Numerical Comparison of RANS and LES Turbulence Model for Wind Flow Over a Cube in a Turbulent Channel using OPENFOAM

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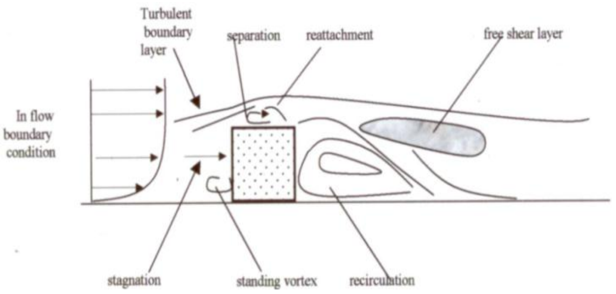
***Abstract*-This paper deals with the turbulent flow over a cube placed in a turbulent channel. Two turbulence model i.e, Reynolds Average Navier Stokes Equation (RANS) and Large Eddy Simulation (LES) are used to compare the results of the various parameters. In case of RANS a 2D model is used and k- ε two equation unsteady state is used to model the flow field whereas in LES 3D model is incorporated and smagorinsky one equation unsteady model is used to find the flow field parameters. The flow domain for RANS 2d case is 60 cm × 30 cm and the 2d cube model (4 cm × 4 cm) is placed at a distance of 20 cm from the entrance at the base of the domain where as for LES 3D case the domain is of the size of 60 cm × 30 cm × 30 cm and the 3D cube model (4cm × 4 cm × 4 cm) is placed at a distance of 20 cm from the entrance at the ground in the centre of the base of the domain. The Reynolds number for the flow in respect of the height of the cube i.e, 4 cm is 65000. For meshing the flow field hexahedral grids were used. Various flow parameters i.e., velocity profile around the cube and flow field, pressure coefficient over the cube, kinetic energy and shear stress, energy spectrum, Drag & lift coefficients, vorticity magnitudes and y+ are being compared with respect to the two incorporated turbulence model. OpenFoam under the Linux Ubuntu is being used for the computational and numerical analysis. PISO algorithm is being employed for LES where as PIMPLE algorithm is used for RANS model.**

Keywords* – *Reynolds Average Navier Stokes Equation (RANS),Large eddy simulation (LES), k-ε, Smagorinsky, unsteady state, 3D cubical model, PISO algorithm, SIMPLE algorithm, Reynolds no., OpenFoam.

I. INTRODUCTION

Unsteady flows past a cube resistance are very significant for many modern engineering problems. A benchmark problem in fluid engineering is turbulent flow over a surface mounted cube with sharp. Many eminent researchers have worked on RANS steady state modelling and 3D LES model on this particular problem to come in with some kind of agreement in terms of flow field parameter. The aim of the present work is to find the various parameters like pressure profile, Kinetic energy and shear stress, velocity profile, dependency of y+ on u+, drag and lift forces etc in time domain around three dimensional flow fields for LES as well as two dimensional cases in RANS . Turbulent flows have huge impact in case of wind flow around bluff bodies such as tall building, towers, urban areas etc which are highly affected by the boundary around the body. The regions which are influenced by the presence of walls or boundary are known as viscous regions and they persist high gradients and hence for true prediction of wall bounded flow the viscous region plays a dominant role. [1]. Turbulence is an utmost unpredictable and is one of the most challenging problems in fluid dynamics. Turbulent flows inherently is attached with eddies or vortices which ranges from very large scale to very small scale in sizes. Energy is transferred from larger to smaller scales of eddies until finally molecular viscosity comes into effect to produce heat from the dissipation of the smallest scales. This energy cascade theory was introduced into physical laws by Russian Scientist Kolmogorov [2].



Many observations of flow in urban area have been done. In numerical modelling Britter & Hanna (2003)[3] point out that numerical studies produces reasonable qualitative results but the performance, when compared with laboratory or field experiments, is little better than that of simple operational models. Large-eddy simulation (LES) is a very good tool for computing unsteady 3-dimensional flows at high Reynolds number or with complex geometry.

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An LES resolves only the large-scale fluid mo-tions and models the subgrid-scale (SGS) motions through filtering the Navier-Stokes equations. When unsteady Reynolds-averaged Navier-Stokes (RANS) methods are used, it is implicitly assumed that there is a fair degree of scale separation between the large time scale of the unsteady flow features and the time scale of the genuine turbulence (Castro, 2003)[4]. Many experimental works are being done successfully on flow around ground-mounted cube in a developed turbulent channel flow. The experimental information are documented in Martinuzzi and Tropea [5] and Hussein and Martinuzzi [6] and also by Meinders' et al. [7] in turbulent channel flow. The Reynolds Average Navier-Stokes (RANS) is generally used for aapplications that only require average statistics of the flow. It integrates the ensemble-averaged equations and parameterizes turbulence over the whole spectrum of eddy. The advantages of RANS are that it is computationally inexpensive, fast. Whereas the disadvantages are that turbulent fluctuation are not captured. Large Eddy Simulation (LES) has its advantages over the other approaches of turbulence modelling. It combines DNS and RANS by treating large scales and small scales eddies in separate manner, based on Kolmogorov's theory. The large eddies are resolved explicitly and the impact of on the large-scale is parameterized. Since the contribution of the small-scale turbulence in the flow field is small, the errors introduced by their modelling are small. In addition, the resolved scales give more information than the mean flow predicted by the RANS approach. LES is therefore potentially much more accurate than RANS. Many of the simulation based on turbulent flow over a cube were done using RANS using various turbulent models [8, 9] and Large eddy simulation (LES) [10,11,12,13,14]. The flow modelling which is done in the present study uses both LES and RANS approaches and found to be in good agreement with real time experimental result.

II MODELS & DESCRIPTIONS

A. RANS Model

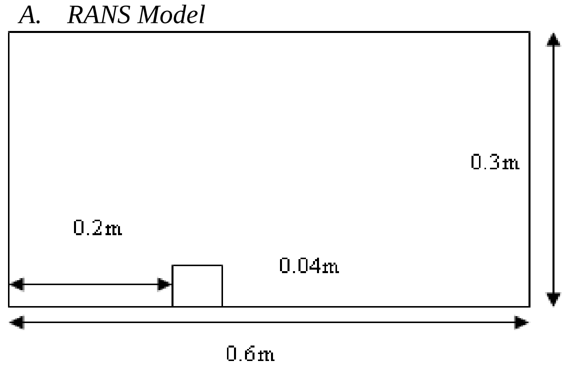

Fig. 1. Computational 2D domain for RANS

The above shown model is a 2D computational domain where a sharp cornered 2D cube model is placed in the ground from 0.2 m from the entrance.

B. LES Model

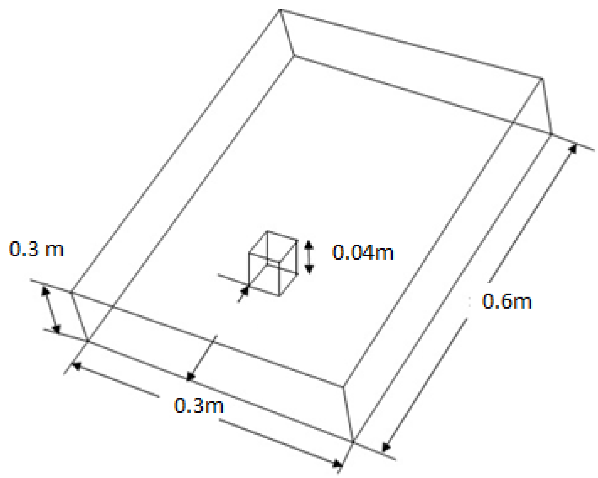

Fig. 2. Computational 3D domain for LES

The above shown model is a 3D computational domain where a sharp cornered 3D cube model is placed in the ground in the centre of the base from 0.2 m from the entrance.

In case of making up the flow field in both the cases the domains are meshed. In case of 1st case (RANS model) a 2D flow field was constructed using BLOCKMESH utility of Openfoam where as in the 2nd case (LES Model) a 3D cube model is built in Freecad and then the model is imported in openfoam where with the use of SNAPPYHEXMESH utility the domain is meshed. In the former case only hexahedra grids were used and in the later case both hexahedral and polyhedral cells were incorporated. The scaled domain for fig no 1& 2 with mesh statistics are given below as a table:

Table 1. Domain and mesh statistics

Parameter	Fig 1 (2D RANS)	Fig 2 (3D LES)
Cube position	(0,0)	(0,0,0)
X axis range	-0.24 to 0.36	-0.24 to 0.36
Y axis Range	0 to 0.3	-0.13 to 0.17
Z axis Range	Not applicable	0 to 0.3
Cells	158400 (Hexahedra)	1099281 (Hexahedra) 15331 (Polyhedra)
Max Aspect ratio	21.83	8.95
Max non orthogonality	0 (avg)	4.15 (Avg)
Max skewness	3.38*10^(-13)	2.79

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II. NUMERICAL SIMULATION AND SOLVER PARAMETERS

The boundary conditions for both the cases are given below:

Table 2. Boundary conditions

Parameter	Fig 1 (2D RANS)	Fig 2 (3D LES)
Inlet velocity	24.5 m/s	24.5 m/s
Outlet	Zero pressure gradient	Zero pressure gradient
Upper Wall	Wall	Wall
Lower Wall	Wall	Wall
Side Walls	Empty	Symmetry
Cube Walls	Wall	Wall

Since OPENFOAM does not work with 2D geometry hence to make a 2D analysis the side walls is taken as empty for 2D case. The inlet velocity for both the cases are taken as uniform 24.5 i.e, fully developed velocity profile is considered. The Reynolds number is calculated based on the height of the cube and hence ReH is considered as 65000.

For RANS simulation PIMPLEFOAM solver is used. The turbulence model used is RAS using k-epsilon 2 equation unsteady model. The delta T is taken as 0.00001 and the solver ran for end time 0.1. For a Pentium III processor with 4 GB RAM it took 26 hours to complete.

For LES simulation PISOFOAM solver is used. The turbulence model used is LES with smagorinsky using filter as cube root delta. The delta T is taken as 0.0001 and the solver ran for end time 0.7. For a Pentium III processor with 4 GB RAM it took 70-72 hours to complete.

At the end of the simulation all the results with respect to various parameters are captured and they are compared with each other for the prediction of turbulence. The study is inclined to find the parameters like drag & lift coefficients, energy spectrum and comparing with the standard curves, velocity and pressure at various time throughout the simulation, velocity and pressure contour, q criteria etc.

The detailed results are put in the section III with various graphs and their significance.

III RESULTS & DISCUSSIONS

A. RANS *k-ε model*

1) Velocity Profile

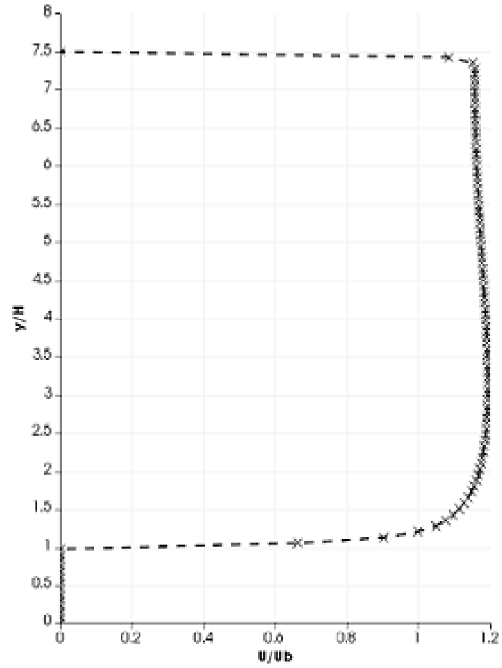

Fig. 3. Velocity profile at x=0

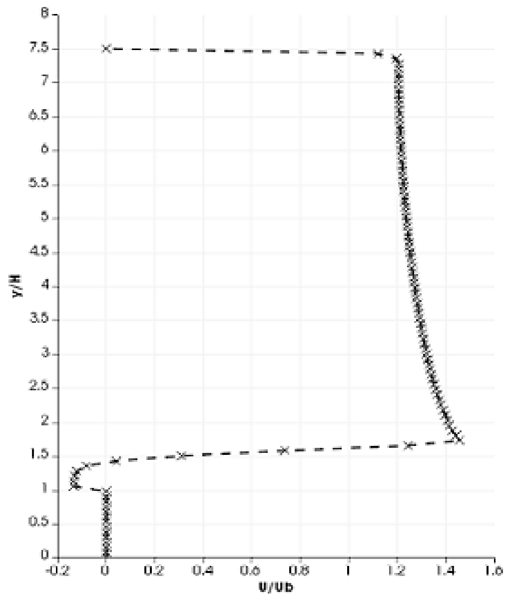

Fig. 4. Velocity profile at x=0.04

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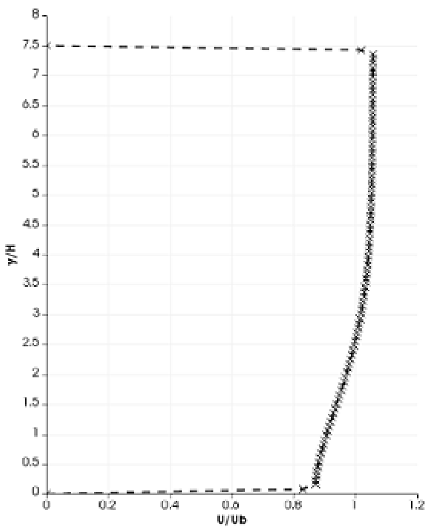

Fig. 5. Velocity profile at x=-0.1

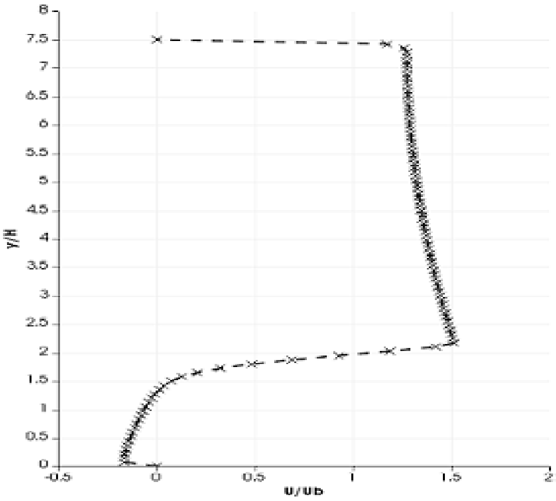

Fig. 6. Velocity profile at x=0.1

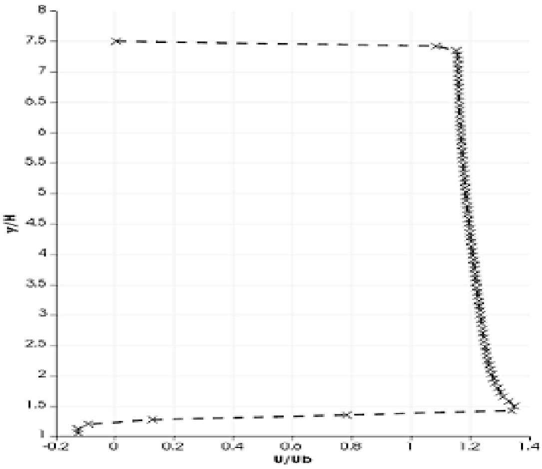

Fig. 7. Velocity profile at x=0.02

Fig 3 to 7 show the velocity profile for RANS model at different points of x=0,0.04,-0.1,0.1&0.02 where x=0 and x=0.04 give the front face of the cube and the back face of the cube respectively Where as point 0.02 gives the mid of the top face of the resistance and -0.1 and 0.01 give the upstream and downstream respectively. From the first two plots it is quite visible that initially the value is zero since the cube face is given as wall and the no slip condition is imposed and after the profile is changed with high gradients and as it moves further in the direction of y the gradient decreases and at last again moved to zero at the top boundary. Because of the cube interference this two shows this type of behaviour. For the upstream point since there is no interference the velocity profile is fully developed as in the inlet but in the downstream though the point is far away because of some kind of interference the profile is not fully developed and hence it can be said that even after some distance from the resistance the fluid experience effect of obstacles before it goes fully developed. For x=0.02 which is the point at the top of the cube face it can be observed that the velocity profile is almost developed but not from the bottom of the domain rather from above the cube.

2) Pressure profile

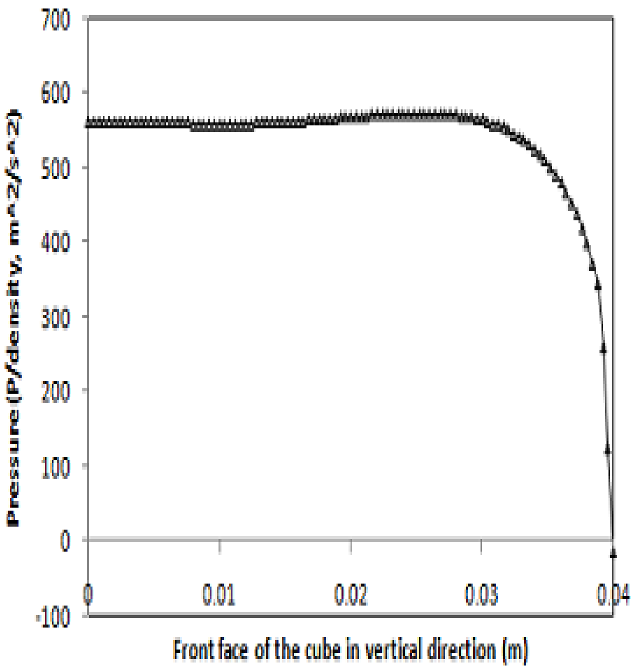

Fig. 8. Pressure at front face of the Cube

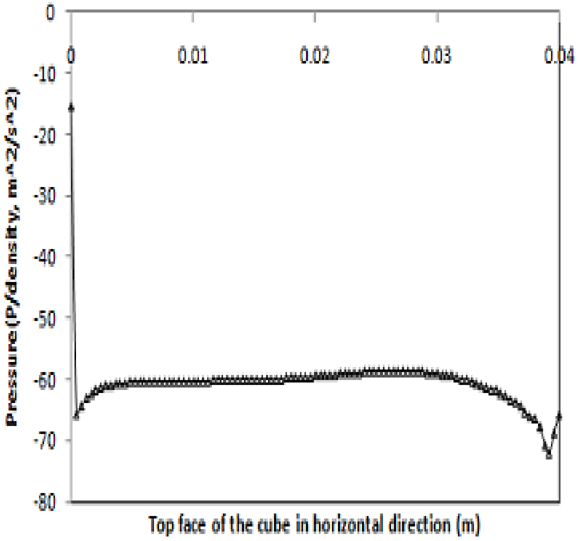

Fig. 9. Pressure at Top face of the Cube

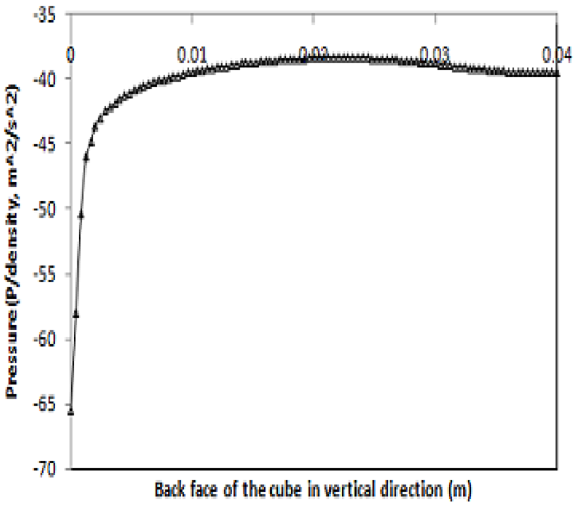

Fig. 10. Pressure at back face of the Cube

Fig 8 to 10 show the pressure profile in all three faces of the cube for RANS. Fig 8 gives pressure profile for front face of the resistance. The plot shows the maximum pressure is nearly 575 m^2/s^2 and dthis value is at the bottom of the cube and at the top corner of the cube the value is almost negligible .Also it can be seen that the the plot is initially at constant value of 575 for almost 2/3rd of the cube height and after that the value decreases and this is because the stagnation point is almost upto a height of 2/3rd of cube height from the base. Also in the back face and at the top face a negative pressure prevails which can be seen from the rest of the two graphs which is because of creation of vortex and eddies because of change in energy

3) Kinetic energy profile

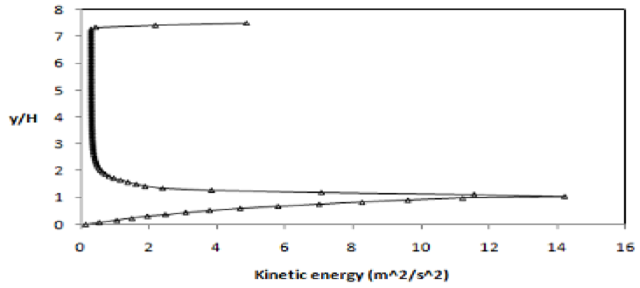

Fig. 11. Kinetic energy at x=0

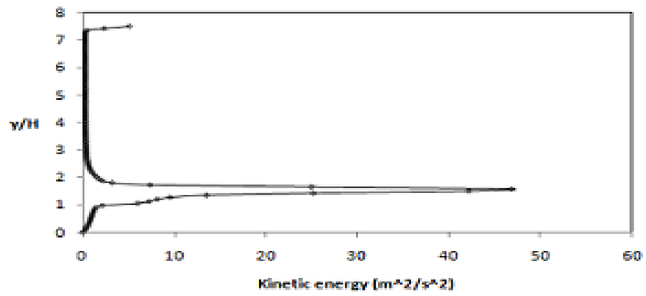

Fig. 12. Kinetic energy at x=0.04

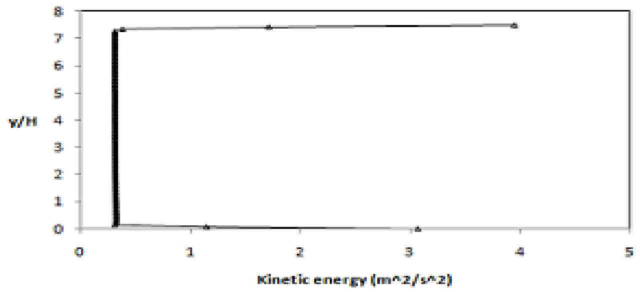

Fig. 13. Kinetic energy at x=-0.1

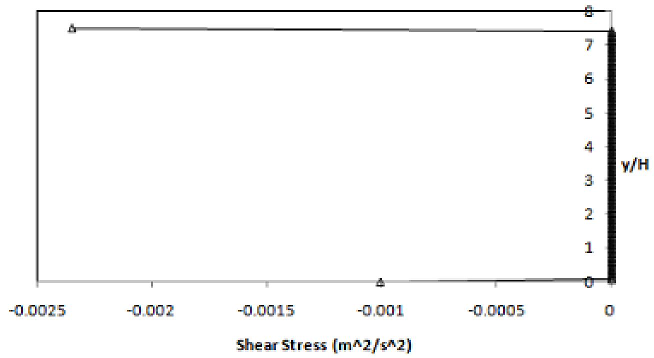

Fig. 14. Kinetic energy at x=0.1

Fig 11 to 14 give the kinetic energy profile at various cut point with respect to x coordinate i.e., x=0,0.04,-0.1 & 0.1.For the first two plots which are at the cube front face and back face respectively it can seen that initially upto the cube height of 0.04 m there is immediate increase in kinetic energy and after that the kinetic energy is almost zero and again near the upper boundary of the domain which is wall the kinetic energy increases which shows whenever there is obstacle because of the change in

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energy the kinetic energy of the fluid increases. For the rest of the two plots which are in the upstream and downstream and quite far away from the cube there is almost no effect of obstacles and hence the kinetic energy is almost constant at negligible values. For the front face maximum kinetic energy goes to 14 m^2/s^2 and for the back face the maximum kinetic energy is nearly 50 m^2/s^2. This means that at the back of the cube the formation of vortex is bigger and more rigorous.

4) Shear stress profile

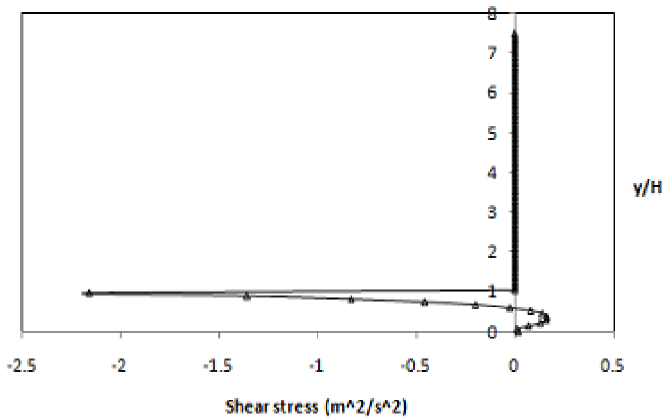

Fig. 15. Shear stress at x=0

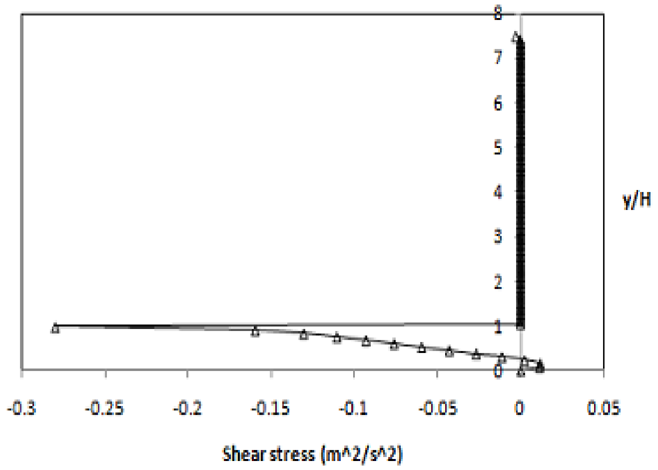

Fig. 16. Shear stress at x=0.04

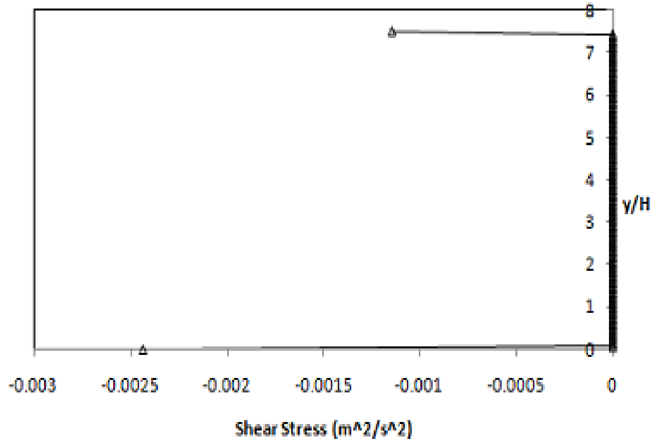

Fig. 17. Shear stress at x=-0.1

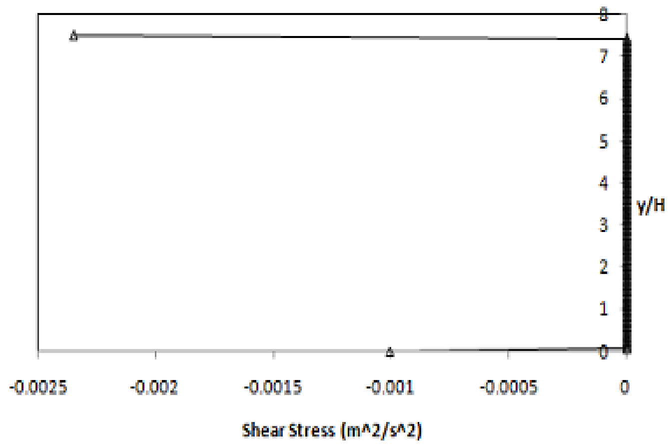

Fig. 18. Shear stress at x=0.1

Fig 15 to 18 show the shear stress profile for the four cutline taken with respect to x coordinate. The first two plots again give the values of the front and back face of the cube respectively. It can be seen from the plots that initially there is a immediate increase in shear stress because of the cube wall and when the eddies form and they get detached from the surface the shear stress diminishes and which is exactly is happening in the case. Hence after the initial increase the negative shear stress comes in picture which is nothing but the detachment of the fluid volume from the surface of the cube. From the last two plots it can be visualize that since the point are very far away from the obstacle at there is no effect of any wall hence the shear stress stays at a legible value of almost zero.

B. LES Smagorinsky model

1) Velocity Profile

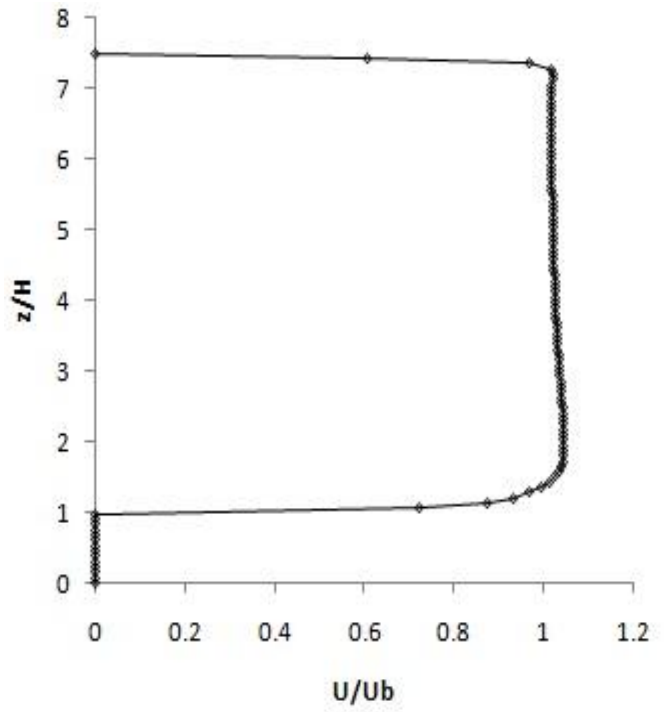

Fig. 19. Velocity profile at x=0

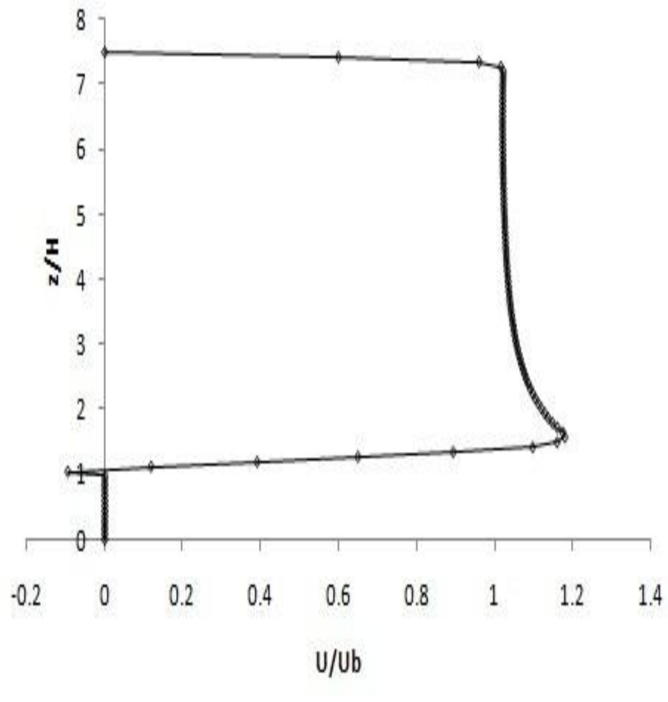

Fig. 20. Velocity profile at x=0.04

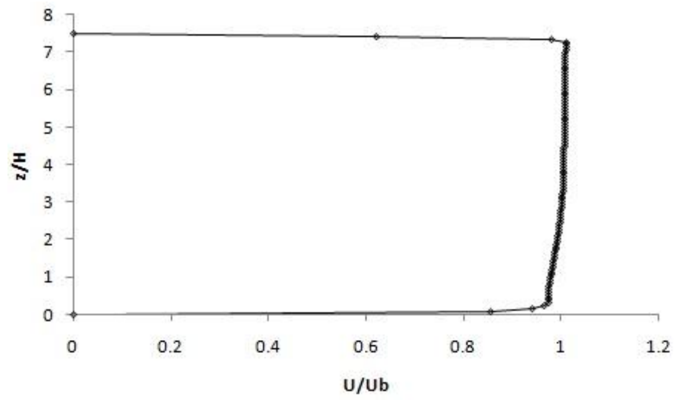

Fig. 21. Velocity profile at x=-0.1

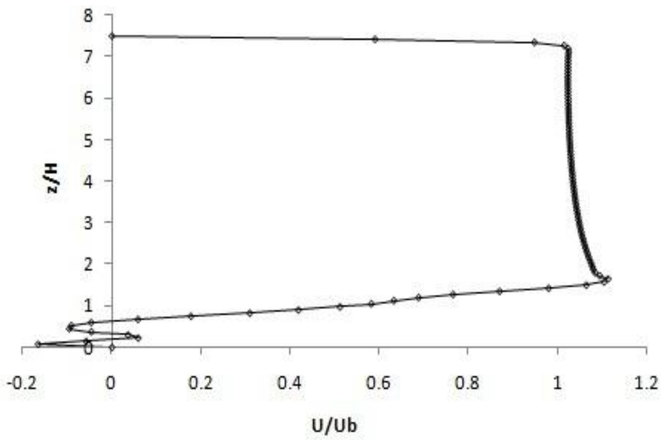

Fig. 22. Velocity profile at x=0.1

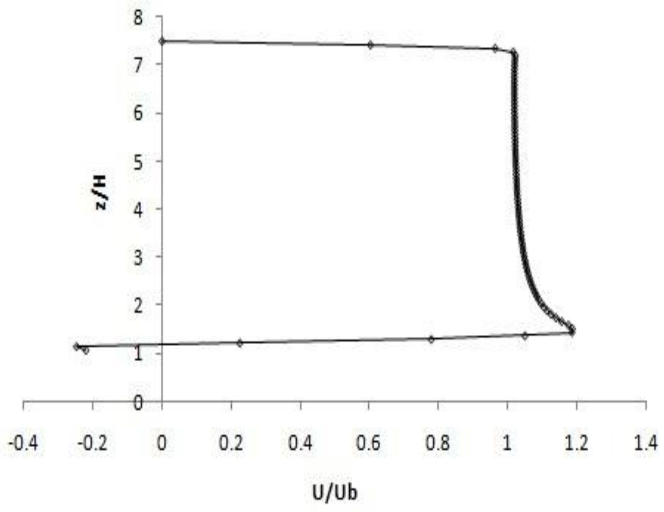

Fig. 23. Velocity profile at x=0.02

Fig 19 to 23 give the velocity profile for LES at various cut point with respect to the values of x axis and the points are 0,0.04,-0.1,0.1 & 0.02. The plots are almost similar to that of the RANS model. For the first two plots i.e., for front face and for the back face because of the cube height at the initial position the velocity profile stays at zero but after the height of the cube the profile starts developing. At the front the development is very smooth but at the back

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face because of the creation of vortex the development is disturbed but after some portion in vertical direction the profile develops. For the upstream point at x=-0.1 the profile is fully developed as it is in the inlet because of no interaction of the cube with fluid but at the same time in the downstream section since the interaction is little more the profile is disturbed initially. At the point x=0.02 which is at the top of the cube the profile is smooth from the top of the cube upto the domain boundary and develops smoothly. Since in both the models the plots are almost similar it can be concluded that for velocity profile both model can be proved a suitable one

2) Pressure profile

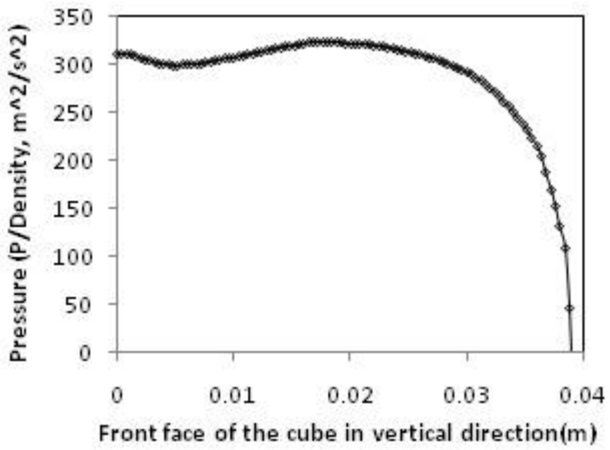

Fig. 24. Pressure at front face of the Cube

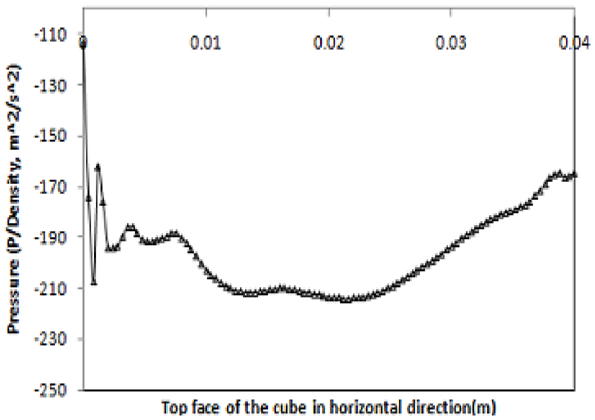

Fig. 25. Pressure at top face of the Cube

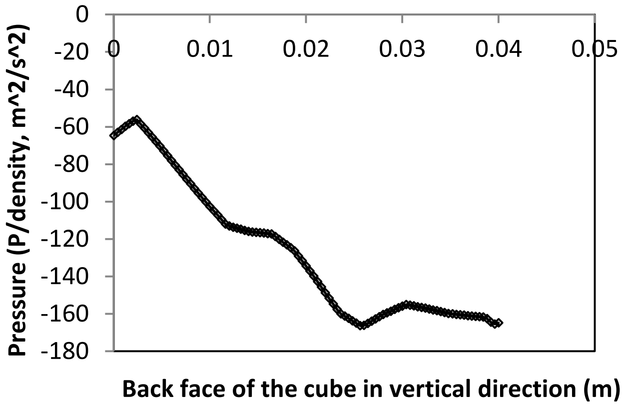

Fig. 26. Pressure at back face of the Cube

Fig 24 to 26 show the pressures at various faces on the cube for the LES model. The first plot show the development of pressure at the front face. Again the maximum pressure is at the bottom corner of the cube which is in this case near about 320 m^2/s^2. The plot is almost at constant value upto half of the cube height and after that the value starts decreasing and eventually at the top corner the value almost goes to zero which means vortex or eddies starts formation at the cube top corner and a low pressure zone gets created. The difference in this case with the RANS model is the value In RANS the maximum pressure is near about 725 m^2/s^2 and also the stagnation point is at 2/3rd of height of the cube whereas in LES the maximum pressure is 320 m^2/s^2 and the stagnation point is nearly half of the cube height. Hence it can be concluded that for pressure variation the LES 3D model captures better resolution than RANS 2D model. In LES also at the top and at the back face the negative pressure zone prevails.

3) Kinetic energy profile

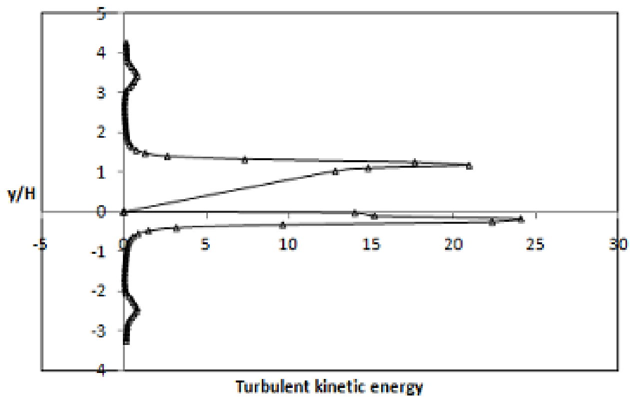

Fig. 27. TKE at x=0.02 through y axis in cube centre line

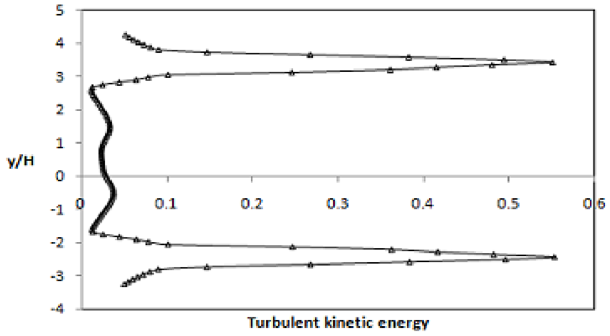

Fig. 28. TKE at x=-0.02 through y axis in cube centre line

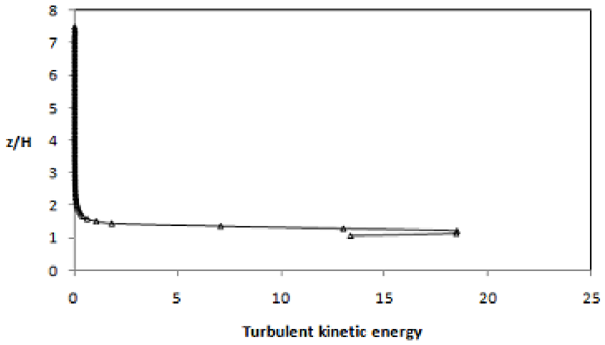

Fig. 29. TKE at x=0.02 through z axis in the cube centre line y=0.02

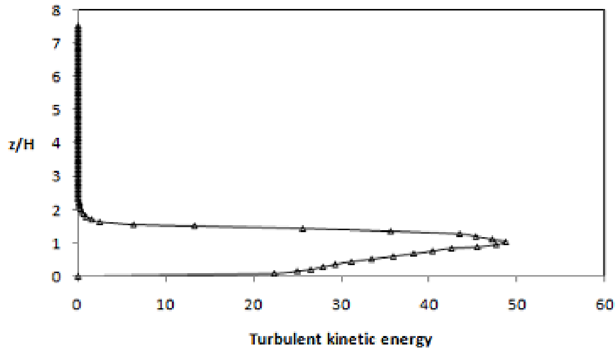

Fig. 30. TKE at x=0.06 through z axis in the cube centre line y= 0.02

Fig 27 to 30 show the turbulent kinetic energy profile for LES model at various cut point with respect to the combination of coordinates. The cutline are take as x=0.02 through y axis in the cube centre line, x=-0.02 through y axis in the cube centre line, x=0.02 through z axis in the cube centre line y=0.02 & x=0.06 through z axis in the cube centre line y=0.02 For the first two plots the profiles are being plotted along the y axis which is the ground surface where the cube is placed at the centre of the surface. The two points are taken as 0.02 & -0.02. It can be seen from the plots that, in the two extreme end of the surfaces the TKE is almost negligible and at the centre there is the sudden increment of the values. This is because at the centre the cube surface is lying and whenever there is obstacle the TKE of the fluid volume will increase. At the upstream point which is at x=-0.02 the maximum TKE is 25 m^2/s^2 and in the downstream at x=0.02 the maximum TKE is 0.55 m^2/s^2 which shows there is very little interference of the cube in upstream rather than downstream. In the last two plots which are plotted against the vertical direction same as RANS model with two points in x direction 0.02 and 0.06. It can be seen that for the first plot the maximum value is 18 m^2/s^2 and for the last plot the value is 50 m^2/s^2 but for the RANS case the values are 15 m^2/s^2 & 50 m^2/s^2 respectively and which are almost equivalent. So it can be said that for kinetic energy both the model gives almost same result.

4) Shear stress profile

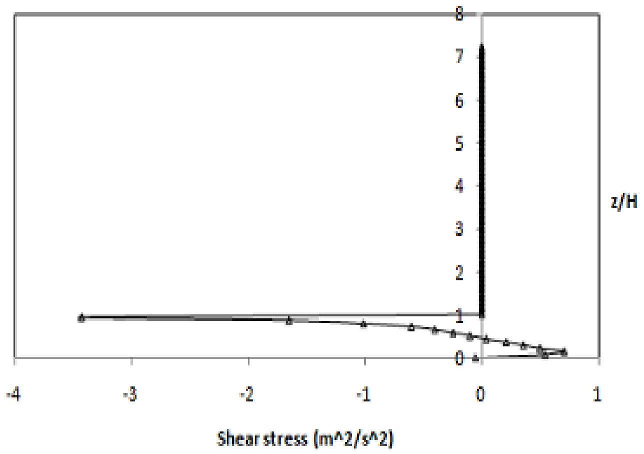

Fig. 31. Shear stress at x=0 and y=0.02 through z axis

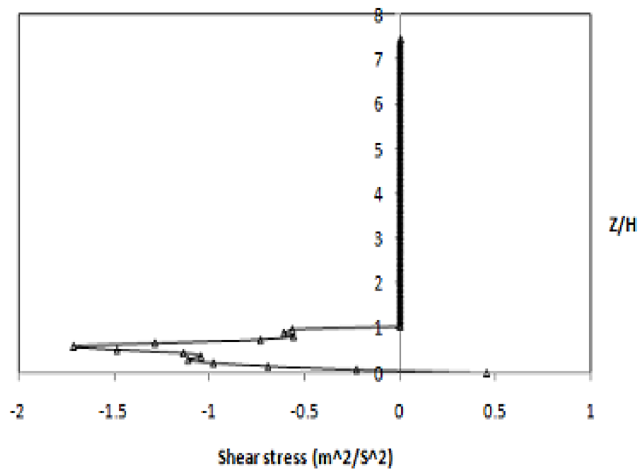

Fig. 32. Shear stress at x=0.04 and y=0.02 through z axis

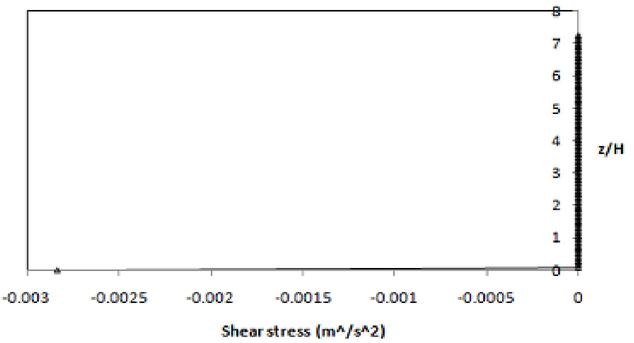

Fig. 33. Shear stress at x=-0.1 and y=0.02 through z axis

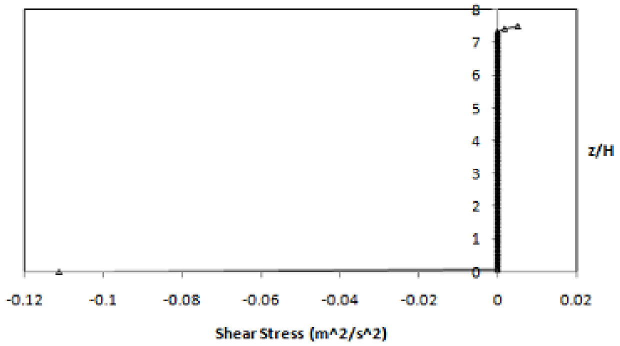

Fig. 34. Shear stress at x=0.1 and y=0.02 through z axis

Fig 31 to 34 show the shear stress profile for LES model where the shear stress are plotted at various x coordinate points 0,0.04,-0.1 & 0.1 and at y=0.02 which is the centre line at the base of the domain through the vertical z coordinates. The first two plots again at the front and at the back face of the cube. The plots are almost similar to that of the RANS model where initially there is a immediate increase in shear stress because of the cube wall and when the eddies form and they get detached from the surface the shear stress diminishes and which is exactly is happening in the case. Hence after the initial increase the negative shear stress comes in picture which is nothing but the detachment of the fluid volume from the surface of the cube. From the last two plots it can be visualize that since the point are very far away from the obstacle at there is no effect of any wall hence the shear stress stays at a legible value of almost zero. Hence it can be again concluded that for shear stress profile both the model can prove good.

C. Energy Spectrum

1) *RANS Model*

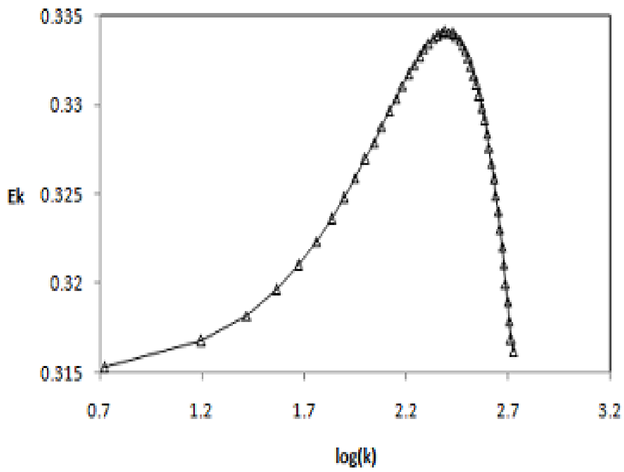

Fig. 35. Energy spectrum

2) *LES Model*

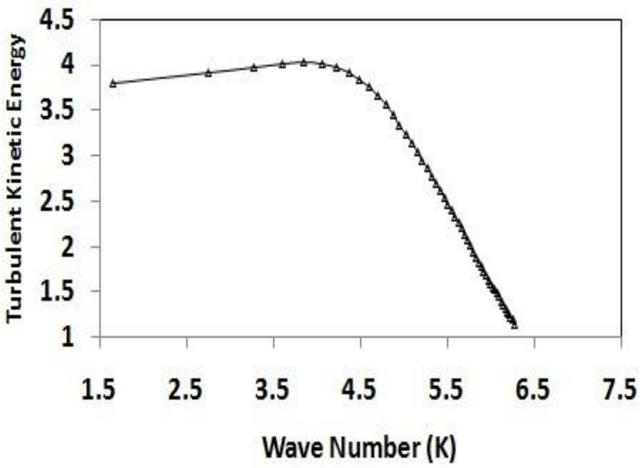

Fig. 36. Energy spectrum

The energy spectrum for both the model are being investigated. For RANS model the plot is Kinetic Energy Ek vs log(k) where k is the wave number and for LES the plot is for Total turbulent kinetic energy vs wave number k. Both the plots are verified with the published literature [15] and the similarity is very much found. In case of LES only the large scale eddies are comes in picture for energy calculation where as for RANS total spectrum is captured and that is why for the first plot the whole spectrum comes and for the later only the large scale are taken in view.

D. Vorticity

1) RANS Model

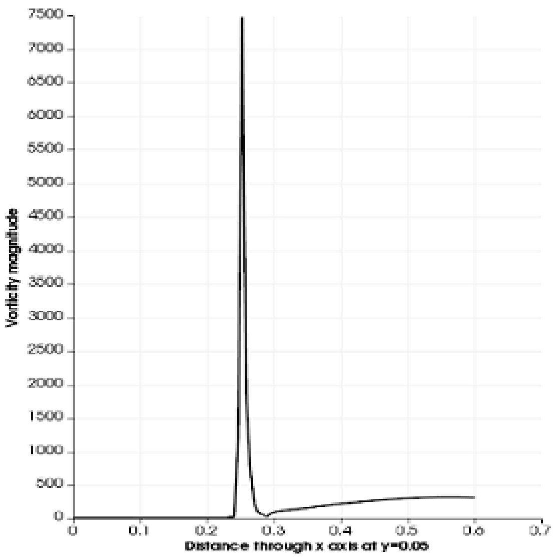

Fig. 37. Vorticity magnitude through x axis at y=0.05

2) LES Model

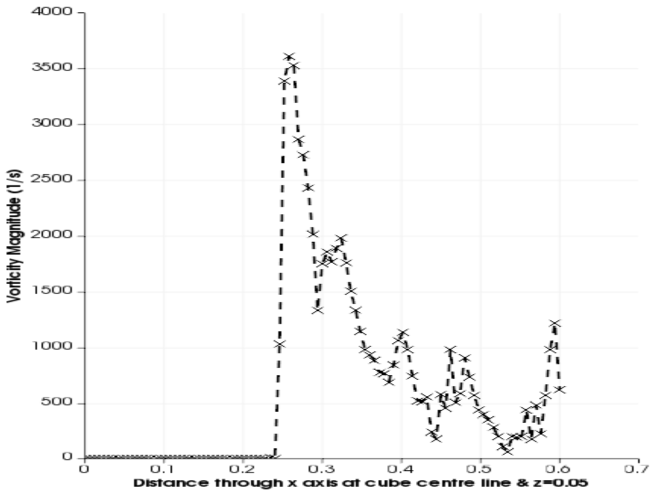

Fig. 38. Vorticity magnitude through x axis at y=0.02 & z=0.05

The vorticity magnitude (1/s) are being calculated for both the model and found that for RANS the value is almost 7500 1/s and for LES almost 3700 1/s.

E. Wall Shear stress

1) RANS Model

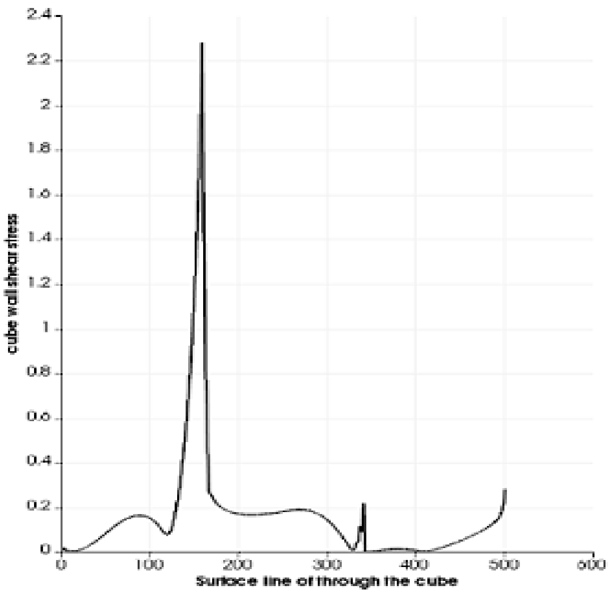

Fig. 39. Wall shear stress for cube wall

2) LES Model

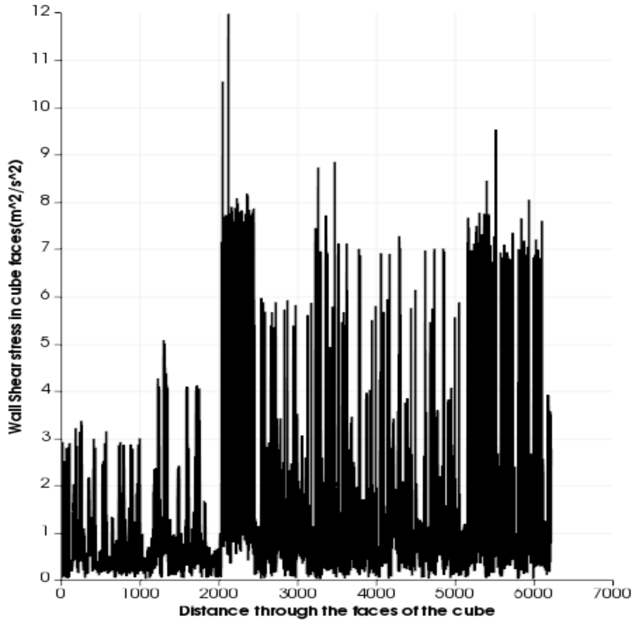

Fig. 40. Wall shear stress for cube wall

The wall shear stress are also being found in terms of cube wall and is found that the variation in RANS model is 0 to 2.4 m^2/s^2 and for the LES it is 0 to 12 m^2/s^2 with an average of almost in between 6-7 m^2/s^2.

F. Y plus for cube wall

1) RANS Model

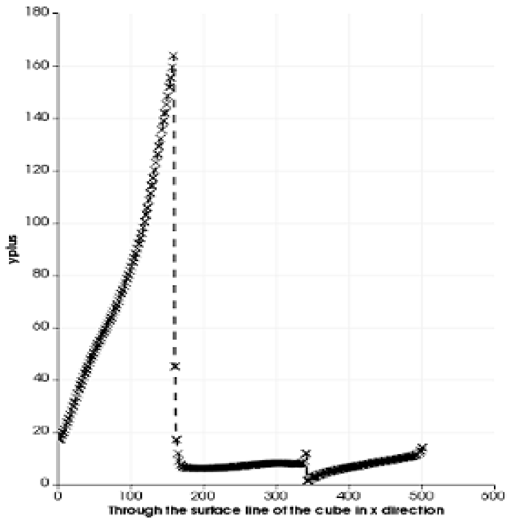

Fig. 41. Cube wall y plus

2) LES Model

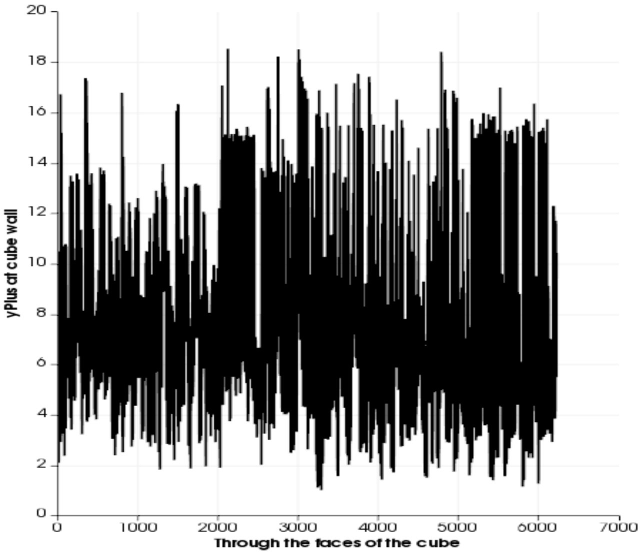

Fig. 42. Cube wall y plus

Y plus is one of the most important factor in the grid resolution which plays a very important role in best grid choice of computation. Generally for Y plus value 0 to 5 gives the viscous zone very close to the wall, 0-30 buffer zone and above 30 gives the zone for the turbulence capture. In this work for the RANS case the range of Y plus for the cube is 0 to 160 where as in LES it is almost 1 to 19 which shows that for 3D case the cube resolution is one of the best so that the full wall property can come in the resolution for capturing the best turbulence property.

G. Y plus for Domain Bottom Wall

1) RANS Model

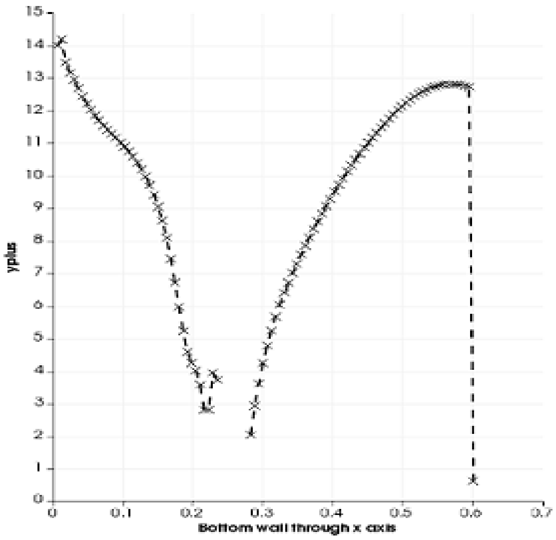

Fig. 43. Domain Bottom wall y plus

2) RANS Model

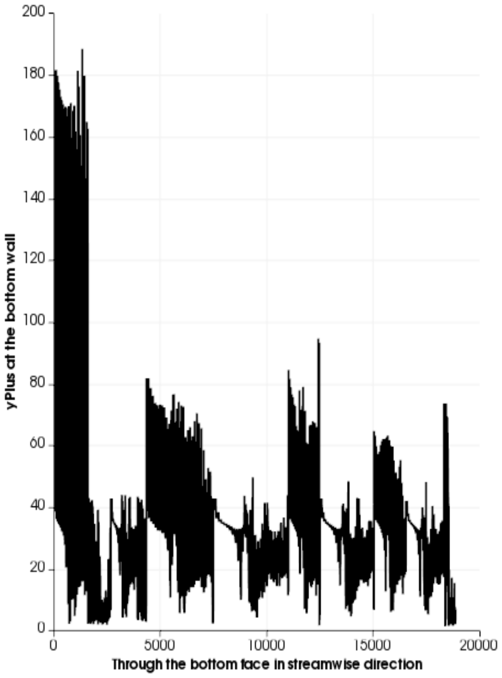

Fig. 44. Domain Bottom wall y plus

For the bottom Y plus of the domain for RANS the Y plus value is between 0 to 14 and in case of LES 0 to 180 both of which are quite acceptable for good grid resolution.

H. Streamline

1) RANS Model

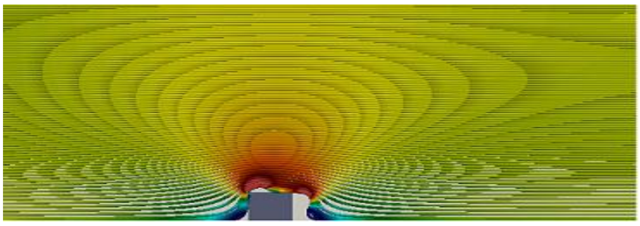

Fig. 45. A

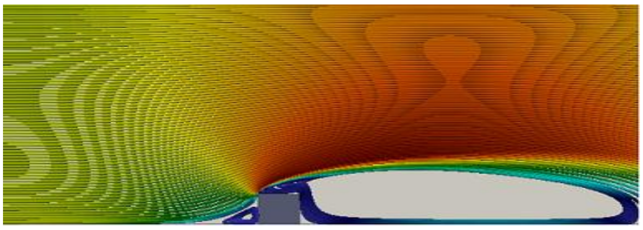

Fig. 45. B

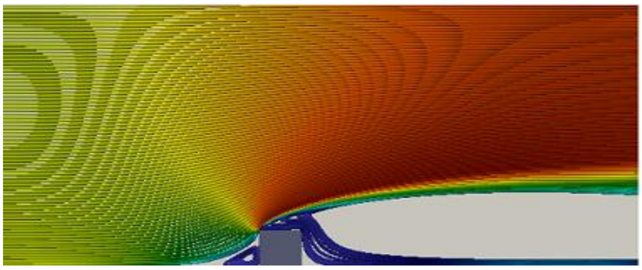

Fig. 45. C

Fig 45 a,b,c represents streamline for T=0, T=0.05 & T=0.1

The streamline surface plots are shown above at various time T=0, T=0.05 and T=0.1. As mentioned earlier the RANS solver ran for T=0.1, so three streamline plot are shown here and dit be seen that initially there is no vortex but there is some tendency of formation of vortex at top, at back and in the corner of the front. At the end of the simulation it can be observed that a big vortex is formed at the back face, a relatively small vortex is at the top and in the corner at the front there is a triangular shape vortex. Experimental study carried out byMartinuzzi and Tropea[5] at Reynolds No. = 40, 000 in LES and they found the same kind dof vortex formation as in our case.

2) LES Model

Fig 46.Horse shoe vortex at the backward face of the cube

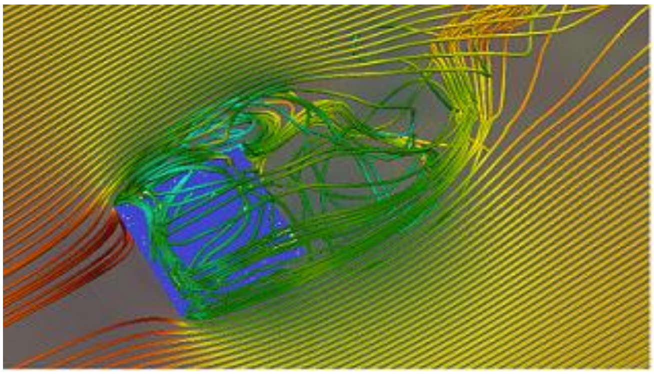

Fig 47. Streamline top view in y normal

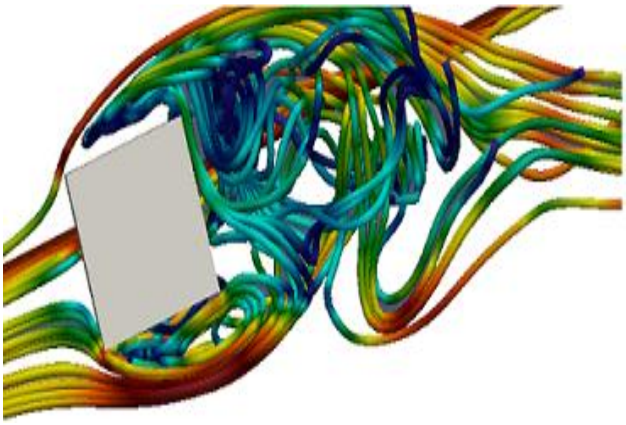

Fig 48. Complex vortex structure at the back of the cube

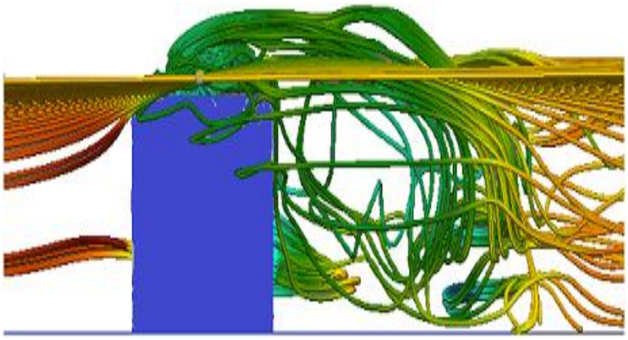

Fig 49. Streamline in side view

The above surface plots are for LES 3D model and the same kind of behaviour are found as are mentioned in the literature. Since LES captures large scale eddies and are 3D and hence the vortex structures are very complex. It is also well documented in the literature regarding the horse shoe type vortex at the back end of the cube and from the figure 46 the same behaviour can be found.

I. Kinetic Energy

1) RANS Model

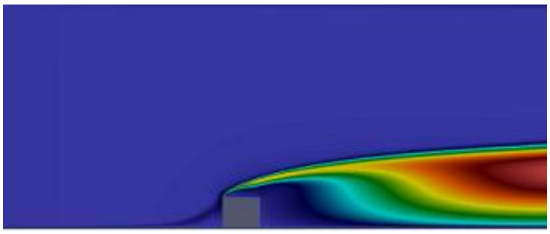

Fig 50. Kinetic energy at time T=*0.0244*

2) LES Model

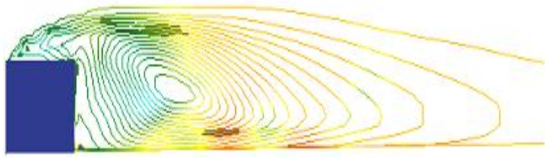

Fig 51. Turbulent kinetic energy contour coloured by Pressure

The above plots are for kinetic energy for RANS at time T=0.0244 and for LES at the end of the simulation.

J. Q criteria

1) RANS Model

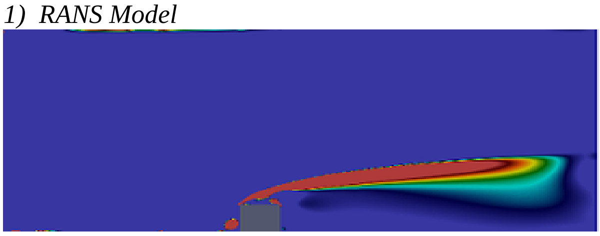

Fig 52. Q criteria and formation of vorticity

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2) LES Model

a)

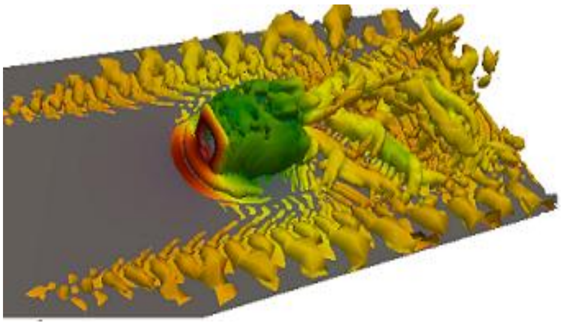

Fig 53. A

b)

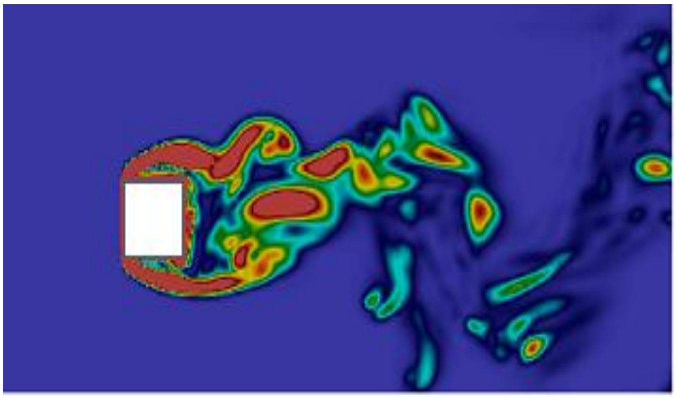

Fig 53. B

Fig. 53 a,b: Q criteria and formation of vortex

The Q criteria are being shown for both the model which shows the real vortex formation over the bluff body within the fluid flow domain.

K. Pressure

1) RANS Model

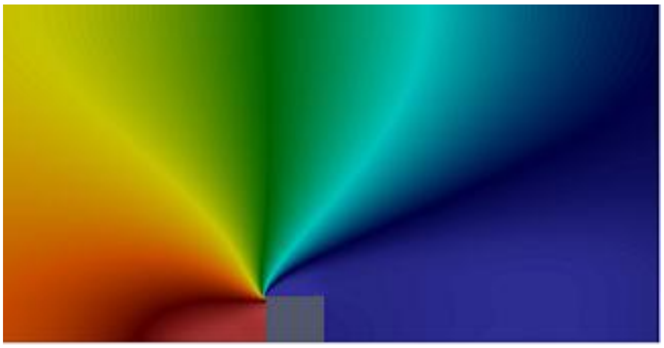

Fig. 54 : Pressure profile ranges -50 to 400 m^2/s^2

2) LES Model

Fig. 55 pressure contour coloured by pressure and the slice coloured by velocity

The pressure contours are shown above and in case of RANS the value of the pressure ranges from -50 to 600 m^2/s^2 and for LES it ranges from -50 to 400 m^2/s^2.

L. Velocity

1) RANS Model

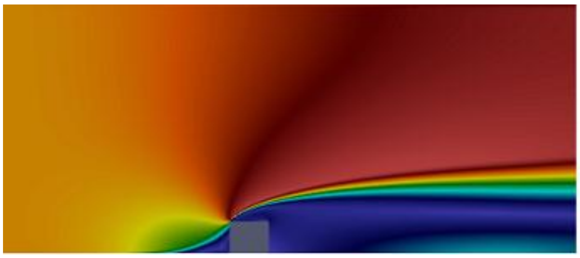

Fig. 56: Velocity profile ranges from 0 to 37.7 m/s

2) LES Model

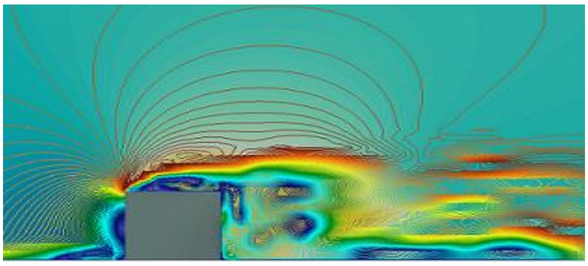

Fig. 57 *Mag u contour coloured by velocity and slice coloured by pressure*

The velocity magnitude contours are shown above and in case of RANS the value of the velocity ranges from 0 to 37.7 m/s and for LES it ranges from 0 to 30 m/s.

M. Drag& Lift

1) LES Model

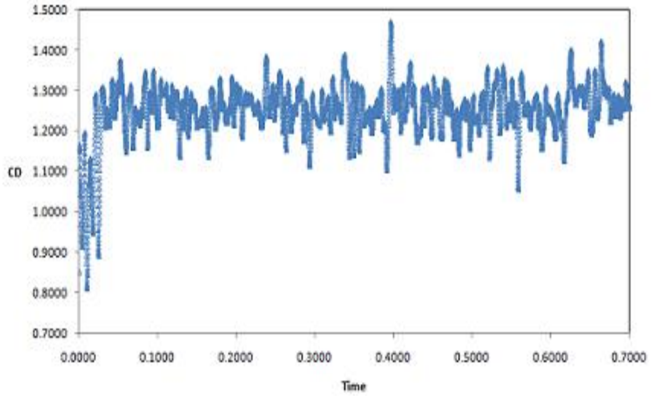

Fig. 58. Drag Coefficient CD over the cube with time

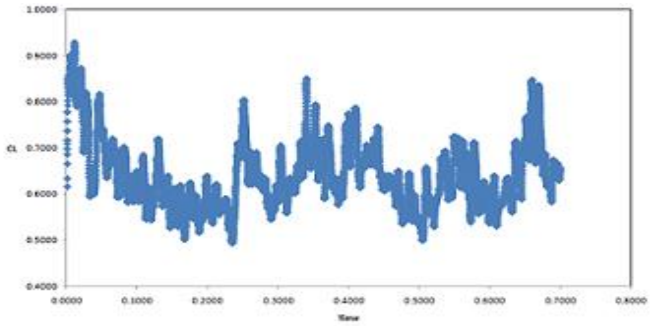

Fig. 59. Lift Coefficient CL over the cube with time

The well documented literature shows that the drag coefficient over a sharp edged cube is within the limit of 1.2 and from the fig 58 it can be seen that the average CD is 1.3 and for lift force it is within the limit 0.6 to 0.8. Since the analysis is unsteady in nature hence there is constant fluction in case drag and lift.

N. U plus vs Y plus

1) RANS Model

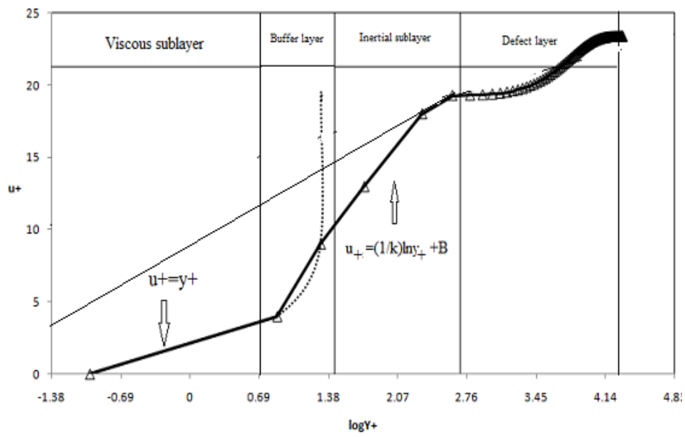

Fig. 60. Verification of model correctness using u+ vs y+

In case of RANS model another well cited literature for verification is the plot between U plus and Y plus. The plot shown above is exactly the same as in the literature cited [16].

IV CONCLUSION

In this work two turbulence model 2D RANS unsteady and 3D LES unsteady model are incorporated to model the flow behaviour and capturing the turbulence for wind flow over a cube. Many parameters like velocity and pressure profile over the flow field, shear stress and kinetic energy profile for the domain for fluid volume, vorticity, wall shear stress, y plus etc are being compared with two model based on the qualitative and quantities analysis. The drag and lift coefficients were also found based on LES 3D analysis and found in good agreement with literature. While comparing it is found that in many cases both model gives suitable result and almost similar but in some case like pressure the results are quite different. In pressure profile the LES would be a best alternative to direct numerical simulation (DNS) which is quite expensive and time consuming. As cited in literature LES proves to be good for moderate to high Reynolds number where as RANS gives better result for low to moderate Reynolds number. In this work the Reynolds number is 65000 which is moderate and hence both the models gives almost similar results. For better practise with little more time consumption and some extensive computational resource 3D LES may be preferred over RANS for better accuracy.

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[16] http://www.cfdsupport.com/OpenFOAM-Training-by-CFD-Support/node311.html