TOWARDS ACCURATE TUNNEL FIRE SIMULATIONS: GRID SENSITIVITY AND LES MODEL COMPARISON IN FIRE DYNAMICS SIMULATOR

[1]Mahfuz Sarwar, [2] K.A.M. Moinuddin

[1]*Fire Rescue Victoria (FRV), Major Community Infrastructure Unit (MCIU), AU*
[2]*Centre for Environmental Safety and Risk Engineering (CESARE), Victoria University, AU*

DOI 10.3217/978-3-99161-087-8-033 (CC BY-NC 4.0)

ABSTRACT

This study examines the grid sensitivity of four Large Eddy Simulation (LES) sub-grid scale (SGS) turbulence models available in Fire Dynamics Simulator (FDS) namely the Standard Smagorinsky, Dynamic Smagorinsky, Deardorff, and Vreman models using a backward-facing step benchmark. Results show that grid resolution has a stronger influence on LES performance than the choice of SGS model, highlighting the inherent challenge of achieving grid-independent solutions in implicitly filtered LES. Among the models assessed, the Standard Smagorinsky model exhibits the most consistent convergence behaviour and produces the closest agreement with experimental data, even though full grid convergence remains elusive. Additional refinement confirms that FDS's second-order scheme can deliver acceptable accuracy when sufficiently fine meshes are used.

These outcomes are directly relevant to tunnel CFD fire simulations, where accurate prediction of smoke movement, temperature distribution, and fire-induced flow fields is critical for occupant safety, ventilation design, and regulatory compliance. By providing a detailed understanding of SGS model behaviour and grid sensitivity, this study highlights the importance of carefully designed mesh strategies and informed SGS selection particularly the Standard Smagorinsky model, which exhibits the strongest convergence tendencies for reducing modelling uncertainty. The insights gained from this work enable more reliable simulation of flow separation, recirculation, and smoke stratification, thereby enhancing the robustness and credibility of FDS-based tunnel fire assessments and supporting better-informed engineering decisions and performance-based design approvals.

Keywords: Fire Dynamics Simulator (FDS), Large Eddy Simulation (LES), Sub-grid scale (SGS) models, Grid sensitivity, Turbulence modelling.

1. INTRODUCTION

The development of FDS was motivated by the need to simulate building-fires. It is a CFD based fire model initially developed to simulate low speed thermal buoyancy driven flows, namely flows of smoke and hot gases generated by fires. Subsequently, pyrolysis and combustion submodels have been added making it a state of the art fire model. FDS is an open source code which employs a second-order numerical scheme and it incorporates an LES model that is invoked by default. FDS offers the user a choice of four SGS models, namely the Standard Smagorinsky, the dynamic Smagorinsky, the Deardorff and the Vreman models. As all of these are implicitly filtered schemes, it poses challenges to the adequacy and efficiency of these SGS models and their sensitivity to grids [1]. In this paper, the grid sensitivity of FDS' SGS models has been studied. In the process, the adequacy of the second-order numerical scheme (accurate in time and space) has also been assessed. A well-defined problem is studied namely turbulent flow over a backward facing step to compare the predicted flow fields with published experimental results. Those presented by Jovic and Driver (1994) [2] for flow over a backward facing step are used for evaluating the various sub-grid scale models.

The backward-facing step was selected due to its simple geometry yet complex flow physics. It is a classical benchmark in fluid mechanics because it captures several key flow features within a canonical configuration, including geometrically induced separation at a sharp edge, the formation of a recirculation zone, downstream reattachment, and strong turbulence and shear-stress gradients. These characteristics make it particularly suitable for validating turbulence models and numerical methods. Despite its geometric simplicity, the configuration is relevant to many practical engineering applications. Moreover, a plethora of well-established numerical and experimental results are available in the literature [3] for the case studied.

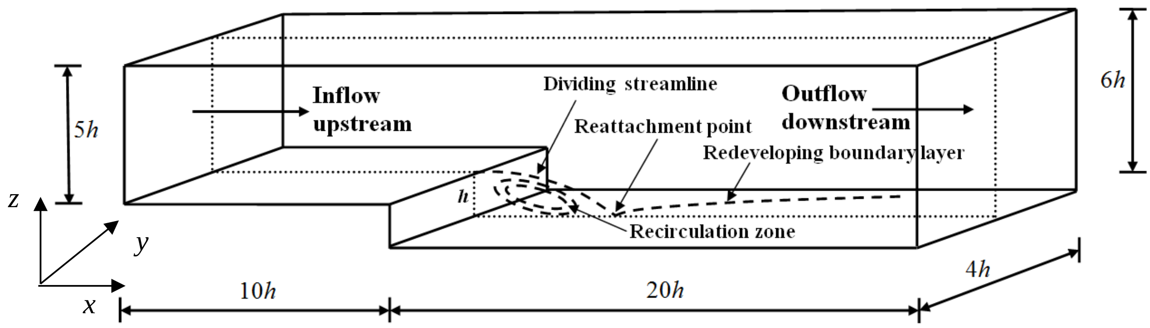


Figure 1: Schematic view of backward facing step flow configuration (not to scale)

Tunnel fires represent one of the most demanding environments for CFD fire modelling. Smoke transport, back-layering behavior, longitudinal ventilation effectiveness, and tenability predictions are all highly sensitive to the accuracy of turbulence representation. LES-based solvers like FDS are increasingly used for smoke stratification assessment under mechanical ventilation, critical velocity determination, analysis of fire-induced flow reversals, performance-based tunnel fire safety design [4].

However, uncertainties in LES turbulence modelling can propagate directly into tunnel fire predictions. For example, over-dissipation from an SGS model may suppress key flow structures, inaccurately predicting smoke spread or back-layering length. Under-dissipation may lead to numerical instabilities or unphysical oscillations, affecting tenability predictions. Grid-sensitive behavior may lead to inconsistent results between mesh configurations, undermining confidence in fire safety decisions and regulatory submissions.

By rigorously evaluating grid sensitivity and SGS model performance under controlled conditions, this research provides foundational insight into how FDS behaves in flows representative of tunnel environments. The conclusions can guide tunnel fire engineers in selecting more robust SGS models for longitudinal tunnel simulations, designing mesh strategies that improve predictive reliability, understanding when convergence is achievable or fundamentally limited, improving interpretation of FDS results used for regulatory compliance or performance-based design. In essence, although this study focuses on canonical flow, its implications extend directly to more reliable prediction of smoke movement and fire-induced flow fields in real tunnel scenarios.

1.1. Rationale for Selecting the Backward-Facing Step Configuration

A full tunnel fire scenario involves buoyancy, combustion, radiation, and ventilation effects that can mask the influence of grid resolution and sub-grid scale (SGS) model behavior. To isolate and evaluate these fundamental turbulence-modelling issues, a simpler but still relevant flow configuration was required.

The backward-facing step (BFS) provides this balance. Despite its simple geometry, it exhibits key turbulent features of flow separation, shear-layer development, recirculation, and reattachment that are directly relevant to smoke movement and fire-induced ventilation flows in tunnels. These mechanisms influence smoke stratification, back-layering tendencies, and mixing processes that are critical in tunnel fire modelling.

Using an isothermal, non-reacting BFS flow removes confounding variables, allowing a clear assessment of how grid refinement and FDS's SGS models affect LES accuracy. Importantly, the BFS is supported by a robust experimental database (e.g., Jovic & Driver, 1994 [2]), enabling objective validation something not feasible for most real tunnel fire scenarios.

As a well-established LES benchmark, the BFS is highly sensitive to grid and SGS choices, making it an ideal test case for evaluating FDS performance. Insights gained from this controlled environment can therefore be confidently extended to improve the reliability and consistency of FDS-based predictions of smoke movement and fire-induced flow fields in tunnels.

2. NUMERICAL SIMULATION

The computational domain of the numerical simulation of the backward facing step is set up exactly according to the well-established numerical study of Le Moin and Kim (1997) [3]. According to their study, it is found that the configuration under consideration is sufficient for capturing all the prominent flow features of turbulent flow over a backward facing step as also in the experiment conducted by Jovic and Driver (1992) [2] and requires less computational resources.

Figure 1 shows a schematic of the configuration, indicating the dividing streamline and recirculation zone that forms as the fluid flows over the step. It also shows the reattachment zone and redevelopment of the boundary layer after the fluid passes the reattachment zone downstream of the step. These complex flow features render it a useful and demanding benchmark case for validation of LES schemes.

The fluid is air at a temperature of $20°$ C, and the kinematic viscosity (ν) and density (ρ) are taken to be $1.53 \times 10^{-5}\,\mathrm{m^2/s}$ and $1.2\,\mathrm{kg/m^3}$, respectively. The step height (h) is 9.6×10^{-3} m. The streamwise length of the upstream portion is $10h$ and the length of the downstream outflow section is $20h$. The flow width is $4h$. The height of the upstream and downstream sections are $5h$ and $6h$, respectively, corresponding to an expansion ratio (ER) of 1.2 and calculated as $ER = L_z/(L_z - h)$. The Reynolds number ($Re_h = hU_0/\nu$) is 5100 based on the step height h and the reference velocity U_0. In the experiment the reference flow speed (U_0) was maintained at $7.72 \pm 0.03\,\mathrm{m/s}$ at section $3h$ upstream of the step. The difficulty to obtain desired reference velocity in the numerical simulation is well known. In this study, the overall velocity is maintained 7.96 m/s for different viscosity models which is almost 2.5% higher than ideally desired at location 3h upstream of the step. The streamwise velocities are normalized using the upstream free stream reference velocity U_0. The reference velocity fluctuation for different viscosity models is maintained within ± 0.02 m/s. Mean velocities and turbulence statistics are analysed at two different stations ($x/h = 4$ and $x/h = 6$) along the streamwise direction. The dimensionless mean(u/U_o) velocity components and turbulence intensities or Reynolds stresses ($\overline{u'u'}$) normalized by the reference velocity U_0^2 are compared against the vertical axis (z/h) in order to obtain agreement between the simulated and experimental data. Generally, energy is transferred from the largest eddies to the smallest ones on a timescale of about one large eddy turnover. In this flow case, one recirculation time

(t_E) near the step height (h) is calculated as $5 \times 10^{-3} s$ which is considered as unit eddy turnover time. The flow achieved statistically steady state at approximately $800t_E$. After an initial run of $800t_E$, the flow velocity is averaged over the time for another $2000t_E$. The average velocity data was obtained at 0.01s interval (that means nearly two eddy turnover time) and statistical average of 1000 data points was taken which is considered adequate.

Three uniform computational resolutions namely coarse, medium and fine, are used along the streamwise(N_x), spanwise (N_y) and vertical (N_z) directions. The grid resolved quantities are physically interpreted as cell means. In implicit LES, the filter width is taken as the cube root of the cell volume, $\Delta = V_c^{\frac{1}{3}}$, the cell volume $V_c = \delta x\, \delta y\, \delta z$; where $\delta x,\ \delta y$ and δz are the grid spacings along the three directions of the Cartesian coordinate system. The filter width to grid spacing ($\Delta/\delta x$) is considered as one since the filter width (Δ) is equivalent to the grid spacing (δx). For the grid sensitivity study, instead of random grid selection, for the convenience grids are refined in terms of the step height to grid spacing ratios ($h/\delta z$) in this study. This grid selection process is adopted from the LES study of flow over a backward facing step by Panjwani (2010) [5] and Toms (2015) [6]. The step height to grid spacing ratios are considered as $h/\delta z = 3$, 5 and 10. Table 1 presents the selected grid resolutions, considered model coefficients of SGS models implemented in the numerical simulation along with the measured wall unit n^+_{min} values which represents the minimum grid spacing in the wall-normal direction at the outflow test section. It can be observed that despite the same grid resolution, resolution in terms of nominal minimum wall can be different.

Table 1: Considered model coefficients and estimated wall unit (n^+) values of SGS models

SGS models		**Smagorinsky**	**Dynamic Smagorinsky**	**Deardorff**	**Vreman**
Model coefficients(C_*)		0.20	--	0.10	0.07
Grid	$N_x \times N_y \times N_z$	n^+_{Wall}	n^+_{Wall}	n^+_{Wall}	n^+_{Wall}
Coarse (C)	$90 \times 40 \times 60$	≤ 3.80	≤ 3.98	≤ 4.34	≤ 4.45
Medium (M)	$150 \times 60 \times 100$	≤ 2.17	≤ 2.32	≤ 2.56	≤ 2.71
Fine (F)	$300 \times 120 \times 200$	≤ 0.83	≤ 1.02	≤ 1.17	≤ 1.28

It is to be noted that in the DNS study of Le, Moin & Kim (1997) [3] the wall unit ranged from $n^+_{min} \approx 0.3$ to $n^+_{max} \approx 31$. Furthermore, while Akselvoll and Moin (1993) [7] performed a LES of backward facing step with $Re_h = 5100$ (based on the step height, h) which is similar to this study, they refined the resolution to a nominal wall unit, $n^+ = 0.8$.

3. BOUNDARY CONDITIONS

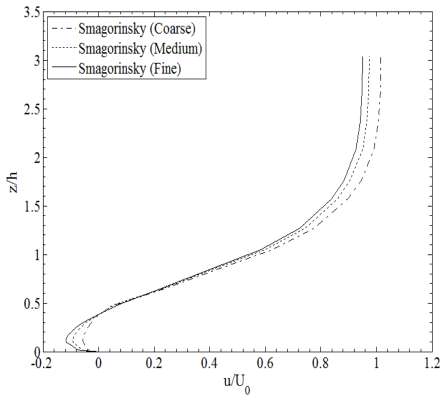
Boundary conditions play an important role in any numerical simulations and this is particularly true for LES to obtain appropriate solutions. Inlet boundary conditions are important as in most of the cases the downstream flow development is largely influenced by the inlet flow behavior. The boundary conditions for the backward facing step simulations are as follows. In Figure 1, at the inflow on the left end of the domain a constant and uniform atmospheric pressure is applied. At the outlet on the right end of the domain gradients of pressure and velocity are prescribed as zero. The lower boundary is a solid wall with the near wall behavior modelled by the Werner-Wengle approximation to the log-law [8]. Zero pressure gradient and a no-slip boundary condition is applied at the walls (side and bottom) while at the upper boundary the vertical velocity is $w = 0$ while streamwise and vertical velocity gradients are $\partial u/\partial z = \partial w/\partial z = 0$ which is consistent with Le, Moin and Kim (1997) [3]. The turbulence was initialized by some random perturbation.

4. RESULTS AND DISCUSSIONS - GRID SENSITIVITY

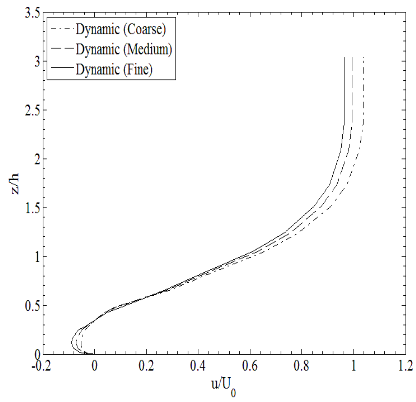
With the implicitly filtered SGS models (the standard Smagorinsky, the dynamic Smagorinsky, the Deardorff and the Vreman SGS models), simulations of flow over a backward facing step were performed for the three grid resolutions (coarse, medium and fine) as shown in Table 1. All the simulations were carried out to examine the influence of refinement of grids on their solutions. The simulated results are analysed based on the mean velocity and the turbulence intensity. Results are compared at two different test locations $x/h = 4$ and 6. The grid sensitivity is analysed both graphically and quantitatively. The main purpose of this analysis is to identify the most promising SGS model among the four for the conversion to an explicit LES model.

4.1. Graphical Comparison - Mean Velocity and Turbulence Intensity

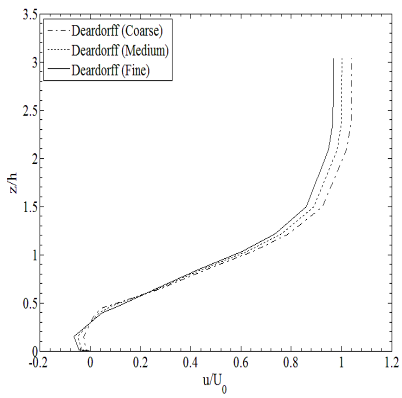
Figure 2 and Figure 3 present the comparison of the mean velocity profiles from simulations with four SGS models at stations $x/h = 4$ and $x/h = 6$. This parameter was averaged in time and non-dimensionalised with the free stream reference velocity U_0. As shown in Table 1, at fine grid resolutions, the wall units (n^+_{min}) along the vertical direction are reported in the range of 0.8 to 1.3 for all the four models. It also appears from the Figure 2 to Figure 5 that the tendency of numerical convergence of the standard Smagorinsky model is relatively better compared to other three SGS models at both locations. It is to be noted that when a coarser grid is used, a thicker boundary layer is predicted near the surfaces compared to the simulations where a finer grid is used.



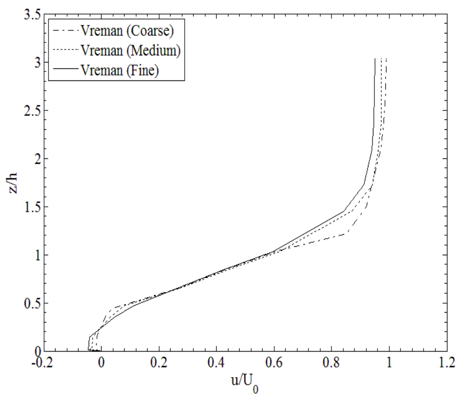
(a) Standard Smagorinsky



(b) Dynamic Smagorinsky

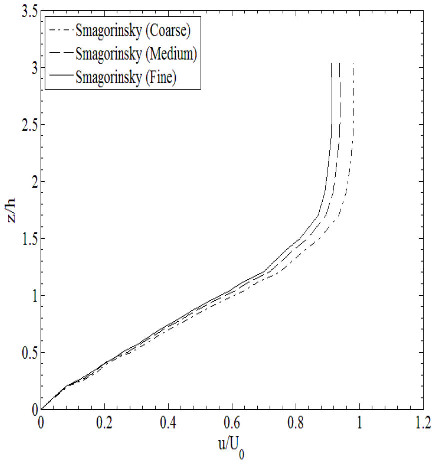


(c) Deardorff

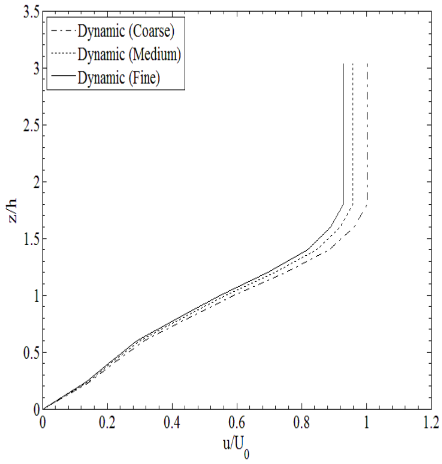


(d) Vreman

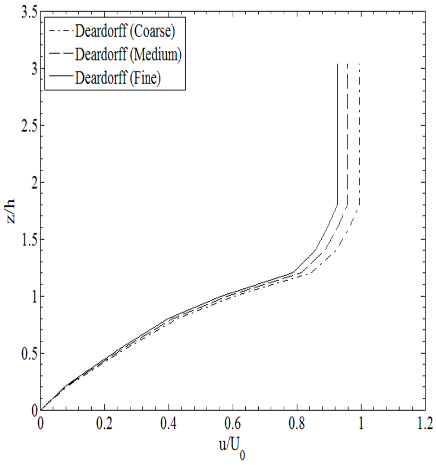
Figure 2: Mean velocity profiles at test section *x/h=4* for the SGS models



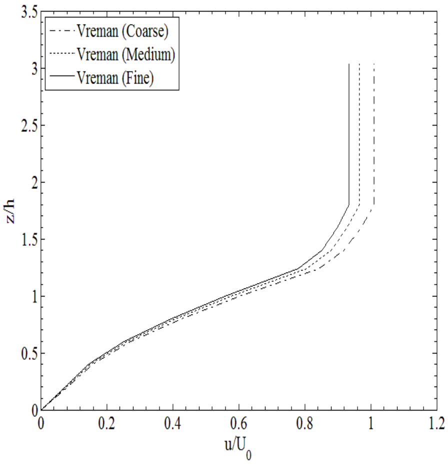
(a) Standard Smagorinsky



(b) Dynamic Smagorinsky

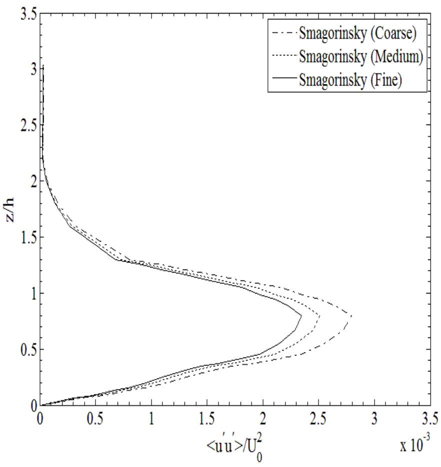


(c) Deardorff

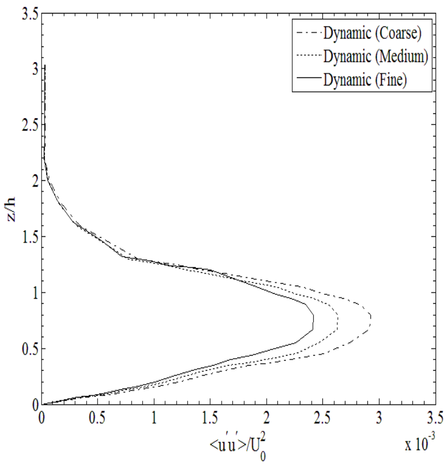


(d) Vreman

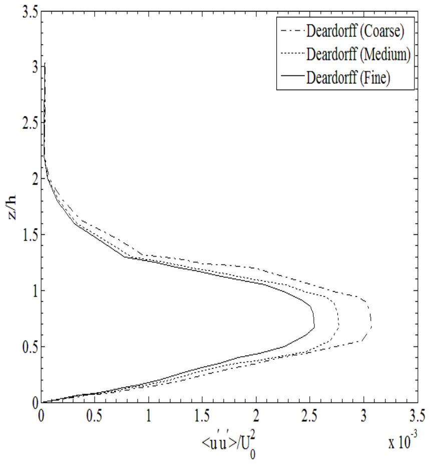
Figure 3: Mean velocity profiles at test section *x/h=6* for the SGS models



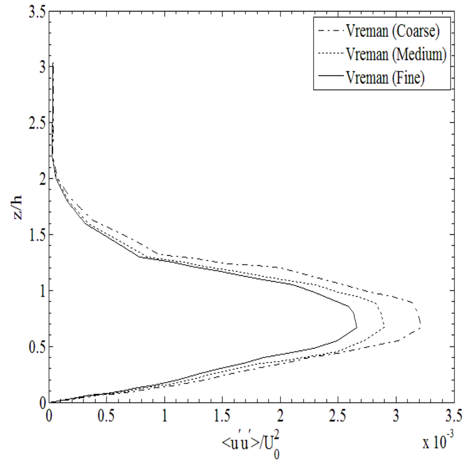
(a) Standard Smagorinsky



(b) Dynamic Smagorinsky

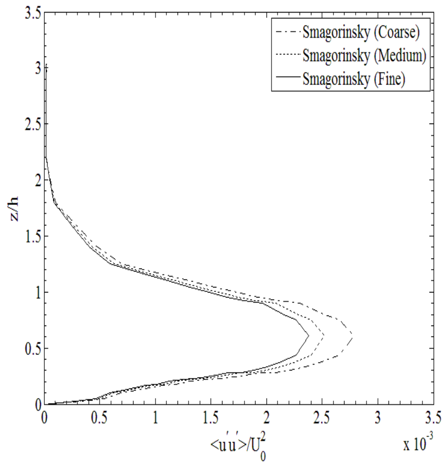


(c) Deardorff

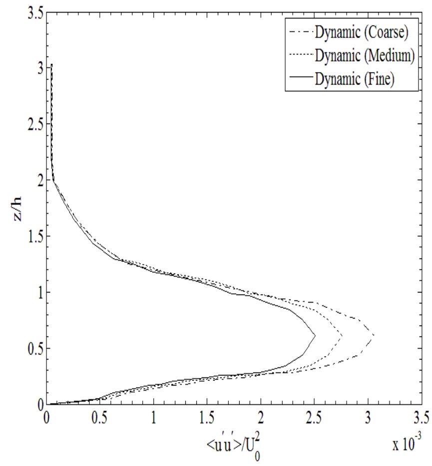


(d) Vreman

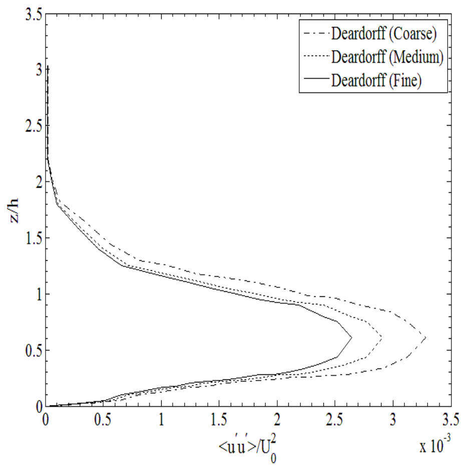
Figure 4: Turbulence intensities at test section *x/h=4* for the SGS models



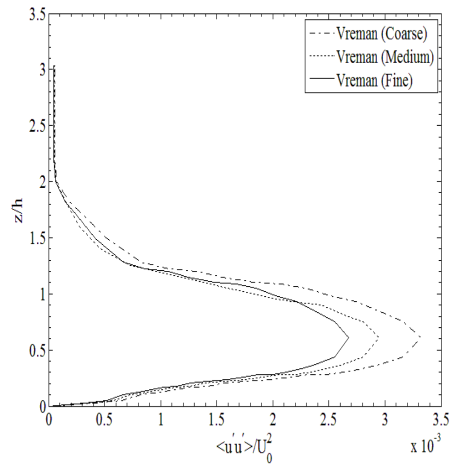
(a) Standard Smagorinsky



(b) Dynamic Smagorinsky



(c) Deardorff



(d) Vreman

Figure 5: Turbulence intensities at test section *x/h=6* for the SGS models

Turbulent flows are highly diffusive in nature due to continuous three-dimensional fluctuations of the fluid throughout the computational domain. Turbulence intensity arises due to the non-linear diffusive nature of fluid flow. It is an important flow parameter to quantify the nature of the turbulent flow.

The rms profiles of the turbulence intensities or Reynolds stresses ($\overline{u'u'}$) at different locations along the streamwise direction are normalized by the reference velocity U_0^2. Figure 4 and Figure 5 present the turbulence intensities at two test locations $x/h = 4$ and $x/h = 6$ for the SGS models. Similar to the mean velocity profile, it appears from the figure that SGS models turbulence intensity profiles at selected test locations are unable to achieve grid convergence. Out of four models, it also appears the tendency of grid convergence of the standard Smagorinsky model is relatively better compared to the other three models which is consistent with Figure 2 and Figure 3. From these figures, it is observed that although the grids are sufficiently refined (up to $n_{min}^+ \approx 1$) but none of the SGS models is able to attain the numerical convergence.

4.2. Quantitative Comparison - Mean Velocity and Turbulence Intensity

From the above graphical presentation of the grid sensitivity study of the mean velocity and turbulence intensity, it appears that none of the flow variables is able to attain grid convergence despite sufficient refinement of the grid resolution. Hence, it is important to evaluate the grid convergence tendency of the four models to identify the most promising one. In this section, the focus was given on estimation of grid convergence error of the mean velocity and the turbulence intensity to quantify their tendency towards the grid convergence.

The grid convergence method was proposed by Roache (1992) [9] to estimate the grid convergence error which is based on the Richardson extrapolation [10]. Roache (1992) [9] and Richardson [10] point out that a grid convergence study requires a minimum of three grid solutions. The grid convergence index (GCI) provides a measure of convergence for grid refinement studies. GCI (%) can be expressed as follows

$$GCI\ (\%) = F_S \frac{\epsilon_{rms}}{r^p - 1} \times 100 \qquad (1)$$

Where, p is the order of the numerical scheme and for second-order scheme $p = 2$, F_s is the factor of safety and the recommended value is $F_s = 3$ (Roache 1992) [9], r represents the grid refinement ratio, can be calculated as $r = (N_{fine}/N_{coarse})^{1/3}$, and ϵ_{rms} is the rms value of the relative error which provide an initial measure of grid convergence for individual points n as

$$\epsilon_{rms} = \left(\frac{\sum_{i=1}^{n} \epsilon_i^2}{n}\right)^{1/2} \qquad (2)$$

where, the relative error (ϵ_i) at a certain point for a flow variable (say velocity u_i) can be calculated as the magnitude between the coarse and fine solutions

$$\epsilon_i = \left|\frac{u_{i,coarse} - u_{i,fine}}{u_{i,fine}}\right| \qquad (3)$$

GCI has been calculated for three grid resolutions presented in Table 1. Results of this comparison in the form of grid convergence values (GCI) of the mean velocity and the turbulence intensity are reported in Table 2 and Table 3. From the comparison, it is found that there is a reduction in GCI values in the successive grid refinements ($GCI_{M/C} < GCI_{F/M}$) for each of the two variables for the SGS models. The GCI of the finer grid ($GCI_{F/M}$) is relatively low compared to the coarser grid ($GCI_{M/C}$) which indicates that the dependency of the numerical solutions of the simulations on the grid size has been reduced.

Table 2: Grid convergence measures (GCI) of the mean velocity profiles at stations x/h=4 and x/h=6 for flow over a backward facing step

Grids	Test sections (x/h)	Grid convergence index (%)			
		Standard Smagorinsky	Dynamics Smagorinsky	Deardorff	Vreman
Medium- Coarse (M/C)	4	12.65	16.19	19.33	22.16
Fine- Medium (F/M)	4	6.32	10.03	15.17	14.52
Medium-Coarse (M/C)	6	13.12	15.94	16.87	19.57
Fine-Medium (F/M)	6	6.45	10.31	12.68	14.11

Table 3: Grid convergence measures (GCI) of the turbulence intensity at stations x/h= 4 and x/h=6 for flow over a backward facing step

Grids	Test sections (x/h)	Grid convergence index (%)			
		Standard Smagorinsky	Dynamics Smagorinsky	Deardorff	Vreman
Medium-Coarse (M/C)	4	15.18	22.67	27.06	31.02
Fine-Medium (F/M)	4	7.58	14.04	21.24	20.33
Medium-Coarse (M/C)	6	15.74	22.32	23.62	27.40
Fine-Medium (F/M)	6	7.38	14.43	14.75	19.75

From the comparison of GCI, it can be seen that the GCI value is almost halved for the standard Smagorinsky model between ($GCI_{M/C}$) and ($GCI_{F/M}$), whereas other three SGS models only reduced the error by roughly one-third. This quantitatively shows that among the four SGS models the grid convergence tendency of the standard Smagorinsky model is relatively high compared to the other three models. Roy (2003) [11] recommended that GCI is should be $\leq$ 4% for both higher and lower order numerical schemes to confirm the quality of simulations. However further grid refinement may provide reduction in GCI leading to grid converged solutions (especially for the standard Smagorinsky model) which may fall in the DNS resolution range ($n^{+}_{min} \approx 0.3$).

5. RESULTS AND DISCUSSIONS - PREDICTED OUTCOMES

The quality and efficiency of the SGS models can be justified by comparing the best converged LES solution (based on the grid convergence study shown above) with experimental results of Jovic and Driver (1994) [2]. This is done quantitatively and graphically in this section.

5.1. Statistical Analysis of Predicted Outcomes

The results using the fine mesh have been selected to determine the statistical relative error between the numerical solution and the experimental data of Jovic and Driver (1994) [2]. The method of Ierardi et al. (2003) [12] has been followed. According to this approach, the relative error (ξ) can be calculated as,

$$\xi = \frac{(\mathcal{R} - \psi)}{\psi} \tag{4}$$

where, $\mathcal{R}$ and ψ are the reference and predicted values respectively. The mean relative error (ξ_m) can be calculated by the absolute values of error in individual points n. Therefore, the over-predictions or under-predictions are of the same magnitude and the resultant error will not be zero,

$$\xi_m = \frac{\sum_{i=1}^{n}\left(\left|\frac{\mathcal{R}-\psi}{\psi}\right|\right)}{n} \quad (5)$$

The relative errors are presented in Table 4 and Table 5 for the mean velocity and turbulence intensity profiles. Relative errors for the SGS models considered are calculated by taking the average of the relative mean errors at each of the two stations. From the Table 4, as can be seen, the relative error of the standard Smagorinsky model at fine resolution is almost two fold less than those of the dynamic Smagorinsky and the Deardorff models and almost three folds less than the Vreman model. Therefore, on the basis of mean relative error analysis, it can be said that standard Smagorinsky is the most efficient model (in terms of obtaining closest to experimental results with the same grid resolution) among the four SGS models for the considered test case. Table 5 results show a sharp increase of relative error in the turbulence intensities than the mean velocity components which indicate that the turbulence intensities are more sensitive to the SGS models. However, once again the standard Smagorinsky model is found to be the most efficient model, this time in relation to the prediction of turbulence intensities.

Table 4: Relative error analysis of the mean velocity profile (fine resolution) at stations x/h=4 and x/h=6 for flow over a backward facing step

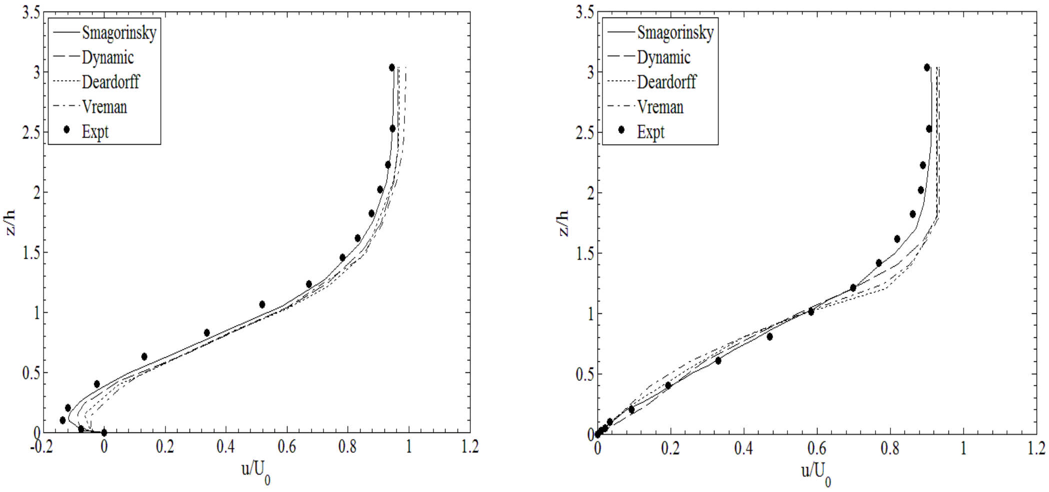
Test Locations (x/h)	Standard Smagorinsky (%)	Dynamics Smagorinsky (%)	Deardorff (%)	Vreman (%)
4	9.32	18.18	22.21	27.59
6	12.56	19.45	23.58	28.93
Average	10.94	18.81	22.90	28.26

Table 5: Relative error analysis of the turbulence intensity (fine resolution) at stations x/h= 4 and x/h=6 for flow over a backward facing step

Test Locations (x/h)	Standard Smagorinsky (%)	Dynamics Smagorinsky (%)	Deardorff (%)	Vreman (%)
4	15.04	25.45	31.09	39.62
6	17.62	28.33	33.01	36.50
Average	16.33	26.89	32.05	38.06

5.2. Mean velocity

Figure 6 represents the results for the dimensionless mean streamwise velocity at test sections x/h=4 and x/h=6 at a fine grid resolution. In Figure 6 (a), at section x/h=4, it appears that a reverse flow takes place between the step height level and wall region. It seems that the standard Smagorinsky model captures the secondary vortices near the step relatively better than other models and shows relatively better agreement with the experimental data. At the same location, among the other three eddy models, the Deardorff and the dynamic Smagorinsky model display almost the same phenomena except near the step height, but the Vreman model demonstrates poor agreement with experimental values compared to the other two models in the region near the step height and away from the wall. At section y/h=6 (Figure 6 (b)), it is appears that the flow is attached to the wall. In that section the standard Smagorinsky model shows relatively better agreement with experimental data but other models exhibit moderate agreement along the vertical axis. From the comparison, as can be clearly seen, the most accurate model (for the given absolute spatial resolution) overall is the standard Smagorinsky model, the dynamic Smagorinsky model is the intermediate and the Deardorff and the Vreman model are the least well performing SGS models.

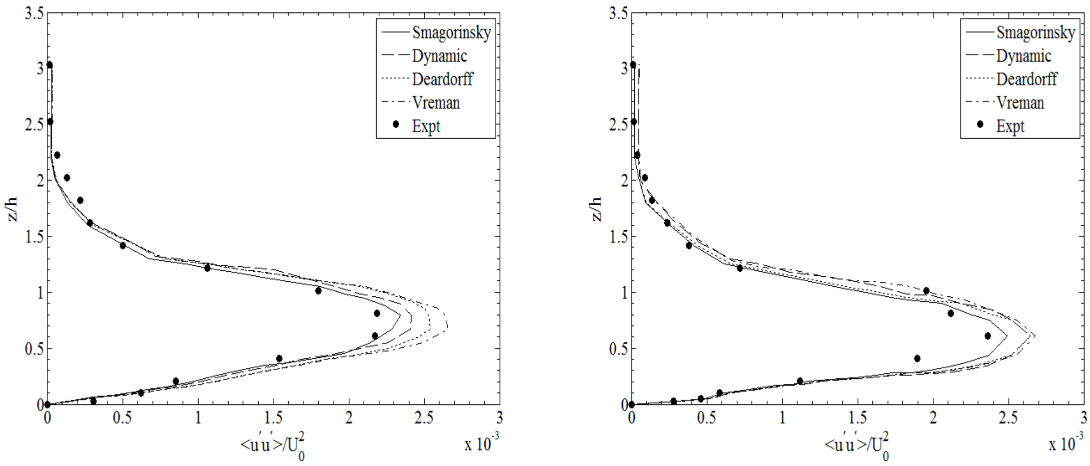


(a) at section *x/h=4* (b) at section *x/h=6*

Figure 6: Comparison of the mean velocity profile at test sections *x/h=4* and *x/h=6* for the SGS models

5.3. Turbulence intensity

Figure 7 represents the results comparison for turbulence intensities at selected test locations at fine grid resolutions. At test sections x/h=4 (Figure 7 (a)) and x/h=6 (Figure 7 (b)), it is found that similar to the mean velocity profiles the overall agreement of the turbulence intensity profiles of the standard Smagorinsky model with experimental data is relatively better compared to the other models. From the comparison, it can be concluded that the most accurate model (for the given absolute spatial resolution) overall is the standard Smagorinsky model, the dynamic Smagorinsky model is the intermediate and the Deardorff and the Vreman model are the least performing SGS models at both test locations for the turbulent intensities which is consistent with the mean velocity profiles in figure 6.



(a) at section *x/h=4* (b) at section *x/h=6*

Figure 7: Comparison of the turbulence intensity profile at test sections *x/h=4* and *x/h=6* for the SGS models

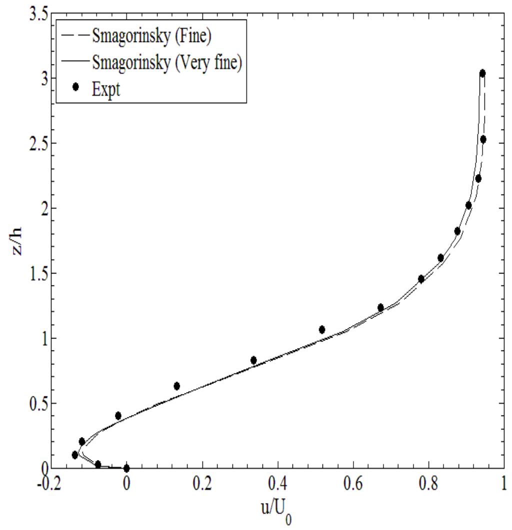
In summary, from the grid convergence study and the statistical relative error analysis along with graphical comparison of the mean velocity and the turbulence intensity profiles with experimental data, it appears that the standard Smagorinsky model is the most promising SGS model in FDS out of four despite it is unable to achieve grid convergence. Akselvoll and Moin

(1993) [7] application of LES to a backward facing step with $Re_h = 5100$ (based on the step height; h) shows that even with $n_{wall}^{+} = 0.8$ resolution, they were unable to achieve a grid converged solution with implicitly filtered LES. It seems the results of this present study are consistent with the findings of Akselvoll and Moin (1993) [7] and Toms (2015) [6] which also exhibit the elusive nature of grid convergence in implicitly filtered LES. However another simulation is conducted with the most promising standard Smagorinsky model when the grid resolution is further refined to $h/\delta z = 20$. This is to assess the adequacy of the second-order scheme.

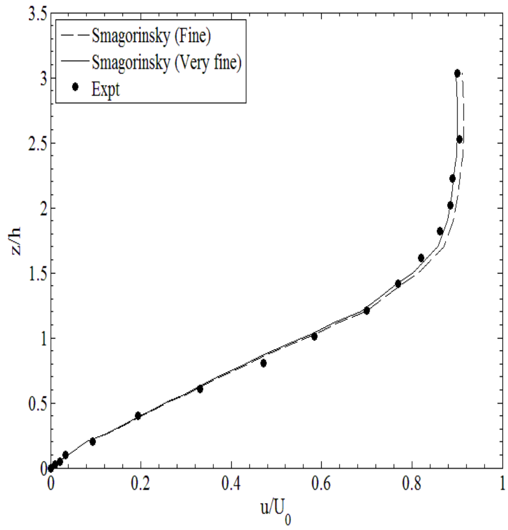
6. FURTHER SIMULATION WITH STANDARD SMAGORINSKY MODEL

To assess the adequacy of second-order scheme, the grid is further refined as $h/\delta z = 20$ (very fine) where the grid resolution is $240 \times 600 \times 400$ and the nominal wall unit is measured as $n_{min}^{+} \approx 0.46$. Results of the mean velocity and the turbulence intensity of the very fine grid (VF) are presented in the Figure 8 and Figure 9 along with fine grid (F) to show VF's tendency of grid converge and also compared with the experimental data. From the figures, it can be said that for both mean velocity and turbulence intensity, the very fine grid shows relatively better agreement with experimental data compared to the fine grid. In the similar way, grid convergence index and relative errors of the mean velocity and the turbulence intensity have been calculated to assess the grid convergence tendency and the relative accuracy of the model with VF grid that are presented in the Tables 6 and 7 respectively.

As mentioned earlier Roy (2003) [11] recommended a GCI value of $\leq 4\%$ to confirm the quality of simulations. From the Table 6, it appears that GCI (%) of the flow variables are around this range, but still some grid sensitivity remains.

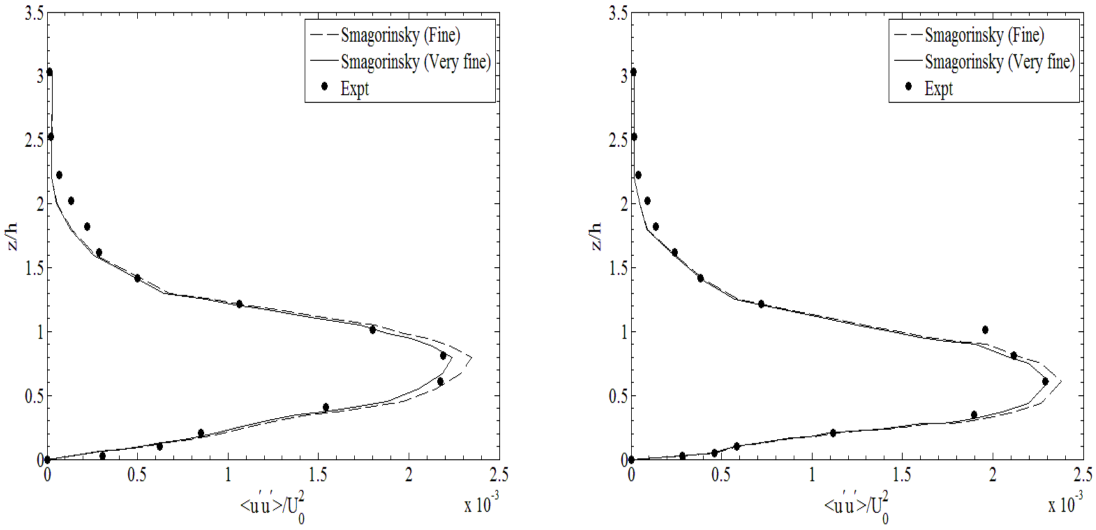


(a) at section *x/h=4*



(b) at section *x/h=6*

Figure 8: Comparison of the mean velocity profile at test sections x/h=4 and x/h=6 for the standard Smagorinsky model for h/δz=20



(a) at section *x/h=4* (b) at section *x/h=6*

Figure 9: Comparison of the turbulence intensity profile at test sections x/h=4 and x/h=6 for the standard Smagorinsky model for h/δz=20

Table 6: GCI of the mean velocity and the turbulence intensity profiles of standard Smagorinsky model at stations *x/h=4* and *x/h=6* with very fine grid (*h/δz=20*)

Grid	Test section *(x/h)*	Grid convergence index (%)	
		Mean velocity	Turbulence intensity
Very fine-Fine (VF/F)	4	3.27	4.18
	6	3.43	4.07

Table 7: Relative errors of the mean velocity and the turbulence intensity profiles of standard Smagorinsky model at stations x/h=4 and x/h=6 with very fine grid (h/δz=20)

Test section (x/h)	Relative errors (%)	
	Mean velocity	Turbulence intensity
4	4.38	6.58
6	5.73	7.12
Average	5.05	6.85

Accuracy of the obtained solution of the mean velocity and the turbulence intensity is presented in the Table 7.

Table **7** shows that average relative errors of the mean velocity and the turbulence intensity at two stations are approximately 5% and 7%. According to Roache (1992) [9] and Roy (2003) [11], for the numerical validation of turbulent flow cases errors are expected to be within 5%. Therefore it can be observed that obtained results of mean flow from very fine grid (VF) simulation are almost within acceptable range. The turbulence intensity failed to satisfy this condition. However from the trend, it can be expected that further refinement of grid may provide more accurate results but it will be similar or higher than that of grid resolution considered in DNS (Le, Moin and Kim 1997 [3]) in terms of nominal n^{+}_{min}. This shows the elusiveness of grid convergence. This particular simulation using standard Smagorinsky model with very fine grid reduces the relative errors of both flow variables within the acceptable range and shows very good agreement with the experimental data which demonstrates the adequacy of the second-order numerical scheme. In the process, this study also shows the elusiveness of the grid convergence of implicitly filtered LES.

7. CONCLUSIONS

This study evaluated the performance and grid sensitivity of four LES sub-grid scale (SGS) turbulence models namely Standard Smagorinsky, Dynamic Smagorinsky, Deardorff, and Vreman using FDS for a backward-facing step benchmark. The results demonstrate that grid resolution has a stronger influence on LES predictions than the choice of SGS model, highlighting the challenges of achieving grid-independent solutions in implicitly filtered LES. Among the models considered, the Standard Smagorinsky model exhibits the strongest convergence tendency, confirmed through additional simulations at very fine grid resolution (nominal $n^{+} \approx 0.46$). Analysis of relative errors and grid convergence indices indicates that the second-order numerical scheme in FDS is adequate when sufficiently fine meshes are employed.

The findings of this paper highlight the persistent elusiveness of grid convergence in implicitly filtered LES, underscoring the critical importance of careful grid design, appropriate mesh refinement, and sub-grid scale (SGS) model selection in CFD based fire simulations using FDS.

8. FURTHER STUDIES

This work demonstrates that grid resolution exerts a dominant influence on LES performance in FDS and that the Standard Smagorinsky model delivers the most stable and consistent behavior among the SGS models evaluated. Although the backward-facing step configuration provided a well-controlled environment for isolating turbulence-modelling effects, further research is required to examine how these insights translate to the more complex flow physics of real tunnel fire scenarios, where buoyancy, heat release, radiation, and ventilation interact in coupled and highly unsteady ways. Future investigations should extend grid-sensitivity and SGS assessments to buoyant, fire-driven tunnel flows and develop mesh-design approaches suited to long, confined geometries. In addition, incorporating formal uncertainty quantification into FDS-based analyses will enhance confidence in numerical predictions and support more reliable performance-based fire engineering for tunnel applications.

9. REFERENCES

[1] Mahfuz Sarwar, Cleary, MJ, Moinuddin, KAM and Thorpe, GR 2017, ‘On linking the filter width to the boundary layer thickness in explicitly filtered large eddy simulations of wall bounded flows’, *International Journal of Heat and Fluid Flow,* Vol 65, pp 73–89.

[2] Jovic, S & Driver, DM 1994, ‘Backward-facing measurement at low Reynolds number Re_h = 5000’, *NASA Technical Memorandum 108807,* pp. 1–24.

[3] Le, H, & Moin, P & Kim 1997, ‘Direct numerical simulation of turbulent flow over a backward facing step’, *Journal of Fluid Mechanics*, vol. 330, pp. 349–374

[4] McGrattan, KB, Klien, B, Hostikka, S & Floyd, J 2014, *Fire Dynamics Simulator Version 6: Technical Reference Guide*, National Institute of Standards and Technology, Special Publication, pp. 1018–6

[5] Panjwani, B, I. S. Ertesvag, A. Gruber, K. E. Rian 2010. Large eddy simulation of backward facing step flow, 5th National Conference on Computational Mechanics, Trondheim, Norway.

[6] Toms BA, 2015. Large-eddy Simulation of Flow over a Backward Facing Step: Assessment of Inflow Boundary Conditions, Eddy Viscosity Models, and Wall Functions, Journal of Applied Mechanical Engineering, vol. 4: pp(169).

[7] Akselvoll, K, & Moin, P 1993. Large eddy simulation of turbulent confined co-annular jets and turbulent flow over a backward facing step, RTF-63. Thermo-sciences Division, Dept of Mech. Engng, Stanford University.

[8] H. Werner and H. Wengle. 1991 Large-eddy simulation of turbulent flow over and around a cube in a plate channel. In 8th Symposium on Turbulent Shear Flows, Munich, Germany, Technische University Munich, pages 155–168.

[9] Roache PJ, 1992. Quantification of uncertainty in computational fluid dynamics, Annual Review Fluid Mechanics, vol. 29:123–60

[10] Richardson, LF 1922, 'The supply of energy from and to atmospheric eddies', Proceedings of the Royal Society of London, vol. 97, p. 686

[11] Roy, CJ. 2003. Grid Convergence Error Analysis for Mixed-Order Numerical Schemes, AIAA Journal, vol. 41, pp no. 4

[12] Ierardi, M. J., & Blevins, R. D. (2003). Analysis of a three-dimensional vortex-induced vibration problem by a statistical relative error method. Journal of Fluids Engineering, 125(3), 526-531.