

Large Eddy Simulation of Flow over a Backward Facing Step using Fire Dynamics Simulator (FDS)

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Abstract: *Flow over a backward-facing step is a widely used benchmark case in the field of Computational Fluid Dynamics (CFD). This paper presents the numerical simulation of backward-facing step using Fire Dynamics Simulator (FDS), open source software CFD developed by National Institute of Standards and Technology (NIST), US. Large Eddy Simulation (LES) is the default mode of its operation. In this paper, the latest version, FDS 6, is used for the numerical simulation of turbulent flow over a backward-facing step. This recent version of FDS incorporates four different eddy viscosity models namely a Constant Coefficient Smagorinsky model, a Dynamic Smagorinsky model, Deardorff's and Vreman's Models. The principal objective of this paper is to compare these turbulence models with a proposed benchmark case. Moreover, these simulated results are compared with standard experimental results of Jovic and Driver to assess the accuracies of the various models.*

Key Words: Computational Fluid Dynamics (CFD), Fire Dynamics Simulator (FDS), Large Eddy Simulation (LES), Benchmark Solution

1. Introduction

The development of the Fire Dynamics Simulator (FDS) was motivated by the need to simulate fire scenarios that occur in practice. It is a CFD based fire model used to solve the Navier-Stokes equation, particularly for low speed thermal buoyancy driven flows, namely flows of smoke and hot gases caused by fire.

Many authors, including Gulbrand [1], Goshal [2], Goshal and Moin [3], You and Mittal [4] and Lund [5] emphasize the importance of capturing the effects of all the scales of flow. This range from large scale turbulent eddies to the small scales on which viscous dissipation occurs. The Navier-Stokes equation applies to the continuum length scale, and this is many orders of magnitude

less than length scales associated with viscous dissipation. Hence accurate solutions of the Navier-Stokes equation are able to account for all of the scales of turbulence. However, because it is necessary to consider such a wide range of length scales the direct numerical solution (DNS) of this equation is computational resource intensive. Solutions that are less resource intensive can be obtained by solving the time, or Reynolds averaged Navier-Stokes (RANS) equations, but fine details of the turbulence are lost in the averaging process. Large Eddy Simulation (LES) is an approach to the solution of the Navier-Stokes equation that captures large scale features of turbulent flows, but which models dissipation on a scale associated with the dimensions of the computational grid. This is many orders of magnitude greater than the scale of the smallest eddies, and research continues on devising subgrid scale models that are accurate.

FDS incorporates an LES model that is invoked by default. The latest version, FDS6, offers the user a choice of four subgrid scale models, namely the constant Smagorinsky [6], the dynamic Smagorinsky [7], the Deardorff [8] and Vreman's [9] models. In this work the accuracy of each of the models is evaluated by comparing the predicted flow fields and factors that characterize turbulence with published experimental results. Those presented by Jovic and Driver [10] for flow over a backward facing step is chosen to evaluate the various subgrid scale models. Similar simulation is also done for FDS 5 and compared with FDS 6 to investigate the performance of the new version.

2. Numerical simulation

The simulation for backward facing step has been done for both FDS 5 and FDS 6. The computational domain of (the numerical simulation) backward facing step using FDS is exactly set according the experimental set up of

Jovic and Driver (1984). Uniform rectangular mesh is used along the spanwise (x), streamwise (y) and vertical (z) directions. The Reynolds number based on step height is 5100 and the expansion ratio (ER) is set 1.2. According to the simulation, the dynamic viscosity of air and density is considered 1.8×10^{-5} kg/ms and 1.2 kg/m^3 respectively at ambient room temperature 20°C .

The streamwise length of the upstream portion is 46 cm and 135 cm for downstream portion. The height of the upstream and downstream section is considered 9.6 cm and 11.5 cm respectively. The

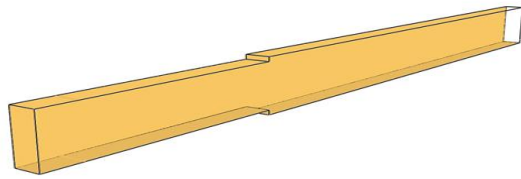


Figure 1. Computational domain of backward facing step in FDS

The streamwise velocities for different eddy viscosity models are normalized using the upstream freestream reference velocity. In FDS, it is very difficult to maintain the upstream reference velocity 7.72 m/s as per experimental study at section $y/h = -3$. The main reason is that the reference velocity at desired test section depends on predefined fluid flow speed at inlet cross section. So in that case to achieve the required reference velocity different inlet velocities was set and observed for various mesh resolutions. The obtained reference velocity fluctuation for different viscosity models is maintained within $\pm 0.03 \text{ m/s}$. The impact of these velocity fluctuations on numerical simulation results are minimized by dimensionless velocity parameter (U/U_0). The dimensionless mean velocity components are compared against the vertical axis (y/h) to find the agreement between simulated and experimental data.

To obtain the time averaged velocity, total simulation time was set for 14 seconds. It was observed that at the required upstream section the fluid flow was fully developed within 4 seconds. The time averaged value of velocity was

step height is set at 0.96 cm and a boundary layer trip wire of height 2 mm is placed at 7.6 cm distance from inlet section. The simulation of back-ward facing step uses $60 \times 900 \times 120$ grid points along the spanwise, streamwise and vertical directions respectively.

The reference flow speed U_0 is maintained $7.72 \pm 0.03 \text{ m/s}$ at section $y/h = -3$ of upstream portion. Mean velocities are measured at different sections along the streamwise direction in the computational domain.

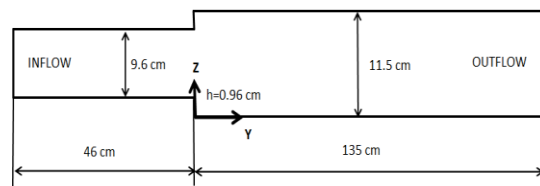


Figure 2. Schematic diagram of backward facing step

calculated from 5 seconds at the rate of 0.01 second time step

3. Results and Discussions

3.1 Mean velocity

From the presented graphical representations, it is found that the constant Smagorinsky model of FDS 6 appears to be more accurate than the other eddy viscosity models in comparison with experimental results at the various test locations. For this reason, the results are analyzed in two different schemes. In the first scheme, results for FDS 5 and the constant Smagorinsky model in FDS 6 were analyzed separately. In the second scheme, FDS 5 and of the other three turbulence models of FDS 6 are compared with experimental results.

From figures (4) and (5) at section $y/h = 4$, near the step height and wall region where the secondary vortices occur FDS 5 shows good agreement compared to standard Smagorinsky model of FDS 6. On the other hand along the vertical direction far from step height Smagorinsky model of FDS 6 is exhibits good agreement compared to FDS 5. For the same location, among other

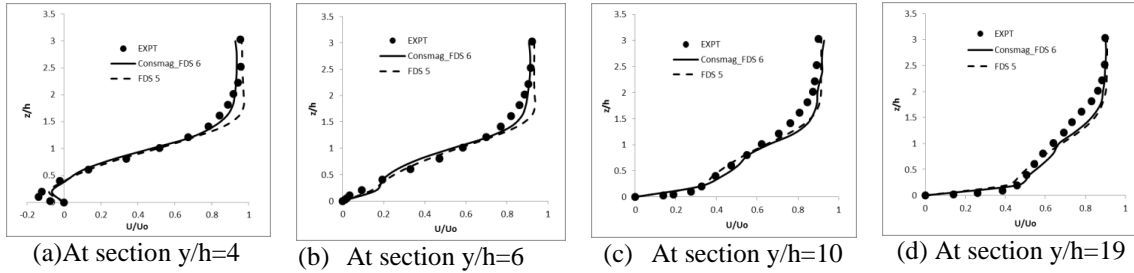


Figure 4. Comparison of mean velocity profile between FDS 5 and Constant Smagorinsky model of FDS 6 at different test locations

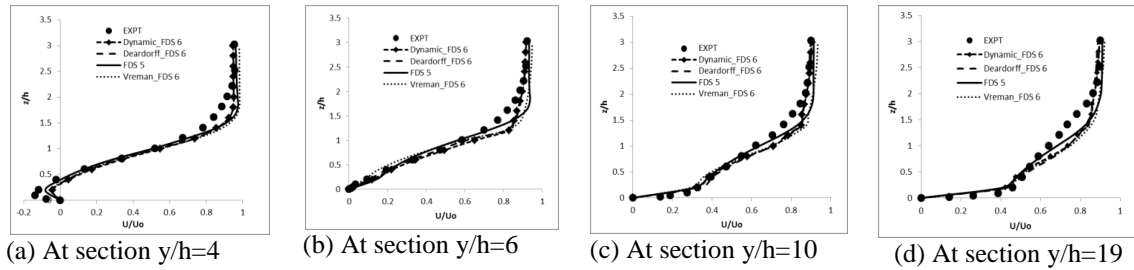


Figure 5. Comparison of mean velocity profile between FDS 5 and other three turbulence models of FDS 6 at different test locations

three models, Deardorff's and dynamic Smagorinsky model displays almost the same nature, and Vreman's models demonstrates poor agreement with experimental values compared to other two models. In case of section $y/h=6$, it is assumed that the flow is attached to the wall. In that section constant Smagorinsky model of FDS 6 displays comparatively good agreement with experimental data but other models are showing moderate nature along the vertical axis. At section $y/h=10$ and $y/h=19$ all the turbulence models are showing moderate nature. In both sections, it was found that all models are showing comparative good agreement close to the wall, but far from wall near the reference section dynamic Smagorinsky and Deardorff's is showing qualitatively good agreement. Near the reference section the influence of wall shear stresses and the effect of secondary fluid flow motions are negligible. Among four eddy viscosity models, it is found that the performance of Vreman's model is comparatively poor. Moreover, close to the wall it was showing good agreements but a noticeable shift is found along the vertical axis near the freestream flow region from the experimental results. In addition, it is found that far from the downward stream section at $y/h=19$, all the models failed to provide qualitative

agreement where it has relatively less effect of turbulence.

3.2 Reynolds stresses

In fluid dynamics, the Reynolds stress is the component that is obtained from the Navier-Stokes equations to account the turbulence intensities from the averaged value of momentum [11]. As LES is always unsteady by its nature, so to calculate the Reynolds stresses it is important to capture the fluctuations of velocities with respect to time at each and every points of interest [12]. LES basically provides the information about the instantaneous values of velocities so to obtain the fluctuations it will need the information about the instantaneous as well as the time averaged values.

The profile of Reynolds stresses ($\overline{u'u'}$) at different locations along the streamwise direction is normalized by the inlet free-stream velocity U_0^2 . The numerical results for Reynolds stresses are shown in two separate graphical representations like mean velocity profile. In figure (6) the comparison shown between the FDS 5 and constant Smagorinsky model of FDS6 with experimental results. It is found that the constant Smagorinsky model is showing relatively good agreement over FDS 5 at every location.

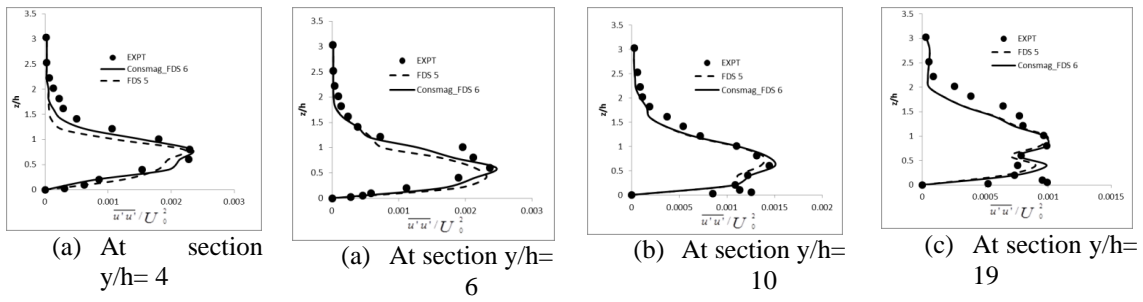


Figure 6. Comparison of Reynolds stresses between FDS 5 and Constant Smagorinsky model of FDS 6 at different test locations

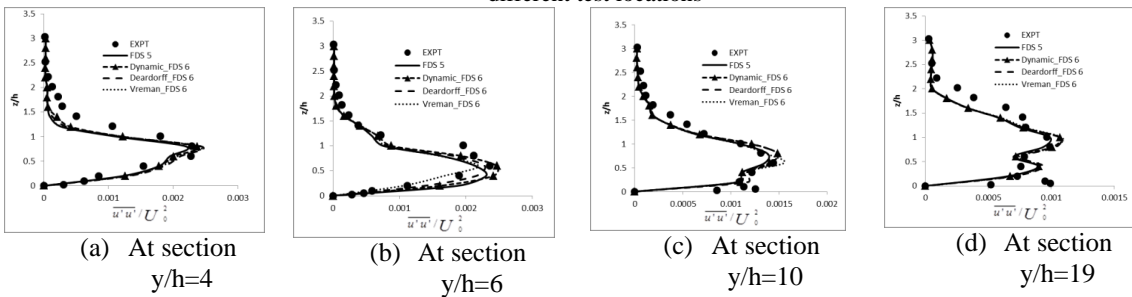


Figure 7. Comparison of Reynolds stresses between FDS 5 and other three turbulence models of FDS 6 at different test locations

In figure (7) the results are compared for the remaining models with experimental data to see the agreement. From figures (6) and (7), for overall comparison at section $y/h=4$ it is found that Reynolds stresses demonstrate good agreement close to the wall for all models but a noticeable shift is observed far from the downstream wall. At this location constant Smagorinsky is showing good agreement with the other models.

Overall, at section $y/h=6$ and 10, the constant Smagorinsky and Deardorff's models provide relatively good agreement compared to other models for FDS 6. At section $y/h=19$, all of the models result in relatively high discrepancies compared to experimental data.

3.3 Grid independence

In our simulations of flow over backward-facing steps, there two grid resolutions have been used to obtain the grid independence. In the first case, the computational grids are $60 \times 900 \times 120$ along three directions and $30 \times 450 \times 60$ are used in second case to check the grid independence. In both cases spanwise (x) and streamwise (y) grids are considered coarse compared to vertical direction (z). For these two cases, in the vertical direction the unit grid cells are considered 1mm and 2mm respectively which can be assumed as fine grids for FDS. In other two directions the unit cells are considered 2mm and 4mm. The unit grid cell ratio is set 1:2 for the grid independence in each case. According to FDS, it assumes that the aspect ratio of the

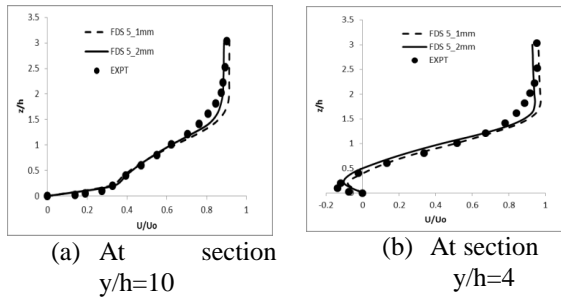


Figure 8. Mean velocity profiles with different grid resolutions for FDS 5

mesh cell beyond 2 should be avoided to obtain better simulation results [13].

Grid independence is tested for FDS 5 and constant Smagorinsky model of FDS 6 at different test locations, but only the best and poorly performing simulation results are given in graphical representation. These models are also compared with experimental data. According to the graphical representation in figure (8) and (9), it is found that the grid independence is showing relatively good agreement at location $y/h=10$ and relatively poor at section $y/h=4$ in case of FDS 5 and good at $y/h=6$ and relatively poor at $y/h=19$ for FDS 6.

Conclusions

For the similar inlet boundary conditions fluid flow over a backward facing step was simulated using FDS 5 and four different turbulence models in FDS 6 to obtain the most accurate turbulence model. To determine the performance of different turbulence models compared to existing experimental data, the mean velocity and the Reynolds stresses were regarded as measuring parameters. According to the result analysis, constant Smagorinsky eddy viscosity model of FDS 6 is found most accurate model among all for comparatively fine grid resolutions. It is found that the Constant Smagorinsky model shows consistent agreement at several test locations. However, among the other three models, the overall performance of the dynamic Smagorinsky and Deardorff's models are relatively good compared to Vreman's model. During the investigation of different turbulence models in FDS 5 and FDS 6, it was found that all the models demonstrate relatively good agreement near the wall and noticeable discrepancies along the vertical direction away from the downstream

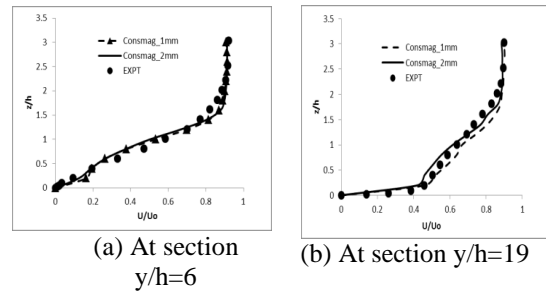


Figure 9. Mean velocity profiles with different grid resolutions for FDS 5

wall for the mean velocity profile and Reynolds stresses. In addition, two sets of grid resolution have been used to investigate the grid independence of the simulation.

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