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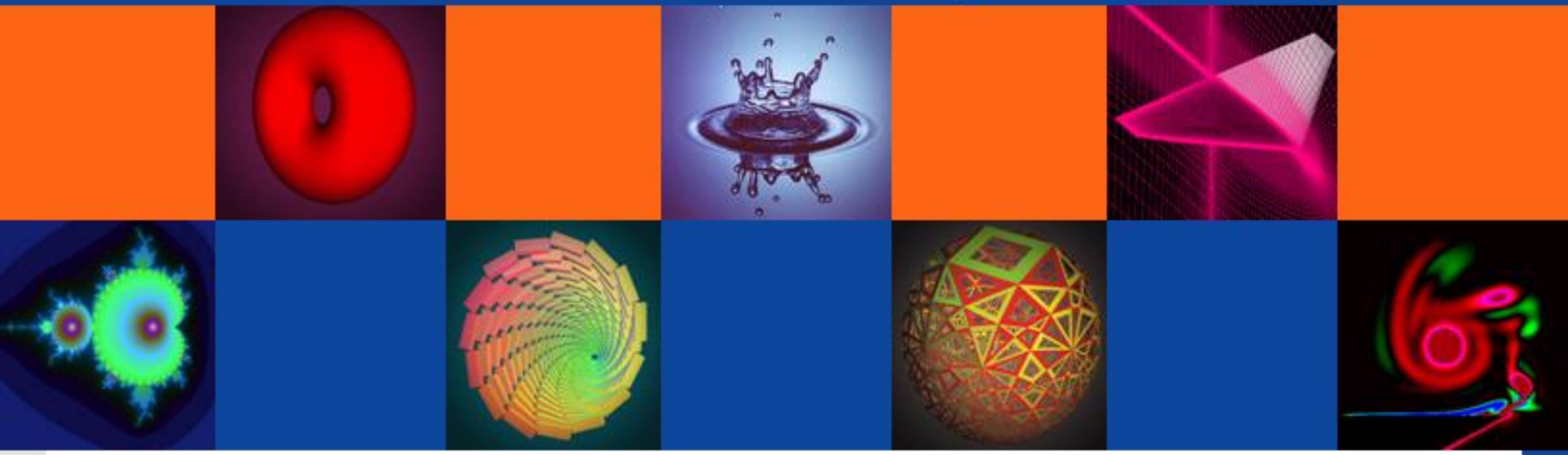

High order LES for Supersonic Backward-facing Step Flow with Turbulent Inflow

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High order LES for Supersonic Backward-facing Step Flow with Turbulent Inflow

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Abstract

In this study, we investigate the Supersonic Backward-facing Step Flow at M=2.0 and Re=4000. The high order large eddy simulation with a fully developed turbulent inlet condition is used to investigate the flow field structures. The three dimensional flow field especially at the separation region is studied in detail. The numerical solution captures the essential features of the flow, such as the reversed flow, recirculation zone length and other mean flow parameters with reasonable accuracy.

I. Introduction

Recirculating flow with complicated vortex structures has long been known to have a incredible influence on shear stress distributions and heat transfer rates. The backward-facing step flow is a standard numerical test and a good research case for recirculating flow. This particular expansion flow has attracted numerous attention over the last few decades[1-4].

For the backwardly-facing step flow, the experimental data of Armaly et al[3,5] has been widely referred. Much two-dimensional numerical work has been done to analyze this recirculating flow[6]. Nevertheless, there are relatively less three-dimensional studies of this problem[7–11]. However, the 3D understanding for the problem is necessary, since the turbulence and the separation are three-dimensional. It is also a strong need to carry out flow analysis in 3Do to get a sufficient understanding of the three-dimensional vortex structure.

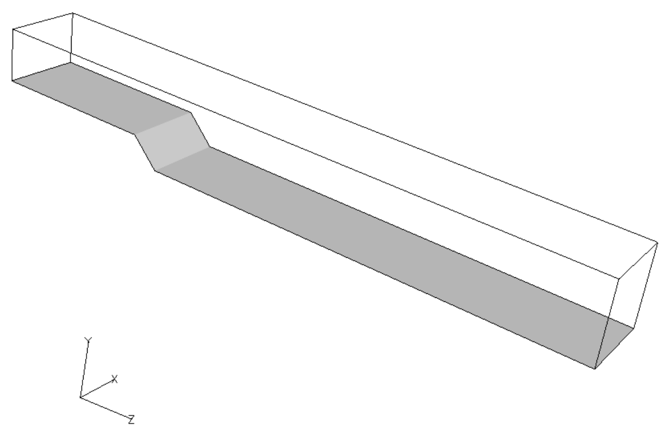
In this study, supersonic back-step flow with a 45˚ slant angel of the step is simulated with the LES. The flow parameters are Ma=2.0 and Re_h=4,000 (h is the height of the step). This problem is a noteworthy example for the separated flow that occurs in aerodynamic devices such as high-lift aerofoils at high angles of attack.We try to understand the mechanism of the recirculating flow induced by supersonic backward-facing step. We also investigated the interaction between supersonic turbulence boundary layer and the separation shock wave in the down stream. In order to make simulations, a kind of large eddy simulation method[12,13] is used by solving the unfiltered form of the Navier-Stokes equations (NSEs) with the 5th order bandwidth-optimized WENO scheme, which is generally referred to the so-called implicitly implemented LES. The paper is arranged as follows: in section II, we give the information of case setup; in section III, the numerical methods we adopted in the LES are specified; in section IV, the results for two validation cases are presented; in section V, the numerical results are discussed in detail and compared to the experimental ones. Finally, we give our conclusions.

II. Case Setup and Grid Generation

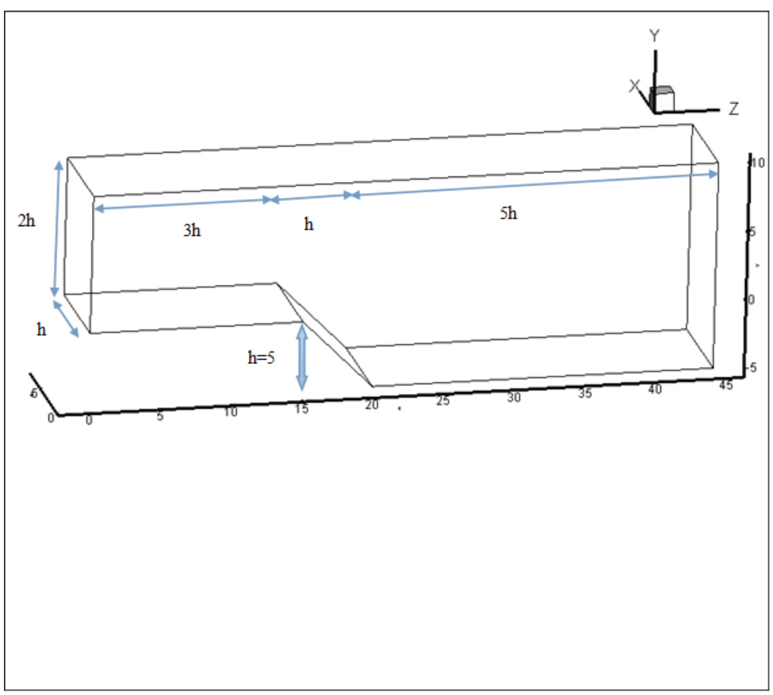
2.1 Configuration and inflow condition

A simplified computation case is simulated (Figure 1a) where the sizes are given in Fig. 1(b). The simplified case will be a typical 3-D domain. The slant angel of the step is set as 45˚.

We are going to conduct a three-dimensional Navier–Stokes flow analysis in the channel using the step geometry given in Fig. 1.



(a)



(b)

Figure 1. Domain of the back-step flow

2.2 Grid generation

The orthogonal grids for backward-facing step flow are generated, they are illustrated in Fig. 2 and 3. A grid of 137*192*1600 grids (see Figure 12, in the x,y and z directions) is used in the simulation. The grids are refined at the corner and at the boundary layer region.

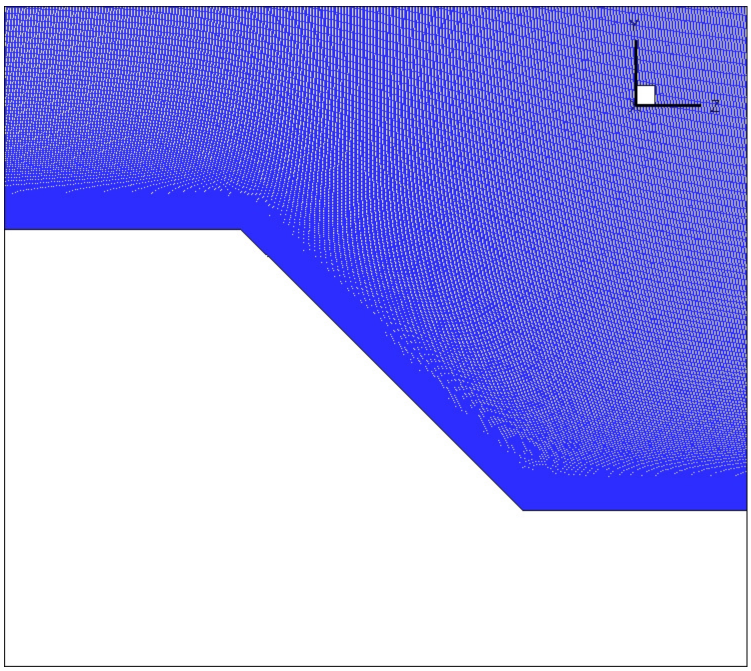
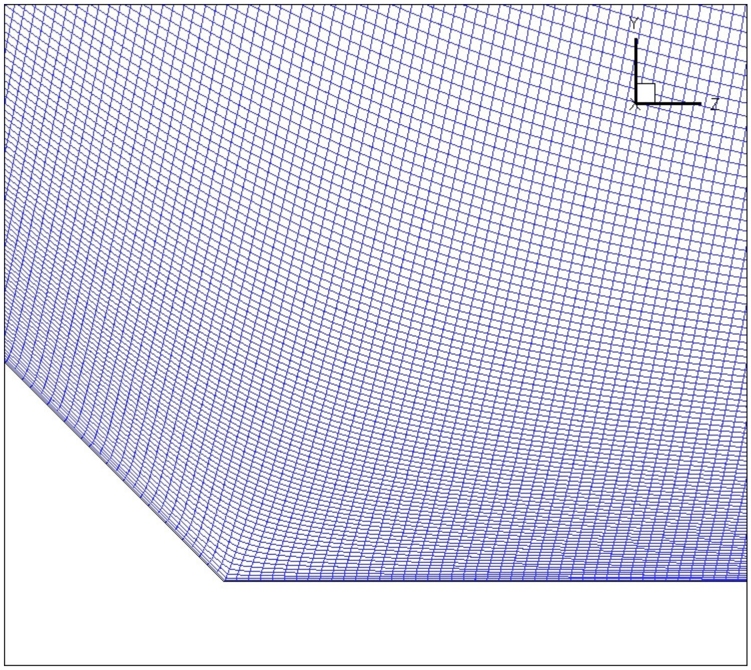
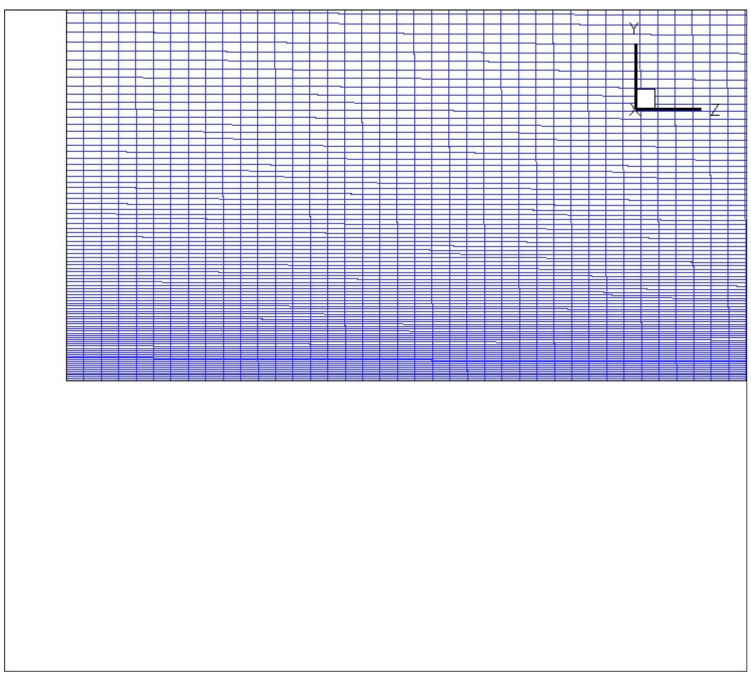


Figure 2. Orthogonal grids for the domain of backward-facing step flow



(a)



(b)

Figure 3. Refined grids at the corner and wall boundary

III. Numerical Methods

To reveal the mechanism and get deep understanding of the flow structure, we need high order DNS/LES. An approach called monotone integrated LES (MILES)[12,13] was adopted by solving the unfiltered form of the Navier-Stokes equations with the 5th order bandwidth-optimized WENO scheme. The LES code was previously validated for unsteady applications in a supersonic inviscid flow around the half cylinder at M=4 and a MVG controlling ramp flow at M=3 and Re=4800[14].

The adiabatic, zero-gradient of pressure and non-slipping conditions are adopted at the wall. To avoid possible wave reflection, the non-reflecting boundary conditions are used on the upper boundary. The boundary conditions at the front and back boundary surfaces in the spanwise direction are treated as the periodic condition. The outflow boundary conditions are specified as a kind of characteristic-based condition, which can handle the outgoing flow without reflection[15].

To generate the true turbulent inlet, twenty thousand turbulent profiles are obtained from DNS simulation and used as the time dependent inflow[16].

The complicated vortex structures in the boundary layer of supersonic flat plate flow is shown in Fig. 4 and 5 which is in accordance with the published works. Fig. 6 shows the inflow boundary layer velocity profile in log-coordinates on the same cross section. There is a well-defined log region and the agreement with the analytical profile is well established. These results are typical for a naturally grown turbulent boundary layer in equilibrium.

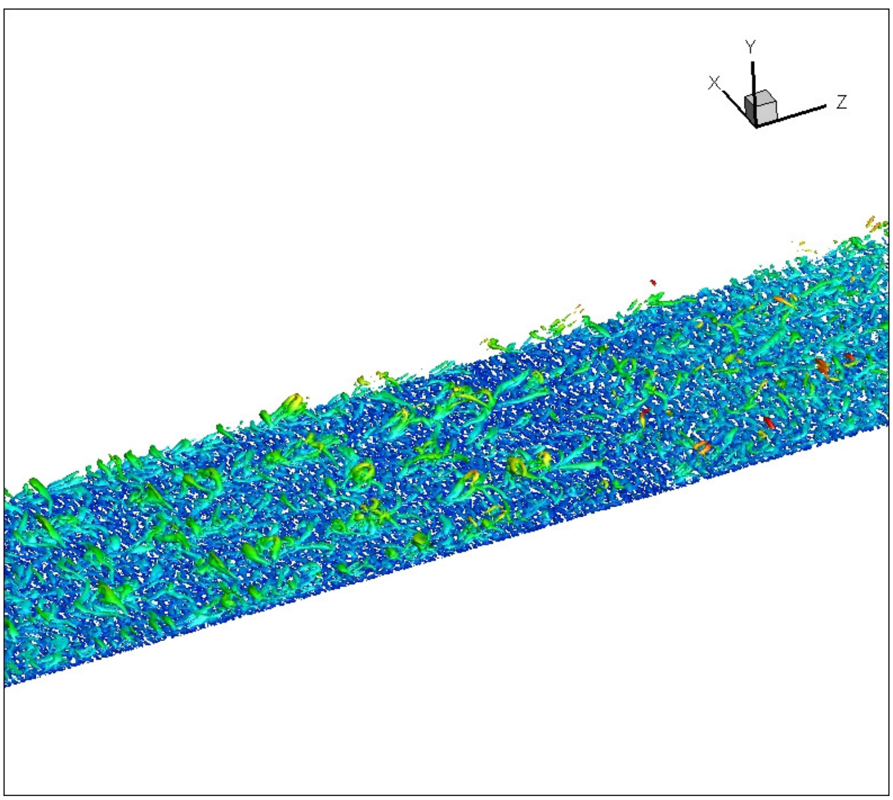


Figure 4. Vortex structure in the boundary layer of supersonic flat plate flow shown by λ_2

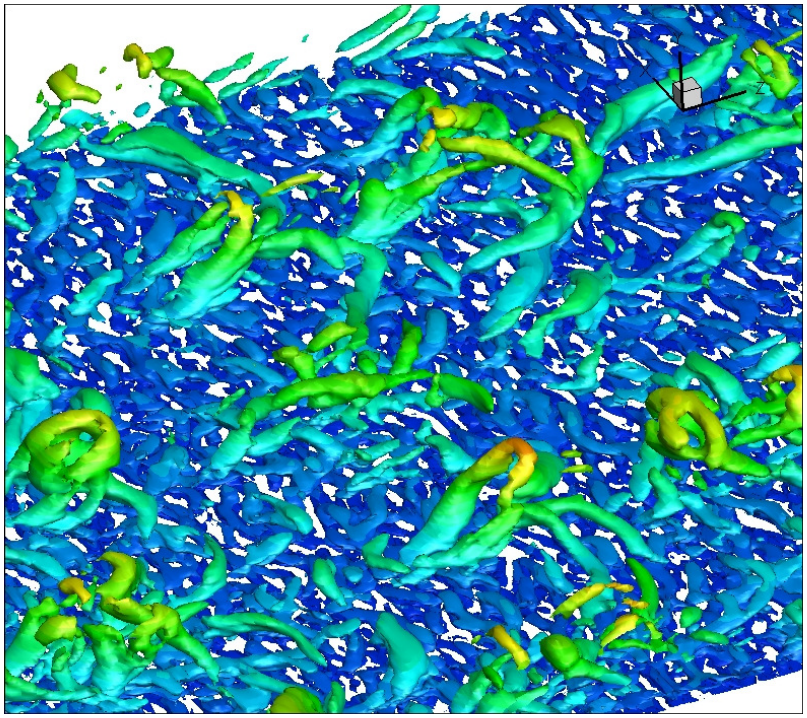
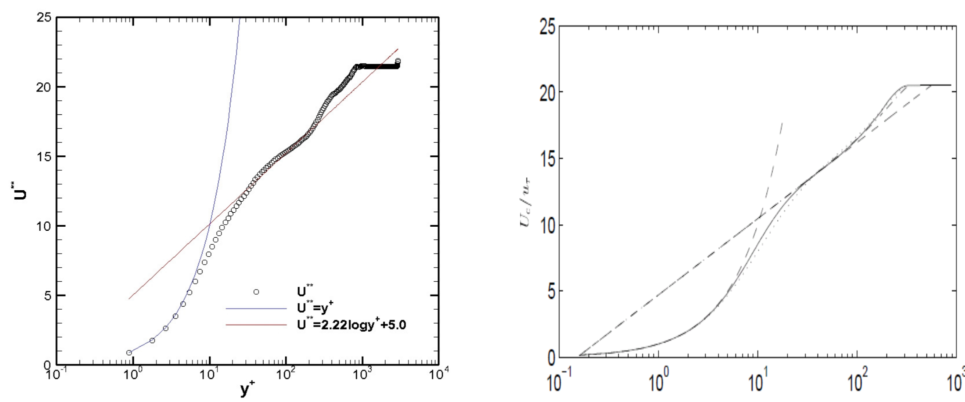


Figure 5. Vortex structure in the boundary layer of supersonic flat plate flow shown by λ_2 (enlarged)



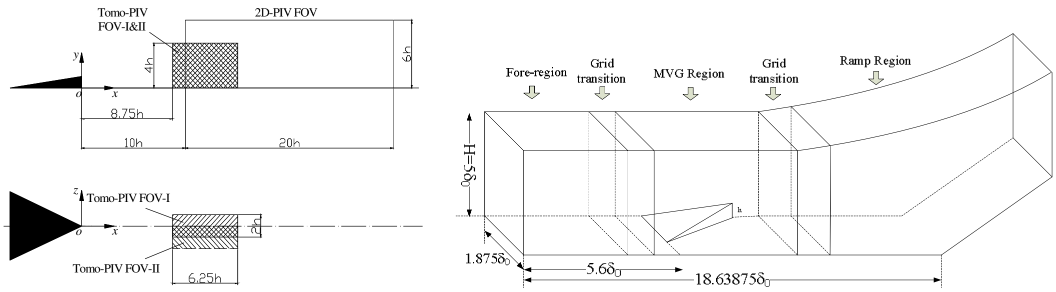
(a) Inflow profile by LES (b) Turbulent flow given by Guarini et al[17]

Figure 6. Turbulent inflow validation

IV. LES Code Validation

4.1 Micro vortex generator

The UTA high order LES code was developed under the support of US Air Force through an AFOSR grant. The code has been validated by UTA Aerodynamics Research Center and Delft University of Technology in Netherlands through 3-D PIV for supersonic flow around micro vortex generator (MVG) (see Figure 7) which is used to reduce the separation and pressure fluctuation induced by shock-boundary layer interaction. The agreement between experiment conducted by Delft and LES conducted by UTA is very well[18] (see Figures 8,9).



(a) Experiment setup (Delft) (b) Computational domain (UTA)

Figure 7. Les and experiment setup for micro vortex generator

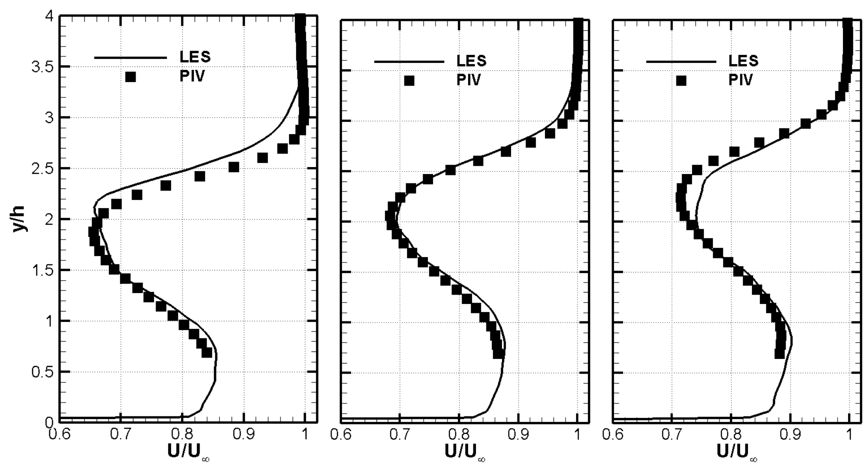
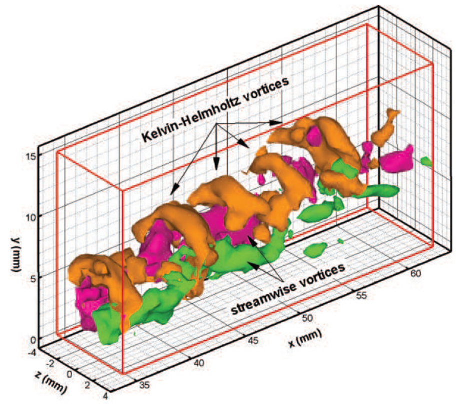
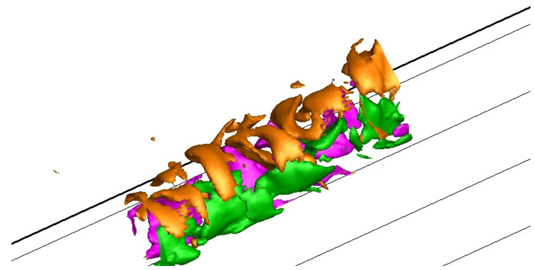


Figure 8. Profiles of *u* comparison in the center plane: (a) *x/h*=10 (b) *x/h*=12 (c) *x/h*=14.





(a) Experiment (Delft) (b) LES (UTA)

Figure 9. Comparison in vortex structure

4.2 Prediction of Pressure Fluctuation for Separated Supersonic Turbulent Boundary Layer and Shock Interaction

This case is to employ the UTA high order large eddy simulation code (LESUTA) to investigate the pressure fluctuation including the instant and time averaged power spectrum of the noise caused by the supersonic turbulent boundary layer and shock interaction (Figure8). The LES results must be validated first by comparison with experiment[19].

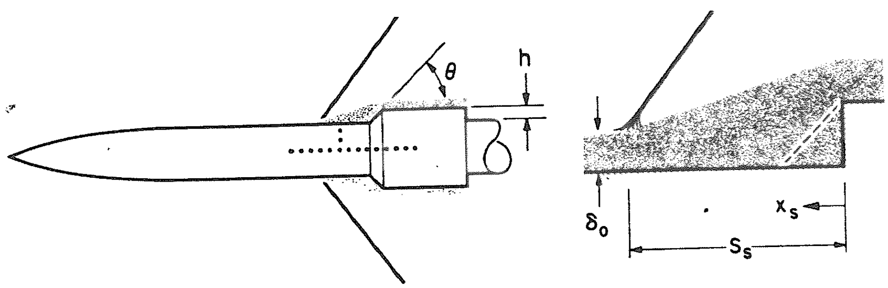
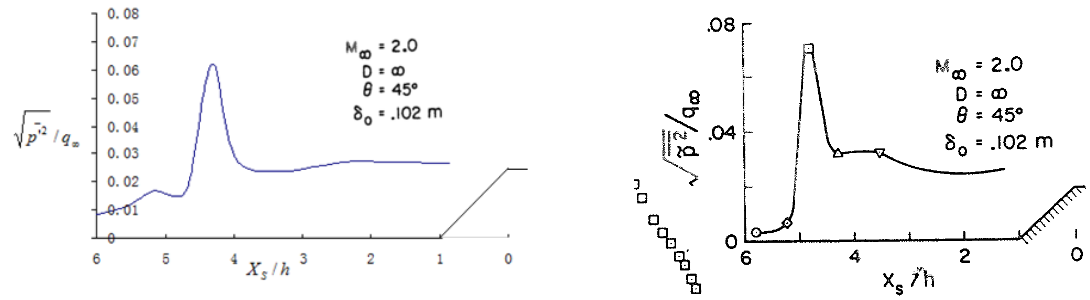


Figure 10. Shock and turbulence interaction around the ramp[19]

The LES results have been compared with experiment[19] The time-averaged pressure distribution, $\frac{\sqrt{(p-p_{ave})^2}}{q_\infty}$ *where* q_∞ is the inflow dynamic pressure. In general, the agreement between our time-averaged LES results and the experimental results are reasonable well. Our LES successfully resolved the averaged pressure fluctuation distribution in the streamwise direction. There are only some discrepancies in comparison. The peak value of $\frac{\sqrt{(p-p_{ave})^2}}{q_\infty}$ is located at 0.44 in our LES, but 0.48 in experiment. The peak value is 0.064 in LES but 0.07 in experiment. The separation zone is about 4.8 obtained from Fig. 11a. which is smaller than the one by the experiment, that is about 5.0. The spectrum of pressure fluctuation induced by the boundary layer separation is also given in Fig. 12 which compare well with experiment.



(a) LES results (b) Experimental results

Figure 11. Time-averaged pressure fluctuation in the central plane

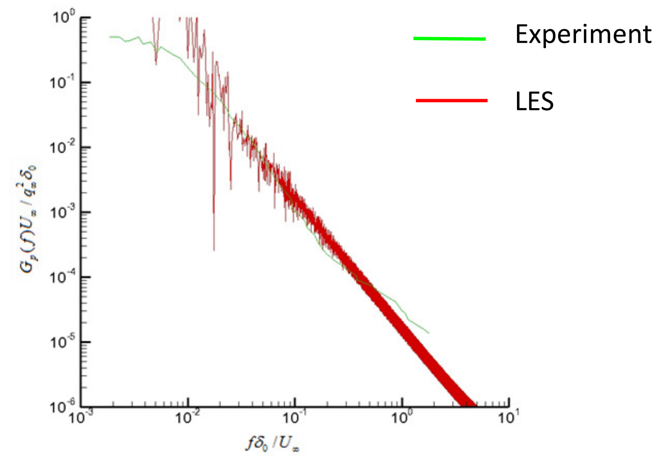


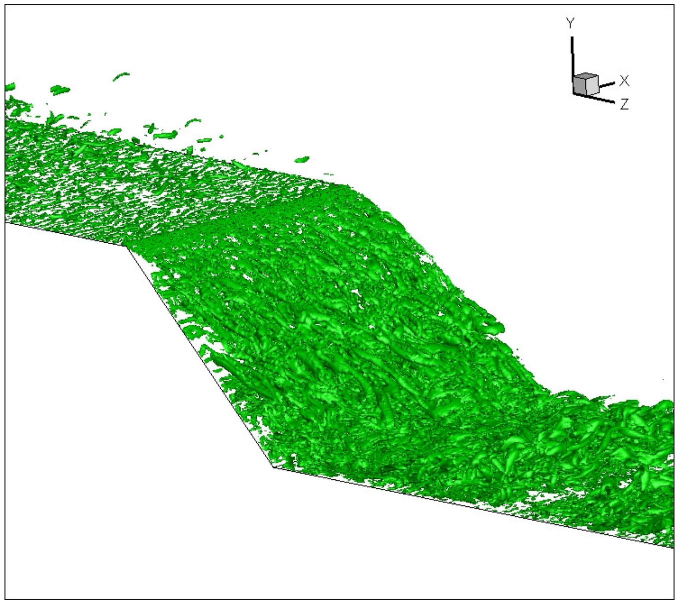
Figure 12. Power spectrum of shock induced pressure fluctuation

V. Numerical Result for Supersonic Backward-facing Step Flow

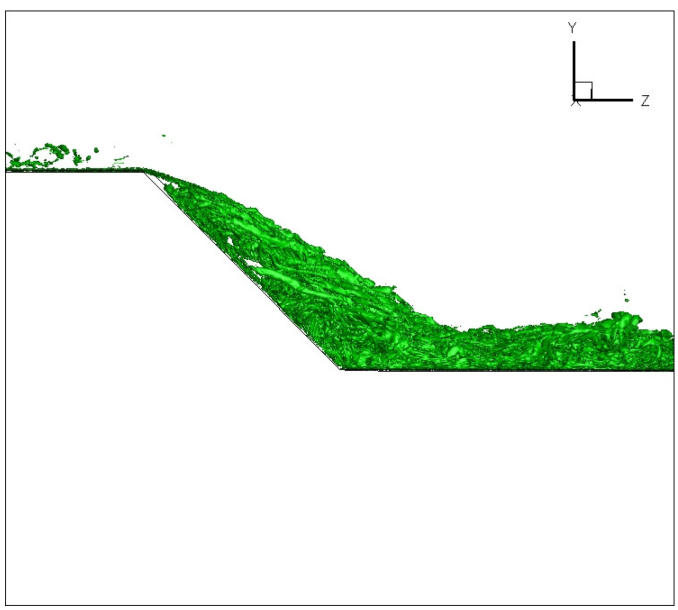
In order to investigate the vortex structure within and after the separation, a technique[20] is used by the iso-surface of the λ_2, which is the second eigenvalue of the 3×3 matrix comprised of velocity gradient, i.e., $M_{ij} = \sum_{k=1}^{3}\left(\Omega_{ik}\Omega_{kj} + S_{ik}S_{kj}\right)$, where $S_{ij} = 1/2\left(\partial u_i/\partial x_j + \partial u_j/\partial x_i\right)$ and $\Omega_{ij} = 1/2\left(\partial u_i/\partial x_j - \partial u_j/\partial x_i\right)$. A small negative value is selected for visualization.

Fig. 13 shows the complicated vortex structures at the back-step part by λ_2 iso-surface. The numerical simulation captures a large separation flow. It can be seen from Fig. 13 that there are a large amount of vortices with various length scales in the concerned region, and many of them are streamwise vortices. Moreover, hairpin vortices with ring-like head are found within the vortices. The weaker of the inflow vortices at the selected iso-surface value means that the intensity of the vortices is stronger in the separation zone. This provides an indirect proof of the amplification of the fluctuation by the flow separation.

Fig. 14 shows the density distribution on the central plane, which captures the expansion wave at the top of the back-step. Fig. 15-17 give the density and pressure distribution which shows the existence of a strong shock wave in the downstream. Our numerical method illustrated the complicated interaction between the vortex structures and shock waves. The distribution of spanwise vorticity is shown in Fig. 18.



(a)



(b)

Figure 13. Vortex structures at the back-step (iso-surface of λ_2=0.006)

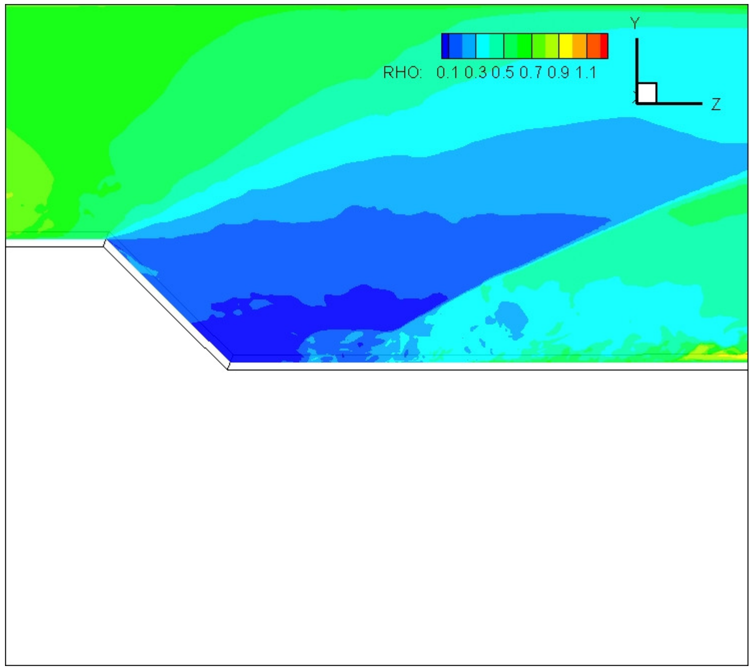


Figure 14. Density distribution on the central plane

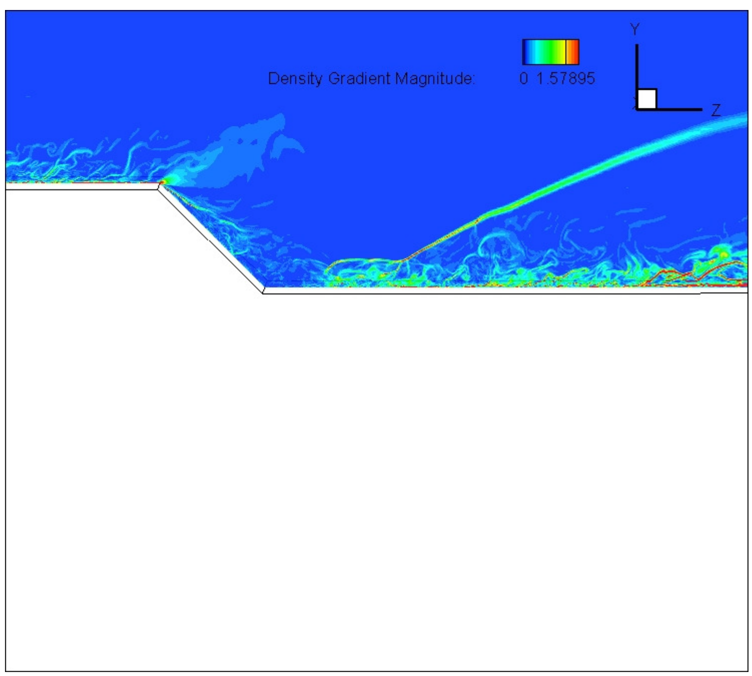


Figure 15. Density gradient on the central plane

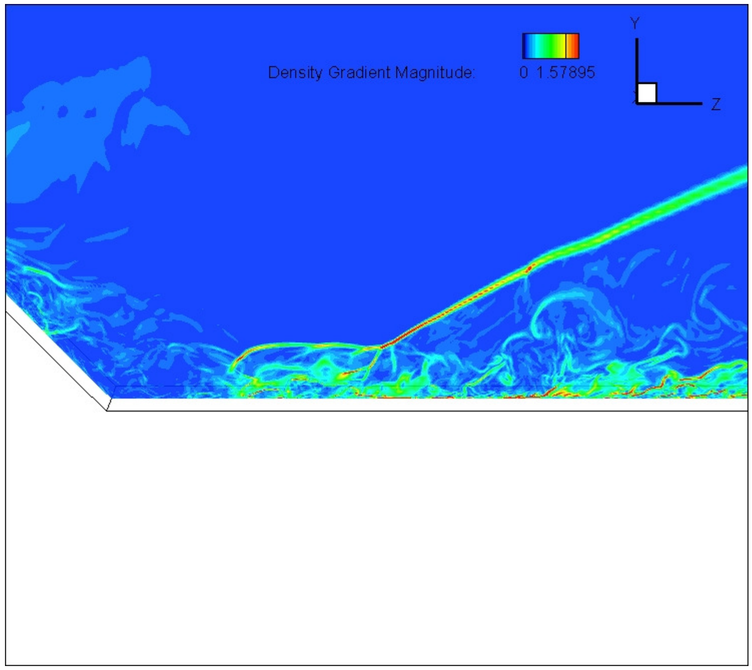


Figure 16. Density gradient on the central plane (enlarged at the downstream of the step)

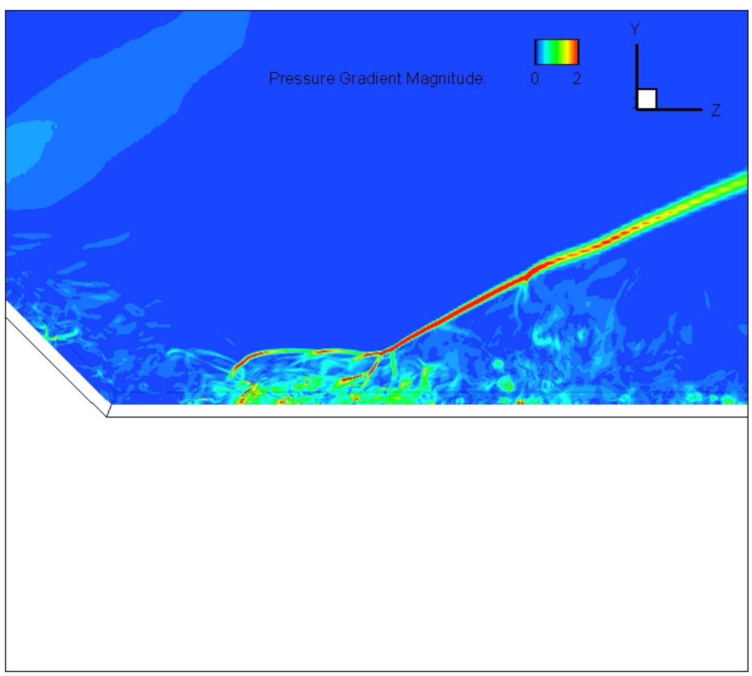


Figure 17. Pressure gradient on the central plane (a shock is formed in the downstream)

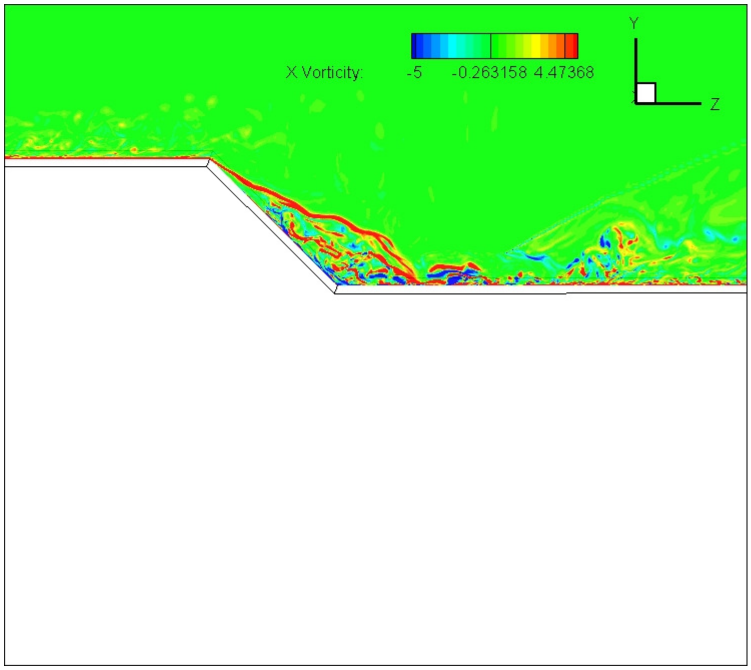


Figure 18. Spanwise vorticity distribution

The flow features at the wall boundary are shown in Fig. 19-22. A recirculation region is observed at the step corner through the streamtrace distribution in Fig. 21 and 22. From our numerical simulation, the separation zone ends at about 1.22h in the downstream of the step.

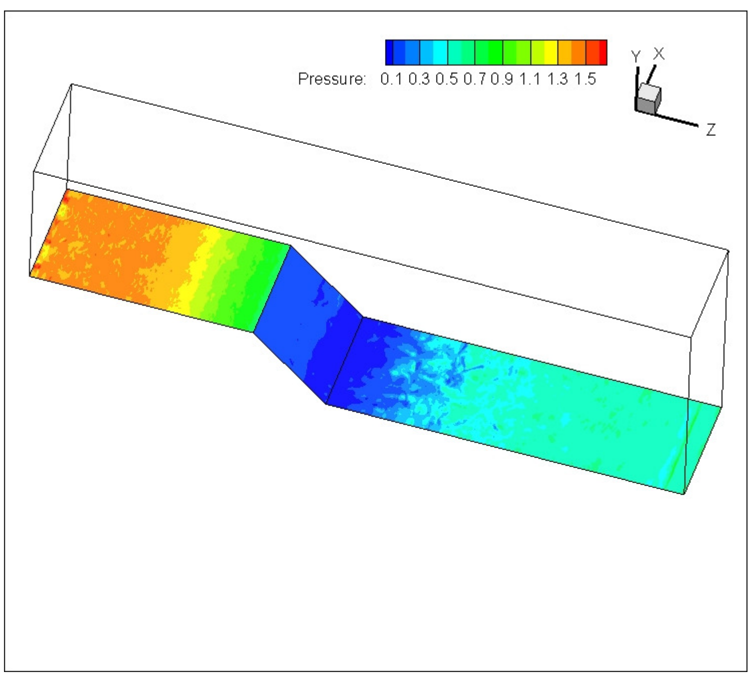


Figure 19. Pressure distribution at wall

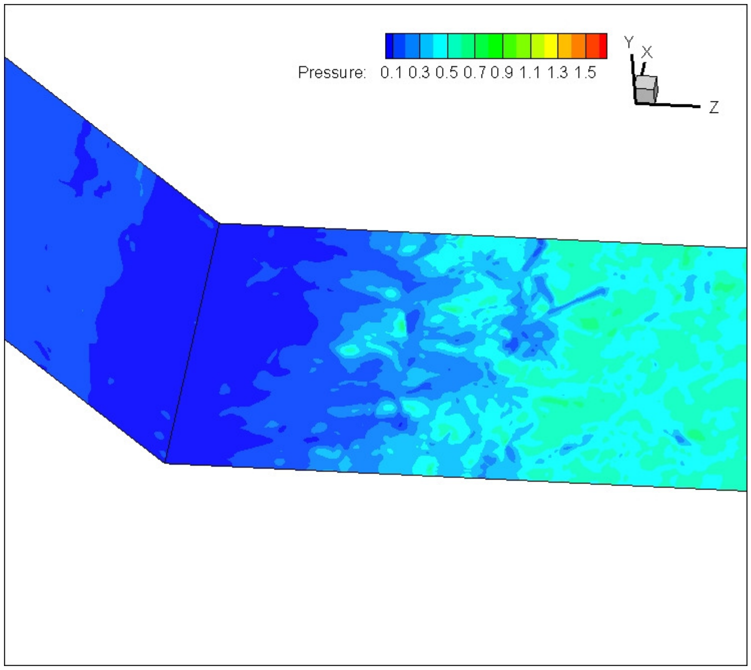


Figure 20. Pressure distribution at wall (enlarged)

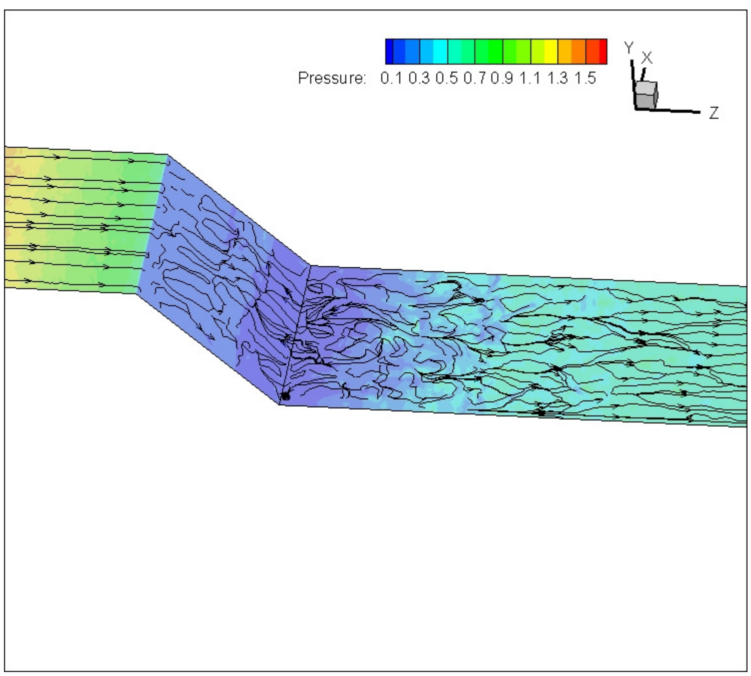


Figure 21. Streamtrace at the wall (with contour of pressure distribution)

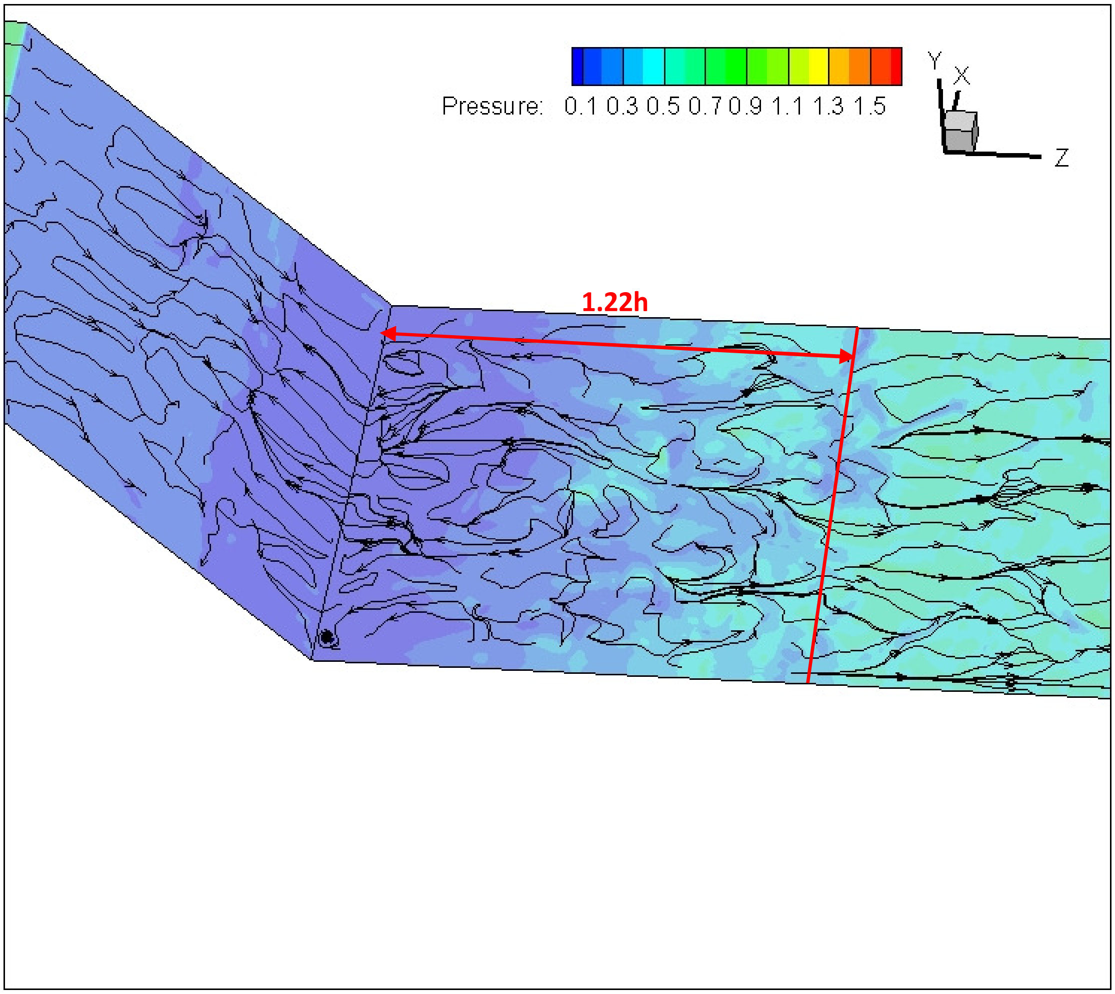


Figure 22. Streamtrace at the wall(enlarged at the separation zone) .

We are still working on the numerical simulation, more results including the interaction between the boundary layer and separation shock wave in the downstream will be reported .

VI. Conclusion

A supersonic backward-facing step flow at M=2.0 and Re=4000 is investigate in this paper. The high order large eddy simulation with a fully developed turbulent inlet condition is used to investigate the flow field structures. The three dimensional flow field especially at the separation region is studied in detail. The numerical solution captures the essential features of the flow, such as the reversed flow, recirculation zone length and other mean flow parameters with reasonable accuracy. The interaction between the boundary layer and separation shock wave in the downstream is also studied.

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