Numerical modelling for assessment of wind flow pattern and wind load on a rectangular cylinder for different aspect ratios

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ABSTRACT

Different cross sections are used to represent structures like buildings, bridges and other architectural features, so the study of wind flow pattern, induced vortex shedding and various wind load parameters around 2D rectangular cylinder with different aspect ratios (R=B/H, is the ratio of breadth of the block to the height in stream-wise and cross stream-wise direction respectively) have been studied and presented in this paper. Different aspect ratios varying from 1 to 0.05 have been used at a fixed Reynolds number 21400 (Re = $\frac{U_{\infty} R}{\nu}$, where $U_{\infty}$ is the Free stream velocity and $\nu$ is the dynamic viscosity of the fluid) based on free stream velocity and height of the cylinder across the free stream.

An effort has been made to capture the effect of turbulent flow around rectangular bluff body on the time averaged flow quantities using two dimensional turbulence models with suitable assumptions. A comparative study of 2D unsteady Reynolds averaged Navier-Stokes equations (URANS) with standard k-ε and RNG k-ε turbulence models accompanying near wall treatment has been investigated for wall Y+ as guidance in selecting appropriate grid configuration using FLUENT 6.3, Results have been compared with the published results by Xinliang Tian et. al. (2012).

Keywords- Wind load, Aspect ratio, Vortex shedding

Introduction

The high rise buildings are affected by wind load due to wind flow around them. Study of flow around long span suspension bridges, chimney, cooling towers, low and high rise buildings, is of great significance from the structural safety point of view. Prediction of flow characteristics using various turbulence models is very demanding issue. The Flow characteristics play a vital role for stable and safe designing of structures.

In flow around square cylinder the separation of flow occurs at leading corner of the body. Vortex formation and aerodynamic characteristics both are strongly dependent on the aspect ratios (R) and show noticeable variations with the increase/decrease in ratio.

Although the three dimensionality of turbulent flow at high Reynolds number the RANS model enables 2D computations even for the Reynolds number greater than the threshold value after hypothesizing that the span-wise turbulent flux is supposed to be homogeneous, the spatial average of its fluctuation in the direction of the span is equivalent to its ensemble average. Franke & Rodi (1993) used the same hypothesis and reported that the estimation of the aerodynamic forces and Strouhal number (St) for flow around square block can be done satisfactorily for 2D URANS model accompanying the wall function.
According to Rodi (1991) while using standard k-ε model with wall functions the simulation of correct hydrodynamic properties cannot be done satisfactorily because of weakened vortex shedding. This is because of the weakened separation, as excessive amount of turbulent kinetic energy is generated near the leading corner by isotropic viscosity effect (Murakami & Mochinda, 1995). But still here in present study the results using standard k-ε model have been obtained to compare the variation of values of hydrodynamic quantities with respect to results obtained by RNG k-ε models.

Lee(1990) performed some experiments on 2D rectangular blocks to see the effect of variation of aspect ratios on drag and base pressure and in his study he found that as the ratio increases, the base pressure falls and drag increases but up to a certain aspect ratio, this fall in base pressure is not a continuous phenomenon because at some specific aspect ratio the path of the separating layer would be hindered trailing edge of the rectangle during the vortex shedding cycle and this aspect ratio is called as critical aspect ratio. Further increasing the ratio after critical the base pressure starts rising and the drag force falls. His experimental work shows the maximum value of drag at aspect ratio approximately 2/3.

Sohankar (2008) performed numerical study of wind flow over sharp edged rectangular cylinder with aspect ratios varying from 0.4 to 4. Author used LES model for numerical simulation for Reynolds number 10^5 with two different subgrid-scale models, the S-model and a dynamic OE-model. XinliangTian et.al.(2012) studied the effect of aspect ratio on 2D square cylinder for Re=21400 using k-ω shear stress transport (SST) turbulence model. Author took aspect ratio values as R=1, 0.8, 0.6, 0.4, 0.2, 0.1, 0.05 and he reported that k-ω SST turbulence model gives satisfactory value of coefficient of drag (C_d) for Aspect ratios 1, 0.8 and 0.6 but as the aspect ratio decreases i.e. R=0.4, 0.2, 0.1, 0.05 the turbulence model applied, does not show a good agreement with the published results. The predicted value of C_{Lrms} for R=1 was within the range of the published numerical results and C_{Lrms} shows similar trend with respect to R as given by Sohankar (2008) at Re= 10^5 for aspect ratios greater than 0.6 . However, for aspect ratios less than 0.6, the variation of C_{Lrms} with aspect ratios reported by author, are not showing satisfying results with respect to results reported by Sohankar (2008).

**Numerical simulation scheme, computational domain**

The size of the whole computational domain has been adopted as 35H by 20H (H is height of cylinder in cross stream wise direction) and the origin of the coordinates is located at the centre of rectangular cylinder, flow inlet boundary is located at 10H upstream from the centre of cylinder and the flow outlet boundary is located at 25H downstream from the centre of the cylinder (see in fig.1). These distances are large enough to eliminate the far field effects from the boundaries.

The pressure implicit with splitting of operators (PISO) scheme is used in the present study. A fully developed turbulent flow was set up at inlet and Reynolds number (Re) taken is 21400 based on the height of the cylinder in cross stream wise direction and free stream velocity. The pre-processor GAMBIT was used to create the geometry defining the domain and discretize the domain, while FLUENT6.3 code is employed to discretize and solve the governing equations. The mesh around a block is shown in fig.2.
Boundary conditions

Boundary conditions adopted in this study have been referenced with study of many authors like Rodi(1993), Murakami (1995), Xinliang Tian et. al.(2012). All the boundary conditions have been shown in fig. 1.

(i) At inlet the velocity inlet boundary condition has been employed which means a uniform flow i.e. $u_{x_1} = U_\infty$ (uniform) & $u_{x_2} = 0$ and the gradient of pressure is zero in $x_2$-direction at inlet boundary. No velocity fluctuations have been prescribed at the inlet boundary.
The specified turbulence intensity ($I$) at inlet boundary has been taken as 2%, and viscosity ratio ($\frac{\mu}{\mu_s}$) is 10 (A.K.Saha et. al., 1999).

(ii) At outlet, outflow boundary condition has been set. Outflow it assumes all the gradients at outlet to be zero in normal direction ($x_2$-direction) except pressure.

(iii) Wall boundary condition has been given to the sides of rectangular cylinder means at all the four wall no-slip condition has been enforced.

(iv) At upper and lower boundaries which are at 10H distance apart from the centre of the cylinder symmetry boundary condition has been employed, which indicates that at symmetric planes normal velocity gradient is zero and also all the variables have zero normal gradients.

**Simulation results and discussion**

Two simulations of URANS turbulent models i.e. standard k-ε model and RNG k-ε for air flow over 2D rectangular cross section cylinders with various aspect ratios(R) varying from 1 to 0.05 for Reynolds number 21400 has been carried out. The effect of aspect ratios on flow characteristics and aerodynamic forces has been examined. All the time averaged quantities $C_{Lrms}$, $C_D$, $St$ have been computed for at least 10 shedding cycles and results have been compared with available experimental and numerical results.

**Hydrodynamic quantities for Square cylinder**

The performance of 2D unsteady RANS Standard k-ε model and RNG k-ε model is being discussed first for aspect ratio(R) equal to 1. The table below shows the some of the published numerical and experimental results by different authors and present work results and the comparison of values of coefficient of drag, coefficient of lift and Strouhal number.

A comparison of the present simulation results and previous results has been shown in table1. The present numerically predicted results of $C_D$ by standard k-ε model and RNG k-ε model show little differences of values compared to previous experimental and numerical studies by Xinliang Tian et. al.(2012), Lyn et al. (1995), Farhadi and Rahnama (2005). The value of $C_D$ is under predicted by both the models but the predicted value of $C_D$ resulted by RNG model is very much close to the experimental value by Lyn et al. (1995) and numerical simulation value by Xinliang Tian et. al.(2012).The reported value of $C_{Lrms}$ by standard k-ε model is also under-predicted but the value coming from RNG k-ε model is in good agreement with the results given by author Xinliang Tian et. al.(2012).

The reported value of Strouhal number by standard k-ε model is under-predicted compared with the values given by Xinliang Tian et. al. (2012), Lyn et al. (1995), Farhadi and Rahnama (2005) but RNG k-ε model shows a good similarity with the published experimental and numerical values but it is less than that given by Farhadi and Rahnama (2005).
Table 1-Hydrodynamic quantities for square cylinder (R=1)

<table>
<thead>
<tr>
<th>No.</th>
<th>Author</th>
<th>Method</th>
<th>Re</th>
<th>$C_D$</th>
<th>$C_{L_{rms}}$</th>
<th>St</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Present</td>
<td>Standard $k$- $\varepsilon$(2D)(wall function)</td>
<td>21400</td>
<td>1.82</td>
<td>1.07</td>
<td>.129</td>
</tr>
<tr>
<td>2</td>
<td>Present</td>
<td>RNG $k$- $\varepsilon$(2D)(wall function)</td>
<td>21400</td>
<td>1.94</td>
<td>1.36</td>
<td>.137</td>
</tr>
<tr>
<td>3</td>
<td>Xinliang Tian et. al.(2012)</td>
<td>$k$-$\omega$ SST (2D)</td>
<td>21400</td>
<td>2.05</td>
<td>1.49</td>
<td>.138</td>
</tr>
<tr>
<td>4</td>
<td>Lyn et al. (1995)</td>
<td>Experimental</td>
<td>21400</td>
<td>2.1</td>
<td>-</td>
<td>.132</td>
</tr>
<tr>
<td>5</td>
<td>Farhadi and Rahnama (2005)</td>
<td>LES (3D)</td>
<td>21400</td>
<td>2.30</td>
<td>.984</td>
<td>.138</td>
</tr>
</tbody>
</table>

Bosch & Rodi (1998) reported that the standard $k$-$\varepsilon$ model gives the weaker vortex shedding and frequency of vortex shedding or the St is lowered if computed by std $k$-$\varepsilon$ model. This effect is due to the strong diffusive nature of this turbulent model. In present study the numerical values of St calculated by std. $k$-$\varepsilon$ model does not have large difference with the experimental value and numerical values published.

The small differences in present statistical values of $C_D$, $C_{L_{rms}}$ and St may be due to the differences in adopted turbulent intensity, boundary conditions, viscosity ratio, choice of numerical scheme, pressure velocity coupling, number of grids and the non dimensionalised time increment.

The length of recirculation region (L) for R=1 as shown in fig.6 (b) by Std. $k$-$\varepsilon$ model agrees with experimental results of Lyn et.al.(1995) and Durao et.al.(1988), but RNG model over-predicts length of recirculation region(L). Xinilang Tian et. al.(2012) study under-predicts this value.

Effect of aspect ratio (R) on hydrodynamic quantities

The values of hydrodynamic quantities $C_D$, $C_{L_{rms}}$ and St for R=1, 0.8, 0.6, 0.4, 0.2, 0.1 and 0.05 have been presented in table 2 and a comparison of $C_D$, $C_{L_{rms}}$ and St has been done with the reported results. In the study of Tamura & Itoh (1999), author observed two kinds of fluctuations in the drag force and lift force for same aspect ratios for different time intervals, for some interval the high aerodynamic forces fluctuating with high amplitude and high magnitude of mean drag, for other time intervals these were fluctuating with less amplitude and the mean drag was less. Variations of RMS value of Coefficient of lift and mean coefficient of drag given by Tamura & Itoh(1999) has been shown in fig.3. One is for large fluctuations and other for small fluctuations.
Table 2: Results at different aspect ratios

<table>
<thead>
<tr>
<th>R</th>
<th>Elements</th>
<th>Time Step</th>
<th></th>
<th></th>
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<td></td>
</tr>
<tr>
<td>1</td>
<td>69200</td>
<td>.0125</td>
<td>1.82</td>
<td>1.94</td>
<td>1.07</td>
<td>1.36</td>
<td>.129</td>
<td>.137</td>
<td></td>
</tr>
<tr>
<td>0.8</td>
<td>69200</td>
<td>.0125</td>
<td>2.12</td>
<td>2.24</td>
<td>1.51</td>
<td>1.83</td>
<td>.152</td>
<td>.158</td>
<td></td>
</tr>
<tr>
<td>0.6</td>
<td>67400</td>
<td>.0125</td>
<td>2.57</td>
<td>3.07</td>
<td>1.73</td>
<td>2.05</td>
<td>.173</td>
<td>.176</td>
<td></td>
</tr>
<tr>
<td>0.4</td>
<td>62000</td>
<td>.0125</td>
<td>2.69</td>
<td>3.04</td>
<td>1.39</td>
<td>1.72</td>
<td>.153</td>
<td>.140</td>
<td></td>
</tr>
<tr>
<td>0.2</td>
<td>58000</td>
<td>.0125</td>
<td>2.74</td>
<td>3.66</td>
<td>.603</td>
<td>1.05</td>
<td>.145</td>
<td>.115</td>
<td></td>
</tr>
<tr>
<td>0.1</td>
<td>62000</td>
<td>.0125</td>
<td>2.54</td>
<td>3.71</td>
<td>.299</td>
<td>.496</td>
<td>.142</td>
<td>.112</td>
<td></td>
</tr>
<tr>
<td>0.05</td>
<td>62000</td>
<td>.0125</td>
<td>2.81</td>
<td>2.81</td>
<td>.160</td>
<td>.160</td>
<td>.138</td>
<td>.138</td>
<td></td>
</tr>
</tbody>
</table>

A comparative study of coefficient of drag and coefficient of lift with Xinilang Tian et.al.(2012), Tamura & Itoh(1999), Sohankar (2008) has been done and the variation of these with the aspect ratio has been shown in fig.3.

As can be seen from fig. 3, the $C_D$ by RNG model is showing maximum at aspect ratio 0.1, decreases further for R=0.2 and 0.4, after this it again rises up to R= 0.6, then value starts decreasing for R=0.8 and 1. By Standard model the maximum value of $C_D$ is seen at 0.2 and after it is decreased.

Present results for mean coefficient of drag obtained from both the standard k-ε and RNG k-ε turbulent models are under-predicted compared to Xinilang Tian’s results, although the results given by Xinilang Tian et.al.(2012) were over-predicted below R=0.6. Results coming from standard model are under-pricted with respect to results by Tamura & Itoh (1999 ) but by RNG model these are over-predicted.

Xinilang Tian et. al.(2012) reported the maximum value of drag at R=0.2 using k-ω SST model at Re=21400, Tamura & Itoh(1999) observed this critical value at R=0.5. Sohankar (2008) performed a 3D unsteady simulation using LES with two subgrid models, the Smagoinsky and one-equation model at Re=10^5 for aspect ratio R=0.4 to 4, his study reported a peak in drag coefficient at R=0.6 and a discontinuity in Strouhal number.

The pattern of variation of Strouhal number with aspect ratio has been shown in fig.3(c). A peak in value of St is appeared at R=0.6. The standard and RNG models showing almost same values at aspect ratios 0.8, 0.6, 0.05.the values by standard model at R=1 and 0.4 similar to that given by Sohankar(2008).

At R=1 by RNG model St is almost same as given by Xinilang Tian (2012) after R=1 and up to 0.6 St is over-predicted by both the models.

$C_{L_{rms}}$ is showing an increasing trend from R=0.05 to 0.6 and after it starts decreasing from R=0.05 to 0.6, after that it starts decreasing so it is showing aspect ratio 0.6 as critical aspect ratio after which magnitude of lift force decreases.
So present pattern of $C_{D}, C_{L_{rms}}, S_t$ have some difference from the previous studies conducted by Xinilang Tian et al. (2012), Sohankar (2008), Norberg (1993).

Fig. 3- Variation of hydrodynamic quantities with aspect ratio (a) mean CDVs $R$ (b) $C_{L_{rms}}Vs R$ (c) $S_t Vs R$
Effect of aspect ratio (R) on vortex formation

Vortex shedding not only affects the drag force but also the other aerodynamic properties depending upon the body geometry and other factors. Fig. 4 shows a detail of vortex pairing from a square cylinder (R=1) at different instant of times (i.e. at t=T, T/4, T/2, 3T/4, here T is the time period of shedding). Here T has been taken at the instant when the lift force on the block is at extreme positions in a cycle. Shedding of vortex from upper and lower faces of the cylinder is of opposite circulation, this alternative unsteady shedding gives rise to a lateral force in lateral direction of flow i.e. in x2 direction.

Fig. 4-Vorticity contours at R=1 at a time interval of T/4 for one full time period cycle, (a) Std. k-ε model, (b) RNG k-ε model
The shear layer separation takes place from the leading edges of the cylinder, the downstream corner of the cylinder tends to move this shear layer in downstream direction, and if the Reynolds number is low the flow can again reattach to the face of the cylinder, but in the present case i.e. at high Reynolds number the flow does not reattaches to the side faces of the cylinder. The separation and reattachment of shear layer also depends on the aspect ratios of the cylinder. For large aspect ratios the vortex are forced to form in the downstream direction. The value of coefficient of drag on the cylinder is affected by the vortex formation and by the separation of shear layer. Roshko(1993), Sohankar(2008) presented the detailed mechanism of formation of vortex and its effects on the drag force on the cylinder. Authors proposed that the high drag on the block is due to strong and quick rolling action or high curvature of shear layer behind the blocks. In similar fashion in present study it is noticed that the length of wake region is continuously decreasing as the aspect ratio is decreasing from R= 1 and below.

**Conclusion**

The present analysis for $C_D$ by std k-ε model shows maximum value at R=0.05, while using RNG model it is showing its maximum at R=0.02 which are not matched with the published results. At R=1 the results for $C_D$ by using Standard and RNG model give satisfactory results but below R=1 i.e. at 0.8, 0.6, 0.4, 0.2, 0.1, 0.05 these are not much in agreement with published results. Below R=1 values of drag coefficient are close to results by Tamura & Itoh(1999). For RMS of $C_L$ the values by both the models are under-predicted compared to Xinilang Tian et.al.(2012) and overestimated a little with compared to other published results.

**References**


