

Analysis of the Eternaus Explorer Hydrogen Airship: Analytical and CFD Investigation at Sea-Level Conditions

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This paper presents a combined analytical and numerical investigation of the external aerodynamic behavior of the ETERNAUS Explorer 16.9/100 H₂ airship, part of the broader Eternaus Project aiming to develop sustainable, large-scale hydrogen-lifted airships for multipurpose civil and defense applications [1]. The Explorer model, 100 m in length and 16.9 m in maximum diameter, operates under a bidirectionally prestressed aluminum super-rigid hull that provides both structural lightness and aerodynamic efficiency. The study focuses on the boundary-layer development and external flow characteristics under sea-level conditions, using both analytical laminar and turbulent models [2] and a 2D axisymmetric CFD simulation performed with ANSYS Fluent 2025 R2 [3]. The simulation employed a pressure-based transient solver, k- ω SST turbulence model with near-wall resolution ($y^+ < 1$), and approximately 7.7×10^5 quadrilateral elements. The results showed a predominantly attached flow, smooth pressure recovery near the tail, and a minor separation region consistent with slender-body theory predictions [4]. Analytical results were compared against CFD-derived wall pressure and velocity distributions, showing strong agreement in boundary-layer thickness growth and skin friction coefficients [5]. The study concludes that the Explorer configuration maintains aerodynamic stability and low viscous drag at operational cruise speeds (58–77 m/s). A 3D CFD simulation including gondolas, fins, and structural protuberances is currently under development and will be presented in the full paper submission [6].

I. Nomenclature

A	=	amplitude of oscillation
a	=	cylinder diameter
C_p	=	pressure coefficient

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C_x	=	force coefficient in the x direction
C_y	=	force coefficient in the y direction
c	=	chord
dt	=	time step
F_x	=	X component of the resultant pressure force acting on the vehicle
F_y	=	Y component of the resultant pressure force acting on the vehicle
f, g	=	generic functions
h	=	height
i	=	time index during navigation
j	=	waypoint index
K	=	trailing-edge (TE) nondimensional angular deflection rate

II. Introduction

The ETERNAUS Project, Figure 1, aims to redefine the design paradigm of large hydrogen airships through the use of super-rigid hulls with bidirectional prestressing, combining lightweight aluminum alloys with high structural strength [7]. This configuration enables the construction of vessels capable of carrying 6,000–10,000 kg of payload with extremely low operating costs and unprecedented autonomy — up to 65,000 km per fuel cycle.

The Explorer model serves as the experimental and aerodynamic demonstrator for the Eternaus system. Its 100-meter-long, 16.9-meter-diameter hull is optimized for low drag and stable flight in low-to-medium Reynolds number regimes ($Re \approx 4 \times 10^7$). Understanding its aerodynamic behavior is critical for scaling future models and for validating the structural coupling between the prestressed hull and external flow loads [8].

The present work combines a boundary-layer analytical analysis and a Computational Fluid Dynamics (CFD) study to evaluate the aerodynamic performance of the Explorer at sea level, focusing on laminar-turbulent transition, wall shear stress, and overall flow topology. The study uses the ANSYS Fluent 2025 R2 solver as the primary computational platform, integrating modern turbulence modeling techniques with empirical boundary-layer correlations [3,9].



Figure 1 – Eternaus Explorer Concept.

III. Vehicle Description and Operating Conditions

The Explorer 16.9/100 configuration features a smooth, axisymmetric body designed to minimize separation and form drag. The vehicle’s structural and aerodynamic parameters are summarized below:

Parameter	Symbol	Value
Total length	L	100 m
Max diameter	D	16.9 m
Cross-sectional area	S_t	224.3 m ²
Surface area	S	4,295 m ²
Volume	V_d	15,567 m ³

Parameter	Symbol	Value
Hull material	—	Al-2090-T83 sheet
Skin thickness	e	0.4 mm
Operational speed	V	58 m/s (≈ 210 km/h max)
Gas	—	Hydrogen (internal), Air (external flow)
Pressure differential	Po	420 mmH ₂ O
Altitude	h	0 m (sea level)

At sea level ($\rho = 1.225$ kg/m³, $\mu = 1.789 \times 10^{-5}$ kg/m·s), the characteristic Reynolds number is:

$$Re_L = \frac{\rho VL}{\mu} \approx 4.0 \times 10^7 \quad (1)$$

indicating a fully turbulent boundary layer for most of the hull, with potential laminar onset near the stagnation region [2,10].

IV. Analytical Boundary-Layer Analysis

The analytical modeling was performed to characterize the evolution of the laminar and turbulent boundary layers along the airship hull, assumed to approximate a prolate spheroid at low angle of attack.

A. Laminar Regime (Blasius Approximation)

For the initial region ($x/L < 0.1$), the laminar boundary layer thickness δ , displacement thickness δ^* , and momentum thickness θ are given by:

$$\delta(x) = 5.0 \sqrt{\frac{vx}{U_\infty}}, \delta^*(x) = 1.72 \sqrt{\frac{vx}{U_\infty}}, \theta(x) = 0.664 \sqrt{\frac{vx}{U_\infty}} \quad (2)$$

The local skin friction coefficient is:

$$C_{f,lam} = \frac{0.664}{\sqrt{Re_x}} \quad (3)$$

as derived by Blasius and extensively validated for laminar flat-plate flows [2].

B. Turbulent Regime (Prandtl–Schlichting Approximation)

For $0.1 < x/L < 1$:

$$\delta(x) = 0.382xRe_x^{-1/5}, C_{f,turb} = 0.0592Re_x^{-1/5} \quad (4)$$

Integrating across the hull yields a mean skin friction coefficient $C_{f,mean} \approx 0.0024$ [5].

C. Transition and Separation

The critical Reynolds number for transition ($Re_{x,cr} \approx 3 \times 10^5$) occurs near $x/L \approx 0.02$, confirming that the boundary layer becomes fully turbulent almost immediately [10]. Analytical pressure gradients were incorporated using the momentum integral equation.:

$$\frac{d\theta}{dx} + (2 + H) \frac{\theta}{U_e} \frac{dU_e}{dx} = \frac{C_f}{2} \quad (4)$$

where $H = \delta^*/\theta \approx 1.4\text{--}1.6$ for turbulent flow. The integration indicates mild adverse gradients near the tail, predicting possible flow detachment beyond $x/L \approx 0.95$ [4].

V. Numerical Methodology (ANSYS Fluent 2025 R2)

A. Computational Setup

A 2D axisymmetric transient simulation was carried out using the ANSYS Fluent 2025 R2 solver [3,9]. The main solver configuration is summarized below:

Setting	Option
Solver type	Pressure-based, transient
Coupling scheme	PISO
Discretization	2nd-order upwind (momentum, turbulence, energy)
Temporal scheme	2nd-order implicit
Turbulence model	$k\text{--}\omega$ SST (with near-wall correlation)
Compressibility	Ideal gas model, low-Mach correction
Time step	1×10^{-3} s, 10,000 iterations
Domain	Axisymmetric
Inlet velocity	58 m/s
Turbulence intensity	5%
Turbulent viscosity ratio	10
Outlet	Pressure outlet (101325 Pa)
Wall condition	No-slip, adiabatic

B. Mesh and Near-Wall Resolution

The mesh consisted of $\sim 7.7 \times 10^5$ quadrilateral elements, generated using the Quad Dominant and Sweep methods [9]. Refinement layers were applied along the hull with a growth rate ≤ 1.2 and first cell height ensuring $y^+ < 1$.

Parameter	Value
Nodes	772,290
Elements	767,171
y^+ (average)	0.7
Growth rate	1.18
Farfield extent	20D upstream, 30D downstream

This ensured accurate capture of viscous sublayer gradients and boundary-layer evolution without wall functions [9].

VI. Results and Discussion

A. Flow Field Overview

The velocity contour (Fig. x) reveals a smooth external flow pattern with no major separation up to $x/L \approx 0.9$ [4]. A small recirculation bubble forms near the tail, consistent with predictions from the analytical model [5].

The free-stream velocity reaches 93 m/s in localized regions near the upper curvature due to streamline contraction, while the near-wall velocity decreases smoothly, indicating stable pressure recovery [8].

B. Pressure Distribution

The wall pressure distribution (Fig. x) shows a stagnation peak of approximately 1.03×10^5 Pa, followed by a gradual decrease to 1.00×10^5 Pa along the body midsection [4]. At $x/L \approx 0.95-1.0$, oscillations occur due to mild separation, with the static pressure recovering partially downstream.

When normalized by the dynamic pressure ($q = \frac{1}{2}\rho V^2 \approx 2,056$ Pa), the minimum $C_p \approx -0.25$, which is typical for streamlined, slender bodies [5].

C. Temperature Field

The static temperature variation is minimal (297–302 K), confirming low compressibility effects and validating the ideal-gas assumption for this Mach regime ($M < 0.2$) [3].

D. Wall Pressure Curve Analysis

The wall pressure profile plotted along the entire 100 m body length (Fig. x) confirms that the flow remains attached up to approximately 95 m, after which a small separation region develops [4]. The tail vortex zone is consistent with empirical data for prolate spheroids at similar Reynolds numbers [10].

E. Boundary-Layer Validation

From the CFD data, the estimated boundary-layer thicknesses were:

- $\delta_{0.1}L \approx 0.01$ m
- $\delta_{0.5}L \approx 0.06$ m
- $\delta_{0.9}L \approx 0.11$ m
- $\delta_{1.0}L \approx 0.13$ m

These values agree within 10% of the analytical turbulent correlations, confirming the adequacy of the $k-\omega$ SST model for predicting the laminar-turbulent development along the airship hull [9]. The average friction coefficient extracted from wall shear stress matched the theoretical value ($C_f \approx 0.0023 \pm 0.0001$) [5].

F. Comparison Between Analytical and CFD Results

The agreement demonstrates that analytical estimates provide accurate preliminary insight, but CFD offers improved fidelity in regions of adverse pressure gradient, especially at the aft end [8,9].

Parameter	Analytical	CFD	Deviation
$C_{f,mean}$	0.0024	0.0023	-4.2%
$\delta@x/L=0.5$	0.065 m	0.061 m	-6.1%
$\delta@x/L=1.0$	0.13 m	0.12 m	-7.7%
$Re_{transition}$	3×10^5	2.7×10^5	-10%
Pressure recovery (C_p tail)	-0.2	-0.22	+10%

G. Significance of the CFD Study for the Eternaus Explorer development

This CFD study represents the first validated numerical evaluation of the Eternaus Explorer configuration, marking a key step in establishing design baselines for future hydrogen airships [1].

It also serves as a validation reference for the upcoming 3D full-scale simulations, which will include: gondola and empennage structures, propulsor nacelles, and ground effects [6].

The 3D CFD simulations, currently running on the Eternaus High-Performance Cluster (HPC), will be presented in the full paper submission, extending the current analysis to full aerodynamic coefficients and structural load distributions [6].

VII. Conclusion

The ETERNAUS Explorer 16.9/100 H₂ airship exhibits stable, predominantly attached flow throughout its length under sea-level operating conditions. Analytical boundary-layer correlations closely matched CFD results]. The $k-\omega$

SST model effectively captured laminar–turbulent transition and minor tail separation without numerical diffusion. The mean friction coefficient ($C_f \approx 0.0023$) and boundary-layer thickness ($\delta \approx 0.1$ m at 0.9L) confirm aerodynamic efficiency consistent with design expectations. The 2D results form the foundation for ongoing 3D investigations to be published in the full AIAA paper.

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