ASSESSMENT OF VARIABLE INLETS, AIR DUCTS AND NOZZLES IN NACELLES FOR HYDROGEN FUEL CELL POWERED PROPULSION

Pedro Aguilera Vassalo, DLR-K, 24.09.2025

M. Kober, S. Kazula, P. Singh

DLR

Overview

1. Introduction

1. Context and motivation

- CO_2 emissions reductions.
- DRL Institute for Electrified Aeroengines: fuel cell for hybrid hydrogen.
- Main challenge of fuel cell systems: cooling in high performance stages.
- Possible solution: variable aerodynamic components such as inlets and nozzles.

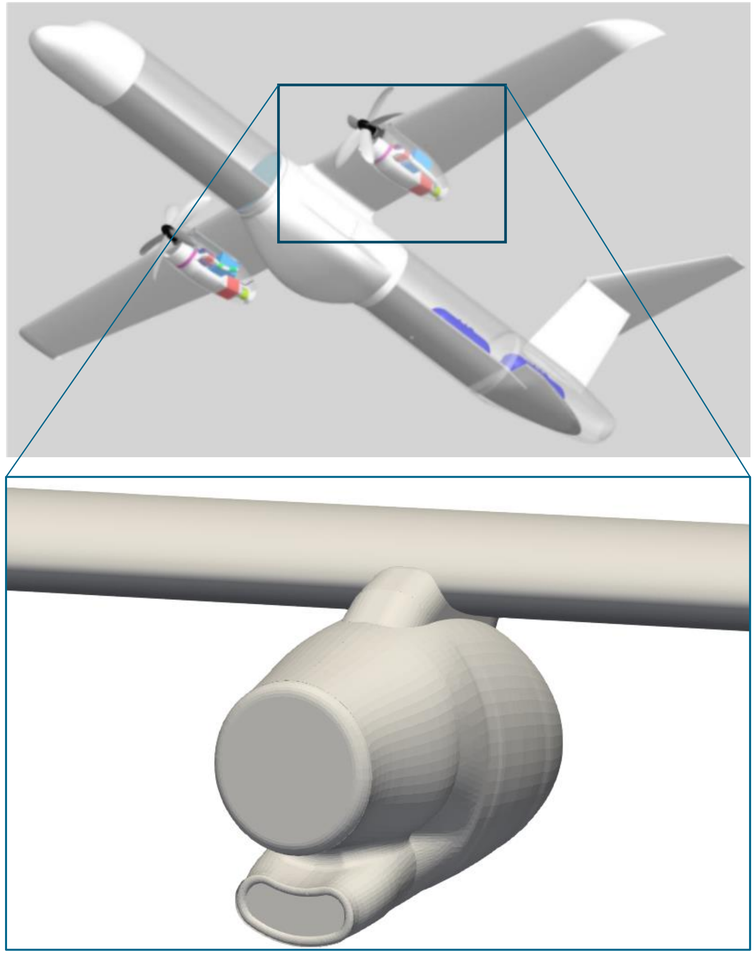


Figure 1: H2 Electra design model. [1]

[1] Stefanie de Graaf, Victor Bahrs, Noah Tarbah, and Stefan Kazula. H 2 electra – a platform for comparative analysis of integration concepts for hydrogen-based electric propulsion in regional aircraft. Journal of Physics: Conference Series, 2716(1):012007, 2024.

2. Objectives of the study

- Do a literature research to stablish the focus of the study.
- Create a methology for calculating sensitivity of mass flow rate to the variable components.
- Apply methodology to obtain results of the sensitivity.
- Analyze and conclude from results.

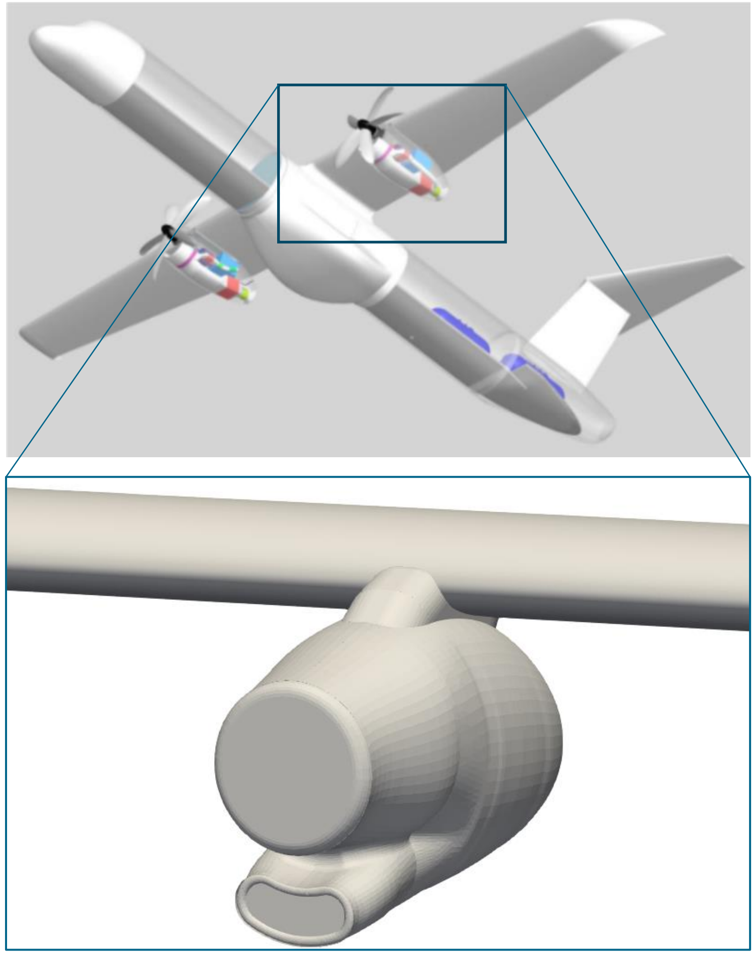
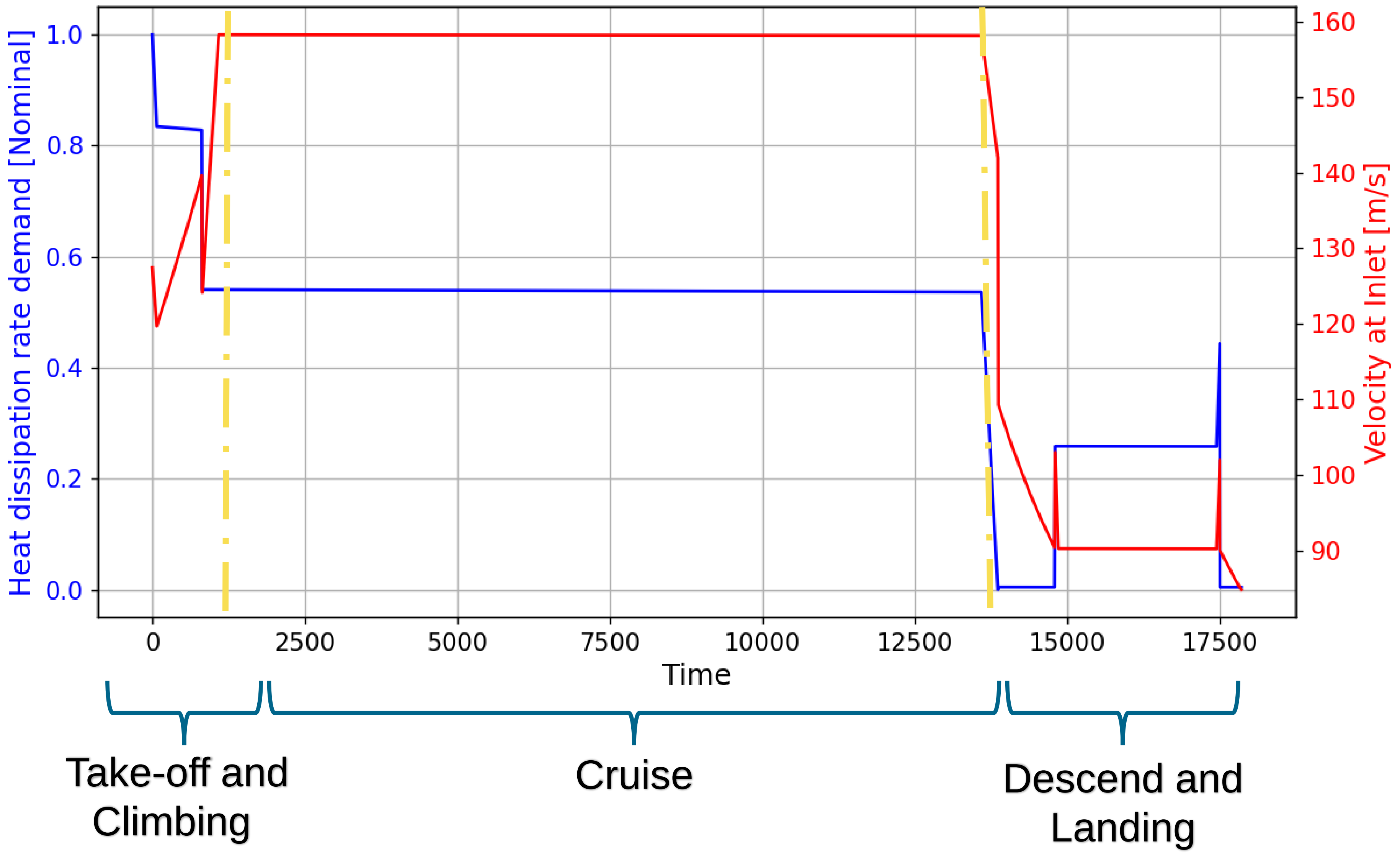


Figure 1: H2 Electra design model. [1]

[1] Stefanie de Graaf, Victor Bahrs, Noah Tarbah, and Stefan Kazula. H 2 electra – a platform for comparative analysis of integration concepts for hydrogen-based electric propulsion in regional aircraft. Journal of Physics: Conference Series, 2716(1):012007, 2024.

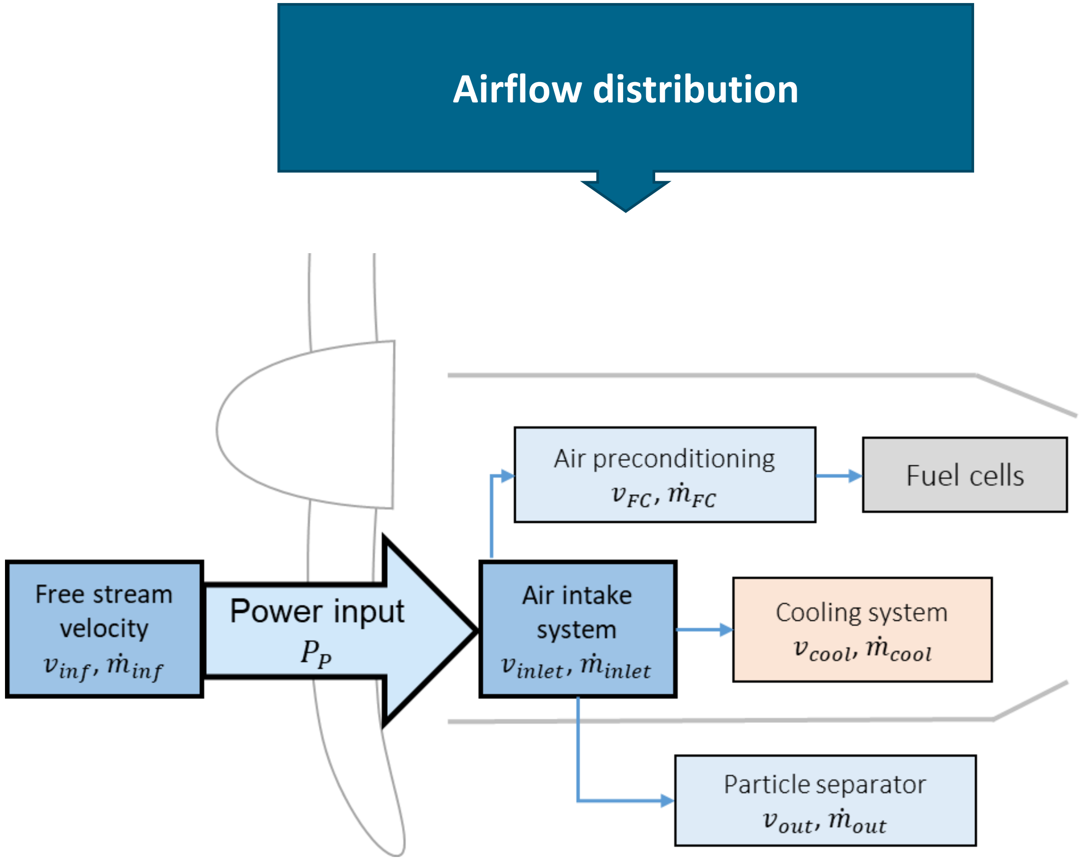
1. Introduction

3. H2 Electra flight mission profile



2. Literature Review

1. Flow characteristics in nacelles



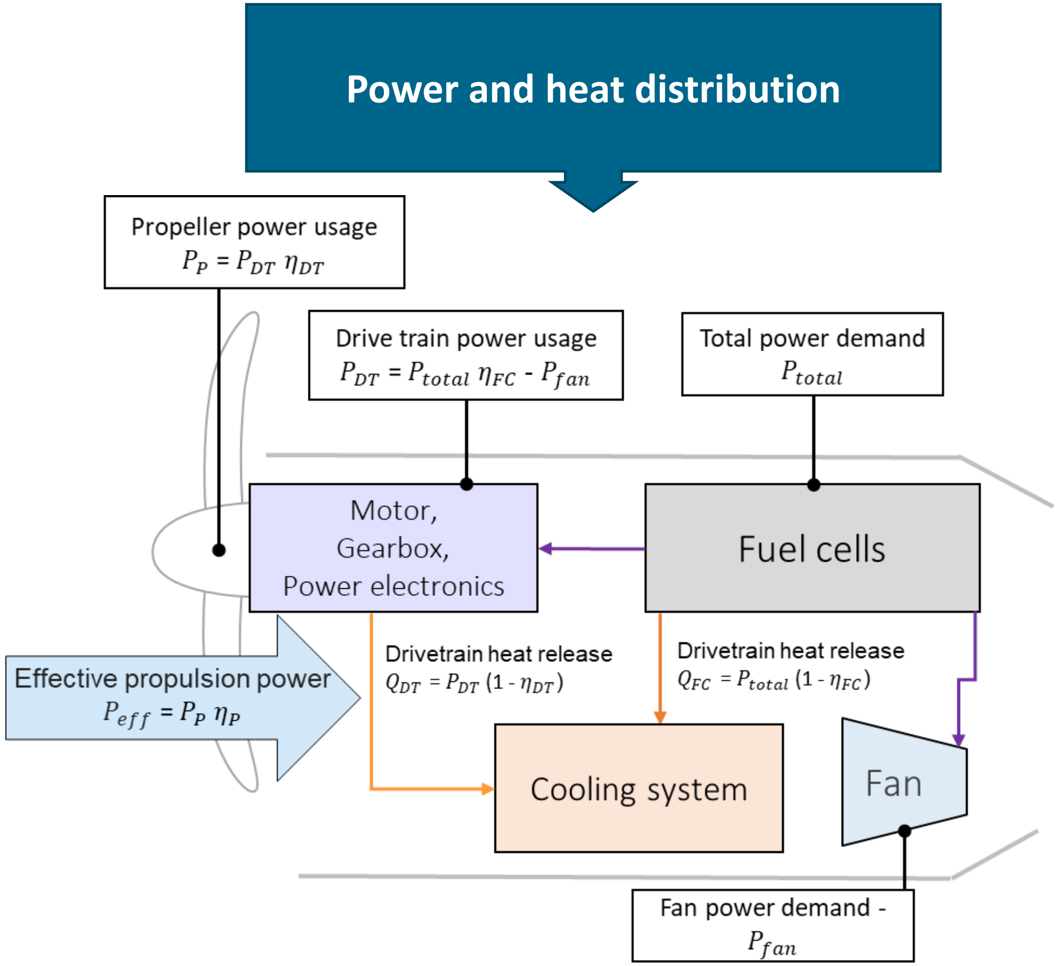


Figure 2: Ariflow and energy distribution throughout the nacelle.

2. Literature Review

1. Flow characteristics in nacelles

- Desirable flow characteristics to reach the heat exchanger:
  - Flow uniformity.
  - Mass flow rate control.
  - Adequate temperature.
  - Low level of particles.

$$Q = \dot{m} c_p \Delta T,$$

Equation 1: Heat dissipation rate for heat exchanger

$$D_{\mathrm{HX}} = \zeta \cdot \frac{\dot{m}^2}{2\rho A_{\mathrm{HX}}}$$

Equation 2: Drag associated to heat exchanger

1. Flow characteristics in nacelles

- Stablish flow characteristics in Nacelle.
- Particle separators and Y-shape ducts.
- Curvature and S-shape ducts.

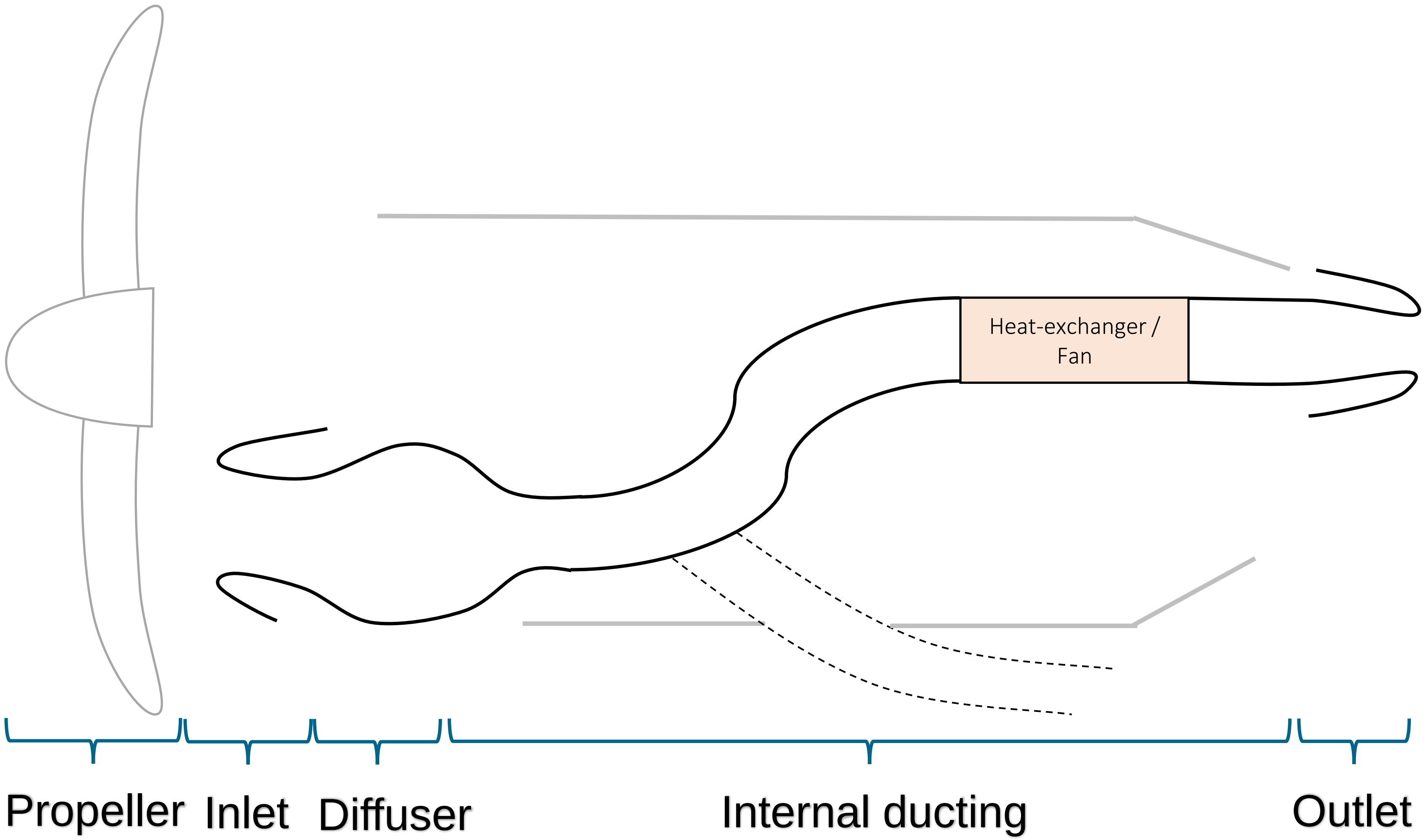


Figure 3: Different aerodynamic sections of nacelle.

2. Literature Review

2. Influence of inlets and outlets on nacelle performance

- Inlets: Lip thickness control for flow detachment
- Outlets (nozzles): Effects in back pressure control and mass flow rate

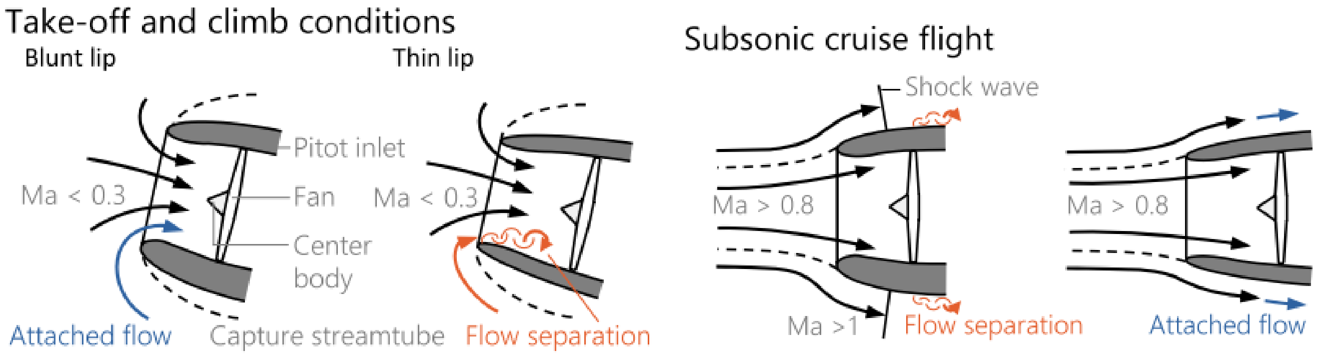


Figure 4: Inlet shape sensitivity to flow detachment. [2]

C_{pe} – pressure coefficient at the inlet lip/edge
k – Empirical factor
V_∞, A_∞ – Capture velocity and area
V_f, A_f – Velocity and area at the point of maximum cross sectional area,
V_e, A_e – Exit velocity and area

$$V_\infty A_\infty = V_e A_e = V_f A_f,$$

$$\frac{A_\infty}{A_e} = \sqrt{\frac{1 - C_{pe}}{1 + k\,(A_e/A_f)^2}},$$

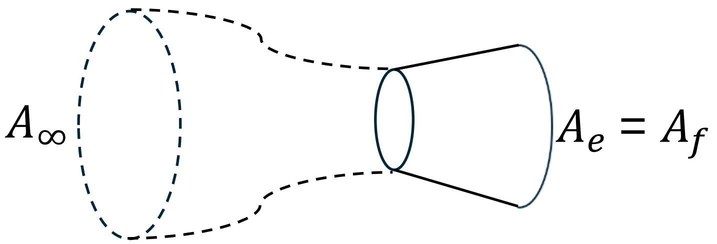


Figure 5: Airflow thourgh a duct, geometrical relations.

[2] S. Kazula and K. Höschler. Review of variable leading-edge patents for aircraft wings and engine inlets and their relevance for variable pitot inlets in future supersonic transport. CEAS Aeronautical Journal, 12(3):685–700, 2021. ISSN: 1869-5582. DOI: 10.1007/s13272-021-00520-y

3. Methodology

1. Geometrical model design

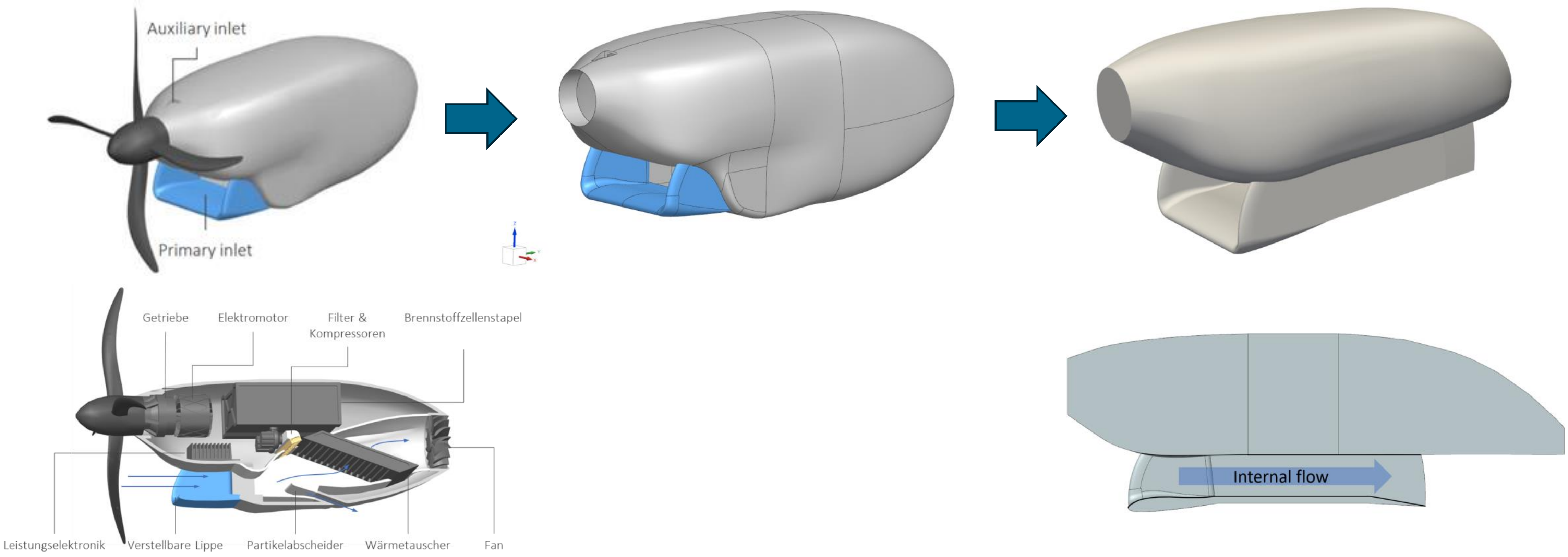


Figure 6: Geometrical development process. [3]

[3] D. Hintermayr and S. Kazula. Design and analysis of the air inlet system for fuel cell-powered electric propulsion systems in regional aircraft. DOI: 10.25967/610194.

3. Methodology

1. Geometrical model design

- Inlet lip variation sensitive to stall.
- Oultet (nozzle) angle and AR: low sensitivity to flow detachment.

Conf.	$\alpha_{lip,in.}$	$\alpha_{lip,out.}$	AR
Open	6°	10°	1.14
Closed	-7°	-4°	0.89

Table 1: Geometrical characteristics of the two configurations.

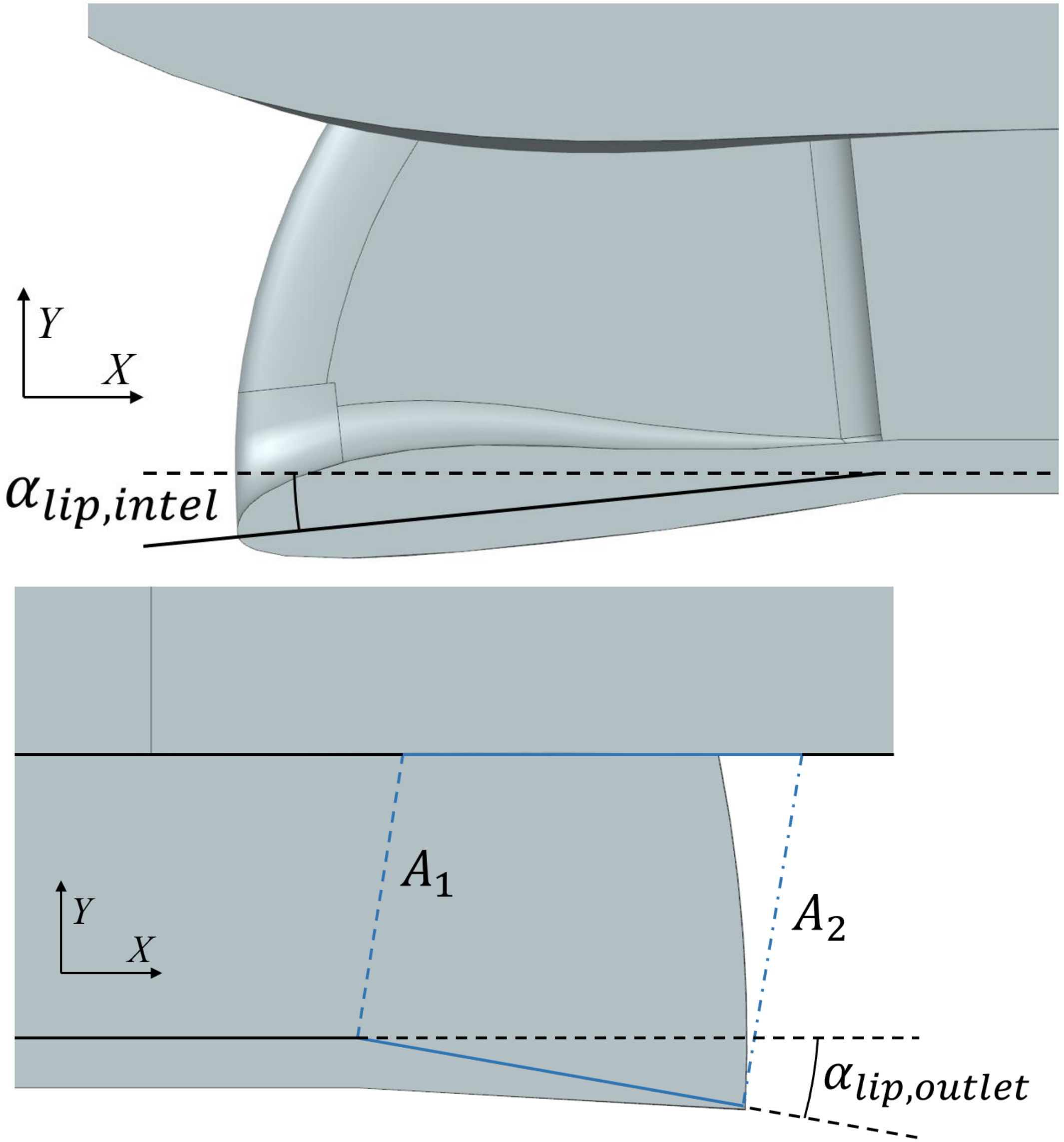


Figure 7 and 8: The upper image shows the geometrical characterization of the inlet lip, while the lower image depicts the outlet (nozzle).

3. Methodology

2. Propeller implementation through Actuator Line Method

- Based on Blade Element Theory to extract local forces.

- Forces projected with a Gaussan function.

$$F_l = \frac{1}{2}\rho A_{\text{elem}} C_l |\vec{U}_{\text{rel}}|^2,$$

$$F_d = \frac{1}{2}\rho A_{\text{elem}} C_d |\vec{U}_{\text{rel}}|^2,$$

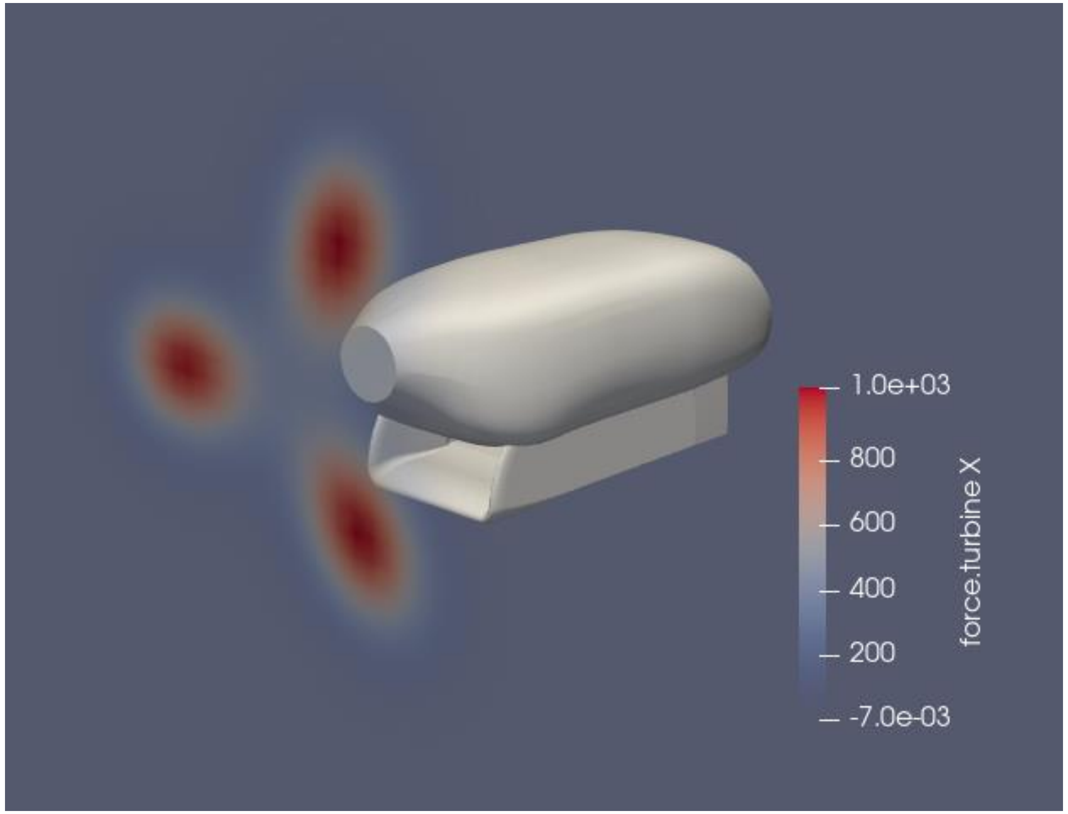


Figure 9: Acuator Line Method distribution in computational domain

3. Methodology

3. Simulation setup and cases

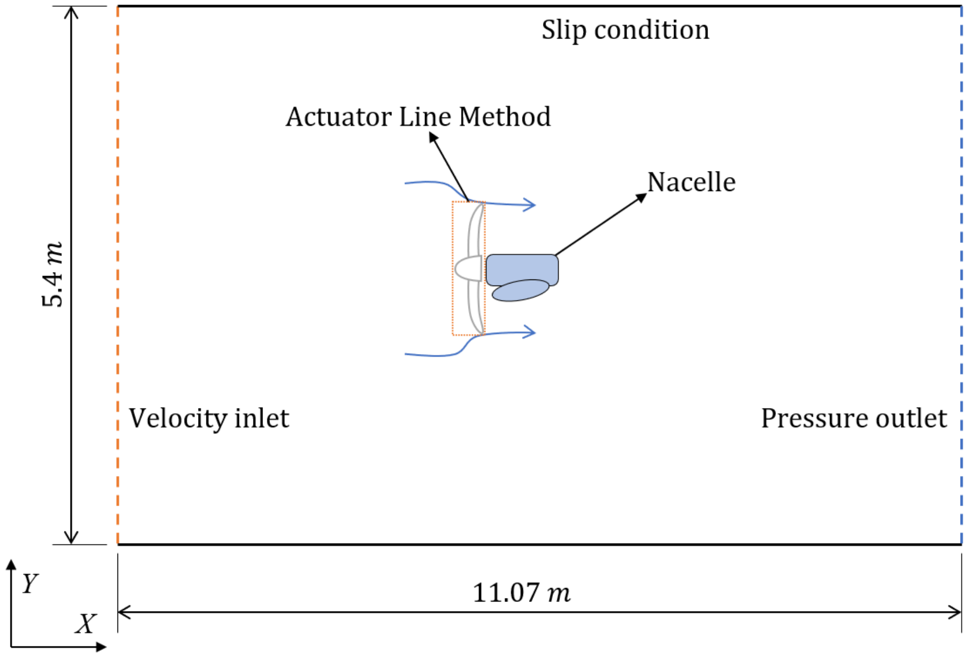


Figure 10: Visual representation of computational domain

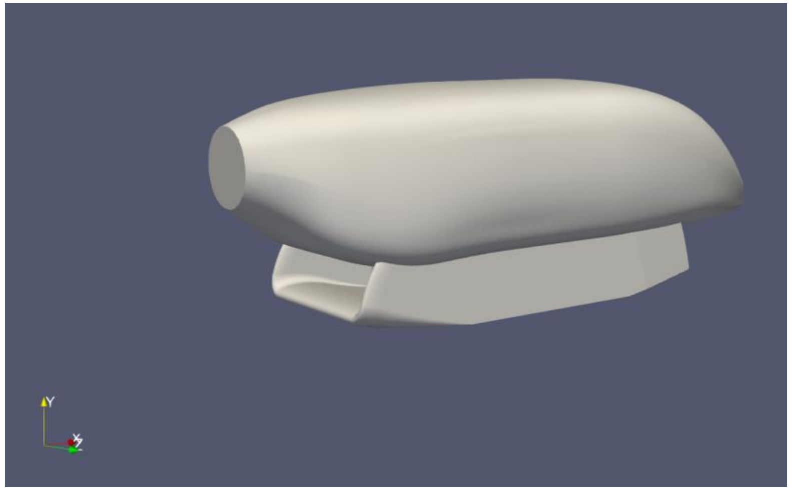


Figure 11: Closed geometrical configuration

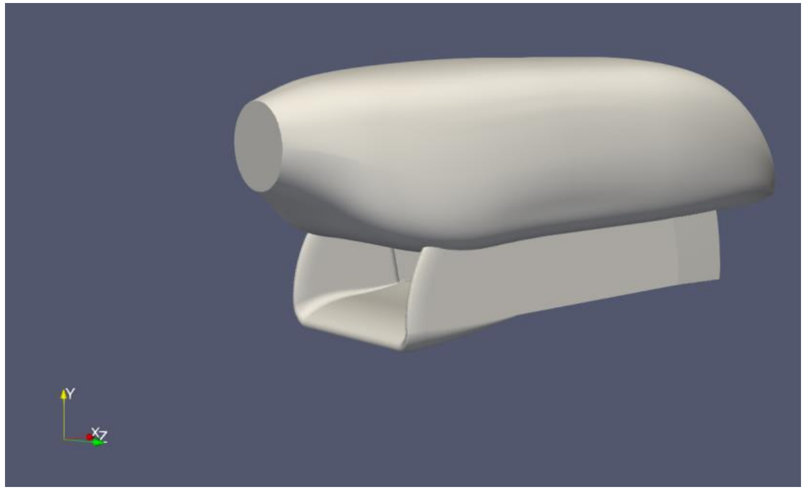


Figure 12: Open geometrical configuration

3. Methodology

4. Validation results

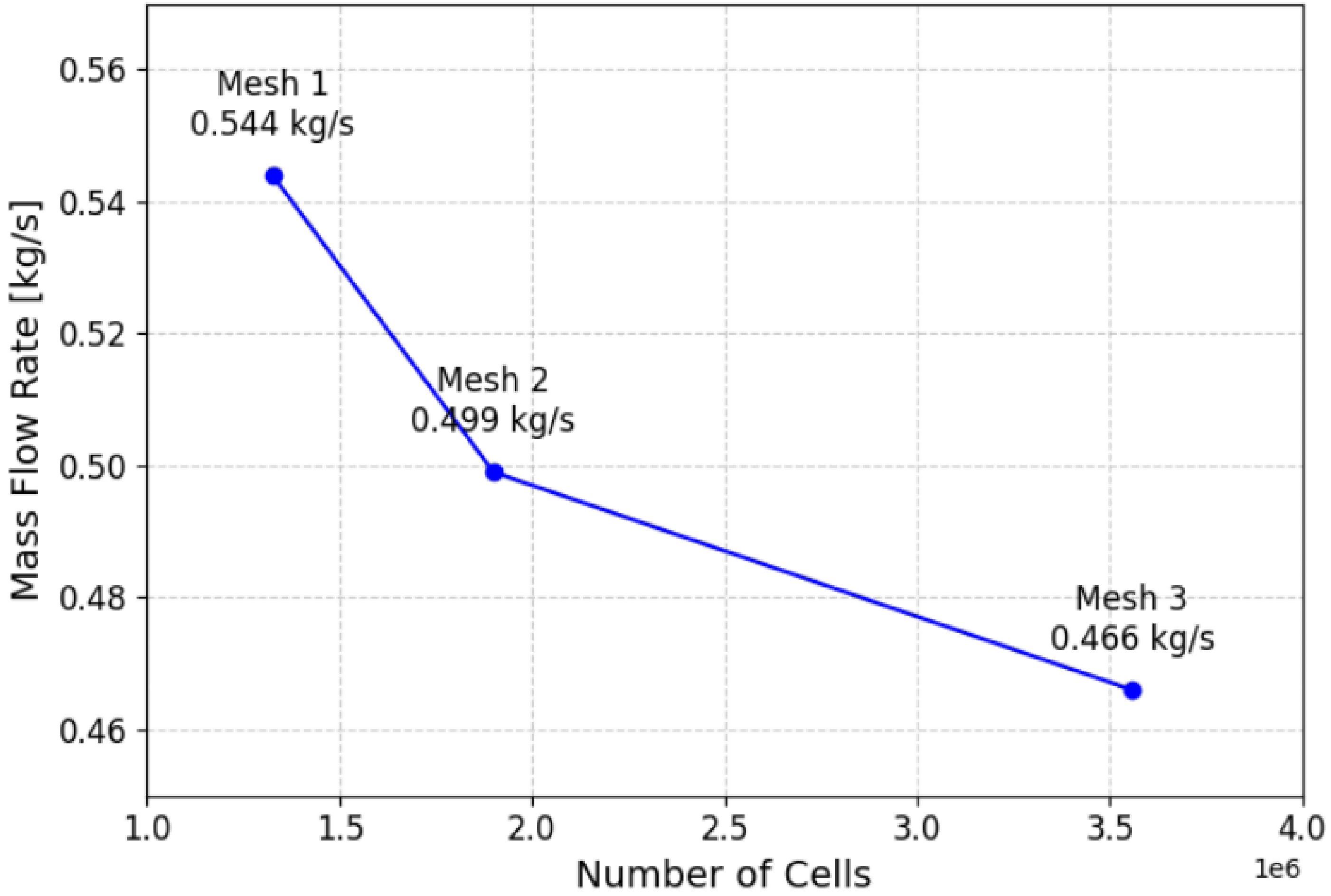


Figure 13: Mesh sensitivity study. Average mass flow rate of the internal duct against number of cells.

3. Methodology

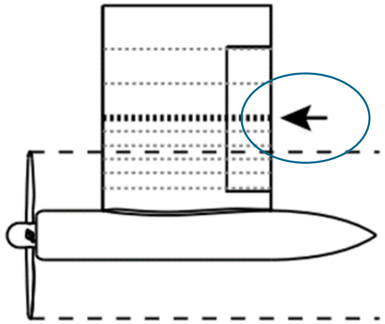
4. Validation results

- Validation with experimental case.

  - Laminar:
    Execution time = 88,308.08 s

  - U-RANS:
    Execution time = 150,096.07 s

  - LES:
    Execution time = 174,075.26 s



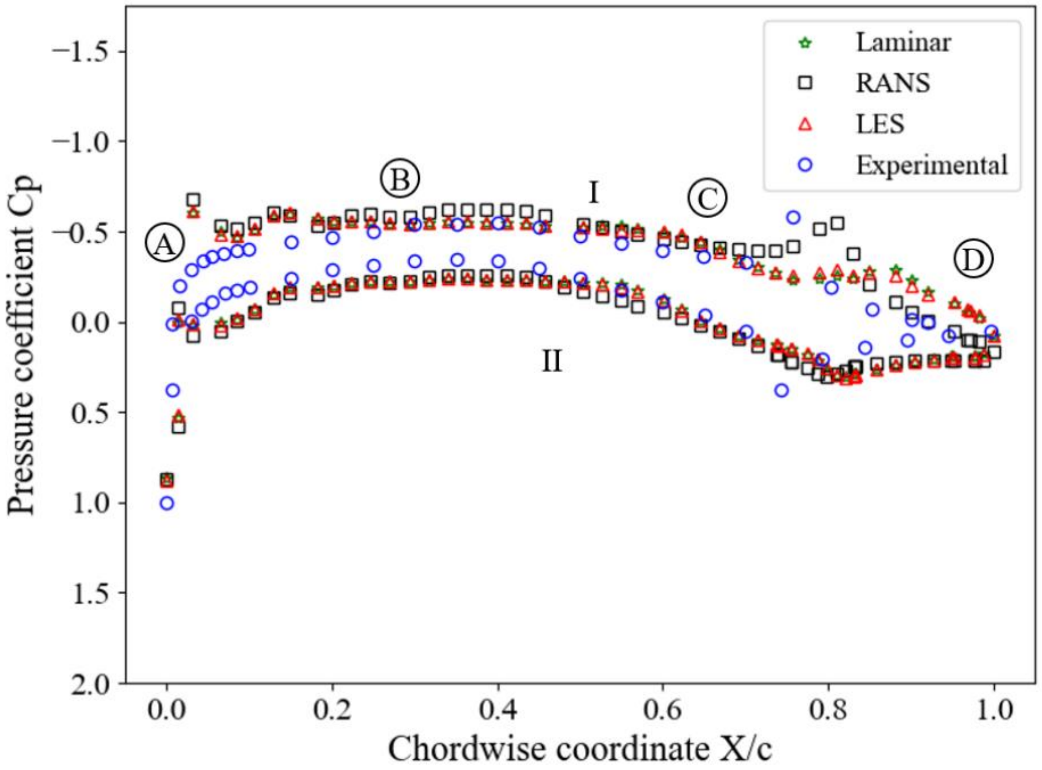


Figure 14: Validation case representation. Pressure coefficient distribution over the surface outside of the propeller slipstream. Nomenclature: I. Suction side. II. Pressure side. [4]

[4] Tomas Sinnige, Nando van Arnhem, Tom C. A. Stokkermans, Georg Eitelberg, and Leo L. M. Veldhuis. Wingtip-mounted propellers: Aerodynamic analysis of interaction effects and comparison with conventional layout. Journal of Aircraft, 56(1):295–312, 2019.

4. Results and Discussion

1. Flow field characteristics

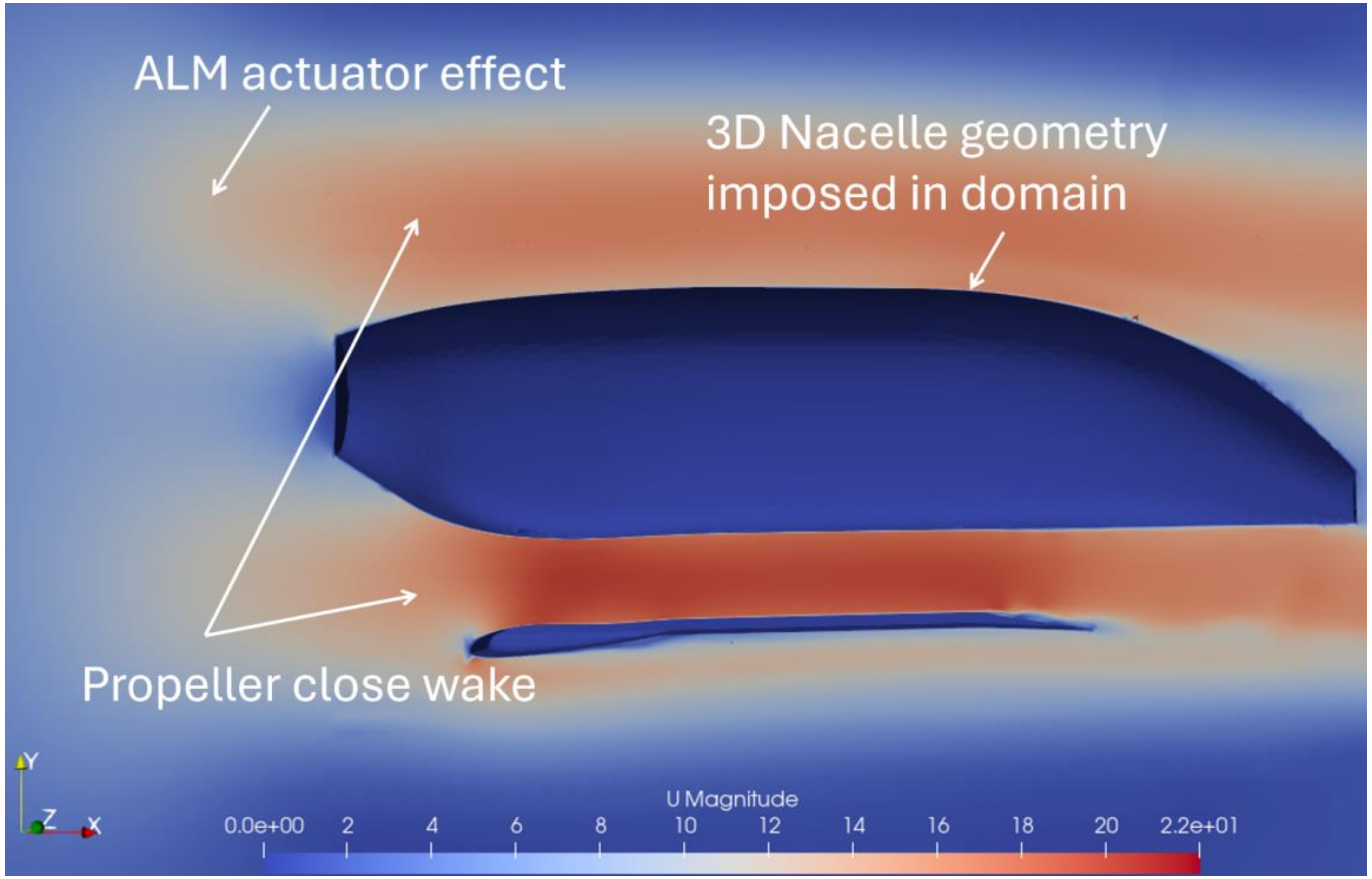


Figure 15: Visual representation of absolute velocity distribution in [m/s].

4. Results and Discussion

2. Comparison between cases

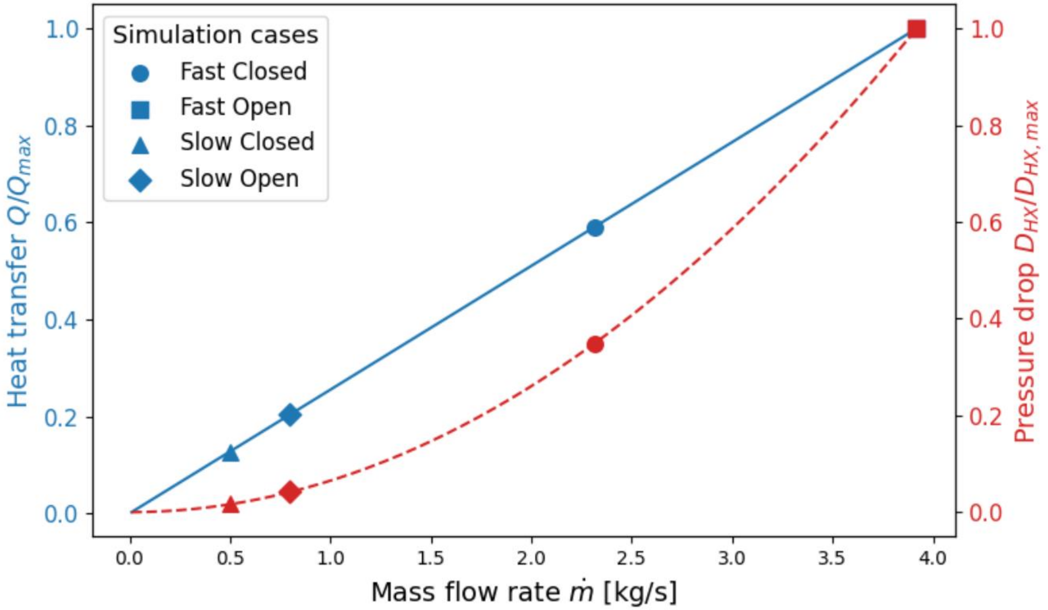


Figure 16:Heat transfer rate and theoretical heat exchanger drag as a function of mass flow rate through the internal duct. Values on the y-axis are normalized relative to the maximum obtained.

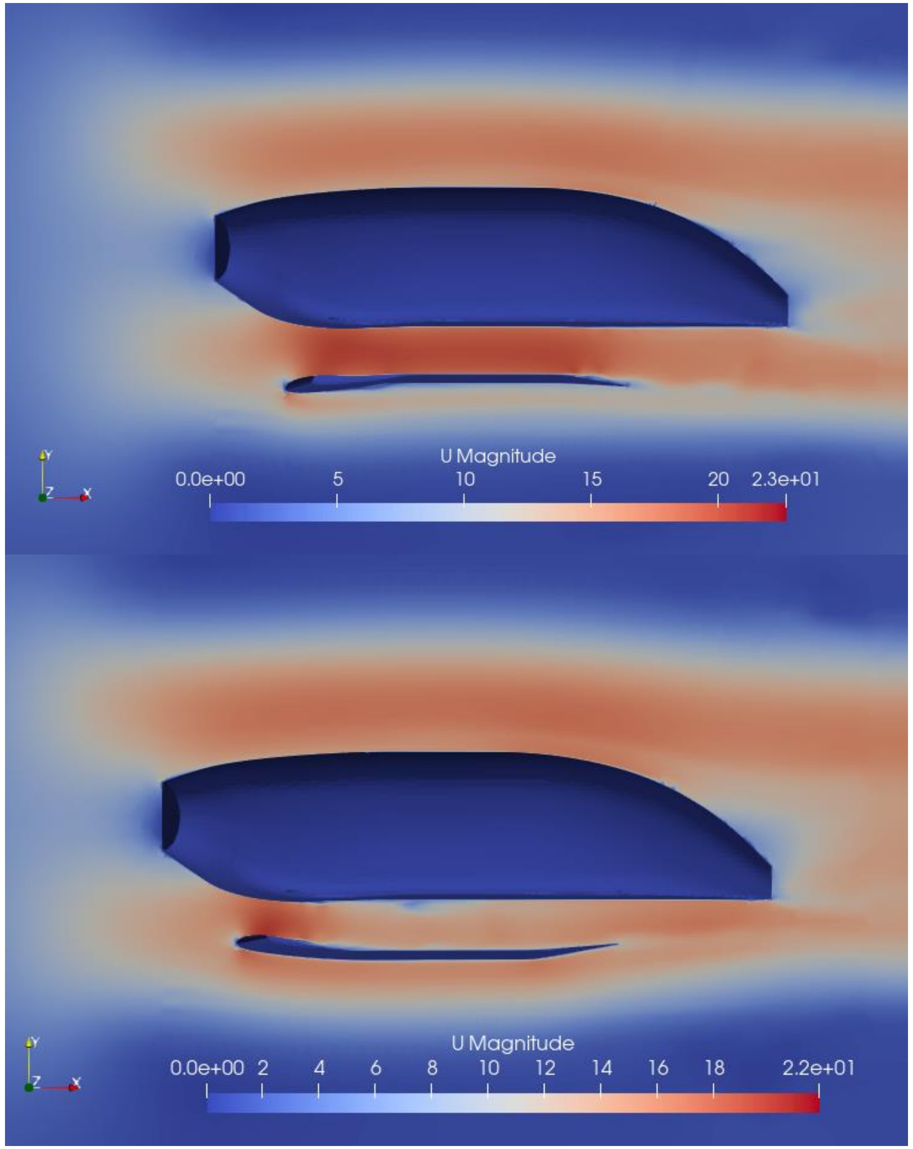


Figure 17: Visual representation of absolute velocity distribution in [m/s]. Upper case open set up and lower case closed set up.

3. Interpretation of results

Mass flow dependence on geometry

- Fast case: ~25% increase in outlet area → +69.4% mass flow.
- Slow case: ~25% increase in outlet area → +60.4% mass flow.
- High speed:
  - Open config. → 2.8× drag vs closed.
  - Heat transfer increase: +59%.
  - Conclusion: drag penalty outweighs benefit in cruise.
- Low speed:
  - Open config. → +65% heat dissipation vs closed.
  - Drag increase: negligible.

Conf.	$\alpha_{lip,in.}$	$\alpha_{lip,out.}$
Open	6°	10°
Closed	-7°	-4°

Conf.	**AR**	$\dot{m}_{fast}$	$\dot{m}_{slow}$
Open	1.14	3.918	0.7989
Closed	0.89	2.313	0.498

Table 2: Geometrical characteristics of the two configurations and results in mass flow rate [kg/s]

1. Summary, limitations of the study and future work.

- Improvements in the validation.

- Increase fidelity:
  - Add porous media
  - Work on mesh quality and resolution

- More cases:
  - Work with full developed design
  - Simulate with small variations in the angles

THANK YOU!

Questions?