

# Towards Reliable Prediction of Hydraulic Resistance in Hollow Channels of Wind Turbine Blades: From Modeling to Experimental Validation

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## Introduction

Wind energy is one of the fastest-growing renewable energy sources, playing a key role in reducing greenhouse gas emissions and dependence on fossil fuels. Improving the aerodynamic efficiency and reliability of wind turbines remains a major research challenge [1].

The performance of wind turbines is strongly influenced by blade aerodynamics, including airfoil shape, chord distribution, and twist angle, which determine lift, drag, and energy conversion efficiency. Advanced methods such as computational fluid dynamics (CFD) are widely used to optimize blade design. Vertical-axis wind turbines (VAWTs), particularly Darrieus-type designs, are of special interest due to their ability to operate under turbulent and multidirectional wind conditions.

In cold climates, blade icing is a critical issue that reduces aerodynamic performance, increases drag, distorts power output, and creates operational risks. Electrothermal anti-icing systems are commonly used, involving complex heat transfer processes such as conduction, convection, and phase change. These processes depend on airflow conditions and turbine operation.

Hydraulic resistance is another important factor affecting blade efficiency. It is related to pressure differences along the blade surface and is strongly influenced by flow regime and Reynolds number.

This study investigates the coupled effects of aerodynamics, hydraulic resistance, and heat transfer in a wind turbine blade with an internal anti-icing system. The results contribute to improving turbine performance and reliability under harsh environmental conditions.

## Methodology

The study was carried out using computational fluid dynamics (CFD) simulations. The blade geometry Fig. 1., based on the NACA 0021 airfoil, was implemented in ANSYS Fluent and represents a troposkien-shaped vertical-axis wind turbine blade fragment with an internal channel for heated airflow.

The computational domain was discretized using an unstructured mesh with predominantly triangular elements (Fig. 2 a, b). Mesh refinement was applied near the blade surface, as well as at the leading and trailing edges, to accurately resolve boundary layer effects and flow gradients.

Special attention was given to near-wall treatment through the use of inflation layers, improving the accuracy of velocity, pressure, and heat transfer predictions. A grid independence study was also performed to ensure the reliability of the numerical results.

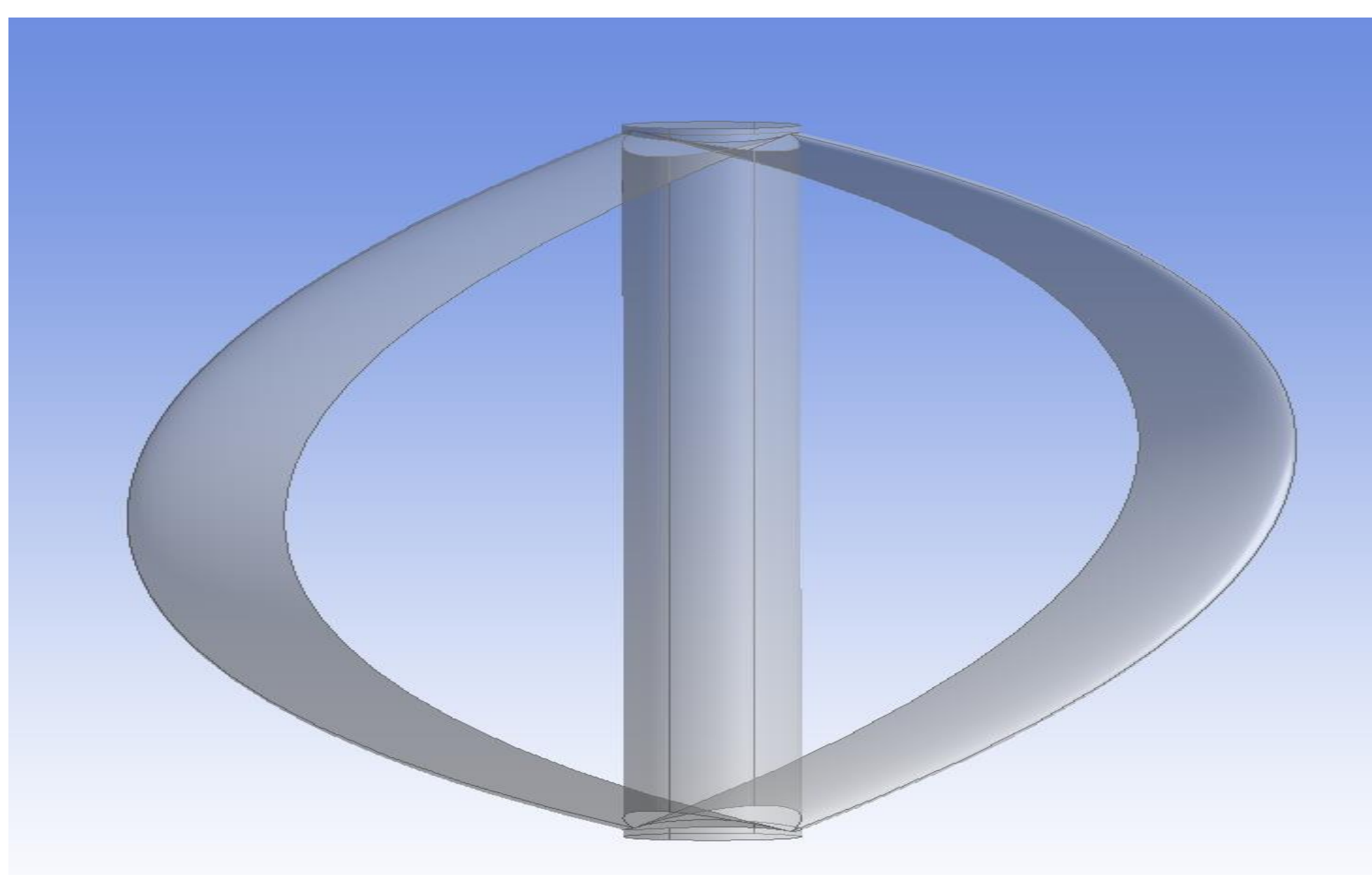


Fig. 1. Geometric model troposkien

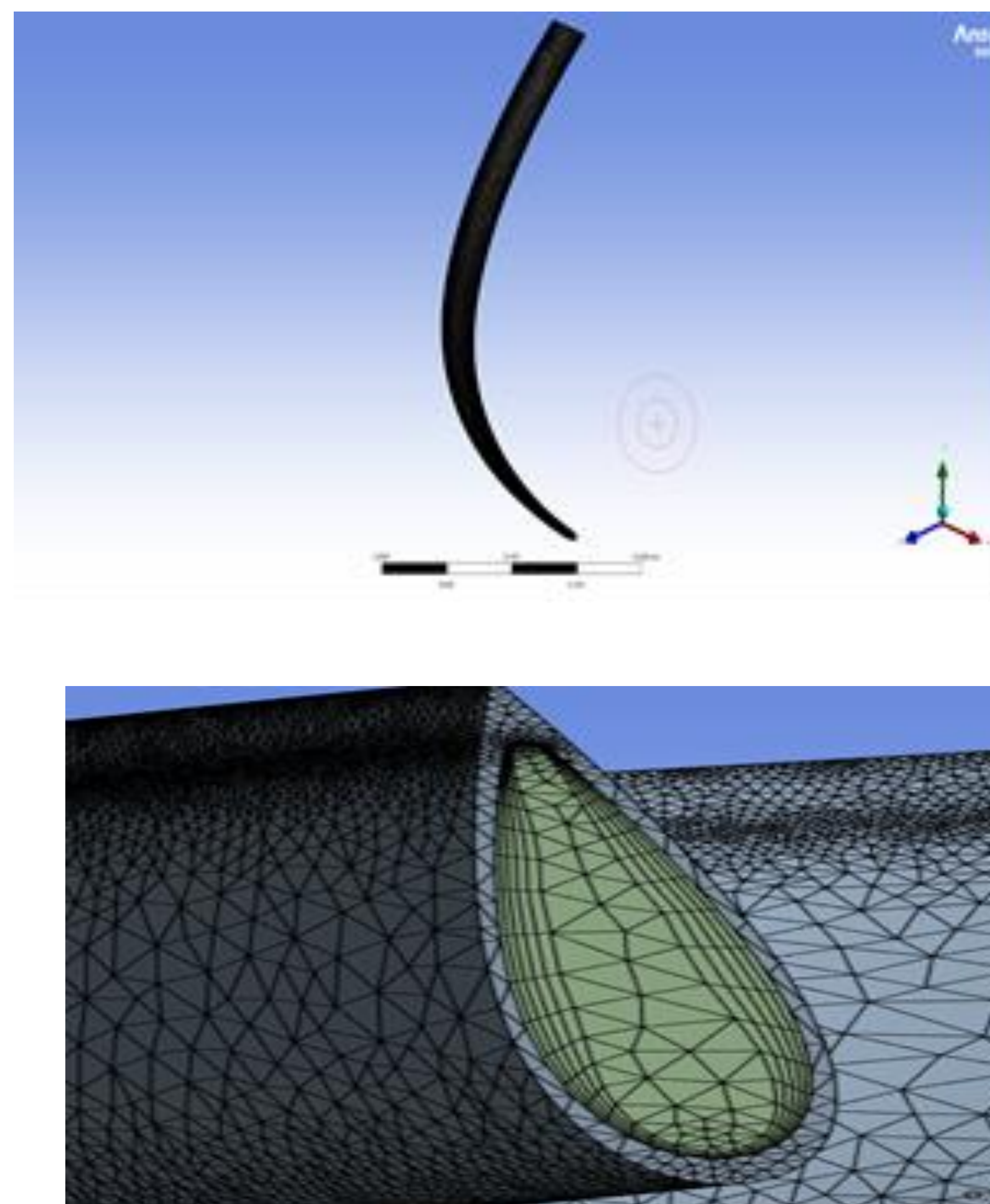


Fig. 2 (a), (b) Computational mesh.

## Results

The aerodynamic characteristics of a wind turbine blade were investigated using CFD simulations to analyze airflow behavior and hydraulic resistance under different flow conditions. The blade geometry, based on a selected airfoil profile, was implemented in ANSYS Fluent. A computational domain with mesh refinement near the blade surface was created to accurately resolve boundary layer effects. Simulations were performed for Reynolds numbers in the range of 10,000–40,000. The results show that the hydraulic resistance coefficient decreases with increasing Reynolds number, indicating improved aerodynamic performance.

CFD results are in good agreement with experimental data and theoretical predictions (Blasius correlation). The relative error decreases with increasing Reynolds number, with an average value of about 17% Fig. 3.

The pressure distribution around the blade demonstrates typical aerodynamic behavior, with distinct regions of high and low pressure along the surface Fig. 4.

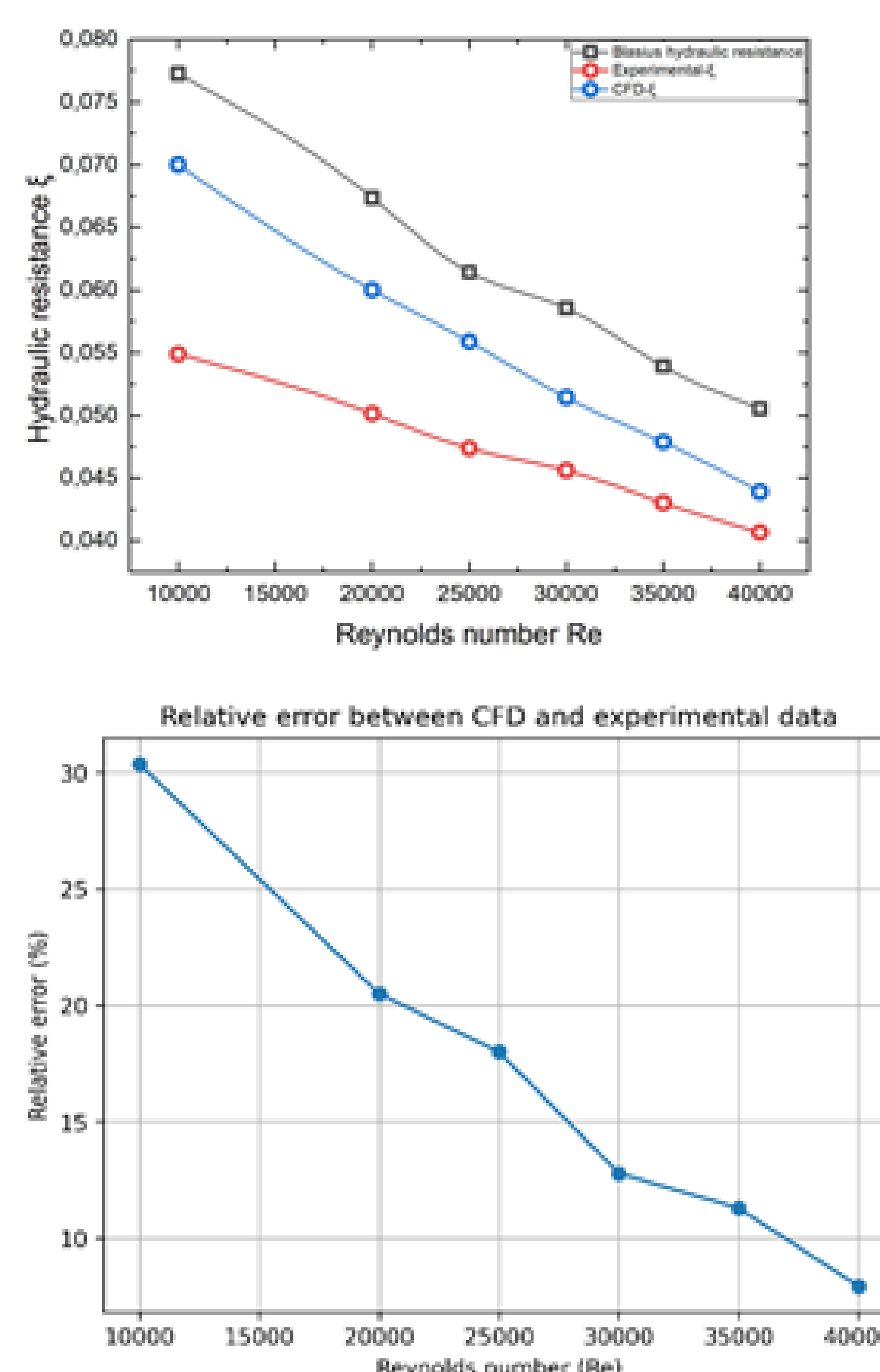


Fig. 3. Variation of the hydraulic resistance coefficient with Reynolds number, Relative error between CFD results and experimental data.

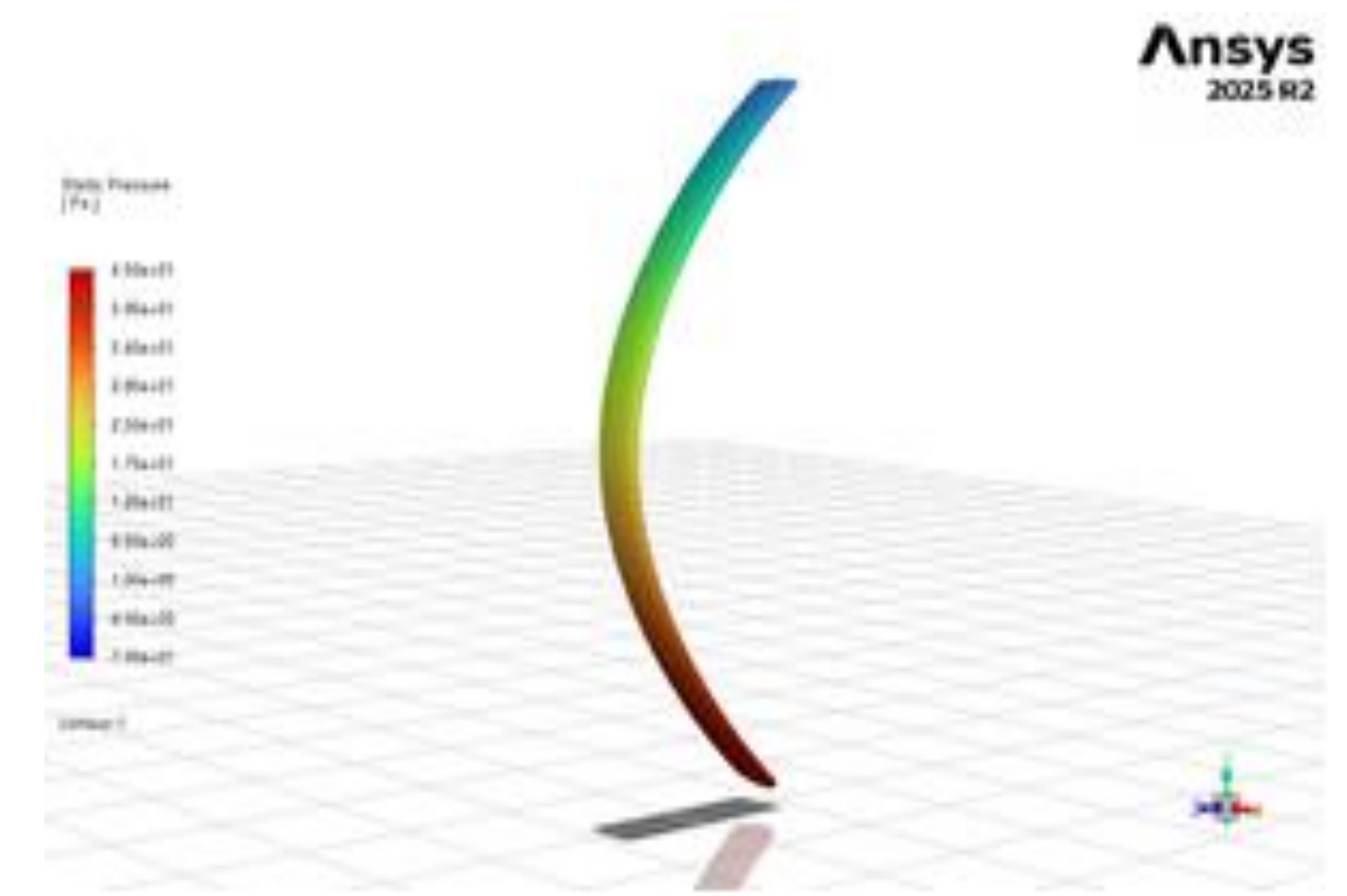


Fig. 4. Static pressure distribution around the wind turbine blade.

## Conclusions

The aerodynamic behavior of a wind turbine blade was analyzed using computational fluid dynamics (CFD) for Reynolds numbers ranging from 10,000 to 40,000. The results show that the hydraulic resistance coefficient decreases with increasing Reynolds number, indicating improved flow attachment and higher aerodynamic efficiency.

Pressure and velocity distributions reveal typical flow features, including boundary layer development and acceleration along the blade surface. CFD results were validated against experimental data and theoretical predictions (Blasius correlation), showing good agreement with an average error of about 17%.

Mesh refinement and near-wall treatment significantly improved solution accuracy, particularly in resolving boundary layer effects and pressure gradients.

Overall, the study confirms that CFD is an effective tool for analyzing aerodynamic performance and hydraulic resistance in wind turbine blades. The developed approach can be used for blade optimization and extended to coupled thermo-fluid analyses, including anti-icing systems, to improve turbine performance in harsh environments.

## References

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