# CFD study on the Atmospheric Boundary Layer

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## 1 Introduction

The shipping industry is responsible for approximately 3% of the global greenhouse gas (GHG) emissions, as well as for the 90% of the transported goods. To reduce the impact of shipping on the environment, the International Maritime Organization (IMO) developed a Greenhouse Gas Strategy to achieve net-zero GHG emissions from international shipping close to 2050. Several different alternative methods of propulsion are being explored, and wind energy is one of them.

In the last two decades, different technologies have been developed to utilize the wind as auxiliary and/or primary propulsion energy and Computational Fluid Dynamics (CFD) is a tool used to study them. One of the focal points for a correct outcome of the numerical simulations is an accurate representation of the wind.

In wind propulsion literature, a uniform wind profile was adopted for simplicity until the community decided to adopt the representation of the wind in open water as the Atmospheric Boundary Layer (ABL) profile. The ABL can be described as a log-law, adopted in Viola et al. (2015) and Bataille et al. (2023), or as a power-law, as suggested by the ITTC (2022) and applied in Garenaux et al. (2020) and Garenaux and Schot (2021). It is important to specify that the uniform wind profile is still relevant when comparing CFD with wind tunnel tests run with a uniform inflow velocity.

Numerically speaking, just prescribing the ABL formula at the inlet, as a velocity inlet boundary condition, it is not enough. There are several relevant aspects to consider to be able to achieve a horizontally homogeneous ABL flow, or sustainable boundary layer. As found in Blocken et al. (2007), Kim et al. (2108, 2021) and Rahnamay Bahambary and Fleck (2022) the turbulent quantities should be defined as function of height, and wall roughness should be applied to prevent streamwise gradients. The importance of wall roughness and the high Reynolds number present in ABL cases, require the use of wall-functions to model the near-wall areas, demanding attention to fit the ABL profile to the wall function profile, Blocken et al. (2007).

It is important to note that all the references adopt a logarithmic profile, except for Garenaux et al. (2020) and Garenaux and Schot (2021) where the ABL power-law is prescribed at the inlet.

The scope of this paper is to find the best numerical setup to simulate an atmospheric boundary layer, described by the power-law, in the numerical code STAR-CCM+.

## 2 Simulations

We decided to investigate the behavior of the Atmospheric Boundary Layer in CFD with a simplified case. It consists in an empty 2D domain with a length of 5000 meters and a height of 960 meters with the following boundary conditions: inlet velocity at the inlet and the top of the domain, pressure outlet at the outlet and smooth no-slip wall at the bottom. Simulations with a uniform flow of 10 m/s and a power-law ABL were carried out. The ABL is described by a power law $U_{ABL} = U_{ref}(h/h_{ref})^{\alpha}$ with the exponent $\alpha$ equal to 1/9 as suggested by the International Towing Tank Conference (2022). The reference height $h_{ref}$ is set to 10 m and the reference speed $U_{ref}$ to 10 m/s. The steady Reynolds-Averaged Navier-Stokes (RANS) equations are solved with the commercial code Star CCM+ 2206

(17.04.007). The equations are solved using a finite volume discretization with a collocated variable arrangement and a pressure-based approach. The coupling between momentum and continuity equations is achieved via the SIMPLE algorithm. The Shear-Stress Transport (SST) k-ω turbulence model is used. Convection and diffusivity schemes are second-order accurate for all the transport equations. The Newtonian fluid simulated is air at 15 degrees Celsius, with corresponding density $\rho$ = 1.225 kg/m$^3$ and dynamic viscosity $\mu$ = 1.802 x 10$^{-5}$ kg/ms. Different trimmed cells and polyhedral meshes were generated to understand the sensitivity of the ABL with respect to the number of prism layers NPL and thickness of the first prism layer cell *y*. The prism layer total thickness $\delta$ was kept constant to 38 meters for all the cases. The number of prism layers and the thickness of the first prism layer cell were varied keeping a constant value of the geometric progression stretch factor equal to 1.35. To keep a good transition between the prism layer mesh and the core mesh, the length *x* of the prism layer cells for the polyhedral mesh had to be modified, while for the trimmed mesh was possible to keep it constant. For all the simulations a $y^+$ value higher than 30 was achieved. A summary of the different meshes is reported in Table 1.

**Table 1 – Summary of the different meshes.**

| **Trimmed Cells Mesh** | | | | |
|---|---|---|---|---|
| Number of cells [-] | NPL | *y* [m] | *x* [m] | δ [m] |
| 8675 | 10 | 1.779 | 10 | 38 |
| 12675 | 20 | 0.0914 | 10 | 38 |
| 16675 | 30 | 0.0045 | 10 | 38 |
| 26675 | 55 | 0.0045 | 10 | 38 |
| **Polyhedral Mesh** | | | | |
| 5936 | 20 | 0.0914 | 26 | 38 |
| 10785 | 30 | 0.0045 | 17 | 38 |
| 28087 | 55 | 0.0045 | 10 | 38 |

Furthermore, we added the turbulence profiles for power-law ABL at the inlet and we studied their effect. The profiles are taken from Rahnamay Bahambary and Fleck (2022), and are set for the turbulent kinetic energy k and the specific rate of dissipation ω. We varied the value $C_\mu$ of the turbulence model between the common value of 0.09 and a value of 0.03, suggested for CFD simulations related to wind engineering. Roughness was not employed in this set of simulations, but it will be considered in future work.

Some preliminary 3D simulations were carried out, both with trimmed and polyhedral meshes, with varying Apparent Wind Angle (AWA) equal to 30, 45, 60 and 90 degrees. This part of the study is still ongoing and not discussed further, but some general observations can already be made.

## 3 Results

We start by comparing the results on all the different meshes for the uniform inflow with semi-empirical formulas for the $\delta_{99}$ and friction coefficient $C_f$ values as found in Liefvendahl and Fureby (2017). As visible in Figures 1 and 2, there is no significant difference between the different numbers of prism layers NPL, except for the case of the trimmed grid with NPL10, where the results are far from the semi-empirical models. Moreover, there is no visible difference between the trimmed and polyhedral meshes as expected, since we are focusing just on the lower part of the domain where the prism mesh is present. Additionally, the preliminary 3D simulations for a trimmed and polyhedral meshes are in good agreement with the 2D simulations and show a similar trend to the semi-empirical formulas.

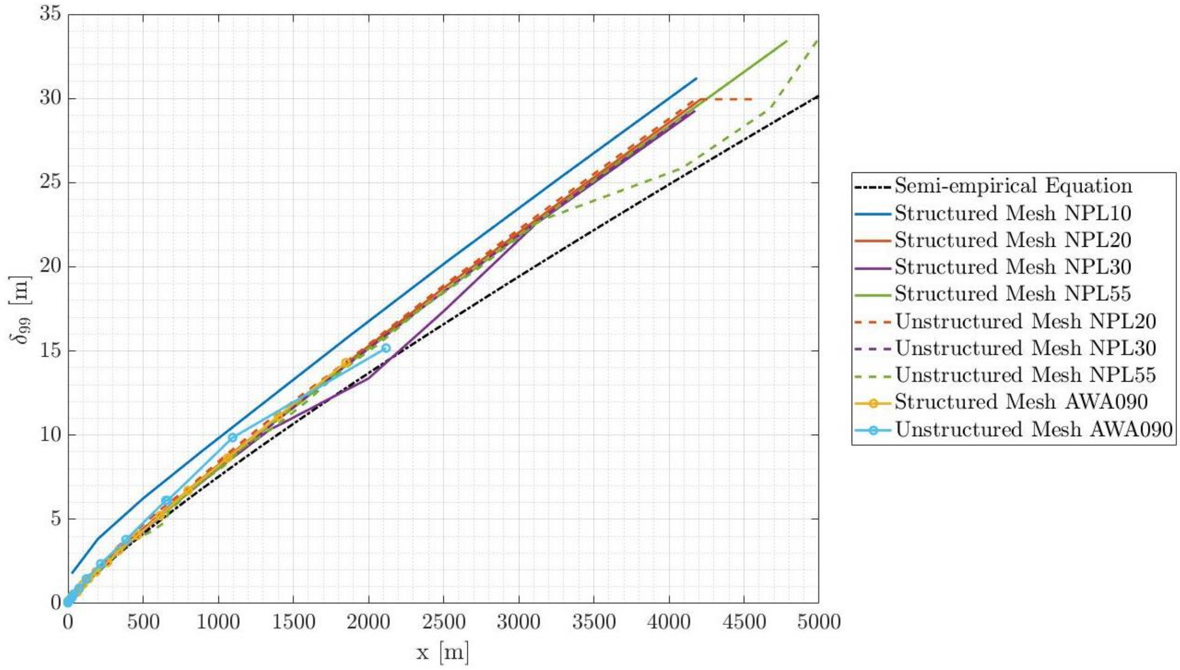


**Figure 1 – Comparison of $\delta_{99}$ between all the cases with a uniform inflow and the semi-empirical formula for the flow over a flat plate.**

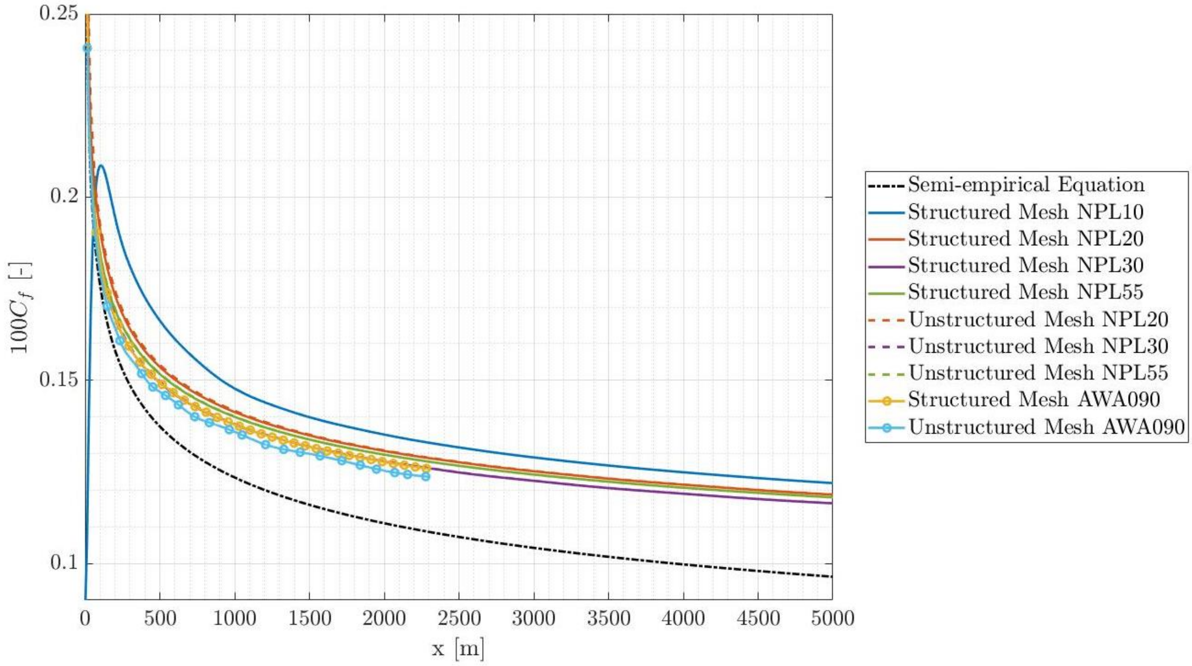


**Figure 2 – Comparison of the friction coefficient $C_f$ between all the cases with a uniform inflow and the semi-empirical formula for the flow over a flat plate.**

Since no major difference was found in the results of the trimmed and polyhedral meshes for the uniform inflow, we limit the study of the ABL with the respective turbulence profiles just to the polyhedral grids. As visible from Figure 3, the presence of the developing boundary layer on the bottom of the domain, disturbs the prescribed ABL profile. The addition of the turbulence profiles should overcome this influence, but unfortunately this is not the case. However, it has a noticeable influence: with the common $C_\mu$ value of 0.09, the lower part of the profile is accelerated, while the upper part is decelerated; and the opposite trend is instead visible for the smaller value of $C_\mu$ equal to 0.03.

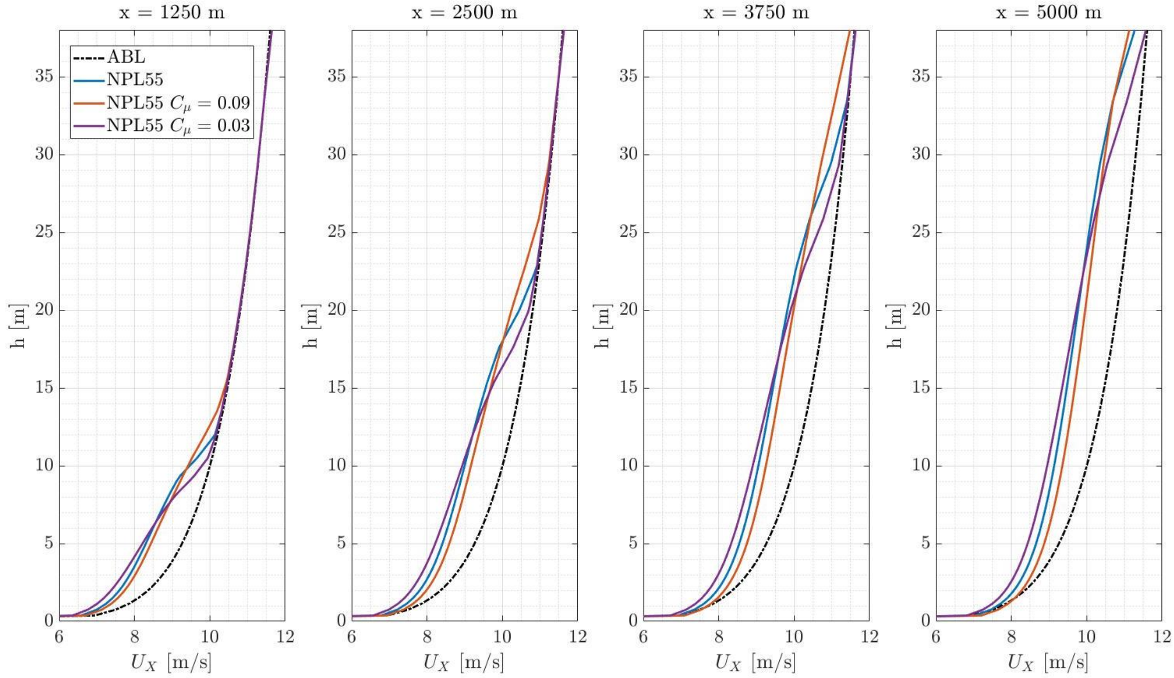


**Figure 3 – Comparison of the velocity profiles in the flow direction for the ABL inflow with and without turbulence profiles and varying $C_\mu$ for the polyhedral grids at different locations along the domain.**

## 4 Conclusions

Those results are preliminary and there are not yet clear conclusions on the best procedures to adopt to simulate a power-law ABL. On the other hand, several observations can be made:

- For the 2D domains with uniform inflow, there is no visible difference between the trimmed and polyhedral meshes, as well as for the prism mesh density.
- The addition of the turbulence profiles for the ABL inflow in the 2D polyhedral meshes, it is not sufficient to overcome the effect of the developing boundary layer on the bottom of the domain.
- From the 3D preliminary simulations was observed that the trimmed mesh is highly sensitive to the inflow angle. Typically, the cases for AWA equal to 30 and 45 degrees diverged for both inflows.
- From the 3D preliminary simulations was observed that the polyhedral mesh is highly sensitive to the number of prism layers. A better convergence was obtained with a smaller number of prism layers.

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