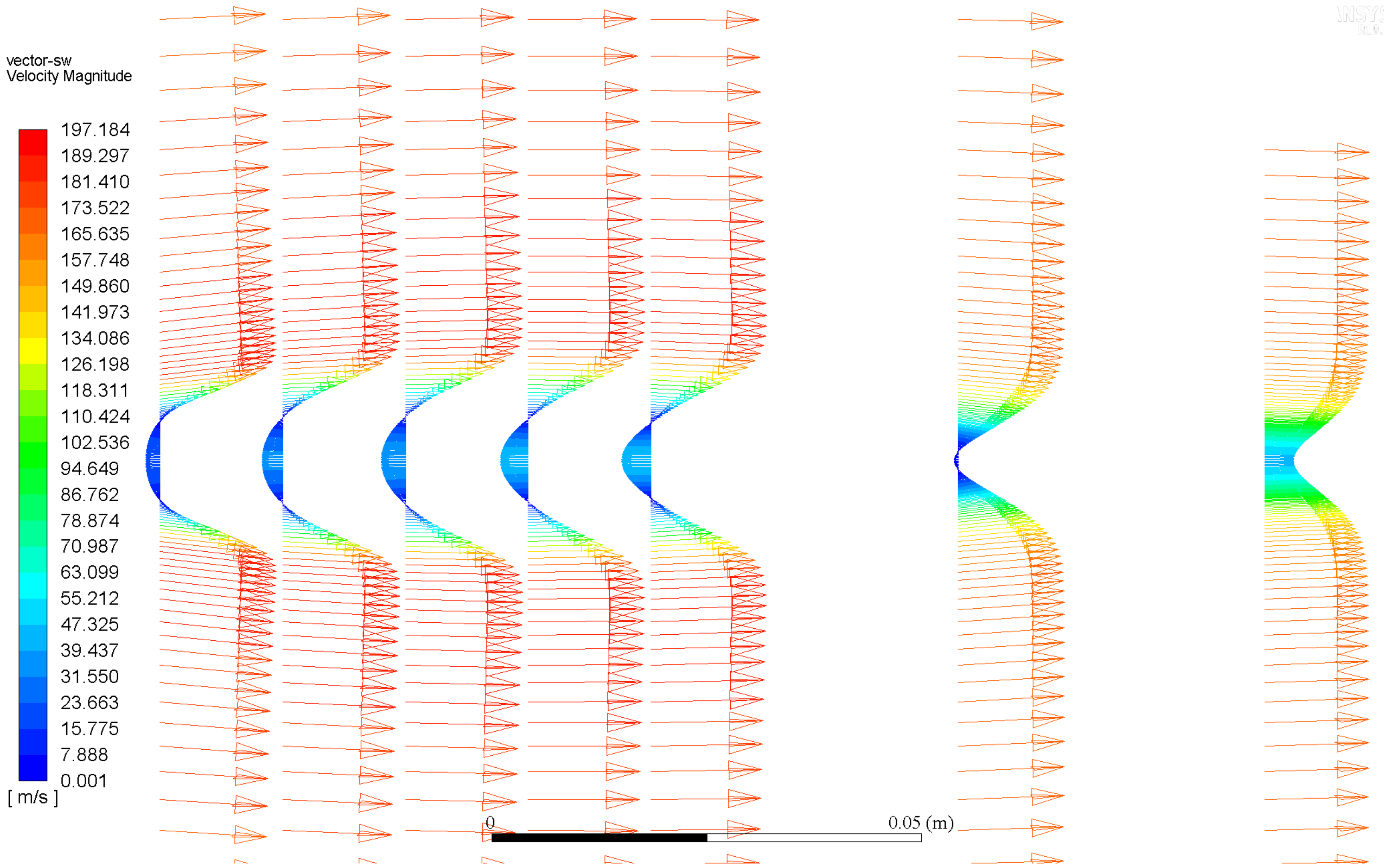
Re = 80




vector-sw
Velocity Magnitude
99.586
95.602
91.619
87.636
83.652
79.669
75.685
71.702
67.718
63.735
59.752
55.768
51.785
47.801
43.818
39.835
35.851
31.868
27.884
23.901
19.918
15.934
11.951
7.967
3.984
0.000
[m/s]
0
0.05 (m)

Re = 160





vector-sw
Velocity Magnitude
197.184
189.297
181.410
173.522
165.635
157.748
149.860
141.973
134.086
126.198
118.311
110.424
102.536
94.649
86.762
78.874
70.987
63.099
55.212
47.325
39.437
31.550
23.663
15.775
7.888
0.001
[m/s]
0
0.05 (m)

Comparison & Discussion

The velocity profiles seen here can be thought of been specifically picked results from the velocity vectors shown before. The same conclusions can be inferred, however further insight and better appreciation can be attained for the increasing influence of the wake region with increase in Re; the velocity profile develops more later.

For $\mathrm{Re} = 20$, no backflow (negative velocity) region is seen.