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Comparative Analysis of Turbulence Models: Evaluating Drag and Lift Coefficients of a NACA 4412 Hydrofoil

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Abstract: This study evaluates various turbulence models for simulating the aerodynamic behavior of a NACA 4412 hydrofoil in water flow using ANSYS Fluent®. Models such as Spalart-Allmaras (vorticity and strain-based), SST k-ω, *k- ε* standard, Transition *k- kl-ω*, and the empirical method XFOIL were assessed for accuracy, focusing on the drag coefficient (*Cd*) and lift coefficient (*Cl*). Simulations were conducted at zero-degree angle of attack, using six different mesh configurations with different refinement. Results showed variations in Cd and *Cl* across different models and mesh settings, with the empirical XFOIL model showing the lowest drag force but highest lift force, potentially due to its simplified assumptions.

Keywords: Drag Coefficient, Lift Coefficient, CFD, XFOIL, Turbulence Models, ANSYS, NACA 4412.

Introduction

Energy is essential for modern life, supporting everything from industry to daily activities. With increasing global population and technological growth, demand for energy continues to rise. Despite this, fossil fuels remain a primary source, contributing to pollution and climate change(International Energy Agency (IEA), 2022). This has driven the search for cleaner, renewable alternatives. Hydrokinetic energy stands out as a viable solution, capable of generating electricity from water flows without emitting greenhouse gases, making it a promising option for sustainable power generation.

The kinetic energy of water is converted into mechanical energy, which is then transformed into electrical power (Jin et al., 2015). These turbines can be divided into two main types based on their axis orientation: horizontal axis and vertical axis. Horizontal axis turbines (HAHTs) are generally used in large-scale applications with high flow rates and more complex systems, making them ideal for high-power industries like large rivers or ocean currents (Khan et al., 2009). In contrast, vertical axis turbines (VAHTs) are better suited for lower velocity flows, such as rivers or tidal areas. They are also valued for their simpler installation and maintenance, as well as their ability to operate in turbulent flow conditions.(Howell et al., 2010).One of the most important factors in optimizing the performance of hydrokinetic turbines is the refinement of their hydrofoil profiles. Hydrofoils are the cross-sectional shapes of the turbine blades, which are designed to interact with water flow to produce lift and drag forces. The lift force acts perpendicular to the flow direction, while drag acts parallel to it. A well-designed hydrofoil balances these forces, maximizing lift while minimizing drag, which is essential for the overall efficiency of the turbine (Bahaj et al., 2007). Each hydrofoil shape has its own unique characteristics, which influence the performance by producing different magnitudes of lift and drag forces. Moreover, the thickness-to-chord, which delineates the ratio between the hydrofoil's thickness and the distance between its leading and trailing edges, plays a significant role in determining its hydrodynamic behavior(Qamar & Janajreh, 2017).

The objective of this study is to evaluate and contrast the performance of different turbulence models in simulating the aerodynamic behavior of a profile in water flow the drag coefficient and lift coefficient with a zero angle of attack and different mesh refinements. The aim of this study is to determine the accuracy and consistency of each model, including variants such as Spalart-Allmaras (vorticity and strain-based), SST k-ω, k- ε standard, Transition k- kl-ω, as well as the performance of the empirical XFOIL method.

Data and methodology

A numerical comparison of blade performance was performed in contrast to XFOIL, it uses a combination of panel methods and boundary layer formulations to predict the aerodynamic performance of hydrofoils, it is particularly popular for its ability to quickly and accurately simulate hydrofoil behavior under various angles of attack and Reynolds numbers (Drela, 1989). The dynamic flow analysis was performed in the Fluent module of the commercial software ANSYS. Lift and drag forces were evaluated for a NACA 4412 blade with an angle of attack of zero degrees. Six simulations were carried out varying the size of the mesh elements and the inflation in each blade, Table 1 shows the configurations of each mesh.

Table 1

Mesh parameter configuration.

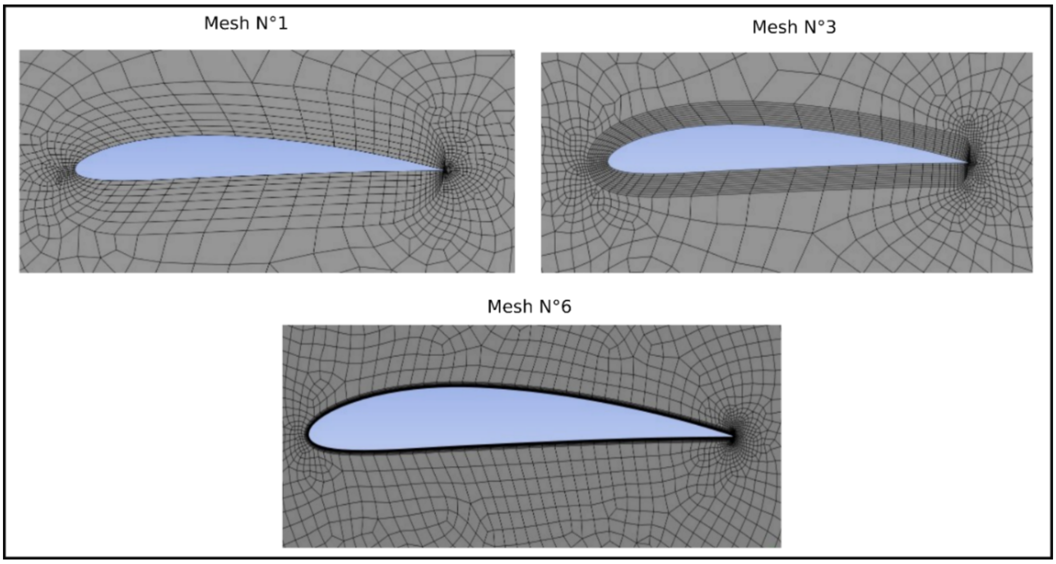
Mesh parameter	**N° 1**	**N°2**	**N°3**	**N°4**	**N°5**	**N°6**
Element Size [mm]	10	10	7	4	4	4
Number layers	7	11	13	14	25	30
Maximum Thickness [mm]	10	4	1	0.7	0.4	0.4

Source: authors own development

The discretization of the control surfaces was carried out in ANSYS Meshing, where rectangles and hexagons were configured to represent the blade in 2D. The different configurations of meshes 1, 3 and 6 are illustrated in Figure 1.

Figure 1

Mesh distribution on NACA 4412 hydrofoil



Source: authors own development

The simulation is carried out in the commercial program Fluent of ANSYS®, the inlet velocity is set to 4 m/s, with atmospheric pressure at the outlet, for a Reynolds of 269561, on the other hand, in the walls of the blades and the stationary domain, the wall condition without slip is established.

Research Results

Figures 2 and 3 show the drag (Cd) and lift (Cl) coefficients, respectively, for each turbulence model evaluated with different mesh configurations (N°1 to N°6), represented with different colors. XFOIL shows the lowest Cd value (0.00856) and the highest Cl (0.4888). However, XFOIL is a two-dimensional aerodynamic analysis tool based on boundary layer theory and panel method, which limits its ability to accurately model three-dimensional effects and turbulence in complex conditions (Drela, 1989).

The configurations that most closely match XFOIL values for the drag coefficient (Cd) use refined meshes (Mesh N°5 and Mesh N°6) with turbulence models like SST k-ω and Spalart-Allmaras. These models are known for their accuracy in capturing boundary layer transitions and turbulence effects (Menter, 1994; Spalart & Allmaras, 1994). The SST k-ω model is particularly effective in flows with adverse pressure gradients, while Spalart-Allmaras is efficient for subsonic hydrofoil analysis. For lift coefficient (Cl) predictions, using SST k-ω or Spalart-Allmaras with Mesh N°4 or Mesh N°5 provides a good balance, offering high Cl values that align closely with XFOIL results, indicating robust lift prediction without sacrificing accuracy (Rumsey et al., 2002). Combining refined meshes with these models improves the capture of flow separation and reattachment, leading to more precise lift approximations.

Figure 2

Drag coefficient vs. mesh turbulence models

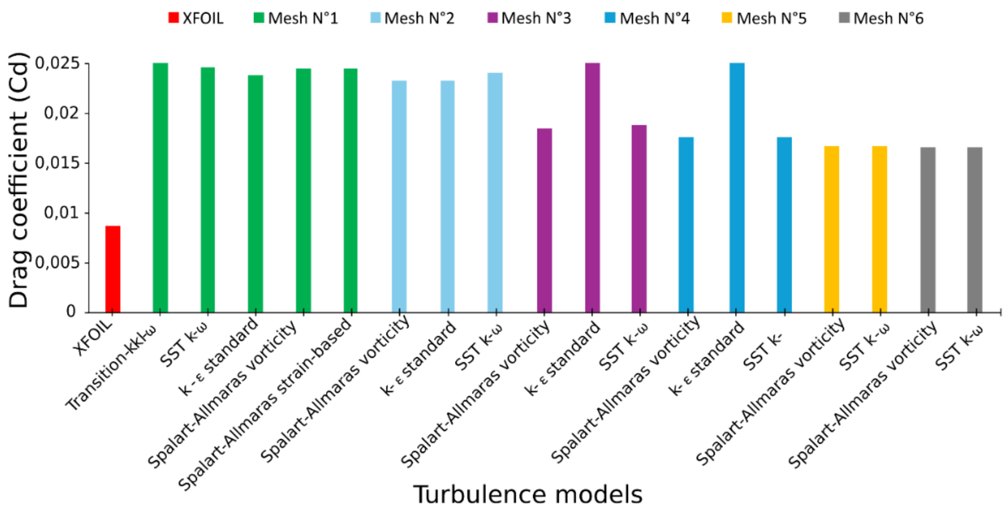
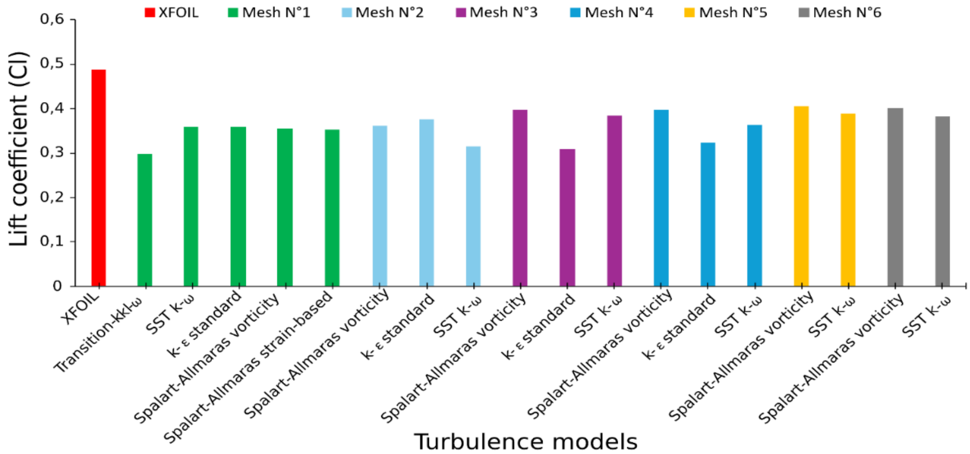


Figure 3

Lift coefficient vs. mesh turbulence models



Source: authors own development

Conclusions

A larger number of elements in the meshes (Mesh N°1 to N°6) tends to provide a more detailed and sometimes more accurate result in fluid dynamics (CFD) simulations. However, the values of drag (Cd) and lift (Cl) coefficients remain generally consistent between the different meshes for each turbulence model, suggesting that mesh resolution may influence, but does not always guarantee a better approximation to XFOIL results. For a balance between drag and lift, the combination of SST k-ω with Mesh N°4 or N°5 seems to be the best choice. This model is known for its accuracy in predicting the turbulent and transitional boundary layer, which is useful in a wide variety of aerodynamic applications. For a less computationally expensive solution, the N°4 mesh configurations may be sufficient, as they provide a reasonable ratio of accuracy to computational burden.

Future research on hydrokinetic turbines could focus on evaluating a wider range of operating conditions and flow environments to better understand their performance. This includes testing different blade designs, turbulence models, and mesh configurations under various flow velocity and angles of attack.

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