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**Research paper****Large eddy simulation of non-reactive flow in burners****M. Zakyani\****Aerospace Research Institute (ARI), Tehran, 1465774111, Iran***Article info:****Article history:**

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**\*Corresponding author:**[zakyani@ari.ac.ir](mailto:zakyani@ari.ac.ir)**Abstract**

Large eddy simulations of non-reactive Delft II and Sydney bluff body flow are performed using different sub-grid scale models. Simulation of non-reactive burners is useful when studying flow characteristics inside reactive burners. As turbulent combustion simulation is rather an intricate task, it is helpful to study cold air flow inside the combustion chamber before igniting the chamber. In order to study the flow inside the mentioned test cases, different sub-grid scale models, i.e., constant Smagorinsky, dynamic Smagorinsky and dynamic WALE model are used to model the unresolved small scales. For the numerical simulations, a finite volume in-house code is used. The code adopts the projection method to solve the fluid flow equations. A second-order accurate scheme is used for spatial discretization. The time integration is done using a second-order accurate predictor-corrector scheme. For solving the resultant pressure Poisson equation, TDMA (Tridiagonal Matrix Algorithm) is used with multi-grid convergence acceleration. Generally, the results show good agreement with available experimental data. As expected, the dynamic WALE model performs better than the other models. To further improve the results, a rather realistic type of velocity inlet boundary conditions are applied to Sydney bluff body flow, i.e., digital filter velocity inflow boundary conditions. The results show drastic improvement using digital filter inflow, which is mainly due to the turbulent nature of the flow field.

**1. Introduction**

Jet flows have long been under investigation by scientists and engineers due to their practical importance in many industrial applications and natural phenomena, e.g., Batchelor [1]. It naturally occurs at the exit nozzle of airplane turbofan engines, in the turbine blade cooling, and it is essential for injecting fuel into the combustion chamber of internal combustion engines. Laminar jets are well studied using

analytical fluid dynamics methods, e.g. Schlichting and Gersten [2]. However, turbulent jets which occur in significant industrial applications are normally studied numerically due to their complexity. Jet in cross flow, impinging jets, and jets with the coaxial secondary stream are different types of jets vastly studied. A comprehensive review of the literature on jets was reported by Ball et al. [3]. Jets with the coaxial secondary stream are studied here due to their paramount importance

in many practical applications. These kinds of fluid flows frequently appear in studying turbulent combustion in burners where the fuel jet is carefully mixed with a coaxial secondary air stream, e.g., Branley and Jones [4]. To have complete combustion, which by itself is important for lower pollutant emission and better combustion efficiency, fuel jet and oxidizer co-flow should mix evenly in the combustion chamber. With the continuous development of digital computers and the help of computational fluid dynamics (CFD), many physical aspects of jet flows are better understood. State-of-the-art turbulence models perform a crucial role in our ability to predict and understand fluid flow phenomena like jets.

Two widely used turbulence modeling approaches, i.e., Reynolds averaged Navier-Stokes (RANS) and large eddy simulation (LES), are frequently used to accurately simulate and predict turbulent flows, e.g., Wilcox [5]. In the current work, LES is properly used to study velocity field of turbulent jets with secondary axial co-flow. LES showed promising results in turbulent flow simulations, especially when large-scale energy containing eddies are resolved. The most widely used LES model was proposed by Smagorinsky [6]. He naturally assumed that the eddy viscosity was proportional to the sub-grid characteristic length scale  $\Delta x$  and to the characteristic turbulent velocity based on the second invariant of the filtered field deformation tensor. The scholarly literature on LES and its applications are so vast and diverse that interested readers are referred to review articles of Lesieur and Metais [7], Piomelli [8], and Zhiyin [9].

The first published study of fluid jets dates back to almost 100 years ago, according to Ball et al. [3]. However, studying jets using LES is a relatively new subject with the first results appearing in the 1980s. Nevertheless, a more recent work by Bogey et al. [10] adopted explicit filtering with and without the dynamic Smagorinsky model to simulate a round free jet at Mach number  $M = 0.9$ . They accurately reported the contributions of molecular viscosity, filtering, and the dynamic Smagorinsky model to energy dissipation. They reasonably concluded that alternatives to the

eddy-viscosity approach by explicitly applying a selective filter to the flow variables would result in minimized dissipation of energy at larger scales. Due to the importance of inflow turbulent condition, Abboud and Smith [11] used a digital filter method and a synthetic eddy method in studying the flow field of a coaxial turbulent jet. They showed using a synthetic turbulent inflow velocity boundary condition will drastically improve the results. Large eddy simulations of the turbulent flows of twin parallel jets are also performed by Li et al. [12], which is important in the development of next generation nuclear reactors.

Other notable application typically includes jet into cross flows, which typically occurs in turbine blade cooling, fuel nozzle discharge, and VTOL aircraft. Jones and Wille [13] used LES to simulate a plane jet in a cross-flow. di Mare et al. [14] and Majander and Siikonen [15] adopted the LES to simulate a round jet penetrating a cross flow. They were able to properly capture the counter-rotating vortex pair, traveling in the stream-wise direction.

The prediction of the jet noise emanating from aircraft nozzles represents another application of jet flows. Bodony and Lele [16] and DeBonis [17] provide a comprehensive review of the relevant research in this field.

Moreover, in a combustion chamber, the fuel jet coming from a fuel nozzle penetrates the air stream, and after sufficient mixing, it will combust. A review of the use of LES for simulating combustion systems can be found in Pitsch [18]. Kim et al. [19] used LES to simulate a lean premixed dry low-NO<sub>x</sub> combustion chamber. The specific purpose was to study the operational capability of LES for the design of realistic hardware. di Mare et al. [14] applied standard Smagorinsky-Lilly to simulate a model gas turbine combustor. They could adequately capture the complex flow pattern inside the combustion chamber successfully. There have been many fundamental researches on using LES in combustion. Pitsch and Steiner [20] used a dynamic procedure to fine-tune the Smagorinsky constant for the simulation of Sandia flame D. Branley and Jones [4] used also the dynamic Smagorinsky procedure to simulate hydrogen diffusion flames. Navarro-Martinez

and Kronenburg [21] presented results for the Sydney bluff-body burner using the dynamic Smagorinsky model.

In this paper, the potential effects of various SGS models on two types of jet flows are investigated. These flows are primarily used to study the combustion of the fuel jet in the surrounding stream of air. This type of flow typically happens in combustion chambers of gas turbines and jet engines when fuel jet mixes and burns with compressed air supplied by the compressor.

To better explain the phenomena in the combustion chamber, studying cold flow is necessary. This would help to analyze the mixing of the jet in the stream of air. The mixing controls the combustion process in the chamber. After cold flow tests, the normally hot test is performed to further study the phenomena.

First, Delft II non-reactive jet flow is used to compare the effects of SGS modeling, and then the Sydney non-reactive bluff-body is used for the comparison of the models. The first case is shear flows without wall, and the second one is a shear flow with the presence of the wall. In the current study, various SGS models are adopted to analyze the ability of the models in capturing important phenomena happening in the mixing chamber. In addition, the effect of the inlet boundary condition is investigated to further improve the results.

## 2. Modeling

In LES a Favre filter is applied to the Navier-Stokes equations Sagaut [22], leading to:

$$\frac{\partial \bar{\rho}}{\partial t} + \frac{\partial \bar{\rho} \tilde{u}_i}{\partial x_i} = 0 \quad (1)$$

$$\frac{\partial \bar{\rho} \tilde{u}_i}{\partial t} + \frac{\partial \bar{\rho} \tilde{u}_i \tilde{u}_j}{\partial x_j} = -\frac{\partial \bar{p}}{\partial x_i} + \frac{\partial}{\partial x_j} \left[ \bar{\mu} \left( \frac{\partial \tilde{u}_i}{\partial x_j} + \frac{\partial \tilde{u}_j}{\partial x_i} - \frac{2}{3} \delta_{ij} \frac{\partial \tilde{u}_k}{\partial x_k} \right) - \tau_{ij}^{sgs} \right] \quad (2)$$

where the sub-grid scale (SGS) stress can be modeled as:

$$\tau_{ij}^{sgs} - \frac{1}{3} \tau_{kk}^{sgs} \delta_{ij} = 2\mu_t (\tilde{S}_{ij} - \frac{1}{3} \tilde{S}_{mm} \delta_{ij}) \quad (3)$$

with the Favre filtered strain rate,  $\tilde{S}_{ij}$ , defined as:

$$\tilde{S}_{ij} = \frac{1}{2} \left( \frac{\partial \tilde{u}_i}{\partial x_j} + \frac{\partial \tilde{u}_j}{\partial x_i} \right) \quad (4)$$

and  $\mu_t$  represent the turbulent diffusion. In the current study, the potential effects of three different sub-grid scale models are investigated: the constant Smagorinsky model, the dynamic Smagorinsky model, and a newly developed dynamic version of the WALE model Ghorbaniasl [23].

### 2.1. Constant Smagorinsky model

In the constant Smagorinsky approach, the turbulent viscosity is obtained by a simple approximation:

$$\mu_t = \bar{\rho} (C_S \Delta)^2 |\tilde{S}_{ij}| \quad (5)$$

where

$$|\tilde{S}_{ij}| = \sqrt{2 \tilde{S}_{ij} \tilde{S}_{ij}} \quad (6)$$

and  $C_S$  is the Smagorinsky constant.  $\Delta$  is the filter width taken here as the cubic root of the local grid cell volume.  $C_S = 0.1$  is used in the present work, following Lesieur and Metais [7].

### 2.2. Dynamic Smagorinsky model

The primary drawback of the constant Smagorinsky model in common is the unrealistic prediction of the turbulent viscosity in near-wall regions. In the constant Smagorinsky model, the turbulent viscosity on the wall does not decay as fast as anticipated. Therefore, the model has difficulties in handling wall-bounded flows. To overcome this practical limitation a damping function can be typically used in the near-wall region. However, the problem of properly tuning  $C_S$  remains a challenge with the limitations of using a damping function. The dynamic procedure proposed by Germano et al. [24] beneficially uses the scale similarity of the turbulent motion of the fluid to properly determine the Smagorinsky constant locally. Since the approach has been described already extensively in the literature, the mathematical

formulation of the dynamic Smagorinsky model is not given here. Interested readers are referred to the original paper by Germano et al. [24] or the review study of Lesieur and Metais [7].

### 2.3. Dynamic wall adapted local eddy viscosity (WALE) model

The wall adapted local eddy viscosity (WALE) model is initially proposed by Nicoud and Ducros [25]. The model, similar to the constant Smagorinsky and dynamic Smagorinsky model, is an eddy viscosity type model. The WALE model is intentionally designed to return the correct wall variation of the sub-grid scale viscosity. The model accounts for the strain and the rotation rate to properly obtain the eddy viscosity. Following this model, we have:

$$\mu_t = \bar{\rho}(C_w\Delta)^2|\tilde{S}_w| \quad (7)$$

where

$$|\tilde{S}_w| = \frac{(\tilde{S}_{ij}^d\tilde{S}_{ij}^d)^{3/2}}{(\tilde{S}_{ij}\tilde{S}_{ij})^{5/2}+(\tilde{S}_{ij}^d\tilde{S}_{ij}^d)^{5/4}} \quad (8)$$

and

$$\tilde{S}_{ij}^d = \frac{1}{2}(\tilde{g}_{ij}^2 + \tilde{g}_{ji}^2) - \frac{1}{3}\tilde{g}_{kk}^2\delta_{ij} \quad (9)$$

where

$$\tilde{g}_{ij}^2 = \frac{\partial\tilde{u}_i}{\partial x_k}\frac{\partial\tilde{u}_k}{\partial x_j} \quad (10)$$

$C_w$  represent the model parameter and should be adjusted accordingly. Like the constant Smagorinsky model, the dynamic procedure proposed by Germano et al. [24] can be appropriately applied to the WALE model. Ghorbaniasl and Lacor [26] developed a dynamic version of the model to precisely adjust the model parameter locally in time and space. The model showed promising results when applied to the periodic channel flow.

## 3. Numerical algorithm

The LES code used for solving the Navier-Stokes equations is an in-house code Zakyani [27]. The flow equations are solved using the projection method of Chorin [28]. The resulting Poisson equation for the pressure is solved efficiently with a tridiagonal matrix algorithm. To accelerate convergence, the multi-grid method is used. The convective fluxes are discretized with a second-order central scheme for the momentum equation. A predictor-corrector method by Pitsch and Steiner [20] is used for time integration of the unsteady Favre filtered Navier-Stokes equations. The code can adequately deal with variable density low Mach number flows. For completeness, the predictor-corrector method used in this study, which is 2nd order accurate in time, is short explained.

### 3.1. Predictor step

Using the second order Adams-Bashforth method with variable step size for time integration of the Navier-Stokes equations, the discretized momentum equations read:

$$\frac{(\overline{\rho\tilde{u}_i})^* - (\overline{\rho\tilde{u}_i})^n}{\Delta t^n} = (1 + \frac{1}{2}\frac{\Delta t^n}{\Delta t^{n-1}})Res_u^n - (\frac{1}{2}\frac{\Delta t^n}{\Delta t^{n-1}})Res_u^{n-1} \quad (11)$$

where  $Res_u$  is defined as:

$$Res_u = -\frac{\partial\overline{\rho\tilde{u}_i\tilde{u}_j}}{\partial x_j} + \frac{\partial}{\partial x_j}((\overline{\mu} + \mu_t)(\frac{\partial\tilde{u}_i}{\partial x_j} + \frac{\partial\tilde{u}_j}{\partial x_i} - \frac{2}{3}\frac{\partial\tilde{u}_k}{\partial x_k})) \quad (12)$$

The corrected velocity field is computed at the corrector step.

$$(\overline{\rho\tilde{u}_i})^* = (\overline{\rho\tilde{u}_i})^* - \Delta t^n \frac{\partial\overline{p}}{\partial x_i} \quad (13)$$

In Eq. (13), the pressure is properly obtained solving the Poisson equation:

$$\frac{\partial(\overline{\rho\tilde{u}_i})^*}{\partial x_i} + \frac{\partial\overline{p}}{\partial t} = \Delta t^n \frac{\partial^2\overline{p}}{\partial x_i\partial x_i} \quad (14)$$

### 3.2. Corrector step

In the corrector step, applying the second order Adams-Moulton method to the Navier-Stokes system, one naturally obtains:

$$\frac{(\overline{\rho\tilde{u}_i})^{n+1} - (\overline{\rho\tilde{u}_i})^n}{\Delta t^n} = \frac{1}{2} Res_u^n + \frac{1}{2} Res_u^{n-1} \quad (15)$$

The corrected velocity field is computed at the corrector step.

$$(\overline{\rho\tilde{u}_i})^{n+1} = (\overline{\rho\tilde{u}_i})^{n+1} - \Delta t^n \frac{\partial \bar{p}^{n+1}}{\partial x_i} \quad (16)$$

In Eq. (16), the pressure is obtained solving the Poisson equation:

$$\frac{\partial (\overline{\rho\tilde{u}_i})^{n+1}}{\partial x_i} + \frac{\partial \bar{p}^{n+1}}{\partial t} = \Delta t^n \frac{\partial^2 \bar{p}^{n+1}}{\partial x_i \partial x_i} \quad (17)$$

## 4. Test case description and numerical computations

### 4.1. Delft II jet flow

The first test case studied in this research is the Delft II jet flow. The Delft II jet, which is primarily designed as a burner for Delft III non-premixed piloted flame, is a suitable test case for the empirical validation of turbulence models. The test case was studied experimentally by Stroomer [29] at Delft University. The Reynolds number based on the jet diameter and jet bulk velocity is 9700. The jet bulk velocity is  $U_j = 21.9\text{m/s}$  which emanates from a nozzle with the diameter of  $D_j = 0.006\text{m}$ . The annulus flow of air encloses the fuel jet, and the pilot enters the domain with a bulk speed of 4.4 m/s. The burner is surrounded by a co-flow of air at 0.4 m/s. A schematic figure of the Delft II test case is depicted in Fig. 1.

For the simulation of the Delft II test case, a cylindrical domain with  $153D_j$  length and  $40D_j$  diameter is used. The computational cylindrical mesh consists of  $216 \times 40 \times 40$  cells with clustering in axial and radial directions near the jet region. Ultimately, the mesh is divided into 9 blocks in the axial direction for parallel computations. The mesh is presented in Fig. 2.

### 4.2. Sydney bluff body jet flow

The second test case studied in this research is the Sydney bluff body jet flow. The Sydney bluff body jet case was also primarily designed as a burner for Sydney bluff body flame. The test case was studied experimentally by the University of Sydney. The specific details of the experiment can be found in Dally et al. [31] and Dally et al. [32]. The Sydney bluff body test case consists of a jet that emanates from a circular pipe with  $D_j = 3.6\text{mm}$  diameter. A bluff body of the diameter  $D_b = 50\text{mm}$ , surrounds the jet. The whole bluff body is surrounded by a co-flow. The Jet velocity is  $U_j = 61\text{m/s}$  and the co-flow velocity is 20 m/s. A schematic picture of the Sydney bluff body test case is displayed in Fig. 3.

For the simulation of the Sydney bluff body flow, a cylindrical domain with  $7.2D_b$  length and  $4.88D_b$  diameter is used. The cylindrical mesh consists of  $192 \times 64 \times 40$  cells. For parallel computations, the mesh is carefully divided into 8 blocks in axial directions. The mesh is illustrated in Fig. 4.

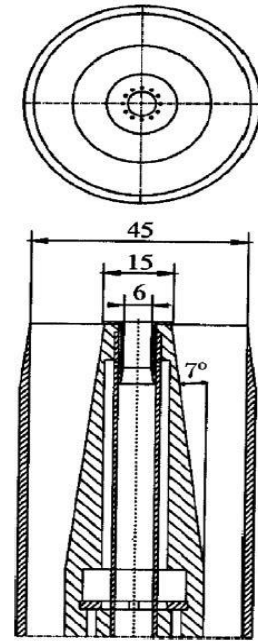


Fig. 1. Schematic picture of Delft II test case burner (jet head) taken from Merci et al. [30].

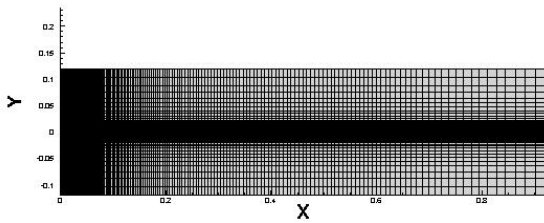


Fig. 2. Mesh generated for Delft II test case.

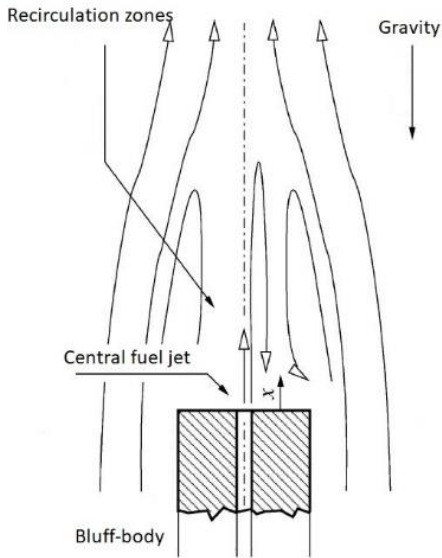


Fig. 3. Schematic picture of Sydney bluff test case taken from Kempf et al. [33].

### 5. Results and discussion

Results are shown for the Delft II test case in Figs. 5 and 6. At the inlet, the velocity boundary conditions are imposed from the given experimental data, and the pressure is extrapolated. At the outlet, the pressure is set to ambient pressure, and the velocity is extrapolated. For the far-field, the velocities are set to far-field values.

To obtain the results, 10 through flow times,  $\tau$ , of calculation was performed based on the jet velocity and the domain length to pass the transient time.

$$\tau \approx \frac{L_D}{U_j} \tag{18}$$

In Eq. (18),  $L_D$  stands for the domain length and  $U_j$  represent the jet velocity. The value of the through-flow times for the Delft II case is about

0.03 seconds. An additional 10 through flow times of calculation was performed to obtain statistically averaged results.

The comparison of the axial velocity with experimental data of Stroemer [29] is made in Fig. 5 for five different cross-sections along the centerline as well on the centerline itself. Also, Figs. 5 and 6 show the comparison between three various SGS models where CSM stands for constant Smagorinsky, DSM for dynamic Smagorinsky, and DWM for dynamic WALE model.

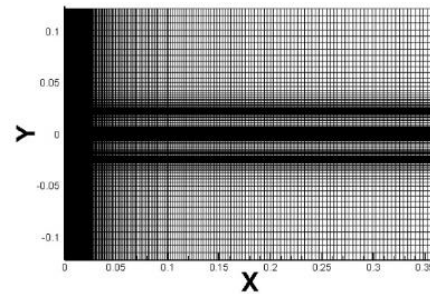


Fig. 4. Mesh generated for Sydney bluff body test case.

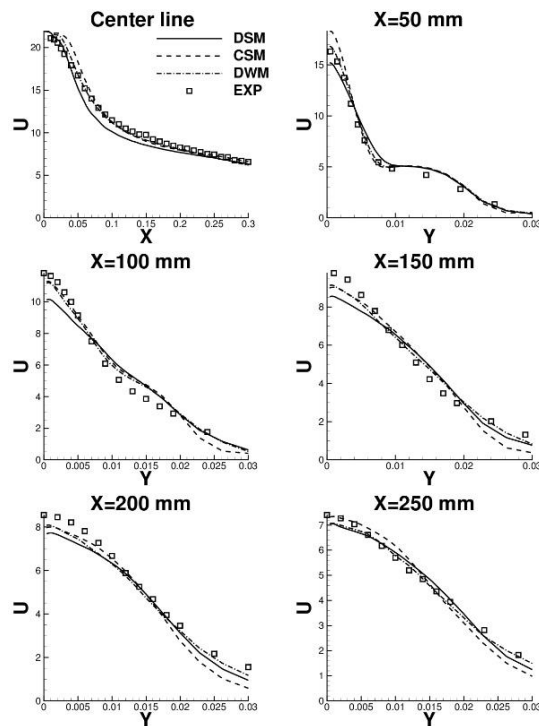
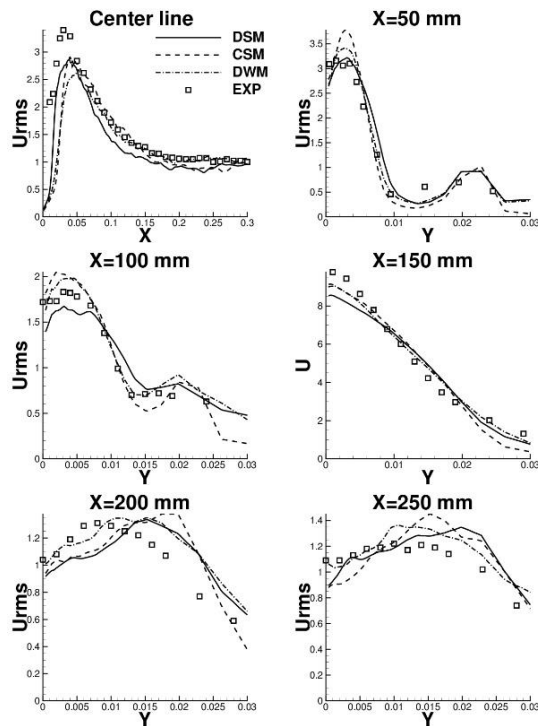


Fig. 5. Comparison of axial velocity with experimental data for Delft II test case.



**Fig. 6.** Comparison of rms of axial velocity with experimental data for Delft II test case.

As it is shown in Figs. 5 and 6, the DWM generally performs better than the DSM and the CSM model. Looking at the axial velocity in Fig. 5, it is seen that the centerline axial velocity decays faster for the DSM than in the other two models. Therefore, it fails to predict the centerline velocity accurately farther downstream. In contrast, the axial centerline velocity is higher than the experimental data for the CSM, especially in the near-field region of the jet. Interestingly, the DWM accurately predicts the axial centerline velocity. The reason for the superior results of the dynamic WALE is due to the ability of the model to capture flows with strong shear forces. As can be seen in Eqs. (8-10), the model adjusts for the high strain rate of the flow field. In the current configuration, these high strain rates happen at the contact surface of the jet and coflow. Also, the dynamic procedure applied to the WALE model helps to further improve the results.

The same is true for the prediction of axial velocity in different cross-sections, especially the cross-sections close to the nozzle. As can be seen in Fig. 5, the diffusion of the jet is very well

predicted by the DWM for section  $x = 50\text{mm}$  and  $x = 100\text{mm}$ . All three SGS models overpredict the axial velocity in the co-flow region at  $7.5\text{mm} < Y < 22.5\text{mm}$ . This can be explained by a lack of turbulence at the co-flow inlet profile.

For the remaining cross-sections, there are slight differences in the prediction of axial velocity. This can be explained that far from the jet, the strain rate is not too high and there is no strong shear force acting on the flow. Therefore, all models behave similarly farther downstream.

Additionally, near the edge of the domain at the far-field, the axial velocity prediction of the DWM agrees with experimental data. Despite a more accurate prediction of the axial velocity near the jet region for the CSM, as the radius increases, the axial velocity drastically deviates from the experiment. The DWM under-predicts the axial velocity near the jet region but obtains better agreement with the experiment in the co-flow region. The DWM provides a good prediction of the axial velocity for both jet and co-flow regions. Generally, in the absence of strong shear force, almost all SGS models behave similarly.

In Fig. 6, the rms of axial velocity is compared against the experimental data for three SGS models. Looking at the rms of the axial velocity along the centerline reveals that all three models underestimate the rms values. However, comparisons of the rms of axial velocity in different cross-sections reproduce the experimental results fairly well. There are no significant differences between all three SGS models in the comparison of the rms of axial velocity.

The next test case is the Sydney bluff body flow. Similar to the previous test case, to obtain the results 15 through flow times of calculation were performed to pass the transient time, and then an additional 15 through flow times to obtain statistically averaged results. Similar to the previous test case, the pressure is extrapolated at the inlet. At the outlet, the velocity is extrapolated, and the pressure is set to ambient pressure. The treatment of the far-field boundary condition for the Sydney bluff body test case is similar to the Delft II test case. However, for imposing the inlet velocity boundary condition, two alternative methods are employed. Initially,

the laminar inlet velocity boundary condition was applied, and then the digital filter of Klein et al. [34] is used to further improve the results.

The Sydney bluff body test case has two distinctive shear layers. The inner shear layer forms because of the jet emanating from the center of the solid bluff body. The velocity difference between the jet and the solid bluff body produces this shear layer. The outer shear layer forms because of the flow passing over the edge of the bluff body. This develops two counter-rotating vortices behind the bluff body that can be clearly identified in Fig. 7.

First, the comparison of the results for three various SGS models using laminar inlet velocity boundary conditions with the experimental data of Dally et al. [31] and Dally et al. [32] is presented in Figs. 8 and 9. The comparison of the axial velocity along six different cross-sections in the stream-wise direction is presented in Fig. 8. There are no significant differences between the results of the three SGS models. However, the DWM seems to be a bit superior to the DSM and CSM. The same conclusion as in the Delft II test case is also valid here.

It is recognized in Fig. 9 that there are two peaks for the rms of the axial velocity at  $x = 3mm$  and  $x = 10mm$ . These peaks correspond to the formation of the shear layers mentioned above.

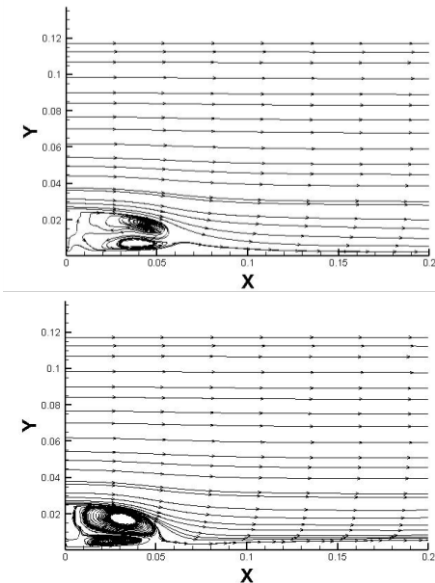


Fig. 7. Streamline for Sydney bluff body test case: without digital filter (up), with digital filter (down).

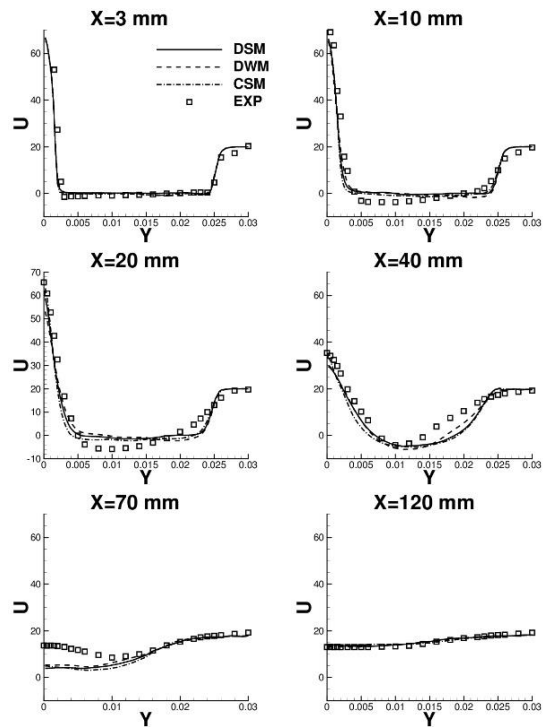


Fig. 8. Comparison of axial velocity for Sydney bluff body test case: different SGS model.

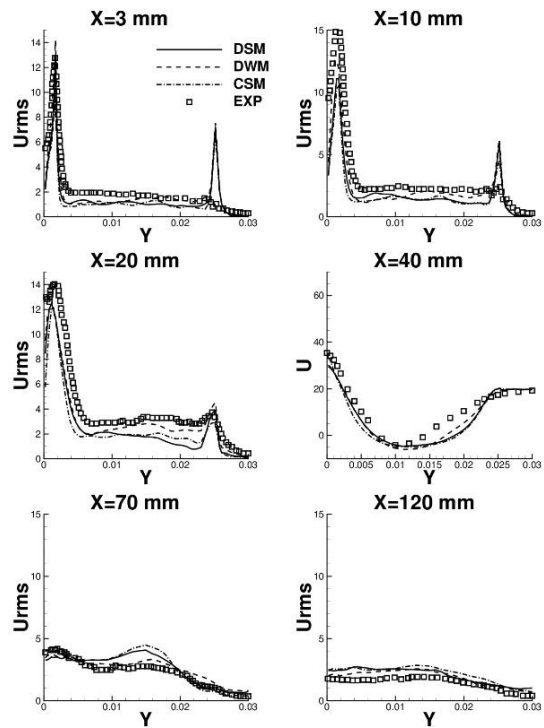


Fig. 9. Comparison of rms of axial velocity for Sydney bluff body test case: different SGS model.



To improve the results, a synthetic digital filter proposed by Klein et al. [34] is applied at the inlet boundary condition. For the SGS modeling, DWM is used as it has shown privileged results in comparison to other SGS models studied before. The digital filter creates a randomly generated turbulent inlet velocity boundary condition that mimics the real condition of the jet at the inflow of the domain. When using a laminar inlet velocity boundary condition, the lack of turbulence at the inflow boundary condition causes over-prediction of the recirculation zone behind the bluff body. After utilizing the digital filter of Klein et al. [34], the results were improved drastically. It can be noted in Fig. 7, that the point of reattachment for the digital filter is shorter than the laminar inlet. That is because increasing the momentum exchange in the shear layers will lead to stronger and more mixing. This is exceptionally critical for combustion applications where the fuel and the co-flow of oxidizer should mix properly to have complete combustion.

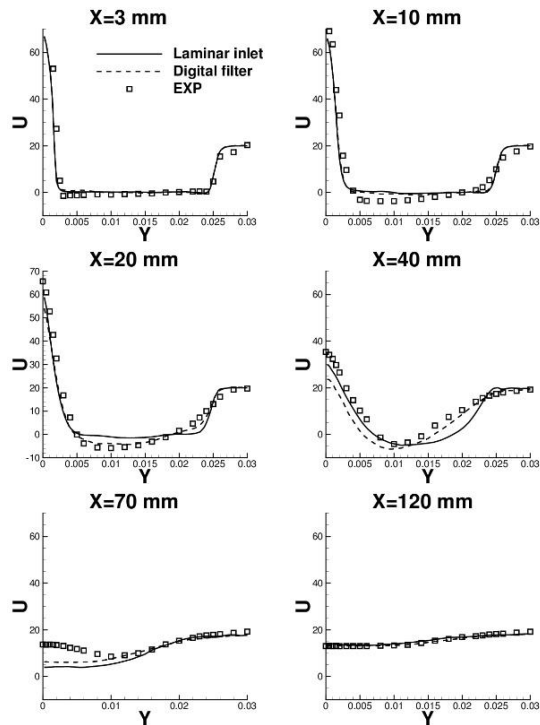


Fig. 10. Comparison of axial velocity for Sydney bluff body test case: different inlet boundary condition.

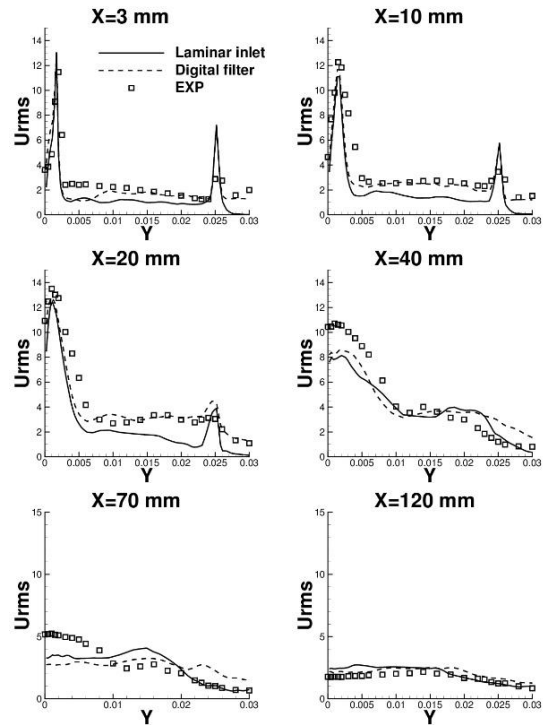


Fig. 11. Comparison of rms of axial velocity for Sydney bluff body test case: different inlet boundary condition.

The comparison between two different inlet velocity boundary conditions using the DSM for the axial and the radial velocities and their rms is shown in Figs. 10 and 11. As it can be observed in Fig. 10, at  $x = 20mm$  and  $x = 40mm$ , where the recirculation region is located, the results are improved considerably. Additionally, it is apparent from Fig. 11 that the rms of axial velocity is improved drastically at mentioned locations due to the improved application of boundary conditions.

### 6. Conclusions

Large eddy simulation of Delft II jet flow and Sydney bluff body jet flow are performed using three different eddy-viscosity based SGS models. The constant Smagorinsky model, the dynamic Smagorinsky model, and the dynamic WALE model are used to evaluate the effects of the SGS model on the prediction of two complex jets.

First, the Delft II jet flow is studied using the three different SGS models. The results show

that the dynamic WALE model is superior in the prediction of the Delft II test case, especially near the jet region.

Next, the Sydney bluff body jet flow is investigated. It is found that the dynamic WALE model is advantageous in the case of Sydney bluff body flow. This is because the model accounts for the right asymptotic behavior near solid walls and shear flows, which present in the current flows.

To improve the results, the synthetic digital filter is properly used at the inlet boundary condition. It is discovered that the turbulence inlet boundary condition causes the results to improve drastically in recirculation regions. To summarize, it is found that the dynamic WALE model produces a more precise prediction of the flow field, especially near the jet region when applying turbulence boundary conditions for the inlet velocity.

To improve the results, it is suggested to study the flow fields using an advanced technique like Detached Eddy Simulations (DES). This approach solves RANS equations in near-wall regions and LES far from the wall when the flow is homogenous.

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